Technical Report

TR-10-01

The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp

SR-Site Biosphere

Anders Löfgren (Editor)
EcoAnalytica

December 2010

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

ISSN 1404-0344
SKB TR-10-01
ID 1272152
Updated 2013-01

The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp

SR-Site Biosphere

Anders Löfgren (Editor)
EcoAnalytica

December 2010

Keywords: Ecosystem, Ecology, Ecosystem modelling, Fauna, Future development, Interaction matrix, Land use, Mass balances, Radionuclide model parameterisation, Vegetation.

Update notice

The original report, dated December 2010, was found to contain editorial errors which have been corrected in this updated version.

Summary

Generally, elements are transported and accumulated in ecosystems to a different extent, depending on the properties of the element and the context it experiences. This report describes the terrestrial ecosystems in the Forsmark and Laxemar-Simpevarp areas by summarizing ecological data and data from disciplines such as hydrology, Quaternary geology and chemistry. The description therefore includes a number of different processes that drive element fluxes in the ecosystems, such as net primary production, heterotrophic respiration, transpiration, and horizontal transport from land to streams and lakes. Moreover, the human appropriation of the landscape is described with regard to land use and potential and actual utilization of food resources both today and in a historical perspective.

Wetlands occur frequently in Forsmark and cover 10–20% of the area, whereas wetlands are less frequent in the Laxemar-Simpevarp area, covering only approximately 3% of the main catchment. The main portion consists of open wetlands. A major difference between the sites is the great calcareous influence on the wetlands in Forsmark, resulting in a rich fen vegetation characteristic of this region. The Laxemar-Simpevarp wetlands have a lower pH and are often dominated by *sphagnum* species. The agricultural land is a major provider of food for humans and is less abundant in the Forsmark area (4%) compared with the Laxemar-Simpevarp area (8%). Production in both areas is dominated by fodder and grass for domestic animals and only around 10% of the agricultural land is used for crops. Clayey till dominates in Forsmark, whereas gyttja clay dominates in the Laxemar-Simpevarp area. At the latter site, arable land is situated in valleys that in many cases are former wetlands, which can be seen as a thin peat layer in many of the arable land areas. Forest land covers 73% and 86% of the area in Forsmark and Laxemar-Simpevarp, respectively, and consists mainly of coniferous forests. The forests feature moister conditions in Forsmark, whereas drier areas and outcrops are more abundant in the Laxemar-Simpevarp area. The calcareous soil provides nutrient-rich conditions, making herbs and broad-leaved grasses abundant in the field layer of the forests of Forsmark. The results of both modelling and the national forest inventory in the region suggest that a number of ecosystem properties are of a similar magnitude such as Net Primary Production (NPP), biomass etc. Generally, the higher latitude of Forsmark would suggest a lower NPP. However, these properties are also dependent on factors such as nutrients, moisture and the age of the forest. The later factor is mainly affected by the forestry management practices applied in the two areas.

Extensive inventories of mammals conclude that the moose populations are of similar size, whereas roe deer have higher densities in Forsmark. Lynx have recently become established in the Forsmark area, whereas red deer, fallow deer and wild boar have become established in the Laxemar-Simpevarp area. Domestic animals have a markedly higher biomass per unit area than free-living animals. However, their spatial distribution is very limited and concentrated to agricultural areas (area for seed production excluded), which are sparse in both the Forsmark and Laxemar-Simpevarp areas.

The yields of six different species of berries and fungi (0.091 gC m^{-2} y^{-1}) were estimated for both sites. Present-day picking and consumption of berries is less than 5% of the yield, but may vary depending on different circumstances. Hunting of moose and roe deer is on similar scale at both sites, approximately 0.5 and 2 individuals km^{-2} for roe deer and moose, respectively.

A conceptual description of terrestrial ecosystems is presented. It consists primarily of descriptions of pools and fluxes of organic matter, but also serves as a conceptual approach for describing pools and fluxes of other elements present in the ecosystems, which are explored from a mass balance perspective.

Detailed descriptions of pools and fluxes of carbon for three localities at each site were undertaken with the aim of describing some dominant and poorly described ecosystems. The vegetation types were two Norway spruce forests of different ages, one alder swamp forest, one oak forest, one alder shore forest and one planted Norway spruce forest on previously drained wetland. Generally, the estimated pools and fluxes from the six localities in Forsmark and Simpevarp were in agreement with similar studies, where available. NPP was estimated to be between 360 and 736 gC m^{-2} y^{-1} for the different forest types at the two sites, where the alder shore forest in the Laxemar-Simpevarp area had the lowest NPP and the Norway spruce forest on drained organic soils in the Laxemar-

Simpevarp area had the highest NPP. All sites seem to have been carbon sinks during the period of the measurements (142–311 gCm^{-2} y^{-1}), except for the oak forest and the alder shore forest, which were close to zero. Nevertheless, the estimates presented here, both single estimates of pools and fluxes and ecosystem emergent properties, are well within expected ranges.

A dynamic vegetation model, LPJ-GUESS, was used to estimate pools and fluxes of carbon for 12 different vegetation types at each site using the local climate as the driving variable. These results were compared with site estimates and literature data. Values were in the upper range of those for boreal forests but not unrealistic in comparison with field data and literature values. The results from this model were also combined with remote sensing data in order to study the variation in NPP of the tree layer. Moreover, the temporal dynamics of a number of ecosystem properties were studied for a forest at both sites during a period of 400 years. Data were also extracted for a 100-year period in order to obtain the mean values of e.g. NPP, biomass and soil organic carbon accumulation, which would approximate a forest cycle under forestry management.

Carbon pools and fluxes, which are used as a proxy for organic matter, were described on the scale of the catchment. The rationale for using the catchment scale is that transport of elements is mediated by water and the catchment will set the boundary for further transport and accumulation. The carbon estimates were based on a combination of field and model estimates of pools and fluxes across a landscape mosaic of different vegetation types and management regimes using a geographical information system (GIS). This modelling exercise showed a net biomass gain of 139 gC m^{-2} y^{-1} and a net carbon accumulation of 79 gC m^{-2} y^{-1} in the soil organic carbon (SOC) pool summed over all catchments for Forsmark. The corresponding figures for Laxemar-Simpevarp were a net biomass loss of –66 gC m^{-2} y^{-1} and an accumulation of 174 gC m^{-2} y^{-1} in the soil organic carbon pool. The flux of carbon from autotrophs to herbivores is close to 1% of the autotrophic production in Forsmark but nearly 5% in Laxemar-Simpevarp. This difference is due to the higher abundance of livestock in Laxemar-Simpevarp, and if these are excluded the consumption is close to 0.5% at both sites. The most important herbivore as regards consumption and production (except for livestock) is roe deer, closely followed by moose in Forsmark, whereas the opposite is true in Laxemar-Simpevarp. Some vegetation types are regarded as more important for long term accumulation of matter. For example, vegetation types periodically inundated by water have a higher accumulation of matter, leading to peat formation, than other terrestrial vegetation types. These vegetation types cover a larger area in Forsmark than in Laxemar-Simpevarp. Similarly, some catchments are more important than others with regard to accumulation of organic matter, depending on their composition. Catchments dominated by younger forests will have a higher potential for assimilating bioavailable radionuclides today than catchments with a large proportion of clear-cuts.

Human appropriation of the landscape was described and analyzed using three different cases: a regional generic case, a self-sustainable case and a case where all potential arable land was used for agriculture. The three case studies of human utilization of food production (crops, meat and milk) showed that production today is far less than the potential production with regard to organic matter. Estimated food production in Forsmark based on regional statistics was only 0.8% of the potential production if arable land is only used for growing crops. The corresponding figure for Laxemar-Simpevarp was 15%, suggesting a higher utilization of the potential resources in that area.

The distribution of 62 different elements among the four compartments mineral soil, humus layer, producers and consumers showed consistent patterns between the sites. Most of the elements found in high content in the vegetation were nutrients. The nutrients are found in the non-metal and metal groups. Many of the other elements found in the vegetation behave analogously to nutrients and are therefore found in the same places. Other elements seem to be restricted to the fine roots, such as U, Cd and Hg. Generally, small amounts were found in the consumer pool. The mass balances of four elements illustrated some different patterns, where the water-soluble micronutrient iodine was to a large extent incorporated into the vegetation and transported further downstream into the lakes. The distribution of the macronutrient phosphorus was similar, but only a small quantity was transported from the terrestrial areas. The mass balance suggested a large retention of phosphorus at the catchment level, of which a large fraction was retained in the vegetation. Thorium and uranium had their largest pools in the mineral soil and to a lesser extent in the humus layer. They showed a less mobile pattern with low amounts found in the vegetation or transported downstream.

The long-term development of the terrestrial landscape in Forsmark and Laxemar-Simpevarp is driven mainly by two factors: shoreline displacement and climate change. Both have affected Forsmark and Laxemar-Simpevarp since the last deglaciation and are still causing a relatively predictable change in the abiotic and biotic environment. In the calculation of dose to humans and non-human biota the focus is on areas that may receive discharge of deep groundwater, which are wetlands and agricultural land originating from drained peatlands in the terrestrial landscape. From this perspective it is important to be able to identify boundaries for important properties such as biomass and NPP and accumulation of organic matter. How these ecosystem properties may change over long periods of time is exemplified with results from dynamic modelling, from comparisons of ecosystem properties over present-day climate gradients i.e. a "substituting time for space"-approach and from paleoecological reconstructions e.g. peat accumulation. A third more short-term factor is human land use, which to a large extent is determined by cultural and socioeconomic factors.

An interaction matrix, describing interactions between different components within ecosystems, is used to illustrate how important processes for the transport and/or accumulation of radionuclides are included in the radionuclide model. The overall conclusion from this exercise is that all important processes identified with the interaction matrix are also considered in the radionuclide modelling.

In the radionuclide modelling, a number of parameters are associated to processes in terrestrial ecosystems and the derivation of these parameter values is described. Additional parameter values for periglacial and global warming climate conditions are also presented for supporting calculations and as a basis for further discussion of their effects on the modelling results.

Contents

1 Introduction

This report is a compilation of previously reported data and new data aimed at describing the terrestrial ecosystems at Forsmark and Laxemar-Simpevarp, the two potential sites for a deep repository of spent nuclear fuel. This report was published in an earlier version /Löfgren 2008/, which now has been extended with Chapter 11 to 13, some minor updates and corrections. Several authors have provided the original texts for this report:

Eva Andersson, Studsvik Nuclear AB. Chapter 12.

Karin Aquilonius, Studsvik Nuclear AB. Chapter 12.

Anna Hedenström, SGU. Sections describing Quaternary geology in Chapter 3, 4 and 10, and the descriptions of regolith parameters for Forsmark presented in Chapter 13.

Anders Löfgren, EcoAnalytica. Chapter 1–2, 5, 6, 8, 9, 11, 13, 14 and parts describing vegetation in Chapter 3, 4 and 10. Coordinating and editing text.

Sofia Miliander, Vattenfall Power Consultants. Chapter 4, the sections describing fauna and land use for agriculture land and forests. Chapter 8, calculations for fauna and human consumption.

Jens-Ove Näslund, SKB, has reviewed and added text to sections describing climate in Chapter 11.

Lotta Rubio Lind, SKB. Chapter 4, the sections describing biomass and production estimates of birds, and berry and fungi yield.

Gustav Sohlenius, SGU. Sections describing Quaternary geology in Chapter 3, 4 and 10, and the descriptions of regolith parameters for Laxemar-Simpevarp presented in Chapter 13.

Karolina Stark, Department of Systems Ecology, Stockholm University. Sections describing wetlands, 4.1.1 and 10.4.1.

Johan Stendahl, Department of Forest Soils, SLU Uppsala. Section 10.2.

Torbern Tagesson, Department of Physical Geography and Ecosystems Analysis, Lund University. Chapter 7.

Kent Werner, Emptec, and Per-Olof Johansson, Artesia Grundvattenkonsult AB. Sections describing climate and surface hydrology.

Many improvements on earlier versions of this report were suggested by: Regina Lindborg (Department of Systems Ecology, Stockholm University), Mike C. Thorne (Mike Thorne Ltd), Tryggve Persson (Department of Ecology, SLU Uppsala, Chapters 5–8), Angelica Lorentzon (SKB, Chapters 1–5 and 10), Björn Söderbäck (SKB, Chapter 10 and 11), Johan Truvé (Svensk Naturförvaltning AB, Section 4.2), Anders Clarhäll (Chapter 11). Eva Andersson, Sara Nordén, Karin Aquilonius, Ulrik Kautsky and Tobias Lindborg have contributed with comments and in discussions on the report content.

Malin Andrée (SWECO position AB) helped with GIS-related support and Linda Falk (SWECO position AB) has contributed a number of GIS-based pictures. Richard Nord has edited the English language in most chapters of this report.

The opinions expressed in this report do not necessary comply with those of the reviewers. Pictures have been taken by the editor if not otherwise stated.

1.1 Background

Radioactive waste from nuclear power plants in Sweden is managed by the Swedish Nuclear Fuel and Waste Management Co, SKB. Both waste and spent fuel are planned to be placed in a geological repository according to the KBS-3 method /SKB 2010d/. According to KBS-3, copper canisters with a cast iron insert containing spent fuel are to be enclosed by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock. Approximately 12,000 tonnes of spent nuclear fuel is forecasted to arise from the Swedish nuclear power programme, corresponding to roughly 6,000 canisters in a KBS-3 repository.

Between 2002 and 2007, SKB performed site investigations with the intention of finding a suitable location for a repository. Investigations were focused on two different sites along the eastern coast of southern Sweden; Forsmark in the municipality of Östhammar and Laxemar-Simpevarp in the municipality of Oskarshamn (Figure 1-1). Data from the site investigations have been used to produce comprehensive, multi-disciplinary site descriptions for each of the sites. The resulting site descriptions were reported in /SKB 2008/ (Forsmark) and /SKB 2009/ (Laxemar-Simpevarp). Based on available knowledge from the site descriptions and from preliminary safety assessments of the planned repository, SKB decided in June 2009 to select Forsmark as the site for the repository. An application for the construction of a geological repository for spent nuclear fuel at Forsmark is planned to be filed in 2011.

One critical task is to characterize long-term safety for a deep repository. To this end a safety report is produced in order to support the application in 2011 /SKB 2011/. The Biosphere synthesis report /SKB 2010a/ summarizes the biosphere assessment from other more detailed background reports in which terrestrial, limnic and marine ecosystems, surface hydrology and other surface system disciplines are described (Figure 1.2). This report is one of those background reports and describes the input data and methodology relating to the site description of the terrestrial ecosystems in the Forsmark and Laxemar-Simpevarp areas. Similar reports describing the marine ecosystems /Aquilonius 2010/ and the limnic ecosystems /Andersson 2010/ have also been published. These three ecosystem reports have also been published in an earlier edition. The additions to the first editions that had the site description in focus, include extensive chapters describing future conditions on the site, radionuclide model parameterization associated with the three ecosystems, a comparison between an interaction matrix describing processes in ecosystems and processes within the radionuclide model, and the description of the radionuclide model (only in /Andersson 2010/).

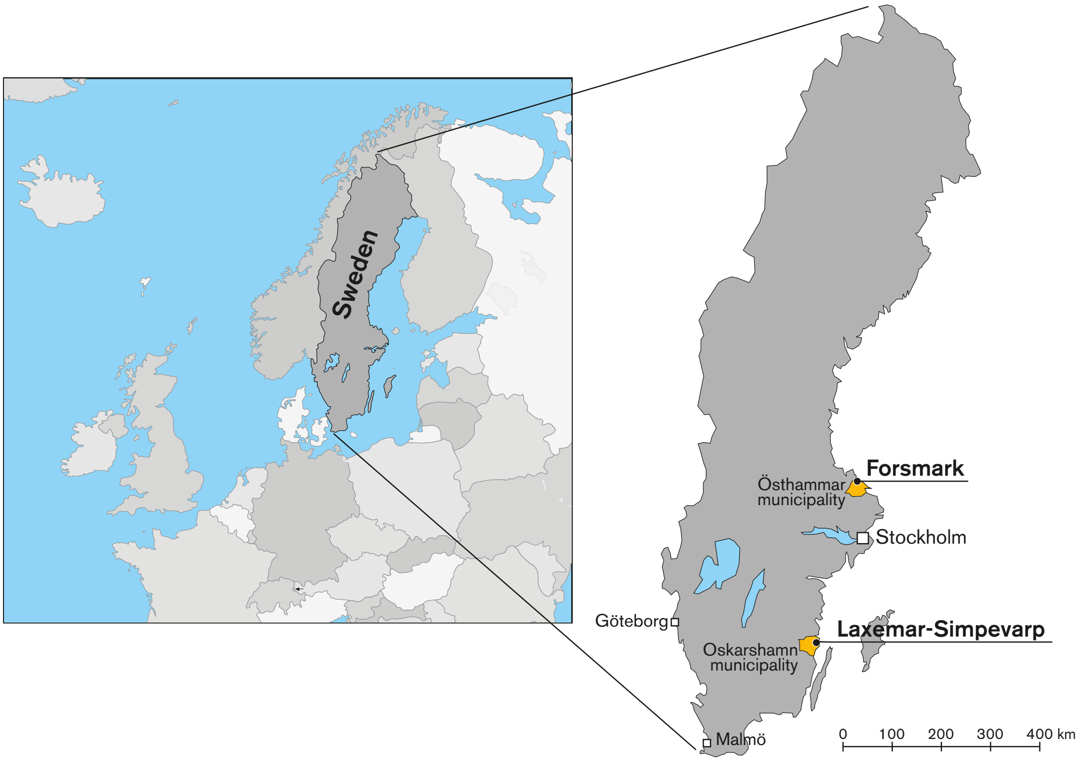


Figure 1-1. *Location of the Forsmark and Simpevarp investigation areas in Sweden.*

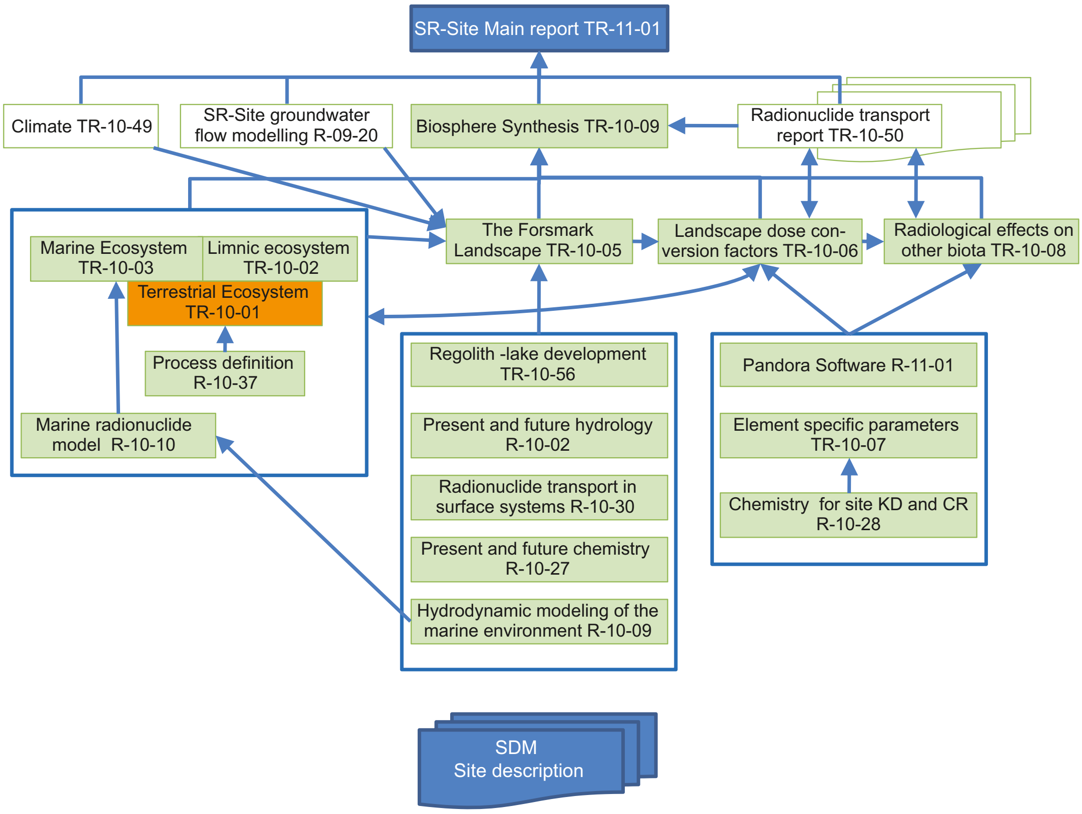


__Figure 1-2.__ The hierarchy of reports produced in the SR-Site Biosphere project. This report (shown in orange) and its dependencies on information from subordinate biosphere reports and other reports within SR-Site are indicated. Arrows indicates major interactions during project work flow of analysis and results, but interactions have been substantial between most parts of the project throughout the process. The sources of data should be obtained from the subordinate reports if not explicitly pointed to in the text. SDM is the site descriptive model (Lindborg (ed.) 2008).

1.2 Aims

The overall objective of this report is to describe the terrestrial ecosystem at the two sites Forsmark and Laxemar-Simpevarp. It summarizes the site investigations that are presented in more detail in separate reports and also presents descriptions and estimates of data not presented elsewhere. The intention is firstly to give the initiated reader a coherent description of the terrestrial ecosystems at each site. Secondly, the data are used, along with other information, to provide overall descriptions of pools and fluxes in those ecosystems of organic matter, water and other elements. Moreover, discussion of historical aspects of land use, successional trajectories and boundaries to important ecosystem properties adds further information to the present-day data. This information is also the basis for the derivation of the parameter values that are used in the radionuclide modelling in the biosphere assessment.

The major outputs of this report can be summarized as follows.

- A description of the current terrestrial ecosystems.
- A compilation and overview (covering ecological aspects) of the different studies conducted during the site investigations.
- Descriptive ecosystem models of pools and fluxes of carbon on a local and a regional scale.
- A description of pools and fluxes of a large number of different elements on a regional scale.
- Description and discussion of some of the potential changes in ecosystem processes that can occur during future development.
- Presentation of a comparison of how different ecosystem processes are handled within the radionuclide modelling using an “Interaction matrix”.
- Presentation of the assumptions, data and calculations for terrestrial parameter values used in the radionuclide modelling.

1.3 Geographical settings

The two potential repository sites, Forsmark and Laxemar-Simpevarp, are located on the Swedish east coast in the drainage area of the Baltic Sea, Figure 1-1. Detailed maps including geographical names, roads, model areas etc are found in Appendix 1 (Forsmark area) and Appendix 2 (Laxemar-Simpevarp area).

Sweden generally has a maritime climate, distinguished by cool summers and mild winters. However, further north in Sweden the climate tends to be more continental with a greater difference between summer and winter. Since the Forsmark area is located north of the Laxemar-Simpevarp area, the climate tends to be more continental in Forsmark than in Laxemar-Simpevarp. The mean annual air temperature is also somewhat lower in the Forsmark area. Both sites are located in the boreonemoral vegetation zone, dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*).

2 This report

This section serves both as a summary and a guide for the reader, while putting the report in a broader context. The objectives are also presented in this section, but perhaps more importantly, it describes how the different sections are related, and how they are used in the different steps of the biosphere safety assessment.

2.1 This report in a broader context

The ecosystem is in most cases the link between radionuclides released from a repository and the exposure of humans and other biota to them. This report describes the terrestrial ecosystems in the Forsmark and Laxemar-Simpevarp areas by summarizing and performing cross-disciplinary analyses of data from a large number of reports produced during the site investigations, Figure 1-2. The report describes the terrestrial landscape, divided here into the three main categories: forests, wetlands and agriculture land, by identifying properties that are important for element accumulation and transport.

2.2 Report contents

Elements are transported and accumulated in the biosphere to a different extent, depending on the properties of the element and the context it experiences. This report describes the biotic and abiotic context at the sites and describes conceptually the potential transport and accumulation of elements in the terrestrial ecosystems and in the landscape. The description integrates knowledge from ecology as well as hydrology, Quaternary geology and chemistry, and includes a number of different processes that drive element fluxes in the ecosystems, such as net primary production, heterotrophic respiration, weathering, leaching etc. The description is based on both a detailed approach involving local measurement of fine-scale quantities and a broader approach utilising more coarse-scale quantities such as climate to elaborate on the potential pools and fluxes of organic matter. Moreover, within the timespan of the safety assessment, several thousand years or more, the landscape will change, largely due to ongoing and predicted shoreline displacement in the area and partly as a response to climate. Due to these processes, marine areas will become lakes that in turn will become wetlands and other terrestrial ecosystems, including agricultural areas. Elements accumulated in the limnic ecosystems will therefore subsequently form a part of the terrestrial system. In the same way, elements previously accumulated in marine ecosystems may become a part of limnic systems as these are formed. The approach used in this report is to describe a number of different aspects of pools and fluxes of elements in the landscape of today, and also take into consideration historical land use and ecosystem succession that are regarded as important for modelling radionuclide transfer and accumulation in an evolving surface system.

The initial Chapters 3 and 4 in this report present an overview and synthesis of the site data presented in other reports (Appendix 3). In Chapter 4, the terrestrial landscape is described in terms of wetland, agricultural land and forest land. These vegetation types are described in terms of different aspects, such as species composition, present land use and ecosystem properties. Chapter 5 provides a conceptual description that serves as a basis for existing and future models. It consists primarily of descriptions of pools and fluxes of organic matter, but also serves as a conceptual approach for describing pools and fluxes of other elements present in the ecosystems. Chapter 6 offers detailed descriptions of pools and fluxes of carbon, a proxy for organic matter, for three localities at each site where data have been collected. Chapter 7 takes a novel approach where the model LPJ-GUESS is used to estimate pools and fluxes of carbon for different vegetation types at both sites using climate as the driving variable. The results obtained from this model are combined with remote sensing data in order to study the variation in Net Primary Production (NPP) of the tree layer. In addition, long-term dynamics of a number of ecosystem properties are studied for forest and agricultural land at both sites. Chapter 8 uses information from Chapters 4 and 7 in combination with the vegetation map to describe the pools and fluxes of organic matter at the catchment scale with a more approximate conceptual model based on the conceptual description in Chapter 5. In Chapter 9 pools and fluxes are used to explore mass balances of phosphorus, iodine, uranium and thorium together with a large number of different elements on the catchment and landscape scales. Chapter 10 describes the postglacial terrestrial development, vegetation change and successional trajectories at the sites. In addition, the historic human land use, which is also described, is also an important component that has in many ways shaped the landscape of the past and present.

Chapter 11 discusses implications of future development on a number of important ecosystem processes focusing on wetlands and land use, which are of importance in the radionuclide modelling. In Chapter 12, an interaction matrix is used to illustrate how important processes for the transport and/or accumulation of radionuclides are included in the radionuclide model. In the radionuclide model, a number of parameters are associated to processes in terrestrial ecosystems and in Chapter 13 the derivation of values for these parameters is described. In the last chapter, which is a concluding chapter, the characteristics of the two sites are briefly summarized based on the different topics that have been described in the previous chapters. This summary is also put into the context of the safety assessment.

2.3 Delimitation of a terrestrial ecosystem

In the site descriptions, the landscape is divided into three ecosystems: limnic, marine and terrestrial. The general difference between terrestrial and aquatic ecosystems is the position of the water table, which has implications for a number of ecosystem characteristics and ecosystem processes, such as plant life form, plant water availability and decomposition (see also Section 4.1.1). The interface between terrestrial and aquatic systems often shows high primary production and accumulation of organic material, e.g. a reed belt in a lake. Some interface areas are highly productive, but lack accumulation, e.g. exposed sea shores with input of marine residues. In some cases, the interface is easy to distinguish, e.g. an outcrop-water interface, but in other cases the boundary between land and water may not be so clear and easy to identify. In general, the interface on a freshwater shore is clearly distinguished, covering a transect of a few metres (the littoral of a lake), whereas a sea shore, with larger fluctuations in water level, may cover a transect of tens of metres. Zones of high production and accumulation, such as reed belts, have been identified around lakes and in sheltered bays in both the Forsmark and Laxemar-Simpevarp areas. In the ecosystem models, these zones are classified as wetlands and treated as part of the terrestrial ecosystem so that all kinds of wetlands are treated in a similar way. The interface zones are regarded as a transient stage in the succession of sea basins/lakes to land.

2.4 Geographical definitions and terminology

When the two sites are discussed in a general sense and without consideration of clearly defined outer boundaries, they are called the *Forsmark area* and the *Laxemar-Simpevarp area*. At the start of the site investigations in 2002, regional model areas with clearly defined outer boundaries were defined for each site for the purpose of regional scale modelling (see Appendices 1 and 2). These areas were denominated the *Forsmark regional model area* and the *Simpevarp regional model area*. Furthermore, two smaller areas were defined within the Simpevarp regional model area, the Simpevarp subarea and the Laxemar subarea, and preliminary site descriptions were produced for both subareas. Since the two subareas are included in the same regional model area, the former Simpevarp regional area is denoted the *Laxemar-Simpevarp regional model area* for the sake of clarity and to avoid confusion.

2.5 Conceptual, descriptive and numerical models

A number of different terms are used in this report, and some of the most frequently used of these are presented in Table 2-1. The terms are also described in the text.

Table 2-1. Definitions of terms used in this report.

Concept/term	Definition
Abiotic	Not directly caused or induced by living organisms.
Autotroph	Organism that produces organic matter from CO_2 and environmental energy rather than by consuming organic matter produced by other organisms. Synonymous here with primary producers.
Biosphere	That part of the environment normally inhabited by living organisms.
Biosphere object	A part of the landscape that potentially will receive radionuclides released from a repository.
Biotic	Caused or induced by living organisms.
Climate cases	SR-Site describes climate cases, which are possible future climate developments at Forsmark.
Climate domain	A climatically determined environment with a specific set of characteristic processes of importance for repository safety.
Conceptual model	A qualitative description of the components in an ecosystem.
Descriptive model	A quantitative description of the components in an ecosystem. May be static or dynamic (see below).
DEM (digital elevation model)	The DEM describes topography and bathymetry of a certain area. The DEM is a central data source for the site characterisation, and is used as input to most of the descriptions and models produced for the surface system.
Discharge points /area	The area where deep ground water reaches the ground surface.
Dose	Dose, as used in SR-site refers to the mean annual dose of the most exposed group. The calculated dose accounts for retention of radionuclides in the human body and exposure from daughter radionuclides, as well as radiation sensitivities of different tissues and organs.
Dose rates to biota	Dose rates for biota represents mean absorbed dose rates in the whole body of a given radionuclide and are expressed uGy h-1.
Dynamic model	A dynamic model describes the behaviour of a spatially distributed parameter system in terms of how one qualitative state can turn into another.
Ecosystem model	Conceptual or mathematical representation of an ecosystem. Breaks complex food webs down into their major components or trophic levels and quantifies them as either numbers of organisms, biomass or the inventory/concentration of some pertinent chemical element.
Exposure	The act or condition of being subject to irradiation. (Exposure should not be used as a synonym for dose. Dose is a measure of the effects of exposure.)
	External exposure. Exposure to radiation from a source outside the body.
	Internal exposure. Exposure to radiation from a source within the body.
Flux	Flow of energy or material from one pool to another.
Food web	Group of organisms that are linked together by a transfer of energy and nutrients that originates from the same source.
Functional group	Collection of organisms based on morphological, physiological, behavioural, biochemical, environmental or trophic criteria.
Geosphere	Those parts of the lithosphere not considered to be part of the biosphere. In safety assessment, usually used to distinguish the subsoil and rock (below the depth affected by normal human activities, in particular agriculture) from the soil that is part of the biosphere.
Glacial cycle	A period of c 120,000 years that includes both a glacial (e.g. the Weichselian) and an interglacial.
Gross primary production (GPP)	Net carbon input to an ecosystem – that is, net photosynthesis expressed at an ecosystem scale (gC m^{-2} yr^{-1}) /Chapin et al. 2002/.
Heterotroph	Organism that consumes organic matter produced by other organisms rather than producing organic matter from CO_2 and environmental energy. Includes decomposers, consumers and parasites /Chapin et al. 2002/.
Infilling	Infill describes the combined processes of sedimentation and organogenic deposition turning lakes into wetlands.
Interglacial	A warm period between two glacials. In SR-Site an interglacial is defined as the time from when the ice sheet retreats from the area (time of deglaciation) to the time for the first occurrence of permafrost.
Mass balance model	The mass balance model calculates the total sum of major sources and sinks for individual chemical elements in the landscape.
Net ecosystem production (NEP)	The difference between gross primary production and ecosystem respiration /Chapin et al. 2002/. $NEP=\Delta C_{org}+E+O_{Xnb}-I$, where ΔC_{org} is the change in organic C storage in the ecosystem, E is the export of organic C, O_{Xnb} is the non-biological oxidation of C and I is the import of organic C /Lovett et al. 2006/.
Net primary production (NPP)	The difference between gross primary production and plant respiration.

Concept/term	**Definition**
Pool	Quantity of energy or material in an ecosystem compartment such as plants or soil /Chapin et al. 2002/.
Radionuclide model	Model used to calculate radionuclide inventories in different compartments of the biosphere, radionuclide fluxes between the compartments and radionuclide concentrations in environmental media (soil, water, air and biota). Exposure calculations for humans is included in the radionuclide model, whereas exposure of non-human biota is calculated separately. The radionuclide model utilises PANDORA and Ecolego modelling tools.
Respiration	Biochemical process that converts carbohydrates into CO_2 and water, releasing energy that can be used for growth and maintenance. Heterotrophic respiration is animal respiration plus microbial respiration, while ecosystem respiration is heterotrophic plus autotrophic respiration /Chapin et al. 2002/.
Sub-catchment	The drainage area of a biosphere object minus the drainage area of the inlets to the object.
Terrestrialisation	The transfer of an aquatic ecosystem (marine or limnic) to a terrestrial ecosystem.
Watershed	The drainage area of a biosphere object

3 General description of the sites

The two sites are briefly outlined with regard to climate, Quaternary deposits and vegetation before a more detailed presentation of the sites is presented in the next chapter.

3.1 The Forsmark area

3.1.1 Abiotic settings

Quaternary deposits

All known Quaternary deposits in the Forsmark area were formed during or after the last glaciation (Figure 3-1). The oldest deposits are of glacial origin, deposited directly by the ice, or by water from the melting ice. The whole area is located far below (> 120 m) the highest coastline, so the area has been located under the sea during the major part of the Holocene. Fine-grained sediment has been deposited in local depressions such as the bottom of the lakes and on the present-day sea floor. Wave action and currents have partly eroded the upper surface of the overburden. Isostatic uplift at Forsmark is still ongoing (6 mm/year), resulting in new land areas emerging from the Baltic. The most notable change in the areas uplifted from the Baltic is the development of organic soils, for example the sedimentation of gyttja in the lakes and the formation of peat in the wetlands. Peat formation is, however, more evident upon leaving the immediate coast and moving inland, where time has allowed a thicker peat layer to accumulate. The minerogenic Quaternary deposits are affected by coastal and soil-forming processes at the surface, but no major redistribution of these deposits has occurred since the area was uplifted. The Forsmark area has less clay and silt (8% compared with 20%) and more till (65% compared with 41%) compared with the national averages. For a complete summary of current knowledge of the Quaternary deposits in the Forsmark area, see /Hedenström and Sohlenius 2008/.

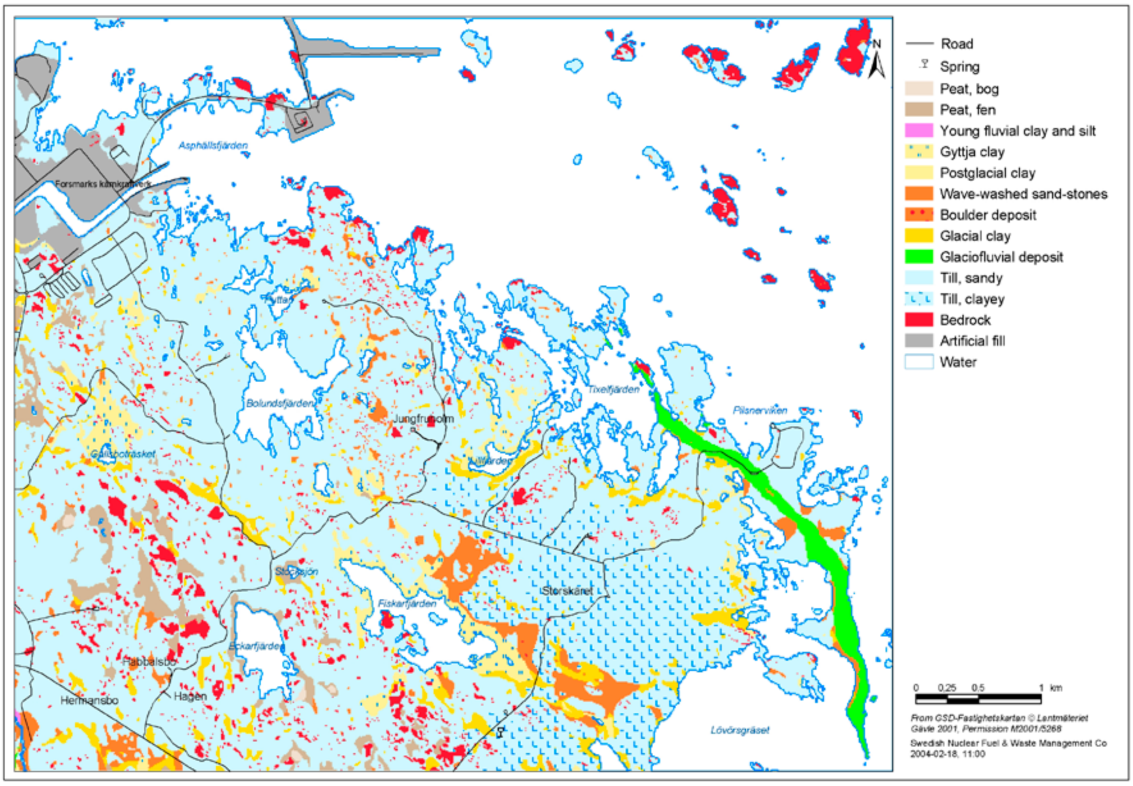


***Figure 3-1.** The spatial distribution of Quaternary deposits in Forsmark /Hedenström and Sohlenius 2008/.*

The surface water and shallow groundwater in Forsmark is characterized by high pH values and high contents of major constituents, especially calcium and bicarbonate /Sonesten 2005, Tröjbom and Söderbäck 2006a/. The main reason for this is the glacial remnants, mostly in the form of a till layer, which were deposited during the Weichselian glaciation and deglaciation /Fredén 2002/. This till layer has high calcite contents originating from the sedimentary bedrock of Gävlebukten about 100 km north of Forsmark. The calcareous influence is typical for the north-eastern part of Uppland County and is manifested in the flora. This is especially evident closer to the coast of the Baltic, due to the more recently uplifted areas that have been less exposed to weathering.

Soil types

The soils in the Forsmark area are typically immature, unweathered, poorly developed soil types on till or sedimentary parent material, which is influenced by calcareous material /Lundin et al. 2004/. The dominant soil types are Regosols but six other soil types also occur. Soils influenced by water, e.g. Gleysols and Histosols, are also frequent (Table 3-1). The spatial distribution of these soil types is described in Figure 3-2. Typical soils for Sweden are Podsols, but this soil type has not yet developed in the Forsmark area. The poor soil development is a result of young age, since most of the candidate area emerged from the sea during the last 1,500 years. As the sea withdrew it altered the soil by wave action at exposed sites, which has partly washed out the surface layer of the till and redistributed the fine-grained material into thin sedimentary deposits. In exposed positions, the regolith was partly washed away, and at many sites there is bare rock or very thin soil cover. Furthermore, former bays of the Baltic which were uplifted and isolated now form inland lakes and ponds which are being transformed into swamps and peatlands. This has resulted in a heterogeneous area with a large variety of soil parent material, from bare bedrock to wave-washed till and water-laid sediments.

Climate and hydrology

The corrected mean annual precipitation was 537 mm for three years of measurements at Högmasten and Storskäret (January 2004–December 2006). The mean annual potential evapotranspiration during the same period is estimated to 509 mm. The annual temperature during the same period was close to +7°C (Table 3-2). The 30-year long term annual average precipitation for 1961–1990, calculated by SMHI, was 559 mm.

Snow cover has been measured weekly during five seasons (2002/03–2006/07) at two sites in forest land and one site in open land. During four of these seasons, the water content of the snow cover has also been determined. During the period of measurement there was a snow cover 105 and 80 days/season on average on forest land and open land, respectively. In general there was a snow cover from the end of November/beginning of December until the end of March/beginning of April. However, during some of the seasons there were periods when the snow cover disappeared. The maximum snow depth recorded was 48 cm in forest land and 25 cm in open land, and the maximum snow water content was 144 and 64 mm, respectively. For details on the measurements, see /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007a/.

Table 3-1. Distribution of soil types for the central part of the Forsmark area updated after /Lundin et al. 2004/, see /Hedenström and Sohlenius 2008/.

Code	Soil class	Forsmark area (%)
	Unclassified	5.1
HI	Histosol	11.2
GL	Gleysol	2.3
GL/CM	Gleysol/Cambisol	24.4
RG/GL	Regosol/Gleysol	42.2
RG/GL-a	Regosol/Gleysol on arable land	6.8
AR/GL	Arenosol/Gleysol	1.8
RG	Regosol	1.5
LP	Leptosol	4.7

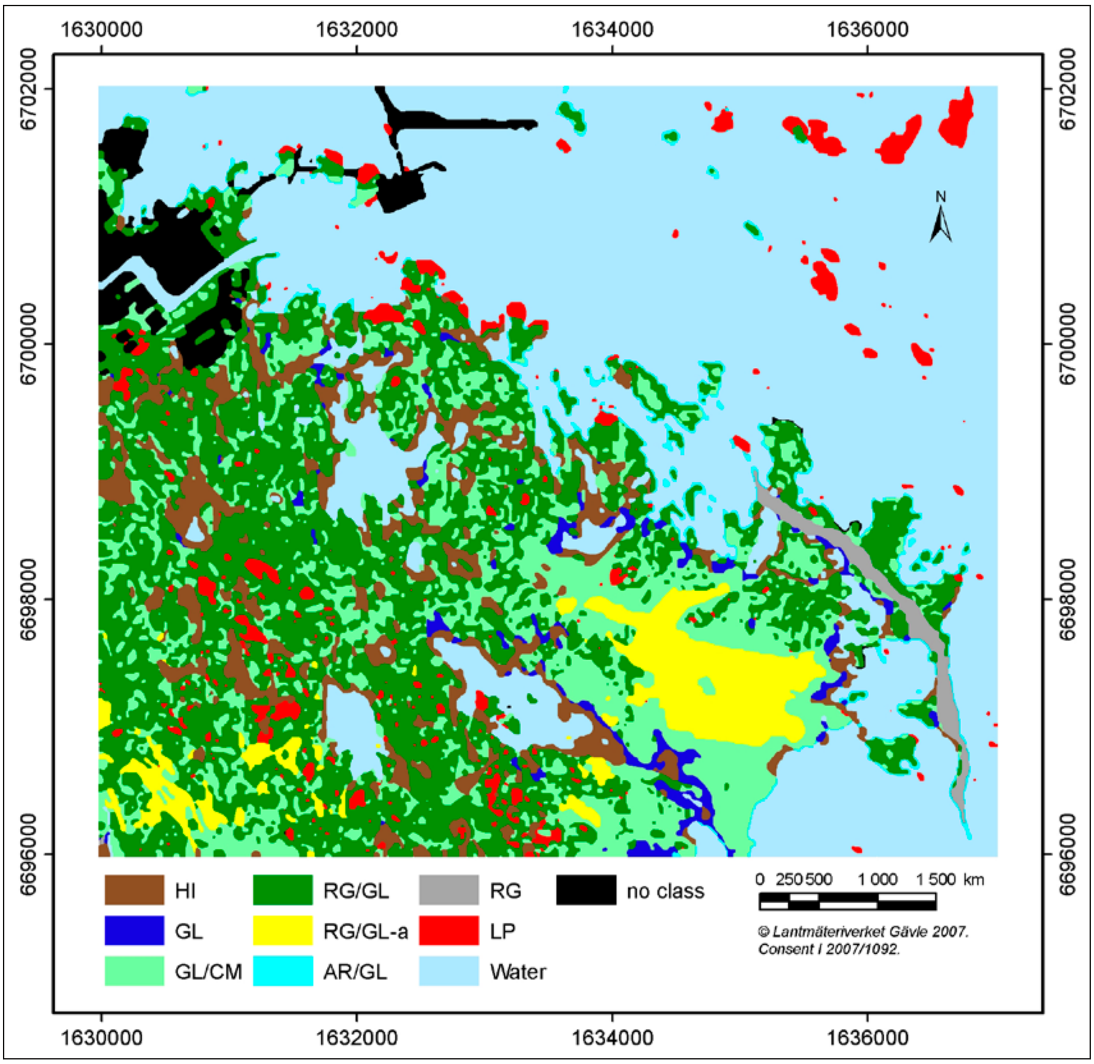


Figure 3-2. *The spatial distribution of different soil types in Forsmark /Hedenström and Sohlenius 2008/. Soil type codes correspond to soil classes in Table 3-1.*

Table 3-2. Some climate characteristics for the Forsmark area. Data are for 2004 to 2006 for Storskäret, Forsmark /Johansson 2008/.

	Forsmark area
Latitude, longitude	60° 22’ N, 18° 11’ E
Mean annual temp.	+7°C
Min.–max. daily temp.	–14 – +25°C
Mean precipitation (mm)	546
Vegetation period	May–September
Length of vegetation period*	204 days

*Starts when 5 consecutive days have a daily mean > +5°. Ends when 4 consecutive days have a daily mean < +5°.

Based on measurements of precipitation, surface discharge, surface water levels and groundwater levels during the period April 15, 2004–April 14, 2007, and taking into account deviations from long-term average precipitation and storage changes, the long-term overall water balance in the area has been roughly estimated: Precipitation = 560 mm/year, actual evapotranspiration = 400–410 mm/year, and runoff = 150–160 mm/year.

Ground frost penetration was measured during three seasons, 2003/04–2005/06, at two sites on forest land and at one site on open land. Ground frost was present for 40 and 80 days/season in forest land and open land, respectively. The maximum ground frost depth on open land was 46 cm, whereas the maximum depth on forest land was only 8 cm. For details on the measurements, see /Aquilonius and Karlsson 2003, Heneryd 2004, 2005, 2006, 2007a/.

In total, 25 "lake-centred" catchments, ranging in size from 0.03 to 8.7 km^2, have been delineated and described within the model area. The 25 mapped lakes range in size from 0.006 km^2 to 0.75 km^2. The lakes are very shallow, with maximum depths ranging from 0.4 m to 2.0 m. No major water courses flow through the central part of the candidate area and a few brooks downstream carry water most of the year, but can still be dry for long periods during dry years such as 2003 and 2006. Many brooks in the area have been artificially deepened for considerable distances for drainage purposes. Wetlands are frequent and cover 10–20% of the areas of the three major catchments, and up to 25–35% of some sub-catchments. Groundwater levels in Quaternary deposits are very shallow, on average less than 0.7 m below ground for 50% of the time. Shallow groundwater levels imply a strong interaction between evapotranspiration, soil moisture and groundwater. Diurnal fluctuations of the groundwater levels, driven by evapotranspiration cycles, are evident in many groundwater wells. Furthermore, groundwater level measurements in the vicinity of the lakes show that the lakes may act as recharge sources to till aquifers in the riparian zone during summer.

3.1.2 Vegetation

The terrestrial vegetation is strongly influenced by the characteristics of the Quaternary deposits and by human land use. The area is fairly young (see 3.1.1 "Soil types") and has a low topography /Strömgren and Brydsten 2008/. The seaside location makes the seashore a prominent feature in the east. Most of the Forsmark land area is covered with conifer forests, where Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) dominate (Figure 3-3, 3-4, Table 3-3). The low topography makes shallow lakes and mires common in the area. Most of the lakes are surrounded by mire vegetation with different extent depending on the depth of the lake and how far the succession of the lake

Figure 3-3. *A view of the Forsmark area.*

has proceeded. Agricultural land is scarce, but the main extent is located in the southeast part of the investigation area. The spatial distribution of a number of different vegetation types was presented by /Boresjö Bronge and Wester 2003/ in a vegetation map that was based on remote sensing (SPOT4, 1999), soil map and field checks, see Figure 3-4 and Table 3-3. This map was updated with regard to clear-cuts in the area using information from the Swedish Forest Agency for the period mid-2000 to mid-2006. The vegetation map was verified by checking the consistency of the map against reality for a number of vegetation types by field visits /Alling et al. 2004a/. They concluded that the map identified wetlands with acceptable accuracy, but was less accurate in distinguishing fertile tree-dominated land from less fertile coniferous woodland.

Table 3-3. Vegetation classes and their spatial coverage in percent of the covered land area (water excluded).

Gridcode	Vegetation type	Area (m^2)	Coverage (%)
11	Old spruce-dominated forest, mesic-wet types	8,126,818	10
12	Young spruce-dominated forest, mesic-wet types	4,221,306	5
13	Old pine-dominated forest, mesic-wet types	8,719,747	11
14	Young pine-dominated forest, mesic-wet types	6,486,363	8
15	Dry pine forest on acid rocks	2,541,419	3
21	Birch-dominated forest	1,871,781	2
23	Aspen-dominated forest	23,690	0.03
26	Ash-dominated forest	1,540,700	2
30	Mixed forest (conifers/deciduous)	4,865,145	6
31	Mixed forest/shrub on bedrock islands	88,237	0.1
41	Old clear-cut, young spruce	398,160	0.5
42	Old clear-cut, young pine	781,956	1
43	Old clear-cut, unspecified conifer	7,088,887	9
44	Old clear-cut, birch thicket	9,516,768	12
45	Old clear-cut, birch thicket/meadow type	1,144,614	1
46	Poor regrowth, meagre ground, boulders	1,878,380	2
50	New clear-cut (2000–2006)	1,025,800	1
61	Forested wetland, spruce-dominated	157,839	0.2
62	Forested wetland, pine-dominated	896,073	1
63	Forested wetland, birch-dominated	1,374,568	2
64	Forested wetland, clear-cut	80,956	0.1
72	Open wetland, lush carpet mire/mud-bottom mire	64,113	0.1
74	Open wetland, lush lawn mire	417,976	1
75	Open wetland, lush lawn mire, with willow, birch	1,347,612	2
76	Open wetland, lush lawn mire, with willow, birch	801,049	1
77	Open wetland, reed-dominated, less wet	3,373,328	4
78	Open wetland, reed-dominated/more lush	551,085	1
79	Open wetland, reed-dominated, wet	413,921	1
81	Arable land	4,068,104	5
82	Other open land (pastures and meadows)	4,337,595	5
83	Coastal rocks	1,189,429	1
91	Holiday house	775,459	1
92	Industry	767,631	1
93	Lowrise house	142,154	0.2
96	Other hard surfaces (e.g. asphalt)	1,297,861	2

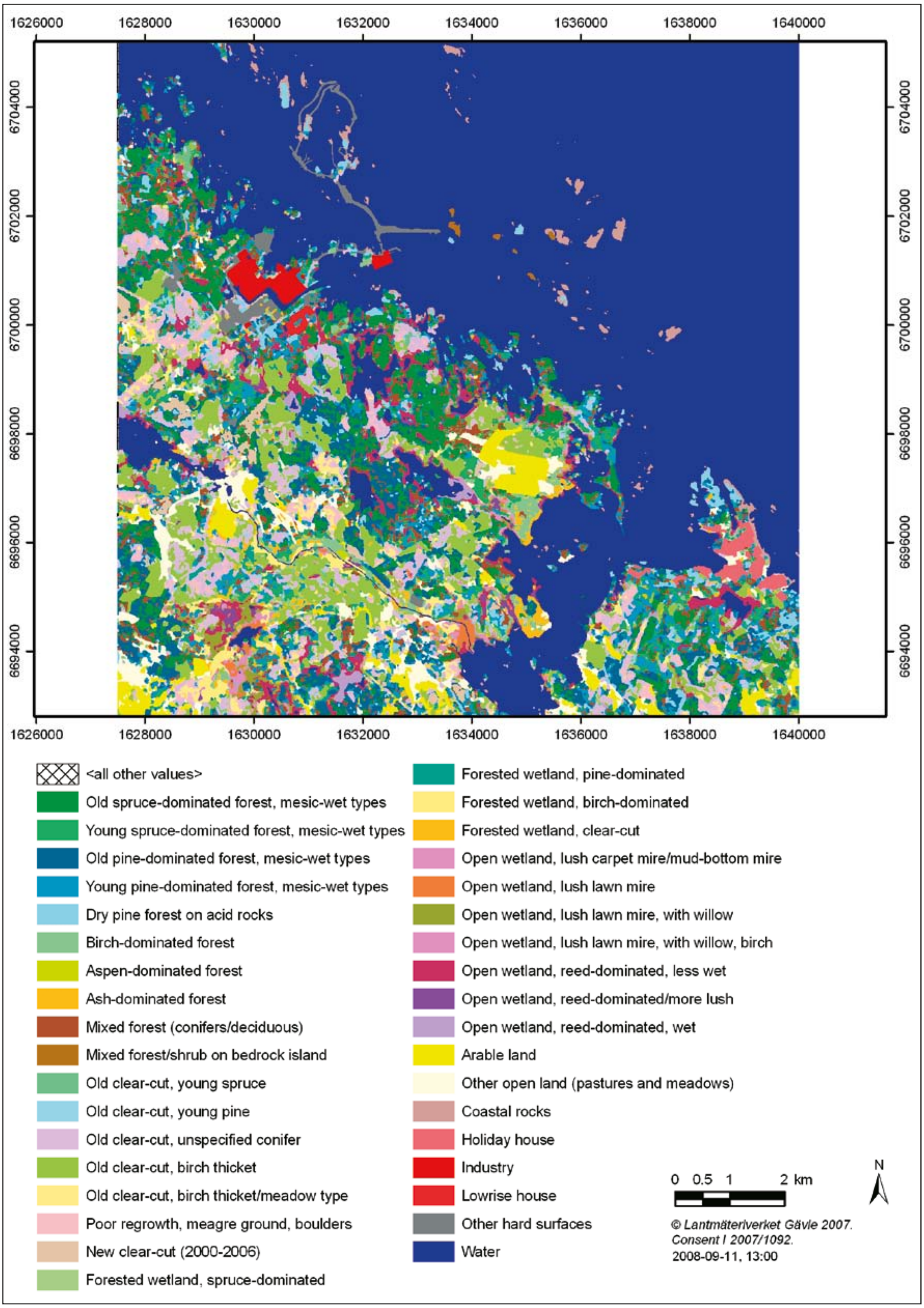


Figure 3-4. *Vegetation map of the Forsmark area, which is a partially updated version based on /Boresjö Bronge and Wester 2003/.*

3.2 The Laxemar-Simpevarp area

3.2.1 Abiotic settings

Quaternary deposits

In a regional perspective, the Laxemar-Simpevarp area is situated in a region with a relatively thin cover of Quaternary deposits. Both the marine and terrestrial parts of the investigated area are characterized by a relatively flat bedrock surface with numerous fissure valleys, which in many cases can be followed for several kilometres. The highest topographical areas are dominated by till and bedrock outcrops (Figure 3-5). The valleys in the Laxemar-Simpevarp area have been sheltered from wave erosion and coastal currents. These low topographical areas have therefore been favourable environments for sedimentation of clay during long time periods. In the terrestrial part of the model area, the groundwater level in the valleys is situated close to the ground surface. As a consequence, a layer of peat often covers the clay. Clay sediments are currently being deposited in the bays along the present coast. Exposed areas have been, and at some sites still are, subjected to wave washing, which has caused erosion and redeposition of some of the regolith. Sand and gravel is currently being transported at the bottom of the most exposed parts of the sea. A sand and gravel layer therefore often covers the valleys at the sea bottom. Forest covers the areas dominated by till and exposed bedrock, which constitute the main part of the investigated area. The areas covered with clay and peat in the valleys are, however, often used as arable land. Artificial ditches have lowered the groundwater table in these cultivated areas.

Soil types

The dominant soil is Podzol/Regosol, comprising thin coniferous forest soils found on till and course sediment soil with fresh soil moisture class (Figure 3-6, Table 3-4). Leptosol covers a mosaic of bedrock outcrops and thin soils typically found in upslope locations in the area. Similar to this class is bedrock, which is distinguished from the latter by the absence of a tree layer, but may have sparse pines, and a field layer of the dry heath type. Umbrisol-Regosol has a fresh soil moisture class and is dominated by deciduous trees in the tree layer, although some mixed forests occur. The Umbrisol-Gleysol type includes open pastures, partly forested moist soils in downslope locations and non-arable soil on clay and silt deposits. A number of histosols were identified and differentiated depending on their surrounding context, i.e. wetland on peat lacking a tree layer, forested peatland in forest-covered drained peatland soils, small peatland in bedrock areas.

Climate and hydrology

The regional mean annual precipitation in the Laxemar-Simpevarp area has been estimated to be 600 mm (Table 3-5) /Werner 2009/. The mean annual temperature in the Laxemar-Simpevarp region is 6–7°C. The mean temperature in January is –2°C and mean temperature in July is 16–17°C. Thus, the temperature in Laxemar-Simpevarp is about 1°C warmer (in January 2°C) than in the Östhammar/Tierp region.

Approximately 17% of the accumulated precipitation during the period September 9, 2003–December 31 fell in the form of snow /Werner 2009; see above/. Snow cover has been measured approximately biweekly during the period 2002/03 to 2006/07 at station ASM100224, Grillplatsen, Äspö. Generally, there was a snow cover from December/January until March/April during this period. However, short periods of snow were recorded as early as October, and late snow cover was recorded at the end of April. The period of snow cover at Grillplatsen, Äspö agrees well with the measured snow cover at four SMHI stations. Snow cover has been measured at the SMHI stations since 1994, making it possible to estimate snow cover for longer time periods in the Laxemar-Simpevarp area. Some kilometres inland from Oskarshamn the ground is covered by snow for on average about 75 days a year, with an average yearly maximum snow depth of 35–40 cm. The coast does not differ much from the conditions 10–20 km inland /Larsson-McCann et al. 2002a/.

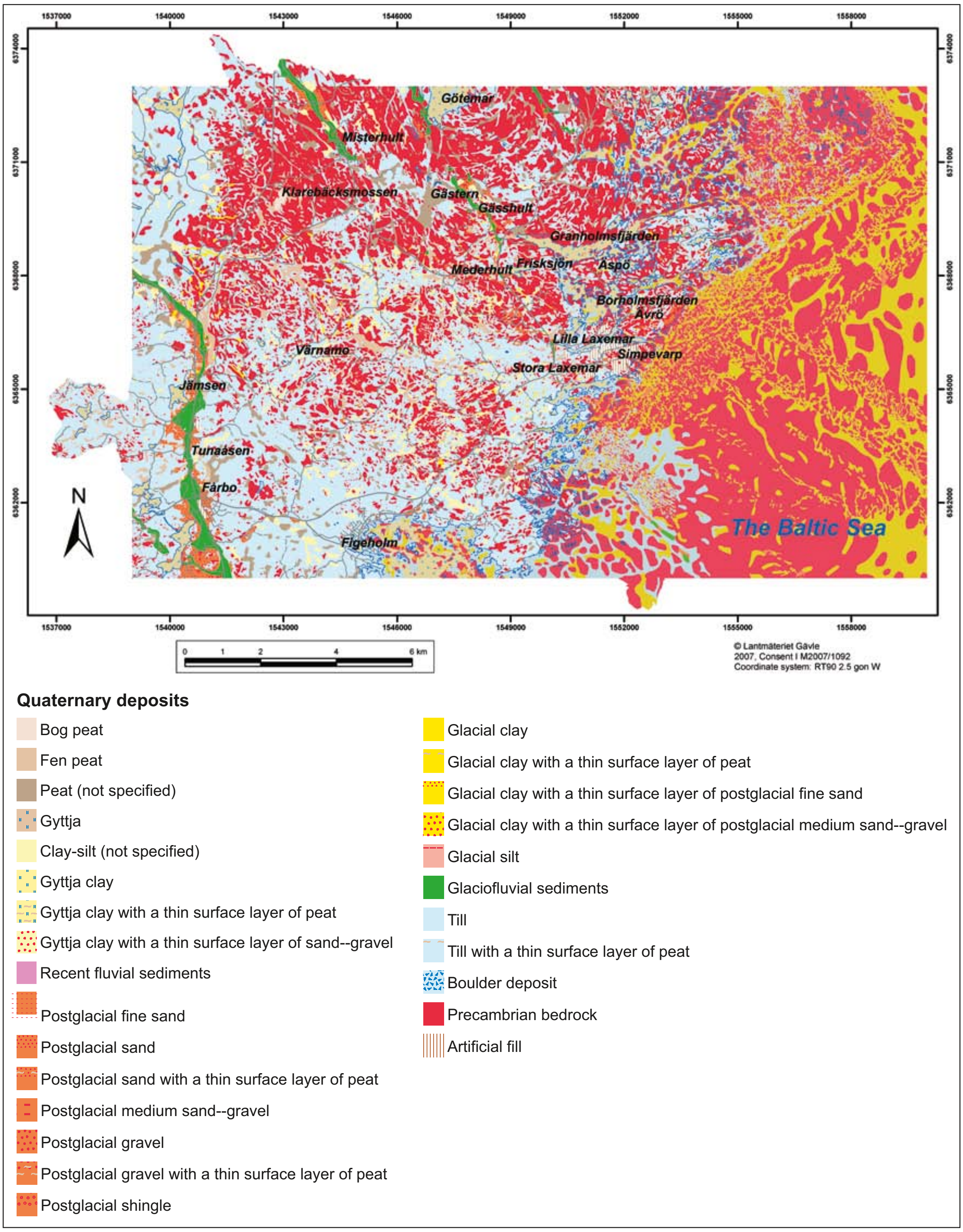


***Figure 3-5.** Spatial distribution of Quaternary deposits in the Laxemar-Simpevarp regional model area. /Sohlenius and Hedenström 2008/.*

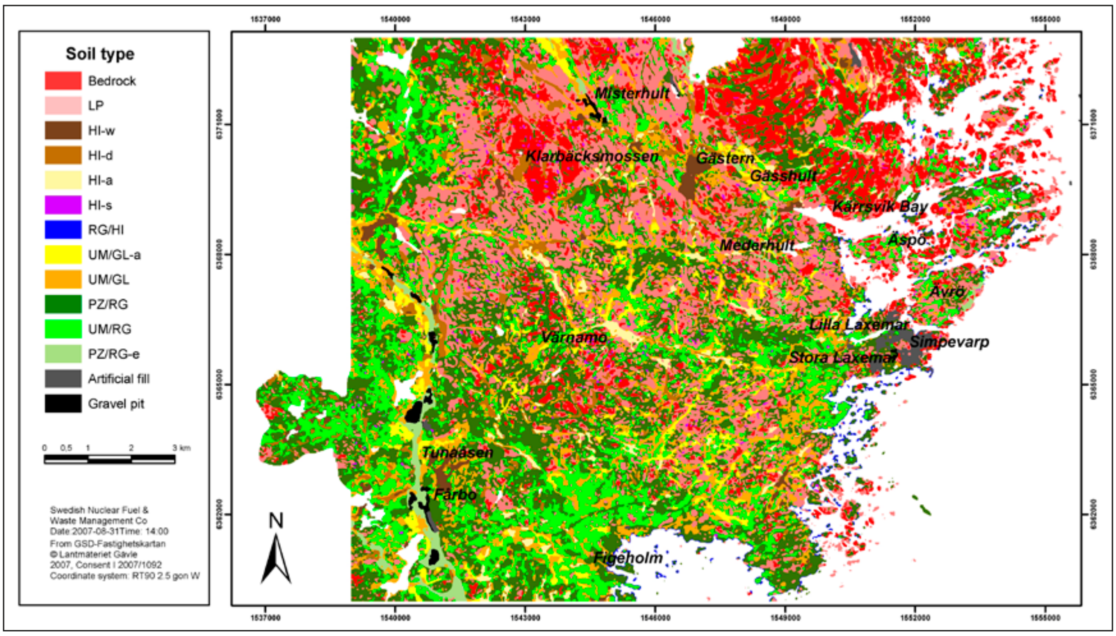


Figure 3-6. *Spatial distribution of different soil types in the Laxemar-Simpevarp area. The map is based on field studies and interpretations of other geographical information such as maps of QD and vegetation. Since the most detailed mapping of QD took place in the Laxemar River catchment, the soil map is more reliable in that area /Sohlenius and Hedenström 2008/. Soil type codes correspond to soil classes in Table 3-4.*

Table 3-4. Spatial coverage of the soil classes in the Simpevarp regional model area. From /Sohlenius and Hedenström 2008/.

Soil class	Land type	GIS map soil class	Laxemar-Simpevarp regional model area Coverage (%)
No soil	Exposed bedrock	Bedrock	11.1
Leptosol	Mostly rock outcrops and till with coniferous forest	LP	23.6
Podzol/Regosol	Mostly till in areas with coniferous forest	PZ/RG	25.2
Podzol/Regosol	Glaciofluvial material with coniferous forest	PZ/RG-e	1.4
Umbrisol/Regosol	Deciduous forest in till-dominated areas	UM/RG	15.7
Umbrisol/Gleysol	Meadows	UM/GL	10.9
Histosol	Forested peatlands, artificially drained	HI-f	3.7
Histosol	Open wetlands	HI-w	1.7
Histosol	Arable land, artificially drained	HI-a	1.7
Histosol	Small peatlands	HI-s	0.6
Regosol/Histosol	Shoreline areas, dominated by till	RG/HI	0.6
Umbrisol /Gleysol	Arable land, mostly artificially drained	UM/GL-a	2.8
No soil	Artificial fill	Artificial fill	0.6
No soil	Gravel pit	Gravel pit	0.4

Table 3-5. Some climate characteristics the Laxemar-Simpevarp area. Data are for 2004–2007 for Äspö, Simpevarp /Werner 2009, Werner et al. 2008/.

	Simpevarp
Latitude, longitude	57° 25' N, 16° 33' E
Mean annual temp.	+8°C
Min.–max. daily temp.	–14 – +24°C
Mean annual precipitation (mm)	600
Vegetation period	April–October
Length of vegetation period * 2004–2007 (Äspö temp. data)	224 days

*Starts when 5 consecutive days have a daily mean > +5º. Ends when 4 consecutive days have a daily mean < +5º.

Precipitation demonstrates a near-coastal gradient, with less precipitation at the coast compared to areas further inland. Based on long-term meteorological data from surrounding stations, the Swedish Meteorological and Hydrological Institute (SMHI) has estimated the 30-year (1961–1990) annual average precipitation to be 553 mm for the Äspö station (on the coast) and 630 mm for the Plittorp station (further inland). For the three years 2005–2007, for which data are available from all discharge-gauging stations (monitoring commenced at one station in Feb. 2005), the site-average specific discharge can be estimated to be c 165 mm y^{-1} (or c 5.2 L s^{-1} km^{-2}), which is within the interval of the regional long-term average estimated by /Larsson-McCann et al. 2002a/. During the same period (2005–2007), annual average precipitation was c 580 mm on Äspö and c 620 mm in Plittorp, whereas potential evapotranspiration was c 540 and 530 mm y^{-1}, respectively. Based on available site investigation data, the site-average water balance for the years 2005–2007 can thereby be estimated to be P = 600 mm y^{-1}, ET (actual evapotranspiration) = 435 mm y^{-1} and R (specific discharge) = 165 mm y^{-1}.

Measurements of ground frost penetration at four locations in the Laxemar-Simpevarp area show that the ground is generally frozen from approximately the middle of November until the middle or end of March. The measured frost depth is usually in the interval 0.05–0.15 m. Depending on air temperature and snow depth, the frost depth can be up to 0.5 m (Äspö, Grillplatsen, Feb. 2003), but winter observations also show zero frost depth (e.g. Grindstugan, Jan. 2006).

The main lakes at the site are Jämsen (0.24 km^2), Frisksjön (0.13 km^2), Sörå (0.10 km^2), Plittorpsgöl (0.03 km^2), Fjällgöl (0.03 km^2) and Grangöl (no size data). These relatively small lakes are shallow, with average depths in the range 1–4 m and maximum depths in the range 2–11 m. All lakes are located above sea level, which means that no sea water intrusion takes place. Wetlands cover a total of c 3% of the delineated catchment areas /Brunberg et al. 2004b/.

Most streams in the Laxemar-Simpevarp area are affected by land improvement and drainage operations. The flow in the streams demonstrates seasonal variability; in particular, the smaller streams are dry during a large part of the year. Groundwater levels in Quaternary deposits are shallow, on average less than 1 m below the ground surface during c 50% of the time. Groundwater-level monitoring below lakes indicates that there is generally little interaction between lake water and groundwater in Quaternary deposits, and such interaction is limited to near-shore areas.

Figure 3-7. *A view of the Laxemar-Simpevarp area in early spring.*

3.2.2 Vegetation

The area is young for the same reasons as in the Forsmark area, see 3.1.1 “Soil types”, but has a higher-relief topography than the Forsmark area e.g. /Brydsten and Strömgren 2005/. A number of intersecting valleys are surrounded by higher-lying till and bedrock outcrops, and agricultural land is located along the valleys. Most of the Laxemar-Simpevarp area is covered with conifer forests, where Scots pine and Norway spruce dominate (Figure 3-7, 3-8, Table 3-6). Mires are common, but not to the same extent as in the Forsmark area. Many of the lakes are surrounded by some mire vegetation, whose extent depends on the depth of the lake and how far the succession of the lake has proceeded. The spatial distribution of a number of different vegetation types was reported by /Boresjö Bronge and Wester 2003/ in a vegetation map that was constructed in the same way as for the Forsmark area and later updated with regard to clear-cuts using information from the Swedish Forest Agency for the period mid-2000 to mid-2006 (Figure 3-8, Table 3-6).

Table 3-6. Vegetation classes and their spatial coverage in percent of the covered land area (water excluded).

Gridcode	Vegetation type	Area (m^2)	Coverage (%)
11	Old spruce-dominated forest, mesic-wet types	5,476,403	2
12	Young spruce-dominated forest, mesic-wet types	5,351,123	2
13	Old pine-dominated forest, mesic-wet types	52,072,419	21
14	Young pine-dominated forest, mesic-wet types	4,548,817	2
15	Dry pine forest on acid rocks	30,424,644	12
23	Coastal deciduous forest (birch/oak) or thicket on clear-cuts on coastal rocks	3,273,737	1
24	Birch forest or oak/maple mixed with conifers (pine/spruce)	6,498,417	3
25	Oak-dominated deciduous forest	3,847,137	2
30	Mixed forest (conifers/deciduous)	34,778,576	14
41	Old clear-cut, young spruce	1,058,477	0.4
42	Old clear-cut, young pine	23,521,837	9
43	Old clear-cut, unspecified conifer	21,795,895	9
44	Old clear-cut, birch thicket	17,003,778	7
45	Old clear-cut, birch thicket/meadow type	1,887,515	1
50	New clear-cut 1999–2006	7,909,199	3
62	Forested wetland, pine-dominated	1,956,094	1
63	Forested wetland, birch-dominated	1,229,725	0.5
71	Open wetland, hummock mire	323,297	0.1
72	Open wetland, poor lawn mire	727,681	0.3
73	Open wetland, lush lawn mire	299,972	0.1
74	Open wetland, very lush lawn mire, with tall herbs	402,731	0.2
75	Open wetland, very lush lawn mire, with willow	91,407	0.04
76	Open wetland, poor carpet mire, Sphagnum-dominated	33,936	0.01
77	Open wetland, lush swamp fen	543,738	0.2
78	Open wetland, lush swamp fen, reed-dominated	1,522,632	1
79	Open wetland, reed-dominated, poorer or wetter	960,251	0.4
80	Floating mats/macrophytes	134,344	0.1
81	Arable land	9,075,976	4
82	Other open land (pastures and meadows)	9,428,792	4
83	Coastal rocks	1,424,564	1
85	Sand or stone pit	576,021	0.2
91	Holiday house	142,066	0.1
92	Industry	111,277	0.04
93	Low-rise house	884,420	0.4
96	Other hard surfaces (e.g. asphalt)	1,219,829	0.5

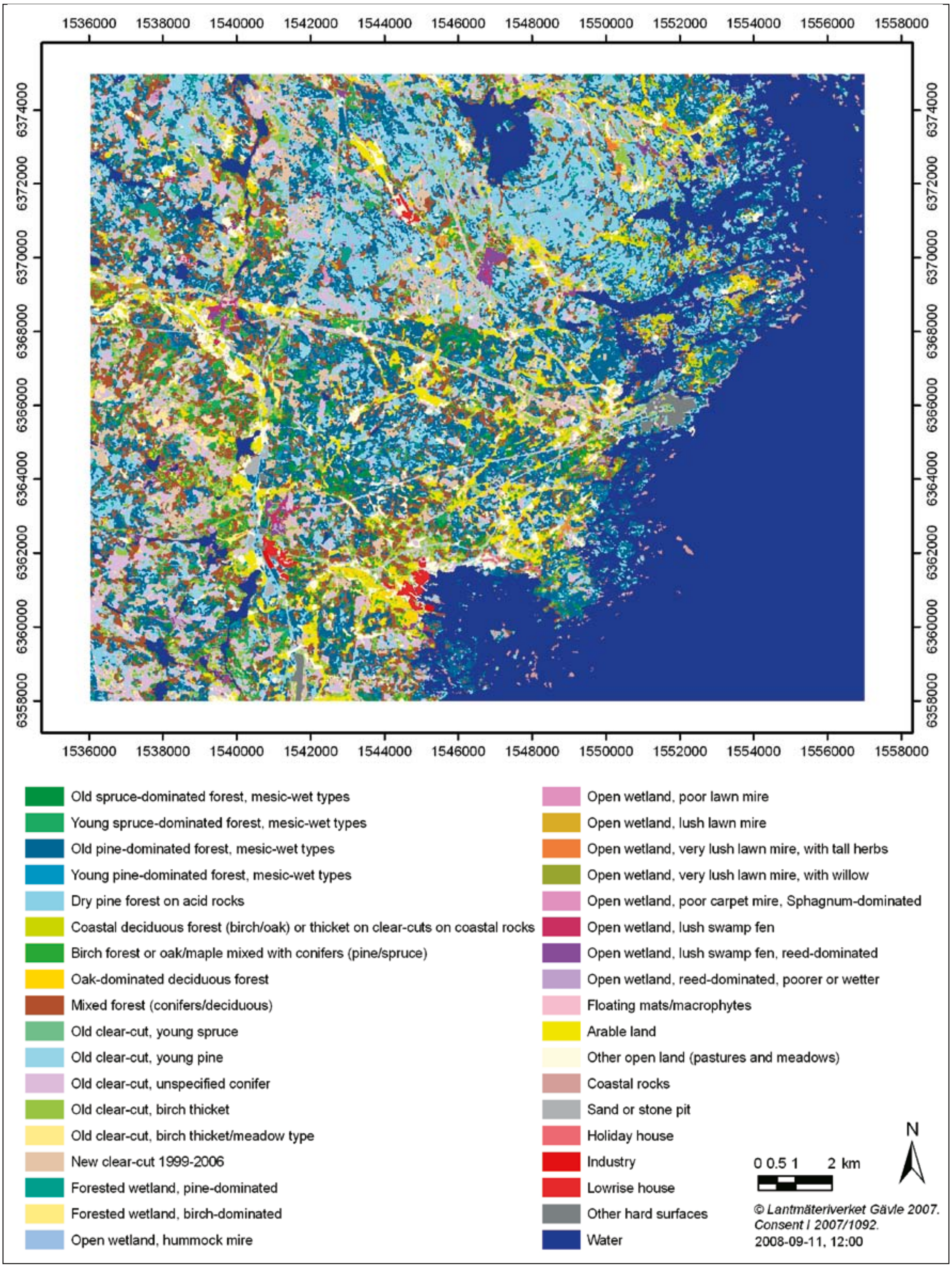


Figure 3-8. *Vegetation map of the Laxemar-Simpevarp area, which is a partially updated version based on /Boresjö Bronge and Wester 2003/.*

4 Detailed descriptions of the terrestrial areas and their characteristics at the two sites

This chapter describes terrestrial biotic and abiotic properties that define and characterize the terrestrial areas in Forsmark and Laxemar-Simpevarp. These descriptions cover important components of the terrestrial ecosystem, such as Quaternary deposits, vegetation, fauna, and interactions between different parts of the ecosystem. They will also be used and further elaborated on in the following chapters.

The landscape was divided into three main ecosystems: lake, sea and terrestrial. The aquatic systems are further described by /Nordén et al. 2008, Wijnbladh et al. 2008/. Wetland ecosystems are regarded as being part of the terrestrial systems (as opposed to aquatic systems) due to similar soil and plant processes (see Section 4.1.1 for a more detailed description).

4.1 Vegetation

The vegetation in the terrestrial system is classified into three major vegetation types: wetlands, agricultural land and forests. This subdivision was chosen due to differences in ecosystem processes, land use and the feasibility of detecting these ecosystems in reality, e.g. by remote sensing. This classification of the vegetation should not be confused with a static view of the landscape, but is rather a convenient way of describing the landscape at a certain point in time.

4.1.1 Wetlands

Introduction

Wetland ecosystems have unique characteristics because they are transition areas and ecological interfaces between aquatic and terrestrial ecosystems in a landscape. Two unique characteristics of wetlands are the waterlogged soil and the resulting anaerobic conditions /Mitsch and Gosselink 2000/. They possess properties from both aquatic and terrestrial systems and provide many ecological services as sources, sinks and transformers of a large number of chemical and biological materials, for example peat accumulation. Due to their hydrological properties they also provide unique habitats in the landscape that serve as nurseries and feeding areas for a large variety of both terrestrial and aquatic species. Wetlands have been called “biological supermarkets” because of the extensive food web and rich biodiversity that they maintain /Mitsch and Gosselink 2000/.

There is a large diversity of wetlands and some of them are among the most productive ecosystems on earth. In general, many names exist for wetland ecosystems and as many as 27 common terms for various wetland types in the world were found by /Mitsch and Gosselink 2000/ The mires in the Nordic countries can be divided into five main groups that can be subdivided into vegetation types and subgroups /Påhlsson 1998/. Because wetlands are a diverse group of ecosystems, it is often a challenge to define and classify them. In this report, we use the following overall definition of wetlands.

Wetlands are land where water, during a large part of the year or all year round, is close to, under, at or just above the ground surface (from /Landin 2002/). In addition, wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes (plants that are adapted to wet habitats); (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is non-soil and is saturated with water or covered by shallow water at some time during the growing season of each year (from /Cowardin et al. 1979/).

Water zones covered with floating vegetation or with submersed species and sparse reed growth, and water zones with a water depth up to 2 m, often included in wetlands, are considered to be a part of the lake or sea ecosystems in this site description. The reason for excluding these water zones from the wetland ecosystem is that the material produced in the littoral zone does not accumulate to the same extent in those areas; instead it is washed out and accumulates at the bottom of the lake or sea.

Location and function

Climate and geomorphology are the major parameters that define the degree to which wetlands can exist. Hydrology affects the physicochemical environment, including the soils, and together they determine what and how much biota, including vegetation, is found in the wetland /Mitsch and Gosselink 2000/.

Wetlands are often situated downstream in watersheds and in depressions that receive large surface runoff or where infiltrated precipitation comes to the surface. Wetlands also alter the hydrology of streams and rivers by impeding water flow and enhancing sediment deposition, and thereby function as a filter for coastal waters with the ability to retain nutrients as well as contaminants. Wetlands have therefore been called “the kidneys of the landscape” /Mitsch and Gosselink 2000/.

Wetlands can be divided into the following functional groups: permanent wetlands, which are constantly saturated, and temporary wetlands, with periodic inundation and a dry period. Permanent wetlands are in general less productive than temporary or seasonal wetlands and some are very unproductive /Horne and Goldman 1994/. The small amount of available oxygen slows down sediment decomposition and nutrient recycling and peat deposits accumulate if conditions are acidic. Permanent wetlands in temperate and tropical climates are generally dense stands of a few species of grasses, reeds or specially adapted trees. In cool, wet, alpine or polar climates, vascular plants are generally scant and the wetland is composed of infertile and acidic peat bogs of *Sphagnum* and other moss species. Temporary wetlands typically have a periodic inundation and a dry period when the whole or most of the wetland regains terrestrial conditions. During the dry season, the decomposed plants produce a rich particulate organic base for the next season’s detritivores. The decomposition process releases some inorganic as well as organic nutrients to the soils. These can in some cases be flushed out during the early spring flooding or be incorporated in organisms that consume water from the wetland. This cycle of wet and dry periods can make these wetlands very productive during the wet period. High rates of primary production usually occur in spring, when wetlands are particularly important as nursing grounds for e.g. birds, fish, amphibians and insects.

Colloidal and particulate material has a high capacity for adsorbing many radionuclides, and the large amount of water seeping through the wetlands may result in an accumulation of radionuclides in these ecosystems. The numbers and position of wetlands in the landscape may hence have a major impact on the transportation of radionuclides. Accordingly, some types of wetlands (temporarily inundated floodplains, riparian swamps) are known to accumulate nutrients and contaminants such as radionuclides /Mitsch et al. 1979, Stark et al. 2006/. However, no major water flows are currently to be found on either of the two sites /Nordén et al. 2008/, potentially limiting both delivery of contaminants to the wetlands and further transport from the wetlands.

In addition to soil properties, topography and vegetation are also of great importance for retention of particulates and associated radionuclides in a wetland ecosystem /Mungur et al. 1995/. For example, when a river or a stream is in flood, the running water, containing colloids and particles, inundates the wetland. Here the water velocity is impeded and the colloids and particles will start to sediment on the ground surface. If the wetland area contains large amounts of tall vegetation, the vegetation itself may filter the colloids and particles in the water. The water velocity will also slow down faster if there is tall and thick vegetation on the inundated area, enhancing the sedimentation rate. The result will be that colloids and particles settle on the vegetation and on the ground surface in the wetland. Radionuclides with a high affinity for colloids and particles such as ^{137}Cs will be greatly affected by these processes (Table 4-1).

Table 4-1. Factors that influence retention of radionuclides (particles), especially ^{137}Cs, in wetlands, (after /Stark et al. 2006/).

Factor	Condition	Mechanism of retention	Reference
Type of soil	peat or mineral soil	^{137}Cs high affinity for clay minerals	/Sawhney 1972, Broberg and Andersson 1991, Avery 1996/
Duration of saturation	permanent or temporary	dry periods; in constantly saturated area ^{137}Cs is more mobile	/Nylén and Grip 1991, Hilton et al. 1993, Saxén 1994/
Type of vegetation	tall or short, thick or scarce	tall and thick vegetation filters colloids and particles	/Horrill 1984, Mungur et al. 1995/
Degree of salinity	marine water or freshwater	freshwater; in saline water Cs^+ is more mobile	/Horrill 1984/
Level of pH	high, neutral, low	high or neutral pH: high level of H^+-ions (low pH) releases Cs^+ from soil particles	/Munthe et al. 2001/
Level of nutrients in soil	high or low	high uptake of ^{137}Cs by plants if low K^+ and high NH_4^+ concentration	/Camps et al. 2003/
Topography	elevated or low areas	hollows and depressions can enhance sediment deposition	/Jeffries et al. 2002, Van Der Perk et al. 2002/

Wetland nomenclature

In English-speaking countries, wetlands are divided on the basis of structure into the following groups: bog and fen, marsh, and swamp. In this site description, the following wetland groups are used, based on the Swedish system for enhancing biological diversity /Landin 2002/: mires (bogs and fens), freshwater shores (wet meadows, marshes, reed belts (*Phragmites*) along lakes and running water), marine shores, and forested wetlands (deciduous and coniferous forest swamps; Table 4-2). Forested wetlands are treated as a separate group (even though some could be classified as e.g. mires) because they often show great biodiversity and are therefore important in risk assessment.

Table 4-2. Wetland groups with subclasses used in this report. After /Landin 2002/ and /Påhlsson 1994/.

1. Mires
  a) bogs
  b) fens
    poor fens
    intermediate fens
    rich fens
    extremely rich fens
2. Freshwater shores
  a) wet meadows
  b) marshes
  c) reed belts
3. Marine shores
4. Forested wetlands
  a) deciduous forest swamps
  b) coniferous forest swamps

Bogs are peat-accumulating wetlands that have no significant inflows or outflows and support acidophilic mosses, particularly *Sphagnum* species. Fens are also peat-accumulating wetlands, but they receive some drainage from the surrounding mineral soil and usually support marsh-like vegetation. This results in a more alkaline pH than found in bogs, which never reach a higher pH than the pH of the precipitation. Freshwater shores along streams and lakes are defined as regularly or constantly inundated wetlands characterized by emergent herbaceous vegetation adapted to saturated soil conditions. In European terminology, wet meadows and marshes do not accumulate peat and have a mineral soil substrate /Mitsch and Gosselink 2000/. Reed belts can accumulate reed peat along lake shores and along sheltered brackish water sea shores which are part of the marine shores. Forested wetlands (swamps) are wetlands dominated by trees or shrubs. In Europe, wetlands dominated by reed are sometimes included in the sub-class swamps, but not in this report (Table 4-2).

Wetlands in the Forsmark area

In the Forsmark area, wetlands occur frequently and cover 10–20% of the area in the three major catchments and up to 25–35% in some sub-catchments /Johansson et al. 2005/ (Figure 4-1). The spatial coverage of different wetland types, forested and open wetlands, in relation to the total land area was estimated based on a vegetation map /Boresjö Bronge and Wester 2002/ (Table 4-3).

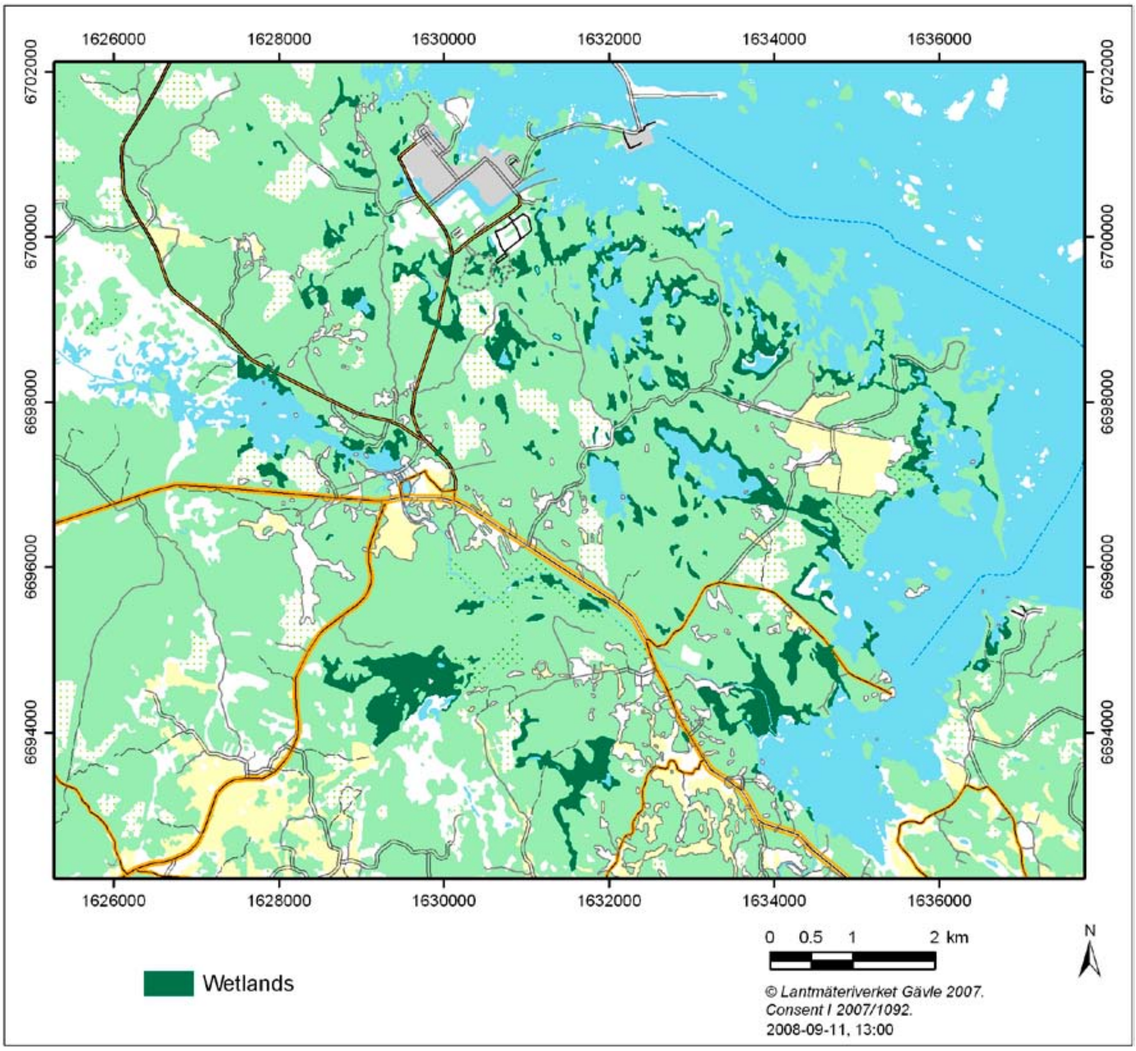


Figure 4-1. *Wetlands identified in the Forsmark area.*

Table 4-3. Wetlands in the Forsmark area. The number of objects, their total area, and their relative coverage of the total wetland area and total land area identified on the vegetation map /Boresjö Bronge and Wester 2003/.

Vegetation class	N	Area (ha)	% of wetland area	% of total area
Forested wetland	472	251	26.5	3.1
Open wetland	1,139	697	73.5	8.5

A major part of the wetlands in the Forsmark area are coniferous forest swamps and fens. The wetlands are characterized by a high calcareous influence, resulting in the extremely rich to intermediate fen types common in this area /Göthberg and Wahlman 2006, Jonsell and Jonsell 1995/. These fen types lack the dominance of *Sphagnum* species in the bottom layer and are instead dominated by brown mosses e.g. *Scorpidium scorpioides*. All mires were classified as calcareous (rich or extremely rich) fens except for one, and two were classified as mixed mires (with bog and fen characteristics) /Göthberg and Wahlman 2006/.

Most fens in the Forsmark area show indications of terrestrialization, resulting in new hydrological conditions when a fen replaces a lake. One cause of this is that many wetlands are heavily dominated by a dense and high stand of common reed (*Phragmites australis*) (Figure 4-2). Most fens investigated have at least some clear open water and sometimes a dense vegetation of *Charophytes* /Göthberg and Wahlman 2006/. In the Forsmark area, large bogs are rare because they have had too little time to develop in the young terrestrial environment (See wetland development in Chapter 10).

Other important wetland types found in the Forsmark area are the freshwater shores (wet meadows or marshes) and riparian deciduous forest swamps along streams that are inundated at least once a year by the stream and affected by overbank sedimentation (Figure 4-3). Such areas can function as sediment traps and thus as traps for nutrients and contaminants. An investigation conducted in parts of the Forsmark area indicates that the flat topography in the area promotes the occurrence of small floodplains /Carlsson et al. 2005/. In their investigations, wetlands along three running waters in Forsmark reflect the general characteristics of the area: a flat lowland area close to the sea with small catchments. Accordingly, they suggest that surrounding wetland areas that are flooded during high-flow periods may be of importance for the retention of different substances that are transported by the water to the sea. The size of flooded areas adjacent to streams is further described in /Nordén et al. 2008/.

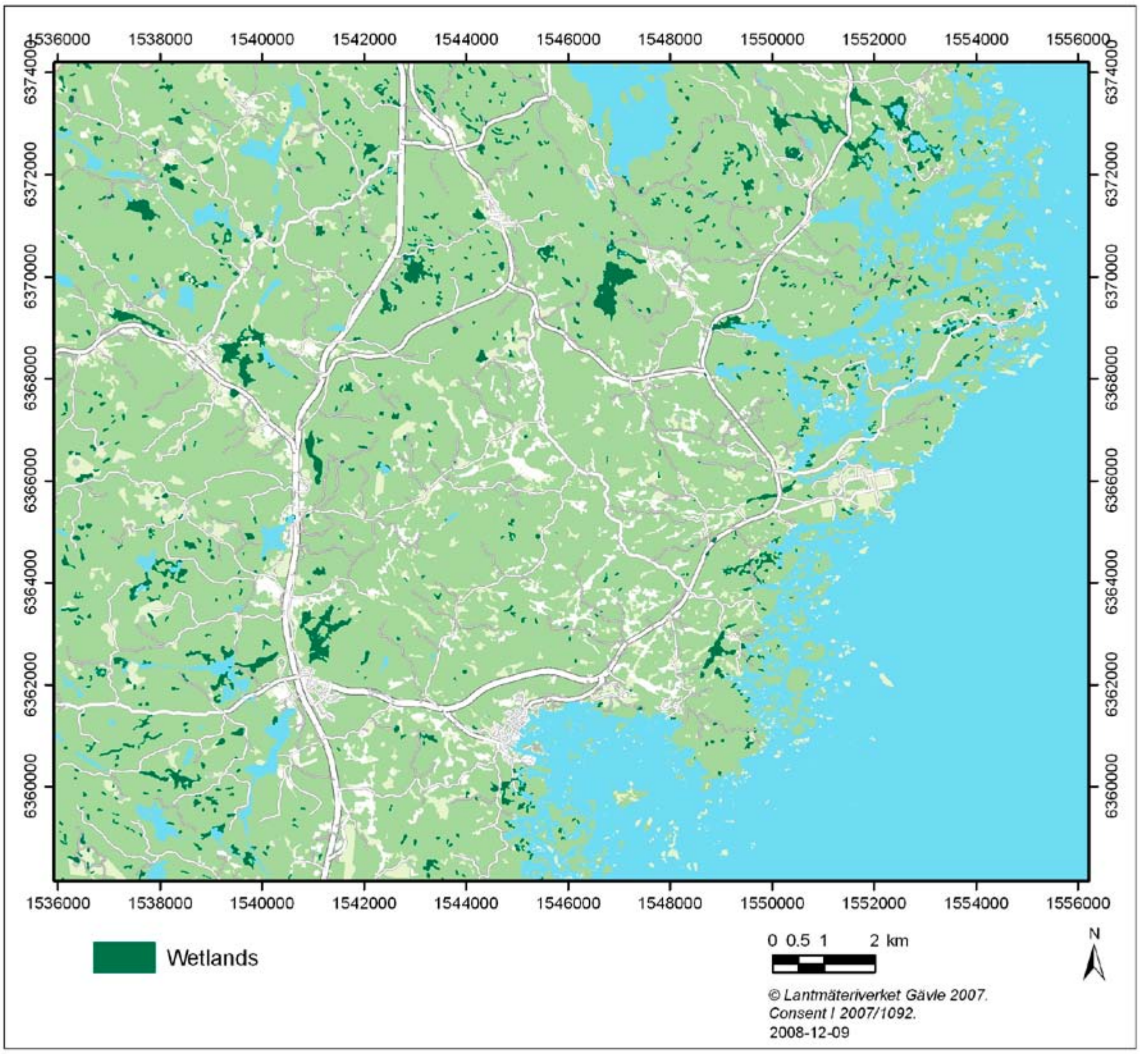
***Figure 4-2.** A wetland in the Forsmark area dominated by reed (Phragmites australis).*

Wetlands in the Laxemar-Simpevarp area

Wetlands are less frequent here, covering only 3% of the area in the main catchments (Figure 4-4), and are characterized by nutrient-poor fens /Rühling 1997, SNV 1984/. Bogs are not yet numerous in the area, partly due to the young age of the terrestrial environments and the low annual precipitation in the area /Rühling 1997/. Most of the wetlands in the Laxemar-Simpevarp area have one of two histories: former lakes or isolated sea bays that have become overgrown due to changed hydrological conditions, and wetlands adjacent to running waters subject to inundation /Rühling 1997/. In the region, wetland areas have been reduced to a great extent due to agricultural activities and extensive ditching. The riparian deciduous forest swamps and inundated wet meadows in particular have probably been reduced/ditched and used for agriculture. However, despite agricultural activities, these kinds of wetlands can still be found in the area. Some alder forest swamps are of small size (500 m^2) and have not been included on the vegetation map. Some peatland areas, former mires, are also used for forestry today.

The spatial coverage of different vegetation types, forested and open wetlands, in relation to the total land area was estimated based on a vegetation map /Boresjö Bronge and Wester 2003/ (Table 4-4).

Figure 4-3. *The largest running water in the Forsmark regional area, the Forsmark river. The bare soil at the river sides indicates fluctuating water levels. The river bank on the right is built up from fine sediments and organic material deposited by the river.*



© Lantmäteriverket Gävle 2007.
Consent I 2007/1092.
2008-12-09

Figure 4-4. Wetlands identified in the Laxemar-Simpevarp area.

Table 4-4. Wetlands in the Laxemar-Simpevarp area. The number of objects, their total area, and their relative coverage of the total wetland area and total land area identified on the vegetation map /Boresjö Bronge and Wester 2003/.

Vegetation class	N	Area (ha)	% of wetland area	% of total area
Forested wetland	585	3,218	40	1.3
Open wetland	1,084	4,907	60	1.9

Flooded areas (riparian wetlands) along streams in catchments 6, 7, 9, and 10 (Figure 8-3) were investigated by /Strömgren et al. 2006/. The length of the stream stretch that was flooded during the period of investigation was noted. Most of the streams investigated (including Mederhultsån, Kåreviksån, Ekerumsån, and Simpevarpån) included flooded areas, although the stretches were often short in comparison to the total length of the stream (See also Table 4-1 in /Nordén et al. 2008/). Streams were also affected by human activities in several places and ran through underground pipes sometimes for long stretches /Strömgren et al. 2006/. The flooded areas of the streams most often occurred downstream close to the outlet into the sea (Figure 4-5). In the northern part of the area where bedrock outcrop is common, small peat-accumulating nutrient-poor wetlands are found in the depressions in the bedrock (Figure 4-6).

Figure 4-5. The largest river in the Simpevarp regional model area, the Laxemarån. The river bank is a regularly flooded deciduous forest on fine sediments deposited by the river close to the outlet into the sea.

***Figure 4-6.** A typical poor wetland in the northern part of the Laxemar-Simpevarp regional model area situated high, surrounded by bare rocks and Scots pine forest on shallow soil.*

Wetland vegetation

The Forsmark area

The large amount of calcareous material in the till in the Forsmark area influences the vegetation and favours calciphilous plants. For example, brown mosses, especially *Scorpidium scorpioides*, are found in many fens where *Sphagnum* species usually occur /Lundin et al. 2004, Löfgren 2005/. Also, a number of orchids such as *Dactylorhiza incarnata*, *D. traunsteineri* and *Epipactis palustris* regularly occur in mires and coniferous forest swamps /Göthberg and Wahlman 2006, Jonsell and Jonsell 1995/ together with other calcareous influence indicator species such as *Carex appropinquata* and *Parnassia palustris* /Göthberg and Wahlman 2006/. Furthermore, more investigated mires had indicator species of calcareous influence than indicator species of bog-like conditions (total sums 114 and 88). In addition, a number of red-listed species have been found in the fens, e.g. *Carex pulicaris* /Göthberg and Wahlman 2006/ and *Liparis loesli* /Hamrén and Collinder 2010/. *Phragmites australis* was dominant in larger fens /Lundin et al. 2004, Löfgren 2005/.

In addition, the results from /Göthberg and Wahlman 2006/ show that the vegetation pattern depends on the level above the sea (Figure 4-7). With increasing level above the sea, bog indicator species became more abundant (Regression, $p < 0.001$). This correlation would probably also be found between age of the wetland and number of bog species because the older wetlands are situated higher above the sea.

Small pools can be found along the rocky sea shores in the Forsmark area. The pools situated closest to the sea regularly receive an influx of brackish water from the sea and do not contain many plant species. In pools further up on the shores, species such as *Eleocharis mamillata*, *Carex acuta,* and *Sparganium angustifolia* occur /Jonsell and Jonsell 1995/. When a pool has ended up above the shoreline due to land uplift in the area, the pool changes its characteristics. The pool becomes nutrient poorer and *Polytrichum commune* and *Sphagnum* mosses start to appear. Eventually, miniature bogs are formed where *Rubus chamaemorus, Vaccinium uliginosum, V. oxycoccus,* and *Empetrum hermaphroditum* are established /Jonsell and Jonsell 1995/. Often the final stage bog is of such a small size that it is not indicated on the vegetation map by /Boresjö Bronge and Wester 2003/.

Shores with wave-washed till are most common in the Forsmark area, while rocky shores and shores with fine sediments also occur. The flat emerging till shores outside Forsmark have a sea shore vegetation zonation that is defined by their tolerance to water inundation and salt sprays /Jerling et al. 2001, Jerling 1999/. The first pioneer woody species is Hawthorn (*Hippophaë rhamnoides*), closely followed by the tree alder (*Alnus glutinosa*). Both these species have a litter that is rich in nitrogen, and this facilitates the establishment of many species. *Festuca rubra* is a common species on all types of marine shores in the area /Jonsell and Jonsell 1995/.

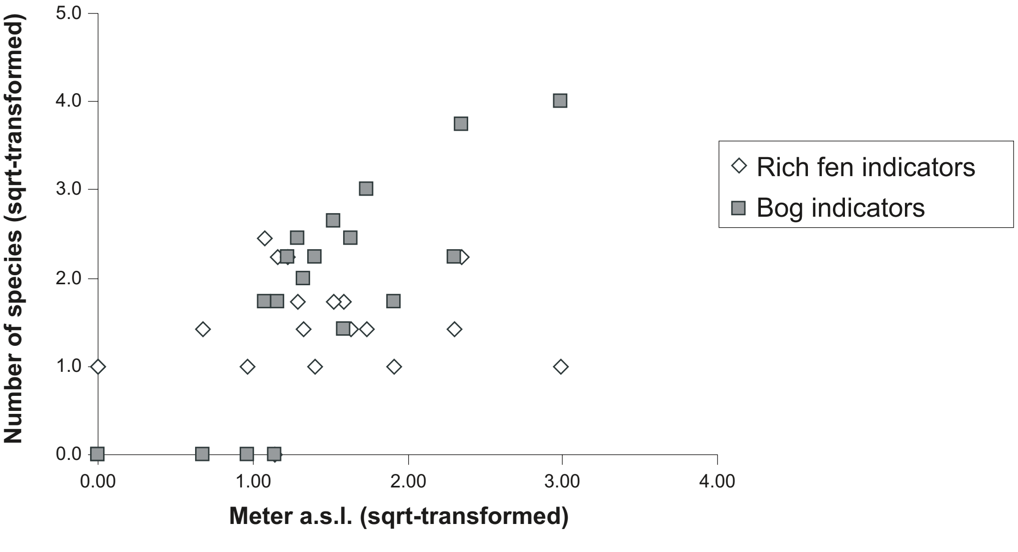


***Figure 4-7.** Number of species, bog indicators and rich fen indicators (calcareous influence), in relation to metres above sea level in the Forsmark area.*

Wetlands along running waters belonging to the group freshwater shores were investigated by /Carlsson et al. 2005/. Vegetation growing along three streams that enter the Baltic Sea from the Forsmark area was identified (further described in /Nordén et al. 2008/. Tall herbs such as *Filipendula ulmaria, Lysimachia trifoliata, Iris pseudacorus* and the tree species *Alnus glutinosa* are often found in riparian alder forest swamps or floodplains functioning as sediment traps.

The Laxemar-Simpevarp area

Poor fens are the dominant type of mires in the Laxemar-Simpevarp area /Rühling 1997/. Vascular plant species found in these poor fens are *Menyanthes trifoliate, Galium palustre, Carex rostrata, C. lasiocarpa, C. panacea, C. echinata, Eriophorum angustifolium, Agrostis canina,* and *Molinia caerulea*. Intermediate fens that have a slightly higher nutrient content can also be found in areas with poor nutrient status if they have access to moving groundwater that increases the nutrient supply to the wetland. *Galium uliginosum, Succisa pratensis, Iris pseudacorus,* and *Carex elata* are often found in intermediate fens in the Laxemar-Simpevarp area. *Equisetum palustre* and *Parnassia palustris* are also occasionally observed. At the edge surrounding fens, usually a five to ten metre zone between the moss-covered part of the fen and surrounding land, tree species *Betula pubescens* and *Alnus glutinosa* and the bush species *Salix cinerea* and *Frangula alnus* are usually found.

As mentioned above, bogs are not so numerous in the Laxemar-Simpevarp area, whereas coniferous forest swamps (with *Pinus* sp.) are more common /Rühling 1997/. Common species in *Sphagnum*-dominated wetlands are *Drosera rotundifolia, Vaccinium oxycoccos, Andromeda polifolia, Rhododendron tomentosum, Rubus chamaemorus* and *Eriophorum vaginatum* /Rühling 1997/.

Marshes (*Sw. mader*) along streams and lakes occur mainly near the larger watercourses and are subject to flooding during periods of high flow. They are characterized by vascular plant species such as *Equisetum fluviatile, Stellaria palustris, Potentilla palustris, Peucedanum palustre, Lythrum salicaria, Lysimachia vulgaris, L. thyrsiflora, Alisma plantago-aquatica, Iris pseudacorus, Carex vesicaria, C. rostrata, C. acuta,* and *C. elata* /Rühling 1997/.

Common species in wet meadows with tall herbs are *Caltha palustris, Ranunculus acris, Thalictrum flavum, Filipendula ulmaria, Geum rivale, Geranium sylvaticum, Lythrum salicaria, Angelica sylvestris, Lysimachia vulgaris, Molinia caerulea* and *Deschampsia cespitosa* /Rühling1997/. Wet meadows occur in areas with running groundwater, in discharge areas, and along creeks and streams.

The most common type of marine shore is the rock outcrop and boulder type, but marine meadows also occur in the area /Rühling 1997/. Marine meadows can be found adjacent to shallow bays where fine sediments deposit and these are dominated by *Festuca rubra, Agrostis stolonifera, Juncus gerardii, Blysmus rufus, Poa pratensis* ssp. *irrigata, Carex viridula* var. *pulchella, Eleocharis quinqueflora, Centaurium littorale, Ophioglossum vulgatum, Tetragonolobus maritimus, Trifolium fragiferum* and *Potentilla anserina*.

Alder forest swamp occurs in the Laxemar-Simpevarp area in moist stream valleys on nutrient-rich soils and near freshwater lake shores /Rühling 1997/. Common species are *Athyrium filix-femina, Phegopteris connectilis, Stellaria alsine, Catha palustris, Ranunculus flammula, R. repens, R. auricomus, Cardamine pratensis* ssp. *dentata, Filipendula ulmaria, Geum rivale, Solanum dulcamara* and *Scirpus sylvaticus*.

Quarternary deposits

The Forsmark area

Current investigations in the Forsmark area indicate that most peatlands are shallow, having evolved from old lake sediments /Bergström 2001, Fredriksson 2004/. During the process of land uplift, the coastal waters of the Baltic Sea continuously became more and more shallow. Finally, the water became stagnant and shallow enough for sediment-rooted vegetation to become established, and a process of terrestrialization started to form the present peatland /Fredriksson 2004/. This can be recognized from the findings in most examined peat profiles. A thin layer of *Phragmites* peat is present at the bottom, above a layer of gyttja of varying thickness. Over the *Phragmites* layer, mostly fen *Carex* peat of a varying degree of humification or more humified fen wood peat is found. On one extensive peatland (an open bog), /Bergström 2001/ found *Sphagnum* peat directly above the *Phragmites* layer in what was previously open water. In the same peatland there were relatively thick layers of fen wood and *Phragmites* peat in areas that had presumably been more sheltered. The current lakes in the area are often bordered by zones of reed wetlands and wooded fens, while still open in the middle, which is consistent with terrestrialization. Depending on the size of the lake and its supply of water, the central parts of the lake subsequently fill up with bog or fen peat.

The most common final stage of the peatlands in this area is probably a pine bog. /Fredriksson 2004/ found that the wood-fen peat was usually highly humified, but the degrees of humification in the *Carex*-fen peat varied independently among the profiles within the same peatland, indicating a variation in conditions for decomposition. Peat has developed in the more elevated areas further up from the sea; the thickness of the peat is usually less than one metre. In more low-lying areas, the peat layer is very thin or missing. The peat is underlain by gyttja and sometimes also by sand and clay layers. From existing borings /Johansson 2003, Werner and Lundholm 2004/ it is known that the peat in the wetlands can rest directly on till or be underlain by gyttja and/or clay above the till.

The Laxemar-Simpevarp area

The peat areas include both current wetlands where peat is currently being formed and former wetlands where the groundwater table has been artificially lowered. Many of the current and former wetlands have, however, not experienced a lake stage and underwent primary mire formation directly after the area was lifted above sea level. Some of the wetlands situated close to the present sea level lack a peat layer, since too short a period has elapsed since the areas were lifted above sea level. The soils in most of the present and former wetlands are dominated by histosol. The peat in some of the former wetlands has disappeared because the lowered groundwater table causes the peat to compact and oxidize and the layer of peat is becoming progressively thinner /Sohlenius and Hedström 2008/, and umbrisol/gleysol has been formed. The areas covered by wetlands have decreased significantly in the landscape, due to the lowering of the groundwater table by ditches. That was done mainly for agricultural purposes but also to improve the rate of forest growth. Several of the areas used as arable land have names ending with “kärret” or “mossen” (fen or bog), indicating an origin as wetlands.

The somewhat larger wetlands not located on bedrock are predominately fens, where the vegetation gets water from the surrounding land areas. Some of the mires are bogs, however, where the vegetation only receives water from direct precipitation. The mires in the high topographical areas generally have a thinner cover of Quaternary deposits (QD) compared to the larger present and former wetlands situated in the bigger valleys. It might, however, be possible to find small pockets with a thicker layer of QD in these small wetlands.

The bottom stratigraphy of wetlands and peat areas in Laxemar-Simpevarp area was investigated by /Nilsson 2004/. The investigation included “true wetlands” (overgrown by reed, and with gyttja as the predominant type of QD), “true peat areas” (bogs and fens), and areas on “dry land”, with just a thin layer of peat or water-laid sediments overlying the till or bedrock /Nilsson 2004/. The investigation showed that a typical top-down stratigraphy in wetlands and peat areas is peat (when present), clay gyttja and gyttja, silt-sand-gravel, postglacial clay, and glacial clay. The individual layers are on the order of 0.5–2 metres, except for the silt-sand-gravel layers, which are generally very thin.

There are numerous small wetlands in the till- and bedrock-dominated areas in the northern part of the Laxemar-Simpevarp area. Most of these wetlands are covered by peat and are shown as histosol on the soil map /Lundin et al. 2005a/. It is possible that the area of peatlands in the Laxemar-Simpevarp area could be underestimated using maps, such as the soil map or the vegetation map, because of their small size.

Surface hydrology

The Forsmark area

The hydraulic contact between the wetlands and the surrounding shallow groundwater largely depends on the stratigraphy. Low-permeable sediments will restrict the discharge of groundwater from up-gradient areas and result in a relocation of the discharge to areas where such sediments are missing. Wetlands are frequent in the more low-lying parts of the area. The gyttja in these wetlands can rest directly on till, or be underlain by clayey gyttja and/or sand and clay above the till. More fine-grained sediments indicate a less permeable layer, which means that the hydraulic contact with the surrounding groundwater system varies among wetlands in the area. Till is the dominant type of QD, covering approximately 75% of the area considered in the detailed mapping /Johansson 2008/.

No major watercourses flow through the area northeast of the main water divide to the Forsmarksån River. The annual variation in rainfall, snowmelt and evapotranspiration typically results in large flows in the brooks in the late autumn and in the spring following snowmelt. The streams downstream of the lakes Gunnarsboträsket, Eckarfjärden, and Gällsboträsket carry water most of the year, but may still be dry for long periods in dry years.

Possible future wetlands were studied in relation to hydrology and transport mechanisms by /Vikström and Gustafsson 2006/. Three lakes were chosen for the analysis: Bolundsfjärden, Eckarfjärden and Puttan. Because of its shallow depth, Bolundsfjärden will probably become a mire in the future. The lake is situated in the downstream part of the regional model area and receives runoff from upstream surface water systems. Eckarfjärden is situated in the upstream part of the catchment at a higher altitude and with a smaller inflow. Puttan is situated above a planned layout of the repository and has the potential to receive discharges from a repository. The lake also lies in the downstream part of a large discharge area. The analyses showed that the hydraulic conditions that exists today will be somewhat altered as peat is formed in the mires. In the case of Bolundsfjärden, a recharge area will be formed during the summer. The same will happen to Eckarfjärden, but Puttan will still be a discharge area after the peat has developed because of its naturally strong discharge position close to the sea.

Results from the transport modelling show that a solute in the bedrock is transported quickly towards the peat surface in discharge areas for Bolundsfjärden /Vikström and Gustafsson 2006/. After about 10 years, a steady state is reached. In the recharge area that develops in large parts of the mire, the solute is transported by horizontal dispersion, which results in much lower concentrations. Puttan has a vertical flow pattern that differs from Bolundsfjärden. The pressure of water on the peat surface is considerably lower, and for a major part of the year, Puttan is a discharge area with an upward flow direction.

The Laxemar-Simpevarp area

The main watercourses in the Laxemar-Simpevarp area have been described by /Brunberg et al. 2004b/ (Figure 8-3). They are further treated in /Nordén et al. 2008/.

There are wetlands in 20 of the 26 catchment areas identified in the Laxemar-Simpevarp area /Brunberg et al. 2004b/, and they only cover about 3% of the area. The results from the investigations of QD show that many of the wetlands in the Laxemar-Simpevarp area contain peat, and that the peat is often thinner than one metre /Rudmark 2004, Rudmark et al. 2005/. Many wetlands that contain peat have been drained. It is therefore likely that drying and oxidation have made the peat cover thinner. The groundwater table in relatively small wetlands has usually not been artificially lowered.

The bottom stratigraphy of wetlands and peat areas in the Laxemar-Simpevarp area was investigated by /Nilsson 2004/. The investigation included “true wetlands” (overgrown by reed, and with gyttja as the predominant type of QD), “true peat areas” (bogs and fens), and areas on “dry land”, with just a thin layer of peat or water-laid sediments overlying the till or bedrock /Nilsson 2004/. The investigation showed that a typical top-down stratigraphy in wetlands and peat areas is peat (when present), clay gyttja and gyttja, silt-sand-gravel, postglacial clay, and glacial clay. The individual layers are on the order of 0.5–2 metres, except for the silt-sand-gravel layers, which are generally very thin. Hence, the results indicate that the bottom layers of the wetlands and peat areas consist of low-permeable materials, indicating limited interactions between groundwater and surface water in these areas.

Management today

In both the Forsmark and Laxemar-Simpevarp areas, as in the rest of Sweden, the agriculture and forestry industries are still affecting wetland hydrology to some extent by cutting trees and building roads for e.g. forest machines that may entail drainage and destruction of wetlands. Other activities in Sweden that entail drainage of wetlands today include peat cutting, construction of roads, development, and construction of golf courses.

Peat cutting for energy production was resumed in the 1980s, after some years of no production, as a result of the energy crisis in the 1970s with rising oil prices. The cutting of peat totally changes the land and the hydrology in the area that is exploited /Svanberg and Vilborg 2001/. When a mire (with a peat layer of at least 40 cm) is used for peat cutting, the field layer is taken away and the area is extensively drained. As a consequence, water-dependent plants and animals in the mire disappear. Adjacent lakes and water courses are also affected by the changes in ecology and hydrology on the mire. Peat cutting on mires usually occurs for 20 years. However, peat cutting for soil improvement purposes can go on for a longer period. When the cutting is ended, the mire is transformed into some type of wetland or is used for forestry. Peat cutting areas occur today near both the Forsmark area in Uppsala County and near the Laxemar-Simpevarp area in Kalmar County /SCB 2000a/.

In addition, golf courses have been built in both Uppsala and Kalmar county /SCB 2000a/, but it is unclear whether these projects have entailed any ditching of wetlands.

In the Laxemar-Simpevarp area, a considerable amount of the arable land that replaced former wetlands in the woodlands remains open to this day. This land is now used for the production of hay. Only a few of the arable areas from the period of expansion in the 19th century are currently abandoned and are now either wooded or covered with bushes and small trees. Some former wetlands revert into wet areas when the former ditches become overgrown, but most former wetlands become wooded areas.

Ecosystem properties

Wetland functions or processes can be placed in five ecosystem-level categories: hydrologic flux, productivity, decomposition, biogeochemical cycling, and community and wildlife habitat /Richardson 1994/. Productivity, decomposition and biogeochemical cycling will be discussed in this section. Carbon will play a major role in the discussion since it is the major constituent of peat.

Biomass and primary production

Supplies of water and nutrients are the major factors for carbon accumulation in the ecosystem, driven by the process of photosynthesis /Chapin et al. 2002/. Wetland productivity is generally very high, and the rate of primary productivity can greatly exceed that of grasslands, cultivated lands, and most forests (Figure 4-8) /Richardson 1995/. The largest flux of carbon is the gross primary production (GPP) in the field and bottom layer, of which approximately 50% is the net primary production (NPP). A large part of the NPP is turned into litter from both above-ground and below-ground plant functional parts. The biggest pool of carbon can be found in the soil, mainly as peat /Chapin et al. 2002/.

/Brinson et al. 1981/ reviewed the primary productivity of freshwater wetlands, and the mean net biomass production of non-forested wetlands was found to vary between 400 and 900 gC m^{-2} y^{-1}. The above-ground biomass of Finnish mires was found to vary between 200 gdw m^{-2} in wet fens and 20,000 gdw m^{-2} in forested spruce swamps /Laine and Vasander 1996/, with the highest values including the tree biomass. The highest field layer biomass values are usually found in dwarf shrub rich site types, where *Ledum palustre* and *Betula nana* dominate /Laine and Vasander 1996/. In addition, a large field layer biomass is produced by communities dominated by tall sedge species. /Löfgren 2005/ investigated the biomass and NPP in the field and bottom layer of an open mire and a forested wetland in the Forsmark area and in the Laxemar-Simpevarp area. The results showed that the most productive field and ground layers overall were in the vegetation types that lacked a tree layer (Table 4-5).

Several investigations have been conducted in order to calculate the biomass of dense reed stands, in order to be able to characterize mires, preferentially in the Forsmark area, wetlands next to lakes and shallow bays (Table 4-6). The relationship between above-ground (AG) biomass and below-ground (BG) biomass seems to be highly variable. /Löfgren 2005/ found the mean AG biomass to be 6% of the BG biomass for five samples in a sheltered sea bay in the Laxemar-Simpevarp area, whereas /Alling et al. 2004b/ found it to be 43% as a mean of six sea bays in the same area. These two studies did not differentiate between living and dead roots, which most certainly can be a large part of the BG biomass.

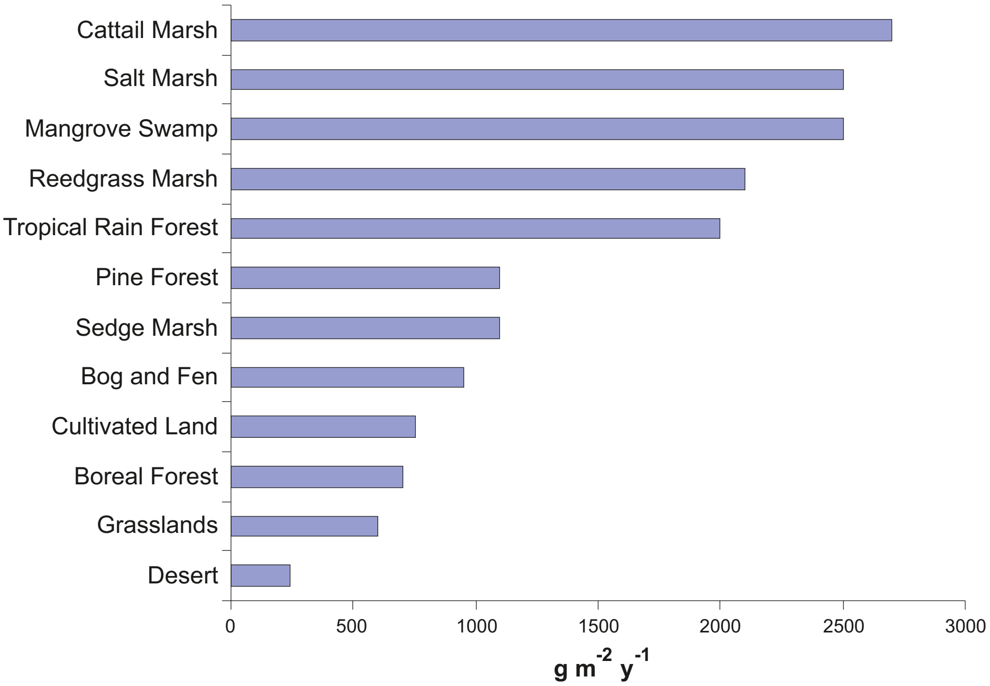


Figure 4-8. *Comparison of net primary production (NPP) between some ecosystem types. From /Richardson 1995/.*

Table 4-5. Calculated biomass and NPP for different wetlands in the Forsmark area and the Laxemar-Simpevarp area. Data describing the fens are from /Löfgren 2005/ assuming a carbon content of 50%. Data describing wetlands with a tree layer are further presented in Chapter 6 (Table 6-9).

Wetland type (Forsmark/ Laxemar-Simpevarp)	Field and bottom layer		Tree layer	
	Biomass (gC m^{-2})	NPP (gC m^{-2} y^{-1})	Biomass (gC m^{-2})	NPP (gC m^{-2} y^{-1})
Rich fen (Fm)	2,186±1,102	253±59	–	–
Poor fen (Sm)	1,453±419	342±102	–	–
Alnus-spruce swamp (Fm)	68±67	25±22	5,903±2144	362±119
Alnus shore swamp (Sm)	53±54	46±46	6,173±4117	263±89

Table 4-6. Estimates of biomass and production in reed stands (*Phragmites australis*). /Alling et al. 2004b/ investigated five sea bays, /Andersson et al. 2003/ investigated a lake and /Löfgren 2005/ investigated one sea bay. The carbon content was assumed to be 0.395 /*Scirpus acicularis*, Kautsky 1995/.

	Forsmark	Laxemar-Simpevarp	Other	Reference
Biomass (gC m^{-2})	–	2,495±1,353		/Alling et al. 2004b/
	187[1]	–		/Andersson et al. 2003/
	–	1,366±663		/Löfgren 2005/
	–	2,349		/Andersson et al. 2006/
NPP (gC m^{-2} y^{-1})	–	627±355[2]		/Alling et al. 2004b/
	187[1]	–		/Andersson et al. 2003/
	–	155±117		/Löfgren 2005/
	–	275±151[3]		/Andersson et al. 2006/

1) Only above-ground biomass in late August.
2) Only above-ground biomass in July.
3) Only above-ground biomass in June.

GPP in the field and bottom layer vegetation in a poor fen in the Laxemar-Simpevarp area was estimated to be 700 gC m^{-2} y^{-1} by /Tagesson 2007/, which was high compared to other fen studies in the Nordic countries with values ranging between 250 and 480 gC m^{-2} y^{-1} /Lindroth et al. 2007/. These ecosystems probably had smaller uptake, since they were situated further north than Laxemar. One of their study sites, Fäjemyren (480 gC m^{-2} y^{-1}), is at a similar latitude as Laxemar, but there are also other factors affecting GPP, such as nutrition, microclimate, biomass, species etc. Assuming that NPP is approximately half of GPP, the two different methods of estimating NPP in the poor fen are in good agreement (350 and 342 gC m^{-2} y^{-1}, Table 4-5).

Soil respiration

Soil respiration is the sum of the respiration from ground vegetation, roots, rhizosphere, mycorrhiza, and microbes. Temperature and moisture are the dominant factors that control soil respiration, and it also varies seasonally /Rayment and Jarvis 2000/. Anaerobic conditions slow the decay rates in wetlands, not only because of a lack of oxygen but also because of low pH, a shortage of calcium, and low soil temperatures. In wetlands where decomposition is fairly rapid and thereby restricts peat formation, there is a more or less thick humus layer on mineral soil, so they have less carbon in the soil organic carbon pool (SOC) /Lundin et al. 2004/. C-mineralization is the largest flux of carbon leaving the mire, and the difference between litter input and C-mineralization is the accumulation of organic matter. The position of the water table is the principal factor affecting CO_2 fluxes from boreal wetlands /Silvola et al. 1996/, which have consistently shown a strong positive relationship between CO_2 fluxes and water-table depth.

Estimates of wetland forest soil respiration were found to be rather high (Forsmark area, Alnus-spruce swamp SS1 450±380 gC m^{-2} y^{-1} and Laxemar-Simpevarp area, Alnus shore swamp S1 730±620 gC m^{-2} y^{-1}) /Tagesson 2007/ in comparison with estimates for a swampy mixed hardwood stand in the Harvard forest in Massachusetts of 140 gC m^{-2} y^{-1} /Davidson et al. 1998/. Others have found higher values, e.g. 396 gC m^{-2} y^{-1} from May to October 1996 for a boreal black spruce forest in Saskatchewan /Swansson and Flanagan 2001/. /Davidson et al. 1998/ explained their low values not only as being caused by wetness but also due to low input of C to the soil. In the Harvard stand in Massachusetts, trees are sparse so NPP is low as well, whereas at the Forsmark and Laxemar-Simpevarp areas, trees are dense /Tagesson 2006a/, which brings a large carbon input to the soils. Soil respiration in the poor fen in the Laxemar-Simpevarp area (990±1,840 gC m^{-2} y^{-1}) was also somewhat higher than other studies done at mires in the same region. In the Nordic countries, estimated values vary between 214 and 456 gC m^{-2} y^{-1}, where the large values were estimated for Fäjemyren, close to Hässleholm in the southern part of Sweden and the low values were estimated for Kaamanen in the northern subarctic region of Finland /Lindroth et al. 2007/.

The anaerobic conditions created in the inundated soil lead to emission of methane and hydrogen gas during decomposition. This emission rate is low compared with the main gaseous product carbon dioxide emitted during heterotrophic respiration (e.g. a boreal bog, 1–2 gC m^{-2} y^{-1} /Alm et al. 1999/ and 4 gC m^{-2} y^{-1} /Waddington and Roulet 2000/). The main determinants of methane (CH_4) emissions from peatlands are water level, temperature, and availability of substrate for fermentation. The highest CH_4 emissions have been measured from wet oligo-mesotrophic fens with abundant sedge vegetation, where annual CH_4 emissions may be over 40 g m^{-2} /Laine and Vasander 1996/. Annual CH_4 emissions from nutrient-poor dry peatlands are less than 10 g m^{-2}. Hardwood-spruce swamps, where the water level is low and moving water has a high oxygen content, may even be sinks for methane, as are mineral soil forests.

There are no estimates of soil respiration in reed belts found around lakes at the sites. However, a model constructed to evaluate the material budget for a reed stand in Austria predicted that between 33 and 48% of the annual above-ground production would decompose within 1 year, while the rest would remain in the anaerobic substrate /Asaeda et al. 2002/. In order to evaluate and calculate the turnover of the BG parts, /Asaeda and Karunaratne 2000/ estimated the annual root mortality to be between 5 and 10% depending on the climate regime.

Transport of organic matter in wetlands

Studies of dissolved organic carbon (DOC) exports to lakes, as a function of vegetation types in a catchment area have shown that wetlands export more DOC than other vegetation types (e.g. /Canham et al. 2004, Humborg et al. 2004/). /Canham et al. 2004/ calculated the export from temperate conifer wetlands, “emergent marches” and forests to be 17.5 gC m^{-2} y^{-1}, 12.5 gC m^{-2} y^{-1} and 3.5 gC m^{-2} y^{-1}, respectively, using a predictive model based on 2,750 lakes and their catchment areas in Canada. The lateral transport from a boreal bog in Sweden was estimated by /Waddington and Roulet 2000/ to be 4.2 gC m^{-2} and 6.7 gC m^{-2} in two consecutive years.

Export of DOC from terrestrial areas were calculated for Forsmark /Tröjbom et al. 2007/ and Laxemar-Simpevarp /Tröjbom et al. 2008/. Forsmark had a mean export of 2.7 gC m^{-2} y^{-1} for eleven catchments, while the corresponding figure for Laxemar-Simpevarp was 4.8 gC m^{-2} y^{-1} for 14 catchments (See Chapter 8).

An example was calculated to illustrate how much the carbon dynamics within the wetland may be influenced by input of carbon from the local discharge area /Lindborg 2005/. This was based on literature data from /Canham et al. 2004/, who estimated leaching of DOC from conifer forests to be 3.5 gC m^{-2} y^{-1}. The size of the catchment area was multiplied by this figure to get a measure of the DOC load on the wetland. Output from emergent marshes was estimated by /Canham et al. 2004/ to be 12.5 gC m^{-2} y^{-1}. The results suggested that the average accumulation of external DOC is 4% of the total input from the local wetland to the SOC pool as litter (field layer and roots). /Brydsten 2004/ found that data from six investigated lakes in the Forsmark area suggested that sediments had a high degree of material of autochtonous origin. Several other factors supported this conclusion, such as small topographic variation (small watersheds), low current velocities and low abundance of fine-grained sediments. This pattern suggests that a similar pattern would be likely for wetlands in the Laxemar-Simpevarp area.

Consequently, the external input of DOC from the drainage area is low in relation to the local flux of carbon to the SOC. In the absence of better data it is therefore assumed that the majority of the carbon deposited in wetlands is from production within the wetland.

The pool of soil organic matter and the accumulation of carbon

The net loss or accumulation of organic matter (OM) in a wetland is determined by the balance between the input of organic matter, mainly produced within the wetland, and respiration. The vertical peat growth rate calculated for Finnish mires ranges from approximately 0.2 to over 4.0 mm y^{-1} in some extreme situations /Korhola and Tolonen 1996/. The average value is about 0.5 mm y^{-1}. /Craft and Richardson 1993/ found the build-up of peat to be 1 to 2 mm y^{-1} on average in Everglades peatlands (USA). The peatlands accumulate large quantities of OM since the peat does not decompose and they therefore form an enormous reservoir of terrestrial carbon. In Everglades peatlands, the accumulation rate of organic carbon was measured to be 54–161 gC m^{-2} y^{-1}, with an average of 104 gC m^{-2} y^{-1} /Craft and Richardson 1993/. In Finnish mires, the average long-term rate of carbon accumulation shows great variation depending on the wetland type, the geographical location, the age of deposit, and the number of fires. In this material, the statistical mean was 19.9±10.7 gC m^{-2} y^{-1}, with a range of 4.6–85.8 gC m^{-2} y^{-1} /Korhola and Tolonen 1996/. The range for the actual accumulation rate was between 8.1 and 23.0 gC m^{-2} y^{-1} (mean 12.1), that is about 2/3 of the long-term rate of carbon accumulation. This suggests that the peatlands in Finland have in general grown to approximately 60–70% of their hypothetical maximal or steady state so far /Korhola and Tolonen 1996/.

For wetlands in the Forsmark area, there are data describing the accumulation of carbon, based on the age of the site (calculated from the height above sea level) and the thickness of the peat layer (Table 4-9), suggesting that wetlands on peat soils accumulate on average 60 gC m^{-2} y^{-1}. Estimates of the long-term carbon accumulation rate were also made using ^{14}C at the bogs Rönningarna in the Forsmark area (38±11 gC m^{-2} y^{-1}) and Klarebäcksmossen in the Laxemar-Simpevarp area (29±4 gC m^{-2} y^{-1}) /Sternbeck et al. 2006/, which were in the expected range of c 20–50 gC m^{-2} y^{-1} (e.g. /Turunen et al. 2002, Malmer and Wallén 2004/). The short-term accumulation of carbon was also estimated using ^{210}Pb at Klarebäcksmossen to be 21±0.3 C m^{-2} y^{-1} by /Lidman 2009/, which is in close agreement with the above long-term estimate. Unfortunately, there are few references in the literature describing carbon cycling in forested wetlands, especially fen-like wetlands. However, in comparison with data from /Korhola and Tolonen 1996/, carbon accumulation in mires in the Forsmark area is in the upper range of the long-term rate of carbon accumulation (Table 4-7), which indicates that the mires in the Forsmark area are younger than the average age of the mires investigated in Finland.

The short-term annual accumulation of carbon in a mire can vary considerably depending on the climate /Malmer and Wallén 2004/. The net ecosystem exchange (NEE) during one year was estimated by /Tagesson 2007/ to be between –290 and 320 gC m^{-2} y^{-1}, which shows that there is approximately zero net carbon uptake or loss from the poor fen (see Table 4-46). This is similar to other studies, e.g. in Fäjemyren there is a net uptake of 20 gC m^{-2} y^{-1} /Lund et al. 2007/ and in Kaamanen, Siikaneva and Degerö NEE is between 0 and 30 gC m^{-2} y^{-1} /Lindroth et al. 2007/.

Table 4-7. Estimates of the accumulation rate of carbon in four wetlands in the Forsmark area. The values are calculated using information on the depth of the peat soil and the approximate time since the wetland emerged from the sea, from /Lindborg 2005/. The lower part of the table shows long-term accumulation rates of carbon in Finnish mires from /Korhola and Tolonen 1996/.

Locality	g $Cm^{-2}y^{-1}$	Reference
Forsmark		
Stenrösmossen	43.2	/Fredriksson 2004/
Lersättermyran	66.3	/Fredriksson 2004/
T1	58.3	/Lundin et al. 2004/
T2	73.8	/Lundin et al. 2004/
Mean	60.4	
Finnish mires		
Long-term mean	19.9	/Korhola and Tolonen 1996/
Long-term minimum	4.6	/Korhola and Tolonen 1996/
Long-term maximum	85.8	/Korhola and Tolonen 1996/

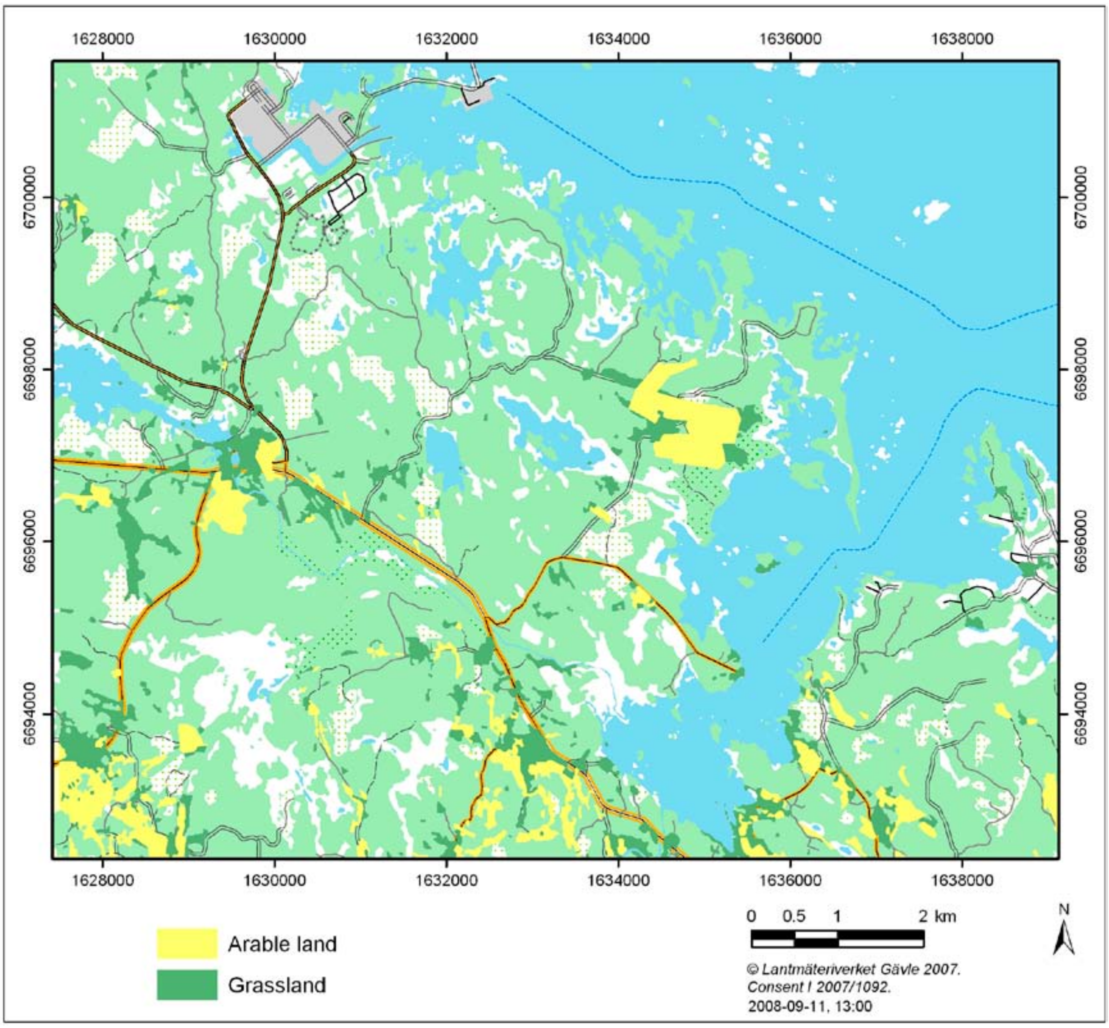
4.1.2 Agricultural land

Agricultural land is the most intensively managed land in the landscape and is a major provider of food for humans, either directly as crop production or as production of fodder for animals. Agricultural land is the arable land and the pastures or meadows (Figure 4-9, 4-10). The arable land is regularly ploughed and harvested, while the other grasslands are used for livestock grazing or hay-making. Arable land, pastures and semi-natural grassland are all found close to human settlements. The previously extensive semi-natural grasslands and traditionally managed species-rich meadows that have never been ploughed or artificially fertilized have now for the most part been abandoned in keeping with the nationwide general regression of agricultural activities /Ekstam and Forshed 2000/. Today, a large part of livestock grazing and hay-making takes place in former arable fields with richer soils and higher nutrient content due to fertilization. According to the land use data (Table 4-49, 4-50), the agricultural area in the Forsmark area and Laxemar-Simpevarp areas comprises 84 ha and 1,021 ha, respectively.

Quaternary deposits

The Forsmark area

The largest arable land unit in the Forsmark area is found on clayey till and is located in the southeastern part of the investigation area at Storskäret (Figure 4-10, 4-13). Smaller areas of mostly abandoned arable land are also found in the area. The soil is Regosol/Gleysol, which are less developed sediment soils and clayey till soils of the Cambisol type. This soil type covers arable land, pasture and abandoned arable land /Hedenström and Sohlenius 2008/.



© Lantmäteriverket Gävle 2007.
Consent I 2007/1092.
2008-09-11, 13:00

Figure 4-9. *Agricultural land in the Forsmark area, divided into arable land and grassland (pasture and semi-natural grassland).*

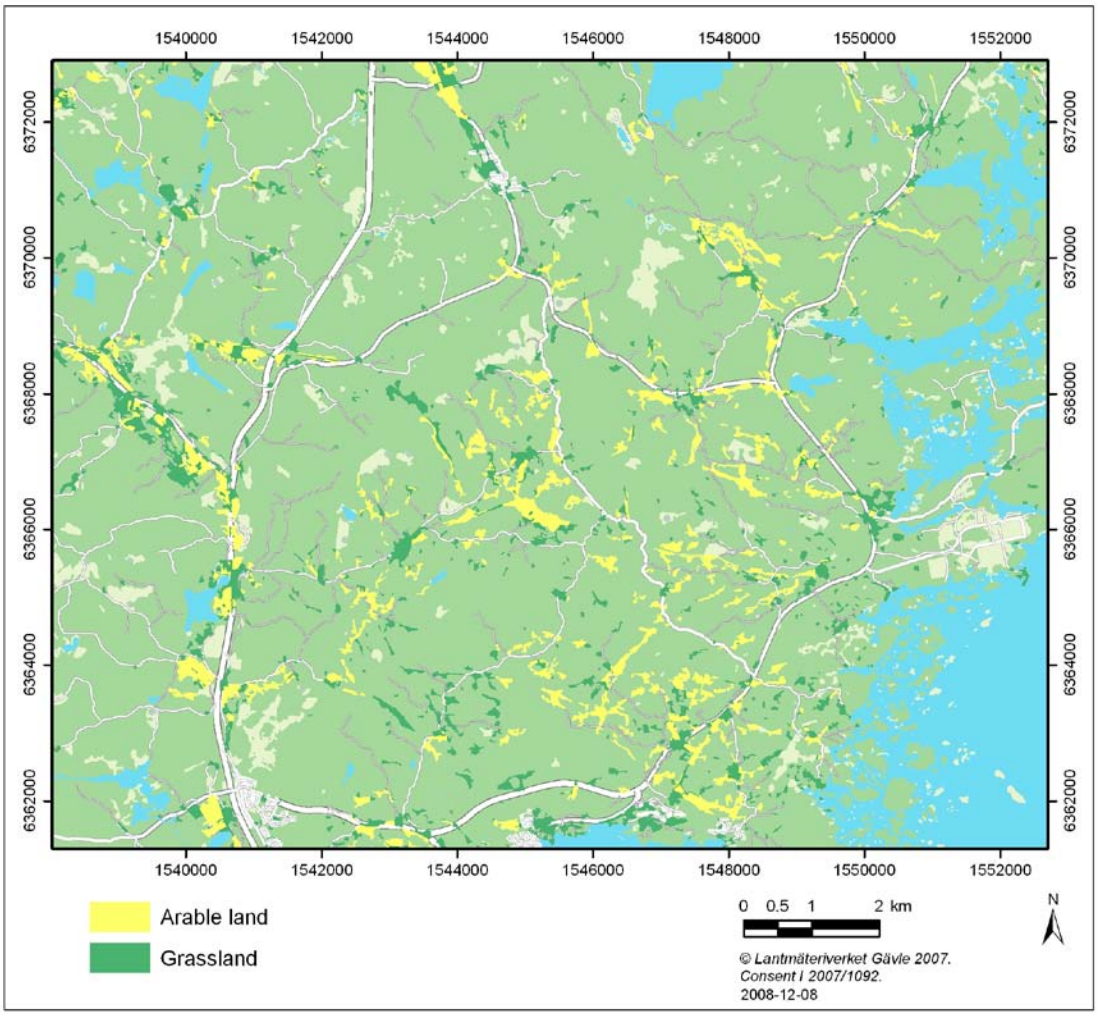


Figure 4-10. *Agricultural land in the Laxemar-Simpevarp area, divided into arable land and grassland (pasture and semi-natural grassland).*

The Laxemar-Simpevarp area

Arable land is situated in the valleys, especially where gyttja clay dominates the floor (Table 4-8). Since the floors of the valleys at many sites are former wetlands, a peat layer covers these sediments in many valleys (see above). The peat layer in these areas is relatively thin and is currently decreasing due to compaction and oxidation as a consequence of draining and ditching. Many areas used as arable land are shown as clay gyttja with a thin peat layer (thinner than 0.5 metre) on the QD map (Figure 3-5). Several of the areas used as arable lands have names ending with "kärret" or "mossen" (fen or bog), which shows that they are former wetlands. The peat in some of the former wetlands has disappeared due to oxidation and Umbrisol/Gleysol has been formed. Umbrisol/Gleysol is the dominant soil type on the fine-grained deposits used as arable land. A large part of the clay areas are, however, not used as arable land, but can be regarded as potential areas suitable for arable land. There are also areas where the type of land use has changed recently. Many small clay and peat areas which are forested today were used as arable land only 50 years ago /Jansson et al. 2004/. The gyttja clay is underlain by post-glacial sand/gravel, which in turn is underlain by glacial clay and till.

Clay gyttja has been deposited in lakes and bays (Figure 4-11). There is no great difference in carbon content between clay gyttja sampled in lakes, fens and bays /Sohlenius and Hedenström 2008/. The highest carbon contents were, however, found in samples from the lakes, where some samples have an organic content of more than 30%. The sediments in the lakes and fens have been deposited both in lakes and bays and show greater variability than clay gyttja from bays, which has been deposited entirely in bays. The clay gyttja in the bays had an organic carbon content between 10 and 20%, whereas one sample analyzed from an area mapped as clay gyttja in the terrestrial parts of the model area had a carbon content of 16%.

Table 4-8. The distribution of Quaternary deposits on the areas used as arable land. From /Sohlenius and Hedenström 2008/.

Quaternary deposit	%
Peat	20.6
Clay gyttja	33.9
Gravel	4.4
Sand	22.1
Glacial clay	7.1
Glaciofluvial material	1.2
Till	10.6

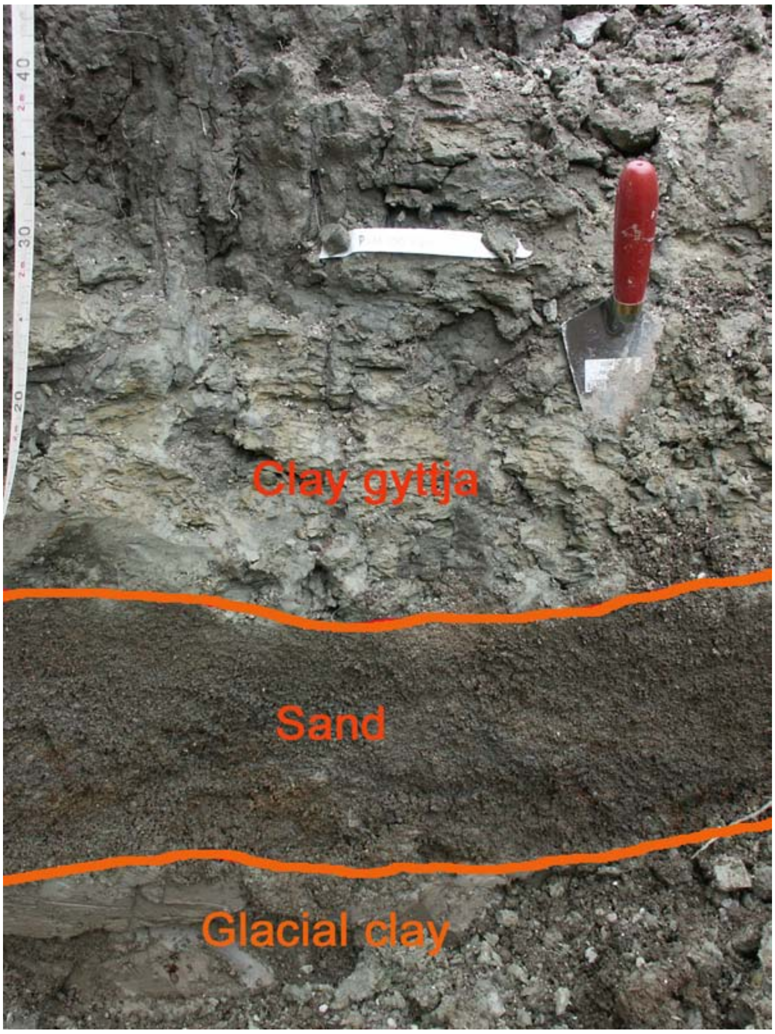


Figure 4-11. Typical distribution of water-laid sediments in the Laxemar-Simpevarp area. The glacial clay was deposited shortly after the last deglaciation. The sand layer represents a long period of erosion by streaming water at the sea floor. The uppermost layer, clay gyttja, was deposited in a sheltered bay. The site is currently used as arable land (PSM007160). Photo: Gustav Sohlenius, SGU.

Surface hydrology

The Forsmark and Laxemar-Simpevarp areas

The land used for agriculture today in the central parts of the Forsmark site investigation area is concentrated to an area covered by clayey till and boulder clay /Hedenström and Sohlenius 2008/. Most of this agricultural land has relatively good natural drainage and no areas have covered drains.

Arable land is often located in low-lying areas where fine sediment or organic soils have been deposited in valleys or depressions /Sohlenius and Hedenström 2007/. Such areas may in many cases be classified as discharge areas, as is the case for the largest arable land unit in the Forsmark area /Werner et al. 2007/. However, most of this agricultural land has relatively good natural drainage and no areas have covered drains. The potential of agricultural land as discharge areas is also emphasized by the thin peat layer associated with arable land in the Laxemar-Simpevarp area /Sohlenius and Hedenström 2007/, which indicates a former wetland stage in many arable land areas. These arable land areas have in most cases been drained in order to lower the groundwater table and make agricultural activities possible. Ditches are characteristically found on agricultural land in both the Forsmark and Laxemar-Simpevarp areas (Figure 4-12). For example, the large arable land unit in the central part of Forsmark has relatively good natural drainage and no areas have covered drains. Neglected management of ditches may cause large areas to become water-logged. Moreover, according to interviews by /Berg et al. 2006/ in the Forsmark area, "bad soils" and the practice of ditching in order to reclaim new land have had the consequence that some of the land, especially the land with organogenic soils, has been compressed, and today these areas are often flooded in the springtime.

***Figure 4-12.** A drained wetland in the Laxemar-Simpevarp area, where the peat soil has been used for agricultural purposes such as hay making and semi-natural grassland.*

Management today

Arable land use in the Forsmark and Laxemar-Simpevarp areas is clearly dominated by production of fodder and grass for domestic animals. Only around 10% of the total agricultural area (arable area and pasture) is used for production of grain and vegetables. According to /Johansson 2005/ the total agricultural area (including effective area assigned to food imports) for food consumed in Sweden 1997–2000 was 4 million ha, or 0.44 ha per capita. The dominant crop type was of fodder crops for animal production, which were grown on 74% of the agricultural area. This means that 26% of the agricultural area is used for production of grain and vegetables for human consumption. Accordingly, the current land use situation in the Forsmark and Laxemar-Simpevarp areas is more concentrated on production of fodder and grass for domestic animals than is the agricultural land area in Sweden in general.

The Forsmark area

The total agricultural area in the Forsmark area is 84 ha (area definition in /Miliander et al. 2004a/), of which 34 ha is arable area and 50 ha is classified as semi-natural grasslands or pastures (Figure 4-13). There is only one farm in the Forsmark area, and it is not possible to obtain crop statistics from SCB (Statistics Sweden) for individual farms. Data for the parish of Forsmark was therefore used to describe the area, according to which only 16% of the arable land area is used for grain and vegetable production, while the rest is used for fodder and silage production (Table 4-9). That corresponds to 6.7% of the total agricultural (field) area in Forsmark parish. The rest of the agricultural area is assumed to be used for fodder production and grazing. A similar relationship between these land use classes in the Forsmark area would suggest that 78.4 ha are used for fodder production and grazing.

Figure 4-13. *The largest arable land area, Storskäret, in the southeast of the Forsmark area.*

The Laxemar-Simpevarp area

Agricultural statistics obtained from SCB for the area (area definition in /Miliander et al. 2004b/) show that 21% of the arable area (138 ha) is used for grain and vegetable production and the rest is used for fodder and silage production (see Table 4-10). The total agricultural area is 1,021 ha, of which 556 ha is arable area and 465 ha is grazing area according to the vegetation map (Figure 3-8). Hence, grain is only produced on 13.5% of the total agricultural (field) area. The rest of the agricultural area is assumed to be used for fodder production and grazing (883 ha). The spectrum of cultivated crops in the Laxemar-Simpevarp area is wide. All the crops grown in the county can also be found in the Laxemar-Simpevarp area except for potatoes, sugar beets and oil seed crops. However, barley is by far the predominant crop in the area, being grown on 66% of the cultivated area (pasture and fodder area excluded).

Table 4-9. Arable land use in the Forsmark parish /Miliander et al. 2004a/.

Cultivated crops in the parish of Forsmark	Average percentage of the arable area (1995+1999)
Grain, vegetables:	
Rye	0.3
Barley	15.6
Oats	0.3
Potatoes	0.2
Total:	**16.4**
Fodder, grass:	
Grass, hay or silage, green fodder	71.8
Pasture/arable land not utilized	0
Pasture, grass land for seed production	9.8
Bare fallow, untilled arable land	2.0
Total:	**83.6**

Table 4-10. Arable land use in the Laxemar-Simpevarp area /Miliander et al. 2004b/.

Cultivated crops in the Laxemar-Simpervarp area	Average percentage of the arable area (1995+1999)
Grain, vegetables:	
Winter wheat	0.8
Rye	1.0
Barley	13.8
Oats	3.5
Triticale wheat, mixed grain	0.6
Leguminous plants	1.8
Total:	**21.4**
Fodder, grass:	
Green fodder, plants for silage	2.2
Grass on arable land for hay or silage	51.8
Pasture, seed lay	12.0
Other plants	0.3
Bare fallow, untilled arable land	10.2
Pasture/arable land not utilized	2.1
Total:	**78.6**

Irrigation

In Sweden, the portion of the arable land that is irrigated is small, 3–4% /Bergström and Barkefors 2004/. The irrigated land is primarily located in the county of Skåne, and the use of irrigation is less common in Northern regions. In Uppsala county the total irrigated area was estimated to be below 100 ha in 2006, and irrigated areas thus make up less than 0.1 percent of the total arable land in the county /Brundell et al. 2008/. According to national surveys, arable land is primarily irrigated with water from lakes and streams, or from surface water storages. Drainage water can also be used for irrigation, and ground water may be used for irrigation in areas with a high ground water supply. SCB has estimated that groundwater contributes with between 20 and 30% to the nationwide water use for irrigation and live stock raising /SCB 2005, Brundell et al. 2008/. Although the fraction of arable land that is irrigated is small, irrigation is frequently used for commercial production of potatoes and horticultural products to secure high and persistent yields. Nationwide, these types of crops make up approximately 50% of the irrigated land, and more than 60% of areas cultivated with potatoes and horticultural are irrigated /Brundell et al. 2008/. For Uppsala County, between 14% and 28% (upper limit) of the land used to produce potatoes and horticultural produce is irrigated. Agricultural plants in general consumes 3 mm water per day during the growing season, or 90 to 110 mm during the summer months /Eriksson et al. 1970/. When the potential water consumption is not covered by precipitation, this results in a net deficiency of water. The water need varies with climate and type of crop and commonly ranges between 50 to 200 mm during the full growing season. In national surveys the water use for irrigation is typically determined from regional water need coefficients. For example, SCB used water need coefficients from a dry year to estimate the water use for irrigation in their latest survey /Brundell et al. 2008/. For the Northern Baltic region, where Uppsala and Forsmark are located, the coefficients used were 115 mm and 150 mm for potatoes and horticultural products respectively. These coefficients corresponds to the irrigation need for year 25 in a row of 30 years, arranged in sequence from lowest to highest irrigation need.

Gardening

A smaller type of arable land is a garden plot, where vegetables and root crops can be grown for personal use. There are no permanent residents in the Forsmark area, but five summer cottages are situated there. A larger number of both permanent and part-time residents are found in the Laxemar-Simpevarp area. Most of these residents probably have garden plots, but the degree of self-sufficiency in different kinds of crops is not known. Although the extent of irrigation of garden plots is not known, the figures in /Bergström and Barkefors 2004/ indicate a general need in drier summers.

Figure 4-14. Agricultural land in the central part of the Laxemar-Simpevarp regional model area.

Seasonal variation

The agricultural land is subjected to different types of changes depending on land use. The pastures and semi-natural grasslands are perhaps less affected by changes in the vegetation and soil, since a major disturbance comes from grazing and trampling by livestock, which may vary from year to year. Grasslands are dominated by perennial herbs and grasses. The arable land is more exposed to seasonal variation due to a very short turnover time, i.e. the soil is turned during ploughing, nutrients are added and the vegetation (the crop) is harvested within a year. Ploughing is done in order to loosen up and aerate the soil and to promote the decomposition of the crop residues and thereby promote the release of nutrients. This is done after harvest as a preparation for the next growing period. The vegetation may in some cases be absent during the winter period until the next vegetation period.

Ecosystem properties

The arable land has most of the biomass above ground, and this biomass is regularly harvested, leaving some root litter. Typically, this land is ploughed one or two times each year, creating a more or less homogeneous soil where no humus horizon is found. Fungi are also present in this vegetation type and are known to form mycorrhiza with fertilized crops /Chapin et al. 2002, van der Heijden and Sanders 2002/. All crop root biomass is turned into root litter, since no roots survive until next year because the fields are ploughed during autumn. In the crop production simulations (Chapter 7), 66% of the leaf biomass was removed from the field and 33% remained as litter /Olsson, HIR Malmöhus pers. comm./. It was also shown that root biomass is 19% of the total biomass /Andren et al. 1990/. The grasslands are dominated by perennial plants and have more biomass below-ground, whereas disturbances are more restricted to the above-ground vegetation, such as trampling and grazing by livestock.

Production in grasslands

Historically, the semi-natural grasslands were situated on less fertile land, whereas the fertile land was used for cultivation. This would suggest a lower production in such grasslands. Wet grasslands are more fertile than dry ones and may produce 200 to 240 gdw m^{-2} y^{-1} over long periods as compared with 50 to 60 gdw m^{-2} y^{-1} in a forested grassland /Borgegård 1994/. /Tagesson 2006b/ estimated the NPP for a semi-natural grassland in the Laxemar-Simpevarp area (assuming that NPP is 50% of GPP) to be 270±180 gC m^{-2} y^{-1} using a closed chamber technique along with measurements of air and soil temperature (Table 4-46), while /Löfgren 2005/ estimated NPP to be 273±101 gC m^{-2} y^{-1} using clipping at the time of peak biomass at the same locality (Table 4-16). Seashore meadows have a long history of being used as hay-meadows in the archipelagos and may have high NPP (Figure 4-15). /Wallentinus 1973/ estimated the NPP of a seahore meadow to be between 441 and 594 gC m^{-2} y^{-1} in southeast Sweden using different approaches (assuming the below-ground production to be twice the above-ground production /Saugier et al. 2001/).

Agricultural products in the Forsmark and Laxemar-Simpevarp areas

Crop production

No site-specific yield statistics are available for crop production in the Forsmark and Laxemar-Simpevarp areas. However, statistics are available describing the standard yields for the yield survey district (SKO area). The Forsmark area is situated in SKO area 0322 and Laxemar-Simpevarp in SKO area 0814 /SCB 2000b/. Barley is the predominant grain grown in both the Forsmark and Laxemar-Simpevarp areas. To obtain total crop production, generic values of threshing loss (×1.05) and straw yield (×1.4) were added (Table 4-11).

The total yield of hay from pastures has been obtained from Statistics Sweden /SCB 2007b/. Hay is the part of the crop that is used as fodder. The amount of carbon in the hay and barley is estimated to be 0.46 gC gdw^{-1}, as for the green field layer in /Fridriksson and Öhr 2003/. The dry weight is 83.5% of the fresh weight of hay and 86% in barley according to /SCB 2000b/. The average standard yields are compiled in Table 4-11.

Figure 4-15. *Seashore meadow characterized by a flora typical for localities with calcareous influences in the Forsmark regional model area.*

Table 4-11. Grain production, including threshing loss and straw yield, and fodder production in the yield survey districts, the county and the country.

Standard yield		kg fw/ha		gC m^{-2} y^{-1}	
		Mean	SD	Mean	SD
Grain (barley)[1]	Forsmark in SKO-0322	4,225	94	167	4
	Uppsala County	6,275	192	248	8
	Laxemar-Simpevarp in SKO-0814	4,800	235	190	9
	Kalmar County	5,710	278	226	11
	Sweden	6,184	65	245	3
Hay pastures[2]	Uppsala County			200	16
	Kalmar County			231	31
	Sweden			205	12

[1] /SCB 2000b–2007a/.
[2] Mean value for 2003–2006 /SCB 2007b/.

The productivity of the land in the Forsmark area is significantly lower (approx. 70%) than the productivity of the land in Uppsala County when barley yields are compared. On the other hand, productivity in Uppsala County is above the average yield in Sweden. The production of pastures is roughly equivalent to the average yield in the country.

The productivity of the land in the Laxemar-Simpevarp area is lower (approx. 84%) than the average productivity of the land in the county when barley yields are compared. Barley productivity in Kalmar County is also lower than the average yield in Sweden. On the other hand, the production of hay pastures is greater than the average standard yield in Sweden.

Production during one year on a recently abandoned arable field in Simpevarp was estimated by /Tagesson 2007/, using field measurements and modelling, to be 355±140 gC m^{-2} y^{-1} (approximately GPP/2, Table 4-46). Other grassland studies have determined a wide range of GPP values between 270 and 1,210 gC m^{-2} y^{-1} covering both natural grasslands and fields /Flanagan et al. 2002, Suyker and Verma 2001, Suyker et al. 2003, Novick et al. 2004/.

In general, the agricultural area represents a larger part of the Laxemar-Simpevarp area than of the Forsmark area. The standard yields for barley and hay are also higher in the Laxemar-Simpevarp area than in the Forsmark area. The estimate from one year in the field was larger than the SCB statistics. Although the field estimate includes root production, this is not high enough to explain the difference. However, the SCB statistics should be more relevant in describing the long-term production of crops and hay.

Meat, milk and egg production and carbon content

According to the agricultural statistics, there is one agricultural enterprise (farm) in the Forsmark area. This farm has beef cattle. The agricultural land is used for grazing and probably some fodder production. For reasons of confidentiality, there are no data concerning production at this single farm. In calculating livestock production in the Forsmark area, the densities of domestic animals in Forsmark parish have been applied to the Forsmark area. Livestock production figures in Forsmark parish and the Laxemar-Simpevarp area are found in /Miliander et al. 2004a, b/ along with calculated values of meat production. Meat production is calculated based on the portion of the slaughtered weight that is consumed. A dairy cow produces approximately 7,495 kg milk per year /Miliander et al. 2004a, b/. The Forsmark area and the Laxemar-Simpevarp area are defined in /Miliander et al. 2004a, b/.

The production figures have been converted to carbon using different sources. The carbon content of mammals is 11.7% of their total (live) weight (44.9% of their dry weight) according to site-specific analysis of the chemical composition of deposits and biota in the Forsmark and Laxemar-Simpevarp areas /Hannu and Karlsson 2006, Engdahl et al. 2006/. The carbon content of milk and eggs can be estimated from their content of proteins, carbohydrates and lipids /Altman and Dittmer 1964, Dyson 1978, Rouwenhorst et al. 1991/:

$$CC_i = 0.53 \cdot Proteins_i + 0.44 \cdot Carbohydrates_i + 0.66 \cdot Lipids_i$$

where CC_i is the carbon content of the i-th food type (kg C/kg fw), $Proteins_i$ is the protein content of the i-th food type (kg/kg fw), $Carbohydrates_i$ is the carbohydrate content of the i-th food type (kg/kg fw) and $Lipids_i$ is the lipids content of the i-th food type (kg/kg fw). The contents of proteins, carbohydrates and lipids in milk (2% milk fat) and eggs (egg 50g, raw) have been found in the Nutrient Database from United States Department of Agriculture /USDA 2007/. The carbon content of milk is estimated to be 5.1% and of eggs 14% .

The production figures have been divided by the total area for grazing and fodder production in Forsmark parish and the Laxemar-Simpevarp area. Production per unit area is shown in Table 4-12 and 4-13. Generally, the density of domestic animals is higher in the Laxemar-Simpevarp area, which is the reason for the higher total meat production. However, total production per unit area is higher in the Forsmark area.

Soil respiration and net ecosystem exchange

Measurements of the CO_2 fluxes revealed that the grassland in the Laxemar-Simpevarp area was a comparatively large net source of carbon during the year when measurements were performed (–324 g·C·m^{-2}·y^{-1} CO_2-C). Net ecosystem exchange was also estimated to be between –660 and –380 g·C·m^{-2}·y^{-1}, suggesting that grassland is a net source of carbon. One explanation for this high figure is that the grassland was ditched, suggesting the presence of oxidizing peat soils causing the high negative net ecosystem exchange of CO_2. Two recently abandoned arable fields, one in the Forsmark area and one in the Laxemar-Simpevarp area, showed similar high soil respiration (Table 4-46), but somewhat lower than the grassland. NEE in the agricultural areas indicates that there is net loss of carbon (on average –190 gC m^{-2} y^{-1}) to the atmosphere. Studies in other areas have obtained a wide range of NEE estimates (–950 to 274 gC m^{-2} y^{-1}) /Suyker et al. 2003, Flanagan et al. 2002, Novick et al. 2004, Maljanen et al. 2001, Byrne et al. 2005, Soegaard et al. 2005, Hollinger et al. 2005/.

Interactions with other vegetation types

Agricultural land is often situated on sediments along valleys or in depressions in the landscape. It has often been ditched to some extent in order to lower the water table, thereby optimizing growing conditions. However, these areas may nevertheless be exposed to flooding due to a higher ground water table in the spring and autumn. This process of flooding is further described in Section 4.1.

Table 4-12. Production of animal products (live biomass and utilized meat), milk and eggs in the Forsmark area (average figures for the years 1995 and 1999) presented as carbon per area and year.

Domestic animal	Production (live biomass $mgC \cdot m^{-2} \cdot y^{-1}$)	Meat production ($mgC \cdot m^{-2} \cdot y^{-1}$)	Milk production ($mgC \cdot m^{-2} \cdot y^{-1}$)	Egg production ($mgC \cdot m^{-2} \cdot y^{-1}$)
Beef	1,160	366	7,343	
Sheep	79	18		
Pigs	0	0		
Chicken	93	50		90
Total		**434**	**7,343**	**90**

Table 4-13. Production of animal products (live biomass and utilized meat), milk and eggs in the Laxemar-Simpevarp area (average figures for the years 1995 and 1999) presented as carbon per area and year.

Domestic animal	Production (live biomass $mgC \cdot m^{-2} \cdot y^{-1}$)	Meat production ($mgC \cdot m^{-2} \cdot y^{-1}$)	Milk production ($mgC \cdot m^{-2} \cdot y^{-1}$)	Egg production ($mgC \cdot m^{-2} \cdot y^{-1}$)
Beef	1,084	342	6,027	
Sheep	17	4		
Pigs	827	353		
Chicken		25		43
Total		**723**	**6,027**	**43**

4.1.3 Forests

Introduction

Forests contain different types of vegetation, all of which have a more or less dense tree cover (> 30%). A forest is often regarded as the climax stage in most parts of the landscape and forest trees are quick to colonize areas previously kept open by human land use. Both sites are found in areas where forest management is intensive.

One important structuring factor in the boreal forests has been the occurrence of fire at various intervals. The fire interval was shorter in areas with shallower soil, so the more fire-tolerant Scots pine is dominant on this less productive soil. More productive and mesic sites are characterized by longer fire intervals and dominated by Norway spruce. Other important disturbances may be insect outbreaks, windstorms and clear-cuts. The spatial scale of these disturbances determines whether they may promote recruitment of new evenly-aged cohorts or multi-aged stand structures. On less fire-prone soils, the gap dynamic is small-scale, and the falling of one or several trees is important for regeneration. Fire has also been an important factor in southern Sweden as forests were often used for shifting agriculture, where areas were cleared, burnt over and then used for sowing crops. These small fields were then abandoned due to a steady decrease in productivity. There was a general trend until the early 20th century for farmland to expand into forested areas. However, as in other developed countries, former agricultural land is now often returned to forest as agricultural production becomes more efficient /Angelstam 1992/. Today, fire has lost its importance in many regions due to efficient fire suppression, but fire does occasionally deforest large areas, resulting in a large turnover of elements previously trapped in the vegetation and soil.

Vegetation

The Forsmark area

Forests cover 73% of the Forsmark land area. The forests are dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) situated mainly on wave washed till (Figure 3-1). Spruce becomes more abundant where a deeper soil cover is found along with more mesic-moist conditions (Figure 4-16). Bare rock is not a widespread substrate in the Forsmark area, making pine forest on acid rocks quite scarce. The calcareous soil material provides nutrient-rich conditions, which can be seen in the predominance of humus forms of the mull type and of the intermediate moder type /Lundin et al. 2004/, indicating a rich soil fauna. Because of the young age of the soils, the Forsmark area exhibits less soil of the Podsol type than most similar areas in Sweden. Instead, the typical soil types are the less developed Regosol soils, together with Gleysols and Histosols, which are formed under moist conditions (Table 3-1). The field layer is heavily influenced by its calcareous content and is characterized by herbs and broad-leaved grasses along with a number of orchid species. The deciduous tree species are dominated by *Betula pendula, Alnus glutinosa* and *Sorbus acuparia*, but *Acer platanoides* and *Fraxinus excelsior* are also fairly common. Especially *F. excelsior* may be abundant along sheltered seashores. *Quercus robur* and *Ulmus glabra* are close to their northern limit and are therefore scarce.

The Forsmark area has a long history of forestry, which is seen today in a fairly high frequency of younger and older clear-cuts in different successional stages in the landscape. *Betula pendula* is the dominant species in many of the earlier successional stages until it is replaced by young Norway spruce or Scots pine depending on soil type and/or management.

Figure 4-16. *Herb-rich Norway spruce forest in the Forsmark area.*

The Laxemar-Simpevarp area

Forests cover 86% of the land area in Laxemar-Simpevarp (Figure 3-8). The forests are dominated by Scots pine (*Pinus sylvestris*) situated on bedrock or nutrient-poor thin soils with shrubs, mostly *Calluna vulgaris*, grasses such as *Deschampsia flexuosa, Agrostis vinealis* and *Festuca ovina*, and lichens and mosses on the ground layer. When these pine forests get moister, *Vaccinium vitis-idaea* and *Vacinium myrtillus* become more common in the field layer. Norway spruce (*Picea abies*) becomes abundant where a deeper soil cover is found, while deciduous tree species are more common near the coast, i.e. mainly *Quercus robur* but also *Corylus avelana*, *Sorbus aucuparia, S. intermedia* and *Acer platanoides*, making the mixed forest the second most common forest type. *Q. robur* is often the dominant tree species when more or less pure deciduous forests are found (Figure 4-17). The character of these forests is a function of boulder frequency, nutrient availability and earlier history of management. The predominant humus form is moder in Scots pine and Norway spruce forests, where Regosol dominates but Podzol becomes more common where there is a deeper soil cover. The mull-like humus form is more dominant as deciduous trees becomes more prevalent /Lundin et al. 2005a/ and here the soil types Regosols and Umbrisols are found (Figure 3-6).

There are areas where land use has changed rather recently. Many small clay and peat areas which are forested today were used as arable land only 50 years ago /Jansson et al. 2004/. The soil properties in such areas are probably greatly affected by that former land use. The Laxemar-Simpevarp area has a long history of forestry, which is seen today as a fairly high frequency of younger and older clear-cuts in different successional stages in the landscape. *Betula pendula* is the dominant species in many of the earlier successional stages until it is replaced by young Norway spruce or Scots pine depending on soil type and/or management.

Figure 4-17. *Deciduous forest with Acer platanoides, Tilia cordata and Quercus robur on bouldery ground in the Laxemar-Simpevarp regional model area.*

Surface hydrology

The Forsmark area

Due to the flat terrain and the shallow groundwater levels, there is a strong interaction between evapotranspiration, soil moisture and groundwater. The groundwater levels in many monitoring wells in Quaternary deposits were less than one metre below ground all year, and the groundwater level on average was less than 0.7 m below ground 50% of the time. Even in what can be considered as typical recharge areas, the average groundwater level was not more than 1.2 m below ground. It is only in locally elevated areas with relative steep slopes that groundwater levels can be assumed to be considerably deeper. The annual variation in the groundwater level is mostly less than one metre in discharge areas, and 1.5 m in typical recharge areas. Diurnal fluctuations of the groundwater levels, driven by evapotranspiration cycles, were evident in the data from many of the groundwater monitoring wells in Quaternary deposits /Johansson 2008/.

Due to the small-scale topography and the hydraulic conductivity profile of the tills that dominate in the area, many small catchments are formed with local shallow groundwater flow systems in the Quaternary deposits, and most of the groundwater moves along these shallow flow paths. During periods of abundant groundwater recharge, the groundwater level, even in most recharge areas, reaches the shallow part of the Quaternary deposit profile where the hydraulic conductivity is much higher and a significant lateral groundwater flow takes place. However, the transmissivity of this upper layer is so high that the groundwater level does not reach much closer to the ground surface than 0.5 m in typical recharge areas /Johansson 2008/.

Direct recharge from precipitation is obviously the dominant source of groundwater recharge. However, the groundwater level measurements in the vicinity of Bolundsfjärden and Eckarfjärden show that the lakes may act as recharge sources for the till aquifers in the immediate vicinity of the lakes in the summer. While the groundwater levels are well above the lake water levels for most of the year, they are considerably below the lake water levels under dry summer conditions. This is very clear close to the lake shores, but even in the middle of the lakes the groundwater levels are slightly below the lake levels under such conditions (the difference is well outside the probable measurement error). The gradients from the lakes to the surrounding areas are created by direct and indirect groundwater abstraction caused by evapotranspiration. However, due to the low permeability of the bottom sediments, the resulting water fluxes can be assumed to be relatively small /Johansson 2008/.

The Simpevarp-Laxemar area

Groundwater levels in the Quaternary deposits are shallow; according to monitoring data; on average the depth to the groundwater level is less than c 1 m during 50% of the time. Generally, there is a larger depth to the groundwater level in high-elevation areas compared to low-elevation areas. However, there is a much smaller range of depths to the groundwater level compared to absolute groundwater levels. There is hence a close correlation between the ground-surface topography and groundwater levels in the Quaternary deposits, which in turn implies that topography has a strong influence on near-surface patterns of groundwater recharge and discharge /SKB 2009/. According to the conceptual hydrogeological model, groundwater recharge primarily takes place in high-altitude areas, dominated by outcrop rock or shallow regolith depths. Groundwater recharge also takes place within the "hummocky moraine" and "glaciofluvial deposits" type areas, characterised by smaller-scale topography and eskers, respectively /SKB 2009/.

Regolith

The Forsmark area

Till is the dominant Quaternary deposit that fills small crevasses in the bedrock, dominated by granite (Figure 3-1). The shoreline of northern Uppland is characterized by a high frequency of boulders from the till. Glacial till is the dominant Quaternary deposit in the Forsmark area, covering 65% of the terrestrial areas. One main characteristic of the till in the Forsmark area is the generally high calcium carbonate content of the fine and gravel fractions of the till.

The dominant soil types are Regosols and Gleysols (Figure 3-2, Table 3-1), which are formed on unconsolidated course-textured parent material and are characterized by a minimal soil profile development as a consequence of young age. Humus forms are mor or moder. Typical soils for Sweden are Podsols but this soil type has not yet developed at Forsmark. This poor soil development is a result of young age.

The Laxemar-Simpevarp area

The regolith in the topographically high areas is generally one or a few metres thick and is completely dominated by forest. The soils in till areas with coniferous forest are dominated by Podzol and poorly developed soils (Table 3-4). The most high-lying areas, which are mainly found in the northern part of the regional model area, are dominated by bedrock with a more or less thin soil layer. In till areas with deciduous forest, Umbrisol and poorly developed soils, Regosol, dominate. The frequent occurrence of Regosol shows that the soil-forming processes have not been active long enough to form distinct soil horizons at all investigated sites. The Laxemar-Simpevarp area is completely situated below the highest coastline and many of the investigated sites have consequently only been subjected to soil forming processes for a few thousand years /Sohlenius and Hedström 2008/.

The areas covered by wetlands have diminished significantly, due to the lowering of the groundwater table by ditches. That was done for agricultural purposes (see Section 4-2), but also to improve the rate of forest growth (Figure 4-18). The soils in the present and former wetlands are dominated by Histosol. The peat in some of the former wetlands has been reduced due to oxidation and Umbrisol/Gleysol has been formed. It was concluded that forest areas covered by peat are underestimated in the peripheral parts of the investigation area, where aerial photos have been used to determine the spatial distribution of peat. Such peatlands are often difficult to recognize in the aerial photos, especially at sites where the groundwater level has been lowered by ditches /Sohlenius and Hedström 2008/. For example, a peat area covering several hectares west of Gästern, not shown on the QD map (Figure 3-5), was found during a field check. Such areas have often been above sea level for too short a period for a distinct peat layer to form.

The soil contents of different elements were in a similar range as in other studies, but deviated from the large-scale soil contents in Sweden where the forested till soils provide poorer conditions in Laxemar-Simpevarp. At the sites investigated here, the arable and pasture lands provide comparably nutrient-rich conditions. For a thorough description of the soil chemistry investigation, the reader is referred to /Sohlenius et al. 2006/.

Figure 4-18. *Ditching to promote forest growth in the Laxemar-Simpevarp area.*

Management today

The forests in the Forsmark and Laxemar-Simpevarp areas are mainly owned and managed by Sveaskog AB. The forest holdings of Sveaskog are managed according to the policies and standards of the Forest Stewardship Council (FSC). FSC provides guidelines for environmentally appropriate, socially beneficial and economically viable forest management. The long-term ambition of Sveaskog is to achieve nature conservation areas covering 20% of the productive forest land. This will be achieved by developing so-called ecoparks and through the creation of nature reserves. According to /Sveaskog 2007/ the forests are managed over their life-cycle based on the descriptions of the different phases of management given below.

Soil preparation

To improve the opportunities for new plants or seeds to become established, a clear-cut area is normally scarified so that some of the mineral soil is laid bare by removing the field and ground layers.

Forest regeneration

70% of the forest area is on average regenerated by plantation, 20% by natural regeneration (with seed trees) and 10% by sowing. Natural regeneration is mainly used in Central Sweden, on poor and coarse soil with less competition from other vegetation. It is not a potential alternative in northern Sweden, due to a colder climate, or in southern Sweden where the soil is normally very fertile. Plantation is preferred when soil fertility is good. Pine is generally used for natural regeneration and sowing. Regeneration must take place within three years after clear-cutting.

Forest clearing

Forest clearing is carried out when the spruce trees are 2–4 metres tall and the pine trees are 4–5 metres tall. It can be done earlier if herbivory by moose is negligible. Unwanted trees, such as damaged trees and trees that are standing too closely together, are cut down. The trees are not removed from the site as in the case of thinning, but are left to decompose.

Forest thinning

Forest thinning is normally performed when the forest is 30–50 years of age. On the most fertile soils, thinning is done three times before clear-cutting, while once or twice is sufficient on poorer soils. At most 30–35% of the timber volume is generally removed by thinning. The remaining trees benefit from the increased availability of light, nutrients and soil water following thinning.

Forest fertilization

Nitrate fertilizers are often added to soils of medium quality. This is not profitable on poor soils or on fertile soils. It is most cost-effective to fertilize the forest about ten years before clear-cutting.

Clear-cutting

The forest is finally cut down at the age of approximately 100 years. On the most fertile soils in southern Sweden, the forests reach a mature age for cutting much earlier, after 45 years of growth at the earliest. The quality, timber volume, dimension and age of the forest determine when the forest is mature for cutting. Clear-cutting without natural regeneration entails that all trees are felled, except old trees (so called nature value trees), high stumps and some smaller groups of trees.

Ecosystem properties

The forest at both sites consists of different vegetation with different inherent properties with regard to different aspects of element accumulation and cycling, e.g. standing biomass and NPP may differ between different forest types. A number of field studies have addressed questions with the aim of describing the range of these properties at the sites.

Tree stand description

An ongoing monitoring project, the National Forest Inventory /SLU 2002/, has done extensive field work covering the whole of Sweden. SKB has been able to use a subset of this database (*http://www-riksskogstaxeringen.slu.se)*, covering the period between 1985 and 2005, in order to describe forests at the sites. A regional area was defined and data from the Inventory subplots was extracted according to specified criteria (classified as forest land, age above 10 y, inventoried between 2000 and 2005 and having a tree biomass above 0) (Table 4-14).

Table 4-14. Description of different properties of forests in the Forsmark and Laxemar-Simpevarp areas using information extracted from the NFI database from a larger region around the sites. Mean ± standard deviation.

Properties	Forsmark area	Laxemar-Simpevarp area
Tree biomass (gC m^{-2})*	7,650±4,362	6,616±4,560
Stem increment (gC m^{-2} y^{-1})	131±87	133±98
Age (year)	65±33	60±39
Number of plots	228	155

*Whole tree except fine roots (< 5 cm) and leaves of deciduous trees.

/Abrahamsson 2003/ and /Andersson 2004a/ performed measurements of a number of forest parameters, such as height and diameter at breast height, in order to describe production at the Forsmark and Laxemar-Simpevarp areas. These investigations were focused on certain vegetation types and cannot be regarded as a representative subset of the forests describing the whole of the sites. In both the Forsmark and Laxemar-Simpevarp areas, Scots pine was the dominant tree in the tree layer in most of the investigated areas. /Tagesson 2006a/ also published descriptions of stand volume and stand breast height age for a number of forest plots in the Forsmark area (3) and the Laxemar-Simpevarp area (9) that were used in his work of describing leaf area index at the sites. His estimates represented mature forests and were therefore higher than the values in Table 4-14.

Field, bottom and litter layers

/Löfgren 2005/ estimated the biomass in the field, bottom and litter layers and net primary production (NPP) in the field and bottom layers in a number of vegetation types in both the Forsmark and Laxemar-Simpevarp area, by collecting the standing crop at the peak of the biomass in one year. Below-ground estimates of roots were corrected for tree roots when a tree layer was present in the investigated vegetation type. The overall most productive field and ground layers were found in the vegetation types lacking a tree layer, such as the mire or the grassland (Table 4-15, 4-16). These were also the habitats that displayed the highest biomass values. The lowest NPP was found in the forested wetland and the coniferous forest.

The amount of litter was highest in the spruce forest (highest in the Laxemar-Simpevarp area and second highest in the Forsmark area) (Table 4-17, 4-18). The vegetation type with the lowest amount of litter was mire.

Although the variation in estimated parameters was relatively large, the results agree fairly well with other investigations at a similar latitude /Fridriksson and Öhr 2003, Berggren et al. 2004/.

Table 4-15. The mean biomass and NPP of the field and ground layers for the investigated vegetation types in the Forsmark area. Biomass value in units of gdwm^{-2} and NPP in units of gdw m^{-2} y^{-1}. The standard deviation is presented after the mean and the range is presented below the mean.

Parameters	Mire	Forested wetland	Herb dominated moist soil	Grassland	Coniferous forest	Thin soil
Biomass	4,371±2,203	295±109	225±108	833±186	503±203	1,141±387
	2,718–7,816	180–471	118–392	659–1,147	219–720	715–1,697
NPP	505±118	32±25	195±106	825±246	137±78	465±335
	353–678	2–65	98–350	538–1,129	34–223	109–1,012

Table 4-16. The mean biomass and NPP of the field and ground layers for the investigated vegetation types in the Laxemar-Simpevarp area. Biomass value in units of gdw m^{-2} and NPP in units of gdw m^{-2} y^{-1}. The standard deviation is presented after the mean and the range is presented below the mean.

Parameters	Mire	Forested wetland	Herb dominated moist soil	Grassland	Coniferous forest	Thin soil	Shore
Biomass	2,905±837	685±696	405±255	968±342	668±296	627±69	2,628±1,300
	1,744–3,991	44–1,834	200–842	653–1,517	392–1,030	553–705	1,125–4,365
NPP	683±403	86±84	277±71	545±202	101±55	94±34	310±314
	303–1,367	34–234	213–396	268–792	44–182	56–142	55–753

Table 4-17. Litter layer described in the Forsmark area. Standard deviation is presented after the mean and the range is presented below the mean. All numbers have the units gdw m^{-2}.

Parameters	Mire	Forested wetland	Herb dominated moist soil	Grassland	Coniferous forest	Thin soil
Weight	539±212	698±277	1,081±861	980±286	1,042±488	595±430
	369–791	339–1,093	133–2,119	639–1,431	408–1,704	164–1,163
Content Dominating component	*Carex, Phragmites australis*	Leaves and branches (*Betula, Alnus* etc)	Leaves, grass	*Elymus repens*	Neddles (*Picea abies*) and grass	Neddles and branches (*Pinus sylvestris*)

Table 4-18. Litter layer described in the Laxemar-Simpevarp area. The standard deviation is presented after the mean and the range is presented below the mean. All numbers have the units gdw m^{-2}.

Parameters	Mire	Forested wetland	Herb dominated moist soil	Grassland	Coniferous forest	Thin soil	Shore
Weight	272±197	1,084±248	489±169	486±449	1,595±1,083	1,216±543	700±305
	71–517	814–1,331	319–665	131–1,264	501–2,860	461–1,782	234–1,034
Content Dominating component	Carex, *Equisetum*	Leaves (*Alnus glutinosa*)	Leaves (*Quercus robur*)	Grass	Neddles, cones, branches (*Picea abies*)	Neddles, thin bark (*Pinus sylvestris*)	Parts from *Phragmites australis*

Birch on clear-cuts

Clear-cuts are rather common in both investigation areas, due to the high amounts of commercial forests. After a clear-cut, a dense birch forest (*Betula pendula* and *B. pubescens,* where *B. pendula* dominates) is allowed to emerge, which partly serves as a protection for the next generation of planted coniferous trees. /Alling et al. 2004c/ attempted to quantify the biomass and net primary production (NPP) of this successional stage now commonly used in the forestry management at both sites. Five localities were censused at each site. Using functions from already published work, the biomasses were calculated for stem, living and dead branches /Marklund 1988/, coarse roots /Li et al. 2003/ and fine roots /DeAngelis et al. 1981/ and leaves separately. Net primary production was calculated using the annual diameter increment, estimated from annual rings, and the biomass functions.

The median total biomass was estimated to be 494 gC m^{-2} and 583 gC m^{-2} for the Forsmark and Laxemar-Simpevarp areas, respectively. The median NPP was estimated to be 162 gC m^{-2} y^{-1} and 213 gC m^{-2} y^{-1}, respectively. The higher values in the Laxemar-Simpevarp area were attributed to higher number of stems per m^2. The annual increment of the birch stems was surprisingly similar between localities and sites (0.18 cm y^{-1}±0.04, N=10) /Alling et al. 2004c/.

LAI

Leaves are the surface where an exchange of matter and energy between the atmosphere and the biosphere takes place. The leaf area index (LAI), expressed as the leaf area projected onto a horizontal plane, of the vegetation cover is correlated with a number of ecophysiological parameters, such as net primary production (see Chapter 7), transpiration and interseption of water in canopies. A LAI map covering an area will therefore constitute an important input to the description of production and regional water balance.

In the investigation areas, the LAIs of coniferous and deciduous tree ecosystems were estimated indirectly through optical measurements using LAI-2000 (LI-COR, Cambridge UK) and TRAC (Tracing Radiation and Architecture of Canopies) /Tagesson 2006a/. On average, measured maximum LAI was 3.40 in the Laxemar-Simpevarp area and 3.43 in the Forsmark area; minimum LAI was 1.65 in the Laxemar-Simpevarp area and 1.97 in the Forsmark area. Forest inventory data showed that LAI was positively correlated with basal area, stand height, stand volume and breast height tree diameter. For the coniferous stands, there was also a linear negative relationship with age, which means that older trees get a lower LAI. LAI was correlated with the normalized difference vegetation index (NDVI) in the Laxemar-Simpevarp area, while in the Forsmark area effective LAI was correlated with NDVI. These correlations made it possible to use NDVI images to construct LAI maps for each site (Figures 4-19 and 4-20).

Above-ground litterfall and decomposition

/Mjöfors et al. 2007/ studied litterfall from trees and the decomposition of litter at three localities at both sites (Table 4-19). The sites were chosen in order to complement the other investigations at those sites describing different pools and fluxes of organic matter. The abbreviations in the text below follows those stated in Table 4-19.

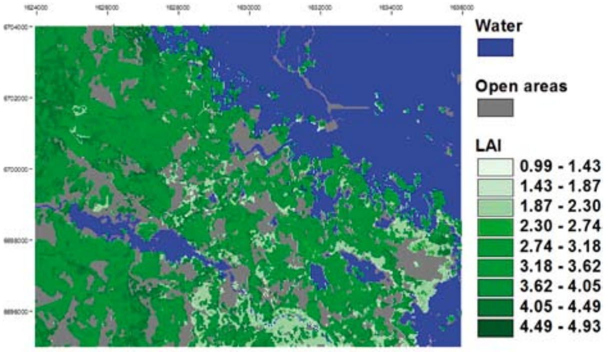


__Figure 4-19.__ NDVI modelled LAI for the Forsmark area from /Tagesson 2006a/.

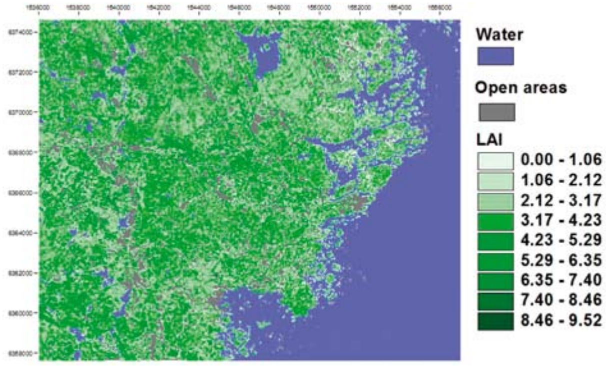


__Figure 4-20.__ NDVI modelled LAI for the Laxemar-Simpevarp area from /Tagesson 2006a/.

Table 4-19. The forest stands that were studied with regard to litterfall in the Forsmark and the Laxemar-Simpevarp areas. The stands are identical with the ones described by /Lundin et al. 2004, 2005a/ in the characterization of soils.

Site	Forest type	Id in /Mjöfors et al. 2007/	Id in /Lundin et al. 2004, 2005a/	X- koord.	Y- koord.	SKB id-codes
Forsmark	Norway spruce	F1	FG1	6698152	1633558	AFM001068
	Norway spruce/Alder	F2	SS1	6698060	1633495	AFM001076
	Norway spruce	F3	B2*	6698733	1633420	AFM001247
Simpevarp	Common Oak	O1	Löv 1	6367828	1552003	ASM001426
	Scots pine	O2	Häll 1	6367322	1552510	ASM001428
	Norway spruce	O3	Gran 1	6369225	1547128	ASM001440

*The site was moved about 300 m from that one described by /Lundin et al. 2004/, denoted AFM001066.

Above-ground litterfall

Annual litterfall from trees was measured from June 2004 to June 2006 using litter traps. The above-ground litterfall in the Forsmark and Laxemar-Simpevarp areas (Figure 4-21) was within the range (120 to 452 gdw m^{-2} y^{-1}) reported by /Berg et al. 1999a/ for Norway spruce stands located from the Arctic Circle in the north of Sweden to the latitude of Malmö in the south. The proportion of needles/leaves in the total litterfall varied between 65% and 75% in the studied stands.

The carbon returned in above-ground litterfall amounted to between 60 and 110 gC m^{-2} y^{-1} in the forests in the Forsmark area. Corresponding figures for the forests in the Laxemar-Simpevarp area were 70 to 190 gC m^{-2} y^{-1}. At site O3, the litterfall was markedly higher during the first year of measurement than during the second (a difference of about 170 gC m^{-2}). This between-year variation in litterfall may have been the result of the storm 'Gudrun', which hit Götaland in January 2005 and partly affected the Laxemar-Simpevarp area. During the first year of measurement, a slightly higher litterfall was also observed in the pine stand (O2), but not in the oak stand (O1). The lack of increase in the later stand was probably due to the fact that the oak trees were already defoliated when the storm came in January. Although the between-year variation in litterfall can be very high due to fluctuations in environmental factors, it was rather low in both areas investigated in this study. The ratio of maximum to minimum annual total litterfall within a site ranged between 1.2 and 1.6. These values are somewhat lower than those reported by /Berg et al. 1999a/ for 12 stands located from Norrbotten in the north of Sweden to Blekinge in the south, where total litterfall was measured during 4 years. The ratios observed ranged between 1.1 and 2.1. This indicates that above-ground litterfall has to be monitored over several years to get a high accuracy in the estimates. The high litter production at site O3 compared with site F3

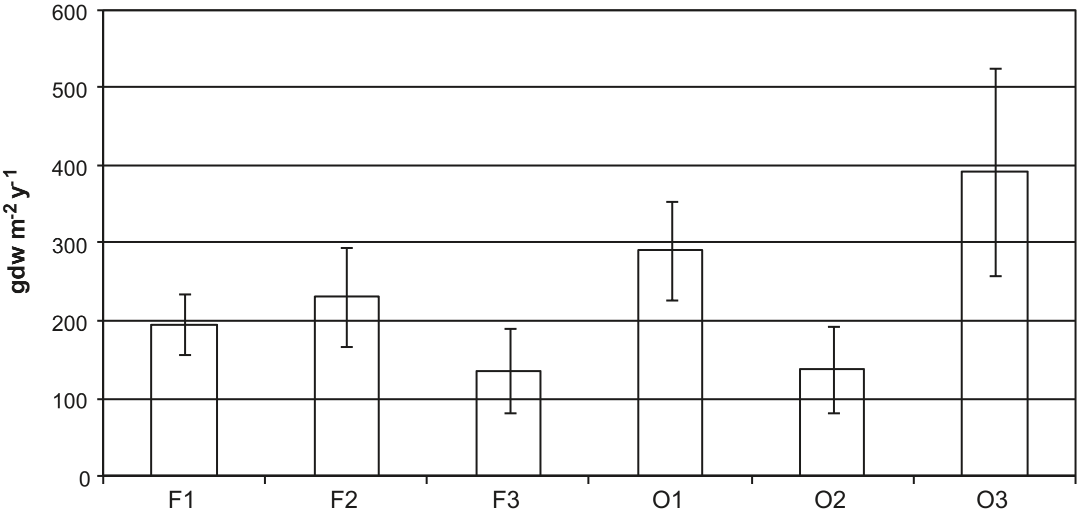


Figure 4-21. *Mean annual total litterfall with standard deviations. F denotes the investigated Forsmark localities, whereas O denotes the localities in Laxemar-Simpevarp. Abbreviations on the x-axis follow the ID codes in Table 4-19. Data from /Mjöfors et al. 2007/.*

can probably be explained by fertility differences between the sites. Site O3 is a drained peatland with spruce on a fresh to fresh-moist soil. These kind of soils can provide high yields /Lundin et al. 2005a/ and thus have a high litter production. Site F3, on the other hand, is a poorer and less productive soil, which can explain the low litterfall at the site. The litterfall produced in the Scots pine stand at site O2 within the Laxemar-Simpevarp area (about 150 gdw m^{-2} y^{-1}) is also within the range (74 to 420 gdw m^{-2} y^{-1}) reported for Scots pine stands in Sweden /Berg et al. 1999b/. However, it is lower than for pine stands of 'normal fertility', which generally have a litter production of around 300 gdw m^{-2} y^{-1} /Berg et al. 1999a/. The Scots pine stand at site O2 was growing on a soil of lower fertility (coarse sandy and sandy-silty till cover of 0.3–1.0 m /Lundin et al. 2004/) and had a low stem density, resulting in a low basal area, which in turn gives rise to a low litter production /Berg et al. 1999b/.

At sites O1 and O3 in the Laxemar-Simpevarp area, about 3.6 gN m^{-2} y^{-1} of N was returned annually to the forest floor by the above-ground litterfall. This was four times more than the N deposited in the Scots pine stand (O2) in the same area (about 0.8 gdw m^{-2} y^{-1}). In the Forsmark area, the N return in litterfall varied between 1.1 and 2.6 gdw m^{-2} y^{-1}, the lower figure for site F3 and the higher for site F2. At site F1 about 1.7 gdw N m^{-2} y^{-1} was deposited. Although the difference is great, the figures are in agreement with results from other studies. /Lundmark et al. 1982/ reported an N return of 0.6 gN m^{-2} y^{-1} in relatively young Scots pine stands located in Central Sweden. /Lundmark 1988/ found (as a mean for five middle-aged stands) that 0.8 gN m^{-2} y^{-1} was deposited with the needle fraction. Furthermore, /Johansson and Lundmark 1986/ and /Johansson and Grälls 1989/ reported an N return of 3.2 to 6.2 gN m^{-2} y^{-1}. That site F2 consists of a mixed spruce/alder stand is evident from the size of the N return in litter. It is much lower than the figure reported by /Johansson and Grälls 1989/ for a pure alder stand (6.6 compared with 2.6 gN m^{-2} y^{-1}).

Decomposition of above-ground litterfall

The decomposition of the site's "own" litter was followed for two years and was predicted for up to 10 years with a dynamic decomposition model /Ågren and Bosatta 1998/. Litterbags containing dried leaves/needles of known weight were put on the ground. Three times a year, one litterbag was collected from each of 25 subplots in the six localities and a weight loss was calculated after the second weighing.

In all three stands in the Forsmark area, the spruce needle litter lost around 33% in mass during the first year, and after two years the accumulated mass loss amounted to 45%. The alder leaf litter decomposed more rapidly and lost 60% in mass during the first year and had reached an accumulated mass loss of 73% after the two years. The extremely high mass loss rate shown by the alder leaf litter was probably due to a favourable chemical composition that promoted decomposition. High N and calcium (Ca) contents in litter are known to stimulate the decomposing microorganisms /Yamaya and Branch 1968/. In general, minor differences were noted in the decomposition pattern for the spruce and pine needles within the Laxemar-Simpevarp area. The pine needles started to decompose at a somewhat lower rate than the spruce needles (16% compared to 18% during the first 77 days), but after two years the pine needles had lost significantly more in mass than the spruce needles (52% compared to 46% for spruce needles), which is a well known phenomenon /Johansson et al. 1986, Berg et al. 1996/ and has been ascribed to a lower concentration of lignin and a higher concentration of ethanol-solubles in pine needles than in spruce needles. Thus, the oak and pine litters had lost about half of their initial mass (51 to 52%) and the spruce litter a somewhat smaller fraction (45%) during two years of decomposition. According to the model predictions, about 80% of the initial mass would have decomposed in needle litters and oak leaves after 10 years, but over 90% the initial mass of alder leaves was predicted to have decomposed.

Mineralization of N started immediately from alder leaves and proceeded at a fast rate for the first five months, after which it slowed down markedly. In general, about 80% to 90% of the initial N amount still remained in the litter after two years of decomposition (100% in the pine needles), whereas alder leaves had lost 60% of their N.

The release of P started immediately from all litter types and was most rapid from the alder leaf litter, which lost about 60% of its initial amount during the first five months. The other litter types generally lost around 10–20% within the same time period. However, oak leaves and the spruce needles at sites O1 and O3 in the Laxemar-Simpevarp area exhibited higher losses (30–40% of the initial amount).

According to the model predictions (Figure 4-22), after 10 years of decomposition about 60–70% of the initial nitrogen and 80 to over 90% of the initial phosphorus would be released from the spruce needles and the oak leaves. Markedly lower releases of nitrogen and phosphorus were predicted for pine needles, 54 and 41%, respectively. The release rate of nitrogen and phosphorus from alder leaves was predicted to be very high and only a few % of the initial nitrogen and phosphorus was predicted to remain in alder leaves after 10 years of decomposition.

Distribution and turnover of roots

The roots of the primary producers constitute about 30 to 50 percent of their total biomass /Gower et al. 2001/. Roots serve as supporting tissue, but perhaps more important from a transport and accumulation perspective they provide the plant with all the water and nutrients that are needed for growth and survival. This means that roots constitute the most important transport route for most of the elements found in plants today, as well as elements that could potentially be found in plants. Tree roots can be distinguished by size into different categories: coarse supportive roots with low turnover rates, small diameter roots with low turnover rates that act as conduits for water and mineral nutrients and very fine mycorrhizal roots (< 1 mm in diameter) with a high degree of soil penetration and high turnover rates /Vogt and Persson 1991/. Quantifying the amount of fine roots in forest ecosystems is

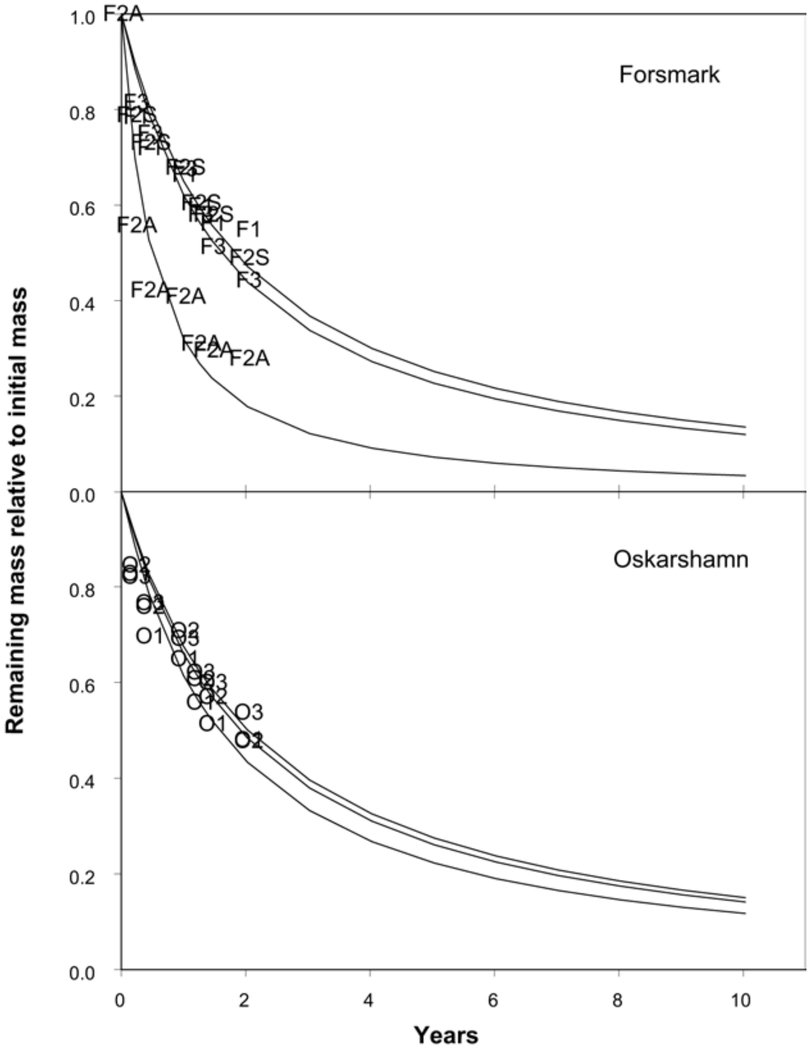


Figure 4-22. The lines represent remaining mass during modelled decomposition relative to the initial amount. Letters represent field data, where F1 and F3 are the spruce sites and F2A the alder fraction of the spruce/alder site in the Forsmark area. O1 denotes the oak site, O2, the pine site and O3 the spruce site in the Laxemar-Simpevarp area /Mjöfors et al. 2007/.

necessary due to their important role as carbon sinks and sources of soil organic matter /Jackson et al. 1996/. However, it may not be advisable, due to the high variability of the fine roots, to estimate the fine-root biomass as a proportion of the total root biomass or to use other structural parts of the tree for such estimations /Persson and Stadenberg 2007a, Vogt and Persson 1991/.

Biomass distribution of fine roots

/Persson and Stadenberg 2007a/ investigated the distribution of root biomasses in tree and field layers at three forest localities in the Forsmark and Laxemar-Simpevarp areas, respectively (Table 6-2). They used the sequential coring technique to estimate root biomass.

The amount of live fine tree roots was high in the humus layer, especially in the uppermost part of the humus horizon. The mean fine-root biomass (< 1 mm in diameter) of tree species for the total profile was 267, 317 and 235 g m^{-2} for the Forsmark localities and 137, 371 and 50 g m^{-2} for the Laxemar-Simpevarp localities. The data on the amount of fine-root biomass and necromass in the Forsmark and Laxemar-Simpevarp areas are within the range of the data from other investigations (cf. /Persson 2000/), taking into consideration the high seasonal variability of the fine roots. The concentration of fine roots in the humus layer seems to be dependent on soil water availability. Figure 4-23 shows fine root density (≤ 6 mm) as a function of depth for the different localities. The rather sharp decrease in Figures 4-19c and d is an effect of the high occurrence of shallow boulders. This makes the sampling difficult, but also affects the root density.

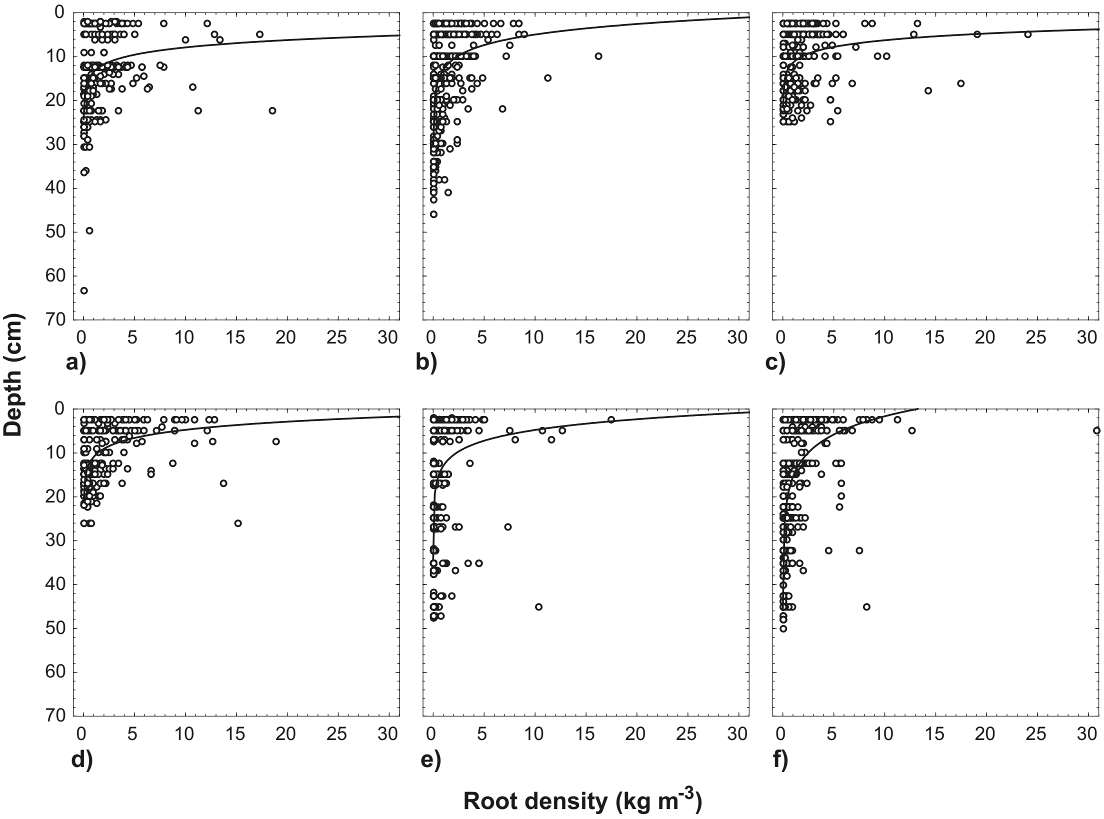


Figure 4-23. *Fine root density (≤ 6 mm) as a function of soil depth for the six different localities in the Forsmark (a–c) and Laxemar-Simpevarp areas (d–f) (see Table 6-2 for more details). a) Norway spruce, b) Alnus swamp forest, c) Norway spruce, d) Pedunculate oak forest, e) Norway spruce, f) Alnus shore forest. Each figure is based on 32 soil corings. A logarithmic curve is fitted to the observations. One outlier was excluded from Figure c showing a sample at 5 cm depth with a density of 51 kg m^{-3}. Data from /Persson and Stadenberg 2007a/.*

The field layer species were substantially more developed in the open forests stands, with a low stem density of the trees. Roots of tree and field layer species generally occupied different soil horizons and therefore compete with each other to a limited extent for water and nutrients. The superficial distribution pattern of field layer species compared with tree species is confirmed by data from other sites /Persson 1975, 1978, 1983/. In the total soil profile, 8–27% of the fine root biomass (< 1 mm in diameter) at the Forsmark and 1–62% at the Laxemar-Simpevarp localities consisted of fine roots of field layer species. It is important to know to what extent the distribution pattern of the tree roots is influenced by competition from the roots of the field layer species. The study suggests that tree roots are generally distributed deeper than roots from the field layer species. The highest amount of roots from the field-layer species was found on the sites with a low number of trees/ha; viz. in the "coniferous fern type forest" in the Forsmark area (780 trees ha^{-1}) and at the "herb rich oak forest" in the Laxemar-Simpevarp area (200 trees ha^{-1}). The forest trees on those sites were among the oldest (the age of the trees was 80–112 years).

Turnover of fine roots

The root function is extremely costly for the organism and is enhanced by a high carbohydrate supply /Ågren et al. 1980, Marshall and Waring 1985/. Available information in the literature suggests substantial fine root production with a seasonal pattern different from needle or leaf production /Persson 1983/. It has been demonstrated that fine roots are sensitive to drought and that their live-to-dead ratios decrease with diminishing water availability in the soil /Olsthorn 1991, Persson et al. 1995, Santantonio and Hermann 1985/. /Persson and Stadenberg 2007b/ also investigated the turnover of fine roots (< 1 mm) at the Norway spruce locality (FG1 in Table 4-19) during one year (October 2004–October 2005) using repeated sampling of soil corings on four occasions. The turnover estimate was the accumulated results of significant differences in biomass between soil corings on four occasions, which were added in order to estimate the production of fine roots. The annual turnover was estimated to be 0.7 of the fine root biomass by dividing the fine root production by the average fine root biomass. The amount of fine root biomass and necromass at the Forsmark locality showed a high seasonal variability (Figure 4-24, cf./ Persson 2000/). A review of literature data from various forest stands, obtained by sequential coring, suggests annual turnover rates of 1–2 times the average fine root biomass. The mean for root diameters < 1 mm was 1.0 (min=0.1, excluded from the mean, and max=1.7) and the mean for root diameters < 2 mm was 1.5 (min=1.0 and max=2.4) /Persson and Stadenberg 2007b/). All those turnover rates are conservative, since turnover occurring between the sampling occasions remained undetermined.

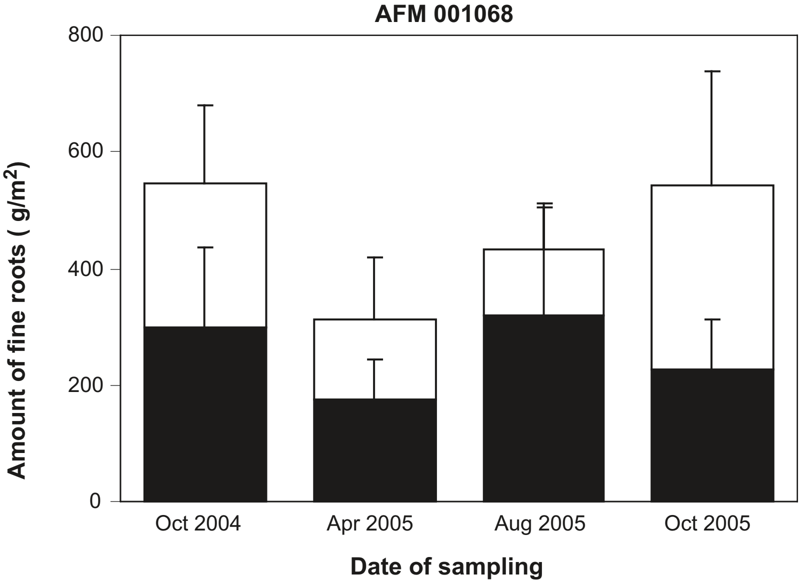


Figure 4-24. *The amount of live (unfilled bar) and dead (black bar) fine roots (< 1 mm in diameter) on the four sampling occasions at the Norway spruce locality in the Forsmark area. Mean values ± SD. From /Persson and Stadenberg 2007b/.*

Depth of the root zone

/Lundin et al. 2005a/ investigated the depth of the root zone, defined as the zone where fine roots (Ø < 5 mm) were found, for a number of different soil types in soil pits in the Laxemar-Simpevarp area. These vegetation types are the same as those used to describe the field and bottom layers (above). Fine root depth was estimated by /Lundin et al. 2005a/ at two localities for each of the studied soil classes except for the mire and the rockpool types. In generally, the samples from the two replicates did correspond fairly well to each other and the largest variation was found between the different vegetation types. The largest deviation from that pattern was found between the two rockpool types (HI-s). The statistics presented in Table 4-20 were obtained from all sub-samples within the vegetation type.

The depth of the root zone was also investigated in a large soil trench in the Forsmark area, where Regosols dominated /Lundin et al. 2005b/. The depth of fine roots varied between 3 and 57 cm, but most of the roots were found between 10 and 40 cm with an average of 25 cm. Coarse roots appeared to have a more shallow location with the deepest root reaching 25 cm, with an average of 10 cm.

An illustration of the variation in rooting depth is from another trench in the Forsmark area /Lundin et al. 2005b/. Depths were measured for fine and coarse roots, subdivided into two classes at a diameter of 5 mm. The soil and site type class was mainly of Regosol/Gleysol type found in upslope locations with fresh soil moisture class. Humus forms were moor or moder. The vegetation was a mixed coniferous forest dominated by Norway spruce with low herbs of bilberry type in the field layer and fresh mosses in the bottom layer. Fine roots were found in most locations and the depth varied from 3 cm to 57 cm from the mineral soil surface (Figure 4-25). At two locations there was bedrock without roots. Most of the roots reached to between 10 cm and 40 cm with an average of 25 cm. Coarse roots were observed at 19 locations with the deepest root reaching 25 cm, but on average the depth was 10 cm (Figure 4-25).

Table 4-20. Statistics describing the depth of the root zone for a number of vegetation types in the Laxemar-Simpevarp area. The class LP was not estimated in /Lundin et al. 2005a/.

Class	Code in /Lundin et al. 2005a/	Mean (SD) (m)	Min–Max (m)	N
Mires	HI-w	0.34 (0.07)	0.30–0.47	7
Forested wetlands	HI-f	0.31 (0.05)	0.25–0.43	10
Herb dominated moist soils on fine texture parent material	UM/RG	0.39 (0.11)	0.20–0.60	16
Semi-natural grasslands	UM/GL	0.18 (0.12)	0.06–0.54	16
Woodland, well drained, herbs, grasses and dwarf shrubs	PZ/RG	0.26 (0.09)	0.15–0.52	16
*	HI-f*	0.22 (0.07)	0.08–0.32	16
Esker	PZ/RG-e	0.29 (0.07)	0.18–0.43	16
Rockpool	HI-s	0.20 (0.12)	0.09–0.40	14
Thin soils with lichen rich heath vegetation	LP	–	–	–
Shore line (bedrock excluded)	RG/HI	0.19 (0.13)	0.00–0.35	15
Arable land	UM/GL-a	0.15 (0.07)	0.07–0.27	16

*Reclassified from "Woodland" to "Forested wetland" by /Lundin et al. 2005a/, but is not used here for the calculation of root depth for both categories.

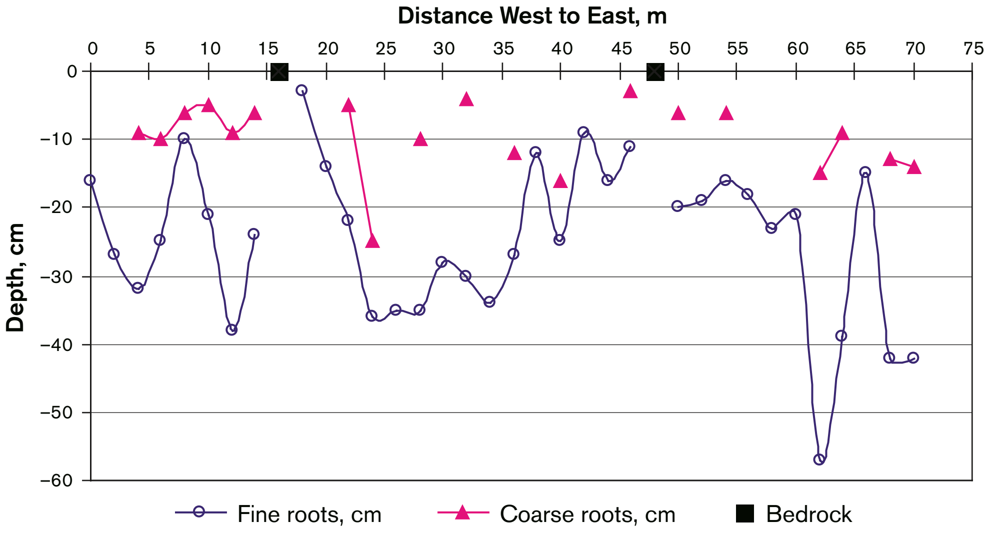


Figure 4-25. Variation in rooting depth of fine and coarse roots along a transect in the Forsmark area. The rooting depth was determined with the mineral soil surface as the upper boundary and the average humus layer thickness was 11 cm. From /Lundin et al. 2005b/.

Coarse woody debris

The coarse woody debris, consisting mainly of logs and stumps, may constitute a significant part of the carbon pool depending on the forest type and how it is managed. Generally, intensive forest management involves an active removal of dead or dying trees but also leads to even-aged tree cohorts. /Andersson 2004b, 2005/ investigated the occurrence of coarse woody debris in the Forsmark and Laxemar-Simpevarp areas for a number of different forest types (Table 4-21, 4-22).

Table 4-21. Biomass of standing and lying logs in gC m^{-2} in the Forsmark area. Medians and first and third quartiles were recalculated from /Andersson 2004b/, who investigated a specific area (column 3) for a number of vegetation types. Grid codes are from the tree layer classification used in /Boresjö Bronge and Wester 2003/. Field-estimated volumes were converted to dry weight using /Benediktson et al. 2005/ and carbon content was assumed to approximate the estimates from litter (0.47, according to /Mjöfors et al. 2007/). Fifth and sixth column presents the lower and upper quartile.

Class	Grid code	Total area (ha)	Woody debris	Q_1	Q_3
No tree layer within forest area	1	6	38	33	49
No tree layer outside forest area	2	87	5	0	9
Old spruce	11	146	63	31	96
Old pine	13	55	52	27	59
Young pine	14	31	3	2	4
Unspecified young conifer	17	16	3	2	5
Birch	21	8	94	53	135
Young birch (thicket on clear-cut)	22	13	5	5	5
Ash	26	4	27	24	28
Mixed forest	30	14	68	48	119

Table 4-22. Biomass of standing and lying logs in gC m^{-2} in the Laxemar-Simpevarp area. Medians and first and third quartiles were recalculated from /Andersson 2005/, who investigated a specific area (column 3) for a number of vegetation types. Grid codes are from the tree layer classification used in /Boresjö Bronge and Wester 2003/. Field-estimated volumes were converted to dry weight using /Benediktson et al. 2005/ and carbon content was assumed to approximate the estimates from litter (0.47, according to /Mjöfors et al. 2007/). Fifth and sixth column presents the lower and upper quartile.

Class	Grid code	Total area (ha)	Woody debris	Q_1	Q_3
No tree layer within forest area	1	57	22	14	41
No tree layer outside forest area	2	66	0	0	0
Old spruce	11	53	48	29	73
Young spruce	12	5	14	7	20
Old pine	13	185	37	21	48
Young pine	14	15	21	20	23
Unspecified young conifer	17	7	23	16	32
Birch	21	4	34	25	36
Young birch (thicket on clear-cut)	22	3	20	17	26
Birch or oak mixed with spruce	24	30	38	30	80
Oak	25	3	77	45	99
Coastal birch/oak	27	4	33	20	45
Mixed forest	30	8	53	33	67

Ecosystem modelling

Dynamic modelling, using the CoupModel, was used as an approach to describe pools and fluxes of carbon for a number of ecosystems in the Forsmark and Laxemar-Simpevarp areas using site-specific input data /Gustafsson et al. 2006, Karlberg et al. 2006/. The CoupModel is a one-dimensional model for simulations of fluxes of water, heat, carbon and nitrogen in a soil-plant-atmosphere system (Figure 4-26). It has been developed to estimate interactions between climate, vegetation and conditions in the soil, and applied mainly to Nordic conditions. A detailed description of the model is given by /Jansson and Karlberg 2004/.

The carbon and nitrogen models are based on three prerequisites: 1) carbon input is governed by solar radiation, 2) carbon flows govern nitrogen flows, and 3) nitrogen in plants determines growth. Plants are represented by one pool of carbon and one of nitrogen for three compartments, stem, leaves (needles), and roots. The stem compartment represents all woody material: stems, branches and roots except fine roots. The organic material in the soil is represented in different ways depending on the purpose of the simulation. Soil organisms such as microorganisms decompose the organic matter, and their activity therefore accounts for the fluxes between different organic pools in the soil. To account for differences in substrate, the model has a minimum representation of two organic pools independent of soil horizon. One is litter, which has a high turnover rate, and the other is humus, representing a low turnover rate. Simulations including different soil temperatures, soil moisture conditions and the soil water flows are based on physical equations. The most important interaction between the carbon turnover and the physical conditions is governed by the leaf area index and the ratio between actual and potential transpiration. Both will in turn influence the input of carbon to the system and both are strongly related to temperature and moisture.

Results

/Gustafsson et al. 2006/ simulated carbon pools and fluxes for coniferous stands and compared averages for the ages 0–30 years, 30–100 years and 0–100 years using climate parameters describing a period of 25 years from each site. A subset of the simulated estimates is presented in Table 4-23.

/Karlberg et al. 2006/ investigated four terrestrial ecosystems in the Laxemar-Simpevarp area: a grassland on fine sand with a high soil organic matter content, an alder forest on peat, a managed spruce forest on peat and a pine forest on till. These systems were selected because they are likely to differ in terms of carbon turnover times, and also because they are commonly occurring in southern and central Sweden. Measured data on soil carbon and nitrogen content at each site were used to parameterize the initial conditions of the litter and humus pools in the site-specific simulations.

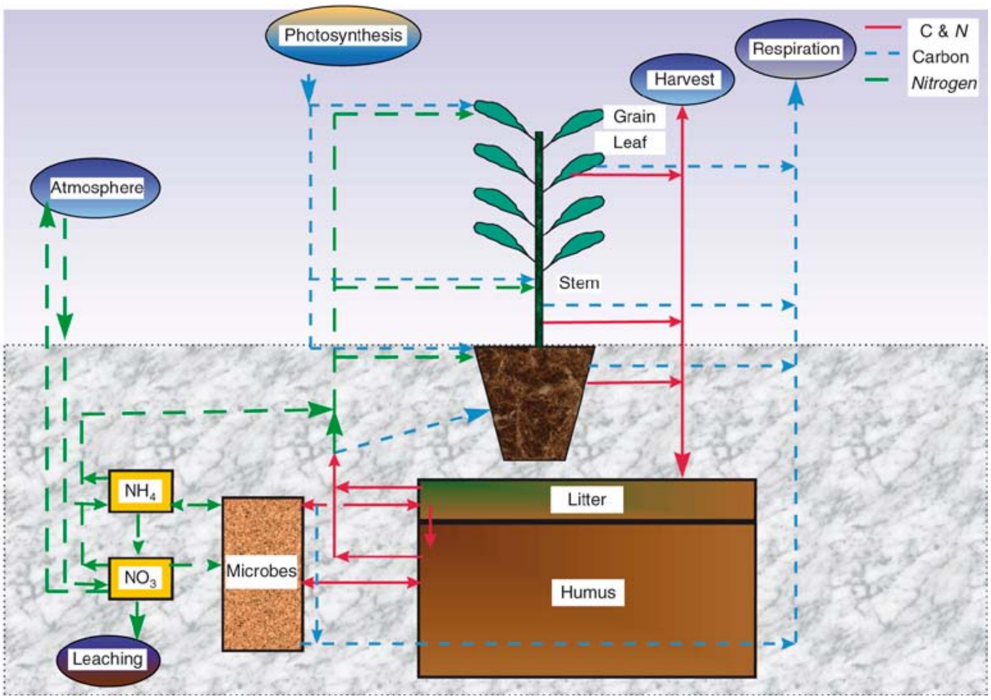


Figure 4-26. *Schematic model of carbon, nitrogen and biomass flows (in one dimension) and storages. The soil is further divided into layers and plant biomass is divided into pools of annual and perennial tissues /Gustafsson et al. 2006/.*

Table 4-23. Simulated pools and fluxes of carbon averaged for a simulated coniferous stand during the period 0–100 years /Gustafsson et al. 2006/.

Property	Forsmark area	Laxemar-Simpevarp area
Biomass (gC m^{-2})	6,743	6,826
NPP (gC m^{-2} y^{-1})	335	360
Litter production (gC m^{-2} y^{-1})	232	242
Soil respiration (gC m^{-2} y^{-1})	228	240
NEP (gC m^{-2} y^{-1})	107	120

Soil respiration estimates from a grassland, a spruce and a pine forest stand /Tagesson 2006b/ were used to calibrate the simulations by adjusting the groundwater level, since this variable was unknown. Due to different exposure to oxygen, a change in groundwater level predominantly affects heterotrophic respiration and has a large impact on soils rich in organic matter such as those at the study site. Continuous series from 1 January 1993 to 5 July 2005 describing precipitation, air temperature, global radiation, wind speed and relative humidity on the site were created. In order to get an estimate of the variance in the different parts of the carbon budgets, the relative variance (i.e. the standard deviation divided by the mean) calculated for four hypothetical systems was multiplied by the mean values from the site-specific simulations, see /Karlberg et al. 2006/.

Soil respiration was generally well described in the model simulations compared with the measurements by /Tagesson 2006b/. None of the ecosystems are in steady state in terms of carbon storage (Figure 4-2). The annual average net ecosystem exchange for the grassland is about –600 gC m^{-2} y^{-1}, while it is close to zero in the spruce forest (–80 gC m^{-2} y^{-1}) and is positive in the alder and pine forests (230 gC m^{-2} y^{-1} and 200 gC m^{-2} y^{-1}, respectively), Figure 4-27. This means that the soil organic content decreases annually in the grassland and the spruce forest, while it increases in the alder forest and remains relatively stable in the pine forest.

Annual water flows were also estimated in the simulations (Figure 4-28). These estimates show that most of the water entering the ecosystems as precipitation leaves as subsurface drainage or surface runoff, except in the alder forest.

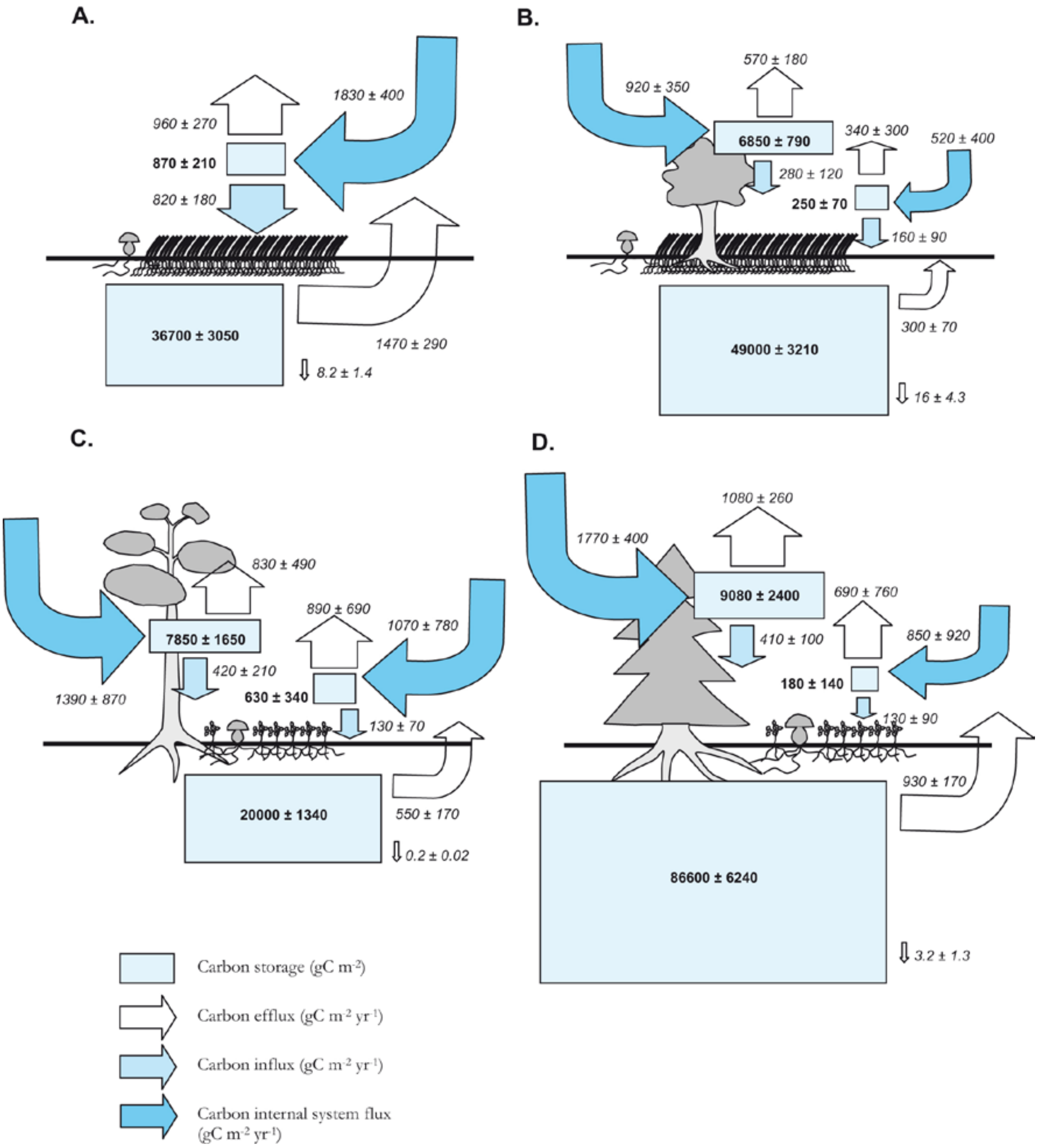


Figure 4-27. *Carbon budgets for the site-specific ecosystems located within the Laxemar-Simpevarp area. a) grassland b) alder c) pine and d) spruce managed forest. Carbon storages (gC m^{-2}) in bold and carbon fluxes (gC m^{-2} yr^{-1}) in italics, including standard deviations. /Karlberg et al. 2006/.*

Interactions between forest ecosystems and other vegetation types

Water transports elements between ecosystems, and most forests at both sites are regarded as recharge areas (e.g. /Werner et al. 2007/). Some wet forests, regularly flooded forests or forested wetlands, e.g. alder swamps, may, however, act as recipients for transported elements. This is further discussed in Section 4.1. Most forests have to be regarded as a continuous source for horizontal transport of elements (weathering) to other ecosystems, such as wetlands, lakes and the sea, although this horizontal transport is usually small in comparison with internal transport within the forest ecosystem.

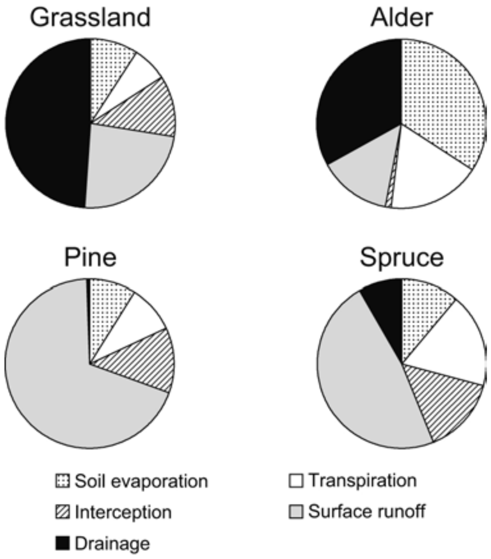


Figure 4-28. Participation of incoming precipitation for four site-specific ecosystems located within the Laxemar-Simpevarp area. /Karlberg et al. 2006/.

4.1.4 Confidence and uncertainties

Ecosystem descriptions

The vegetation has been used to categorize both the drier and the wetland parts of the terrestrial area. Moreover, agricultural land and forest land have been used as domains for further descriptions of properties. Each of these may be broken down to further units, both because of successional trajectories within these domains (e.g. clear-cut and forest), but also because of abiotic differences affecting the vegetation type (e.g. minerogenic fen and bog). This generates variation in regard to many describing parameters, while other may be less variable e.g. soil conditions.

Generally, the descriptions are based on many sources of information, where data are compared and discussed in relation to other similar studies of which some are presented in this report. For a more comprehensive discussion and comparison with similar studies, the reader would also be recommended to read the underlying reports that are referenced. Further evaluation, comparison and discussion of data and assumptions is also provided in the following chapters that extend and formalize the descriptions in terms of pools and fluxes in ecosystems.

4.2 Fauna and fungi

The fauna has been investigated at the sites in a number of different investigations. Much effort has been put into characterizing and estimating densities of functional groups, i.e. large mammals, small mammals, birds, amphibians and reptiles, and thereby underpinning calculations of potential fluxes of organic matter to and between these groups (Figure 4-29). Other important functional groups are found below ground, where for example the potential transport of organic matter by soil fauna (bioturbation) might be significant. Another process of importance is mineralization, estimated as a part of soil respiration, which is an important process in evaluating the turnover of organic material in ecosystems. Fauna is treated separately from flora, mainly because larger fauna species are often more difficult to associate with specific habitats on an annual basis. However, for some species or functional groups an attempt has been made to distribute their consumption in the landscape, either by using their habitat preferences or their feeding preferences or both. From the perspective of being exposed to contaminants, i.e. radionuclides, species with more specific food requirements, associated with a certain habitat, would generally be more exposed if that habitat is contaminated than generalist species using a broader range of food sources from different habitats. In the case of other functional groups it is easier to directly link their occurrence with certain vegetation types, e.g. soil fauna and soil microbes.

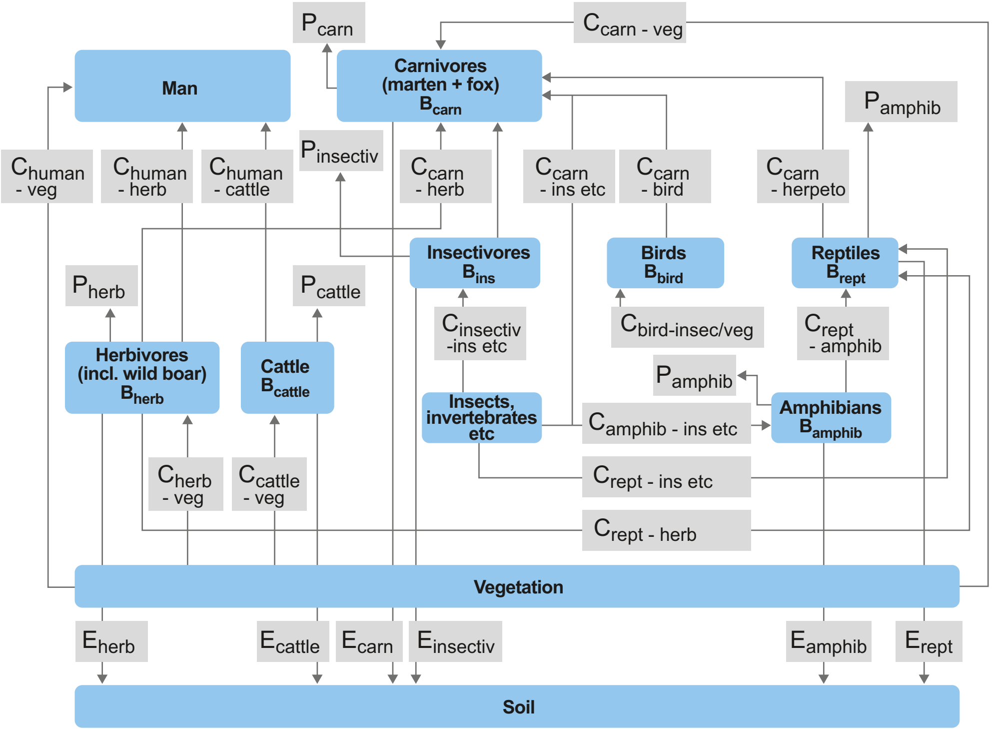


Figure 4-29. Food web describing the pools (boxes) and fluxes (arrows) of organic matter in a terrestrial ecosystem. P is predation, C is consumption, B is biomass and E is egestion. The configuration is adapted to the information presented below in this section and the food web is therefore applicable to both sites. Estimated values for each box and arrow are found in Tables 4-31, 4-32 (mammals), 4-43, 4-44 (amphibians and reptiles) and 4-38 to 4-41 (birds) for both the Forsmark and Laxemar-Simpevarp areas, except for the box representing insects (discussed in Section 4.2.4). Vegetation and soil are described in Chapters 6 to 8.

The aims of the studies describing the fauna at the sites can be summarized as follows.

- Describing which species or functional groups occur in the area.
- Establishing reliable density estimates for larger animals, many of which are used as a food sources for humans.
- Quantifying important pools/fluxes from the sites, for use in the ecosystem models.
- Establishing a baseline for an ongoing monitoring programme that can be used to relate different kind of disturbances to wildlife population changes.

In this chapter the focus is mainly on the first three points. This chapter also serves as a basis for the calculations of fluxes associated with consumers in the ecosystem modelling and mass balance models presented in Chapters 8 and 10.

4.2.1 Mammals

Description of the monitoring activities

From the site investigations, it has been possible to estimate the population densities for most of the mammal species found in the Forsmark and Laxemar-Simpevarp areas. The mammals that have been included in the surveys are listed in Table 4-24. The chosen study area was centred around the drilling activities in the Forsmark (approx. 110 km^2) and Laxemar-Simpevarp (approx. 120 km^2) areas. In addition to these areas, one reference area was selected in the same region of each site to provide further data for evaluation of the results from the specific sites. The reference area chosen for the Forsmark area was near Hållnäs, north of the Forsmark area, and the reference area chosen for the Laxemar-Simpevarp area was near Blankaholm, north of the Laxemar-Simpevarp area.

Table 4-24. Density estimates are available for a number of mammal species from the Forsmark and Laxemar-Simpevarp areas. The density estimates are calculated from the surveys that are shown in the table / Truvé and Cederlund 2005/ and /Truvé 2007/.

Species English (Swedish)	Latin	Surveys in the Forsmark area	Surveys in Laxemar-Simpevarp area
Herbivores (Even-toed ungulates)			
Fallow deer (*Sw: Dovhjort*)	*Dama dama*	*Not found*	Pellet: 2007
Moose (*Sw: Älg*)	*Alces alces*	Pellet: 2002,2003,2007 Aerial: 2002,2004	Pellet: 2003,2007 Aerial: 2003,2007
Red deer (*Sw: Kronhjort*)	*Cervus elaphus*	*Not found*	Pellet: 2003, 2007
Roe deer (*Sw: Rådjur*)	*Capreolus capreolus*	Pellet: 2002,2003,2007	Pellet: 2003, 2007
Herbivores (Lagomorphs)			
European (common) hare (*Sw: Fälthare*)	*Lepus europaeus*	Pellet: 2002,2003,2007	Pellet: 2003, 2007
Mountain hare (*Sw: Skogshare*)	*Lepus timidus*	Pellet: 2002,2003,2007	Pellet: 2003, 2007
Carnivores			
Lynx (*Sw: Lodjur*)	*Lynx lynx*	Snow tracking:2002	Not found
Marten (*Sw: Mård*)	*Martes martes*	Snow tracking:2002,2007	Snow tracking:2003
Red fox (*Sw: Rödräv*)	*Vulpes vulpes*	*	*
Omnivores			
Wild boar (*Sw: Vildsvin*)	*Sus scrofa*	Pellet:2007	Snow tracking: 2003 Pellet: 2003, 2007
Rodents			
Bank Vole (*Sw: Skogssork*)	*Clethrionomus glareolus*	Trapping: spring and autumn 2003	Trapping: spring and autumn 2003
Field vole (*Sw: Åkersork*)	*Microtus agrestis*	Trapping: spring and autumn 2003	Trapping: autumn 2003
Water vole (*Sw: Vattensork*)	*Arvicola terrestris*	Trapping: spring and autumn 2003	Trapping: spring and autumn 2003
Wood mouse *(Sw: Mindre skogsmus*)	*Apodemus sylvaticus*	Trapping: spring and autumn 2003	Trapping: spring** and autumn 2003
Yellow necked mouse (*Sw: Större skogsmus*)	*Apodemus flavicollis*	Trapping: spring and autumn 2003	Trapping: spring** and autumn 2003
Insectivores			
Common shrew (*Sw: Vanlig näbbmus*)	*Sorex araneus*	Trapping: spring and autumn 2003	Trapping: spring and autumn 2003

* Density estimation not possible through snowtracking.
** Spring trapping only included mice in forests, not in fields.

Population sizes for large mammal species were estimated using pellet counts conducted during at least two separate years, while small mammal populations where estimated using traps in the spring and autumn of 2003 and the autumn of 2004. The size of the moose population was also estimated by means of aerial surveys (Figure 4-30). Marten, lynx and fox were studied solely by snow tracking. The density estimates, generated from the surveys that are shown in Table 4-24, have been used to calculate a mean density for each species. As rodent density differs greatly between spring and autumn, the density has been estimated from the mean value for 2003. In the Laxemar-Simpevarp area, trapping for field vole and mouse (in the field) was only done in the autumn, while water vole was only trapped in the spring in 2003. The densities used for these species are therefore based on a single survey /Cederlund et al. 2004/.

The bat fauna of the Forsmark and Laxemar-Simpevarp areas was surveyed using ultrasound detectors during the summer of 2004 /de Jong and Gylje 2005, Ignell 2004/. Mist nets were also used in the Forsmark area. The objective was to map the distribution of all species in the area, to identify important foraging areas and colonies and to get rough estimates of the abundance of the species.

Figure 4-30. *Moose spotted during airborne inventory.*

Description of the mammals in the Forsmark and Laxemar-Simpevarp areas

This section presents the mammals found at the two sites, including a short description and estimates of their population densities (Tables 4-31 and 4-32).

Moose

The aerial surveys and pellet counts performed in the winter of 2002–2007, after the hunting season, show that the mean density in the Forsmark area is 0.70 moose·km^{-2} (0.74 in Hållnäs). The low age of harvested bulls reported from the Forsmark area indicates a high hunting pressure on bulls. The average age is 2.7 years for bulls compared with 4.9 for cows. This is a consequence of a sex-biased harvest strategy. The average carcass weight is 165 kg for bulls and 154 kg for cows (2002–2006) /Cederlund and Lemel 2007a/. Fecundity (eggs/cow) among adult females is relatively high, but does not deviate from other populations in this part of the country.

In the Laxemar-Simpevarp area, the mean density between 2002 and 2007 is 0.77 moose·km^{-2} (0.41 in Blankaholm). The low carcass weight (on average 156 kg for bulls and 146 kg for cows 2002–2006) and low age (in average 2.1 years for bulls and 2.8 years for cows) reported from Oskarshamn indicate a high hunting pressure /Cederlund and Lemel 2007b/. Fecundity (eggs/cow) among adult females is moderate, but probably not lower than among other populations in this part of the country.

The moose diet consists mainly of deciduous trees and larger shrubs (approx. 45%). In the summer the moose also feeds on herbs and low shrubs to a large extent, while coniferous browse is common in the winter /Truvé and Cederlund 2005/.

Table 4-25. Density estimates from surveys of large mammals 2002–2007 in the Forsmark, Laxemar-Simpevarp and the control areas from /Truvé and Cederlund 2005/ and /Truvé 2007/.

Species	Study area	Year	Method	Mean (ind/10km²)	SE	n
Lynx	Forsmark	2002	Snowtracking	0.2		
	Forsmark	2007	*Regional survey**	0.5		
Marten	Forsmark	2002	Snow tracking	2.4		
	Forsmark	2007	Snow tracking	14.44	14.57	
	Hållnäs	2002	Snow tracking	4.2		
	Hållnäs	2007	Snow tracking	4.69	7.28	
	Simpevarp	2003	Snow tracking	1.3		
	Blankaholm	2003	Snow tracking	0.5		
Wild boar	Forsmark	2007	Pellet	0.43	0.49	774
	Hållnäs	2007	Pellet	0.25	0.34	886
	Simpevarp	2003	Snow tracking	0.4		
	Simpevarp	2003	Pellet	2.6	1.95	887
	Simpevarp	2007	Pellet	3.36	1.62	955
	Blankaholm	2003	Snow tracking	0.5		
	Blankaholm	2003	Pellet	1.2	0.8	746
	Blankaholm	2007	Pellet	6.66	3.23	866
Red deer	Simpevarp	2003	Pellet	0.3	0.18	887
	Simpevarp	2007	Pellet	1.34	0.6	955
	Blankaholm	2003	Pellet	1.5	0.58	746
	Blankaholm	2007	Pellet	1.81	0.64	866
Fallow deer	Simpevarp	2007	Pellet	0.36	0.32	955
	Blankaholm	2003	Pellet	0.4	0.34	746
	Blankaholm	2007	Pellet	0.41	0.36	866
Roe Deer	Forsmark	2002	Pellet	59.3	11.86	656
	Forsmark	2003	Pellet	93.6	20.77	595
	Forsmark	2007	Pellet	33.3	9.34	774
	Hållnäs	2002	Pellet	37.7	9.20	549
	Hållnäs	2003	Pellet	48.0	8.24	908
	Hållnäs	2007	Pellet	24.28	6.32	886
	Simpevarp	2003	Pellet	49.0	9.30	887
	Simpevarp	2007	Pellet	37.7	8.3	955
	Blankaholm	2003	Pellet	51.6	11.00	746
	Blankaholm	2007	Pellet	34.7	8.1	866
Moose	Forsmark	2002	Aerial	2.4	0.9	
	Forsmark	2002	Pellet	8.3	2.09	656
	Forsmark	2003	Pellet	12.3	2.77	595
	Forsmark	2004	Aerial	6.5**	0.69	
	Forsmark	2007	Pellet	5.63	1.33	774
	Hållnäs	2002	Aerial	12	2.9	
	Hållnäs	2002	Pellet	6.3	1.65	549
	Hållnäs	2003	Pellet	6.7	1.62	908
	Hållnäs	2004	Aerial	6.5**	0.69	
	Hållnäs	2007	Pellet	5.53	1.08	886
	Simpevarp	2003	Aerial	7.8	1.8	
	Simpevarp	2003	Pellet	5.7	1.08	887
	Simpevarp	2007	Aerial	9.1	1.3	
	Simpevarp	2007	Pellet	8.34	1.34	955
	Blankaholm	2003	Pellet	4	1.06	746
	Blankaholm	2007	Pellet	4.2	1.03	866

Species	Study area	Year	Method	Mean (ind/10km^2)	SE	n
Hares – field	Forsmark	2002	Pellet	3.2	1.75	832
	Forsmark	2003	Pellet	3.2	1.90	883
	Forsmark	2007	Pellet	9.5	10.24	1,077
	Hållnäs	2002	Pellet	2.5	0.40	2,402
	Hållnäs	2003	Pellet	22.8	8.50	658
	Hållnäs	2007	Pellet	22.16	9.66	740
	Simpevarp	2003	Pellet	35.1	13.11	1,113
	Simpevarp	2007	Pellet	9.65	4.32	949
	Blankaholm	2003	Pellet	19.1	7.37	1,257
	Blankaholm	2007	Pellet	17.38	9.43	1,076
Hares – forest	Forsmark	2002	Pellet	4.4	3.80	1,274
	Forsmark	2003	Pellet	2.3	2.08	595
	Forsmark	2007	Pellet	24.11	20.54	774
	Hållnäs	2002	Pellet	2.3	1.97	1,048
	Hållnäs	2003	Pellet	1.5	2.23	908
	Hållnäs	2007	Pellet	3.44	2.74	886
	Simpevarp	2003	Pellet	5.2	2.83	887
	Simpevarp	2007	Pellet	10.36	5.5	955
	Blankaholm	2003	Pellet	3.2	1.86	746
	Blankaholm	2007	Pellet	2.78	3.12	866

* According to /Truvé 2007/ a regional survey performed by the County Administrative Board in Uppsala County shows that there is one family group in Forsmark and one in Hållnäs. A family group consists on average of 5.5 individuals. As the investigation area in Forsmark is 110 km^2 /Cederlund et al. 2004/ the density can be estimated as 0.5 ind per 10 km^2.

** Density estimates for 2004 are for an area including both Forsmark and Hållnäs.

Table 4-26. Density estimates from surveys of small mammals 2003–2004 in the Forsmark and Laxemar-Simpevarp areas / Truvé and Cederlund 2005/.

Species	Study area	Year	Season	Method	Mean (ind/0.01km^2)	SE	n
Mouse – forest	Forsmark	2003	spring	trapping	0.7	0.19	11
			autumn	trapping	2.8	0.38	11
		2004	–	–	–	–	–
			autumn	trapping	2.5	0.39	4
	Simpevarp	2003	spring	trapping	4.8	0.81	5
			autumn	trapping	8.9	0.74	10
		2004	–	–	–	–	–
			autumn	trapping	11.5	0.85	4
Mouse – field	Forsmark	2003	spring	trapping	0.4	0.30	4
			autumn	trapping	6.4	2.34	3
		2004	–	–	–	–	–
			autumn	trapping	0.2	0.15	4
	Simpevarp	2003	–	–	–	–	–
			autumn	trapping	6.4	2.34	3
		2004	–	–	–	–	–
			autumn	trapping	6.7	0.78	4
Bank vole – forest	Forsmark	2003	spring	trapping	2.3	0.36	11
			autumn	trapping	3.2	0.43	4
		2004	–	–	–	–	–
			autumn	trapping	7.4	0.82	4
	Simpevarp	2003	spring	trapping	4.1	0.83	5
			autumn	trapping	4.8	0.56	10
		2004	–	–	–	–	–
			autumn	trapping	3.7	0.59	4

Species	Study area	Year	Season	Method	Mean (ind/0.01km^2)	SE	n
Water vole	Forsmark	2003	spring	trapping	5.7	1.47	5
			autumn	trapping	4.8	1.35	5
		2004	spring	–	–	–	–
			autumn	trapping	7.9	1.28	4
	Simpevarp	2003	spring	trapping	5.7	1.47	5
			autumn	trapping	–	–	14
		2004	–	–	–	–	–
			autumn	trapping	4.5	0.96	4
Field vole – forest	Forsmark	2003	spring	trapping	0.1	0.03	11
			autumn	trapping	0.1	0.04	11
		2004	–	–	–	–	–
			autumn	trapping	1.5	0.13	4
	Simpevarp	2003	–	–	–	–	–
			autumn	trapping	0.3	0.06	10
		2004	–	–	–	–	–
			autumn	trapping	0.9	0.11	4
Field vole-field	Forsmark	2003	spring	trapping	0.4	0.11	4
			autumn	trapping	0.1	0.06	4
		2004	spring	–	–	–	–
			autumn	trapping	10.2	0.35	4
	Simpevarp	2003	–	–	–	–	–
			autumn	trapping	4.2	0.18	3
		2004	–	–	–	–	–
			autumn	trapping	2.3	0.17	4
Common shrew	Forsmark	2003	spring	trapping	0.2	0.09	15
			autumn	trapping	2.7	0.30	15
		2004	spring	–	–	–	–
			autumn	trapping	2.7	0.30	8
	Simpevarp	2003	spring	trapping	0.5	0.29	5
			autumn	trapping	1.5	0.26	14
		2004	–	–	–	–	–
			autumn	trapping	4.4	0.38	8

Roe deer

Roe deer is the most numerous cervid species in both Forsmark and Laxemar-Simpevarp. In the Forsmark area there was a mean density of 6.2 roe deer·km^{-2} (3.7 in Hållnäs) based on the three density estimates between 2002 and 2007. Although it is well known that roe deer density varies considerably between adjacent local areas, there is no reason to believe that the densities found in this study are exceptional /Cederlund et al. 2004/. In the Laxemar-Simpevarp area, the mean density was 4.3 deer·km^{-2} (4.3 in Blankaholm) based on estimates for 2003 and 2007.

The winter diet of a roe deer is diverse and consists mainly of deciduous browse (37%), low shrubs (26%), lichens (Sw: *lav*) (12%) and coniferous trees (10%). The summer diet consists primarily of herbs /Truvé and Cederlund 2005/.

Fallow deer and red deer

Fallow deer and red deer have only been found in the Laxemar-Simpevarp area. The average density of red deer was estimated to be 0.08 red deer·km^{-2} based on inventories in 2003 and 2007. The red deer density was more than four times larger in 2007 (0.13 ind·km^{-2}) than in 2003 (0.03 ind·km^{-2}). The red deer population is larger in the control area Blankaholm, with an average of 0.17 deer·km^{-2}. The considerable variation between the Laxemar-Simpevarp area and Blankaholm is probably a result of a common clustering of deer. According to local managers, the populations are increasing, as is the entire population in Sweden /Cederlund et al. 2004/. Fallow deer was not found in the Laxemar-Simpevarp area by pellet counts in 2003, but was found in 2007. The density was estimated to be 0.04 fallow deer·km^{-2}.

Red deer mainly eat grasses and sedges (Sw: *halvgräs*) in the summer (62%) and even to some extent in the winter, along with low shrubs, deciduous browse and coniferous trees. Fallow deer mainly feed on grasses and sedges, foliage of broad-leaved deciduous trees and Scots pine and forbs. These four categories of food accounted for about 73% of the diet, which is similar to red deer diet /Truvé and Cederlund 2005/.

Hare

The density estimates of hare have been assigned to different habitats, where the European hare mainly feeds in open fields and the mountain hare mainly feeds in forested habitats.

In the Forsmark area, the average hare density in open field habitats was 0.53 hares·km^{-2} (European hare) based on inventories between 2002 and 2007, while it was on average 1.0 hare·km^{-2} in forests (mountain hare). In the control area of Hållnäs, the densities are reversed: higher in the fields (on average 1.6 hares·km^{-2}) than in the forests (on average 0.24 hare·km^{-2}). The high figure in the Forsmark forests is a result of a high frequency of pellets in 2007. Excluding 2007, the density would be 0.34 hare·km^{-2}. In the Laxemar-Simpevarp area, the average hare density in the open field habitat was 2.2 hares·km^{-2} based on the years 2003 and 2007, and somewhat lower, 1.8 hares·km^{-2}, in the control area of Blankaholm. The mean density was much lower in the forest, 0.8 in the Laxemar-Simpevarp area and 0.3 in Blankaholm.

Mountain hares feed mainly on grasses and herbs in summer, but in winter they browse on deciduous trees and occasionally on evergreen species. The European hare feeds to a large extent on agricultural crops and pasture vegetation all year around, and does not browse to the same extent as Mountain hare /Truvé and Cederlund 2005/.

Small mammals

The small mammals occurring in the forest are bank vole, a few field voles and mice. The mice included in the mammal survey are yellow-necked mouse and wood mouse. The common shrew inhabits both forests and open field areas. The water vole inhabits the banks of ditches, rivers, streams and lakes.

In the forests of the Forsmark area, bank vole is the most numerous rodent (275 ind·km^{-2}), followed by mice (175 ind·km^{-2}) and field voles (10 ind·km^{-2}), according to a mean value of the spring and autumn in 2003. In field areas, mice are most frequent (340 mice·km^{-2}). There are only 25 field voles per km^2. Furthermore, there are 525 water voles per km^2 in the specific habitat of water vole and 145 common shrews per km^2 in the Forsmark area. The common shrews are evenly spread over the forest and field area.

In the forests of the Laxemar-Simpevarp area, mice are the most numerous rodents (685 ind·km^{-2}) followed by bank voles (445 ind·km^{-2}), according to a mean value for the spring and autumn of 2003. There are also a small number of field voles (30 ind·km^{-2}). The abundance of mice is almost the same in the field areas (640 ind·km^{-2}) as in the forests. The field areas are the habitat of most of the field voles (420 ind·km^{-2}). The density of common shrew is 100 ind·km^{-2} and the water vole has a density of 570 ind·km^{-2} /Truvé and Cederlund 2005/.

All voles are herbivorous generalists and consume green plants to a large extent during the summer. Seeds and fruits are also important food items, especially in winter. Voles collect hoards of food in the summer, which they consume during the winter. Mice are omnivores and feed on insects and larvae, but their diet consists mainly of vegetable matter. Like voles they store food when availability is high. Shrews are insectivores and feed mainly on small invertebrates such as insects, spiders and earthworms, but also on carrion /Truvé and Cederlund 2005/.

The spatial distribution of water voles

Water voles inhabit the banks of ditches, rivers, streams and lakes and the density investigations have been performed using traps along streams in the area. Their home range is estimated to be 1,904 m^2 based on allometric data in /Truvé and Cederlund 2005/. According to /BBC 2004 /, the males have home ranges of about 130 m along the river banks, whereas females have smaller ranges of about 70 m. If an average length of 100 m is assumed for the home range, the home range will cover a 10-metre wide zone along each side of the streams. The habitat of water voles in the Forsmark area and in the Laxemar-Simpevarp area is illustrated in Figures 4-31 and 4-32.

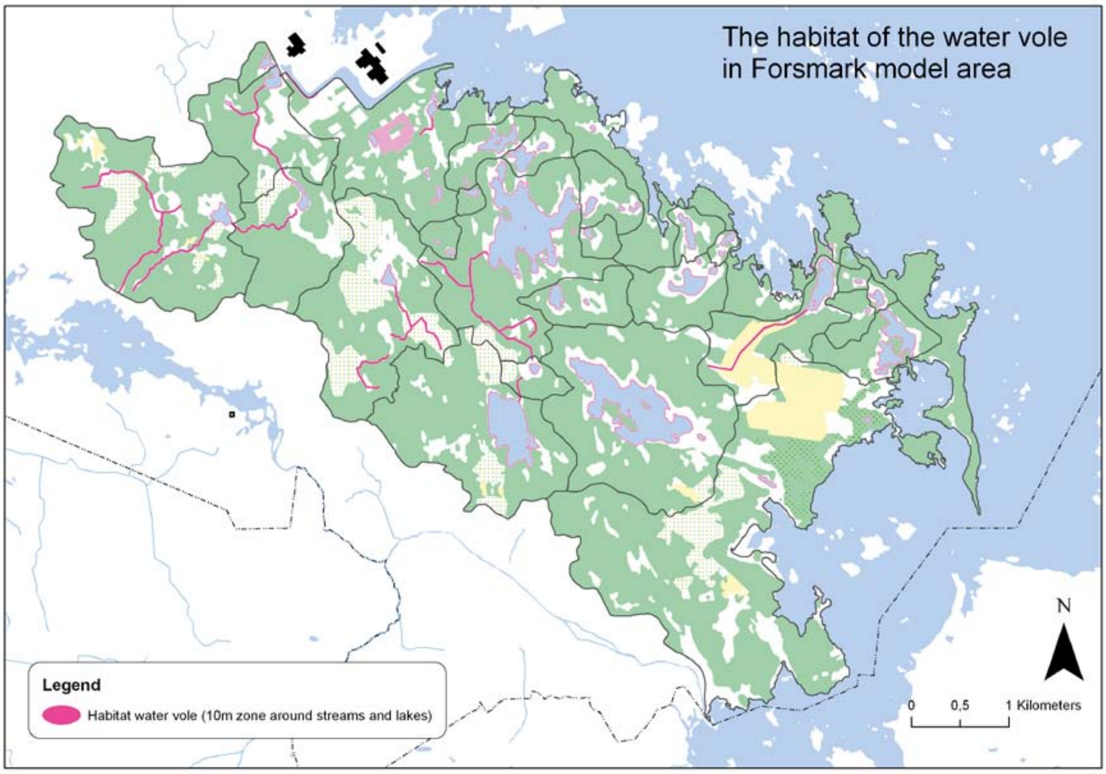


Figure 4-31. The water vole habitat in the Forsmark area, calculated and illustrated in ArcGIS using the hydrographical data in the topographic map.

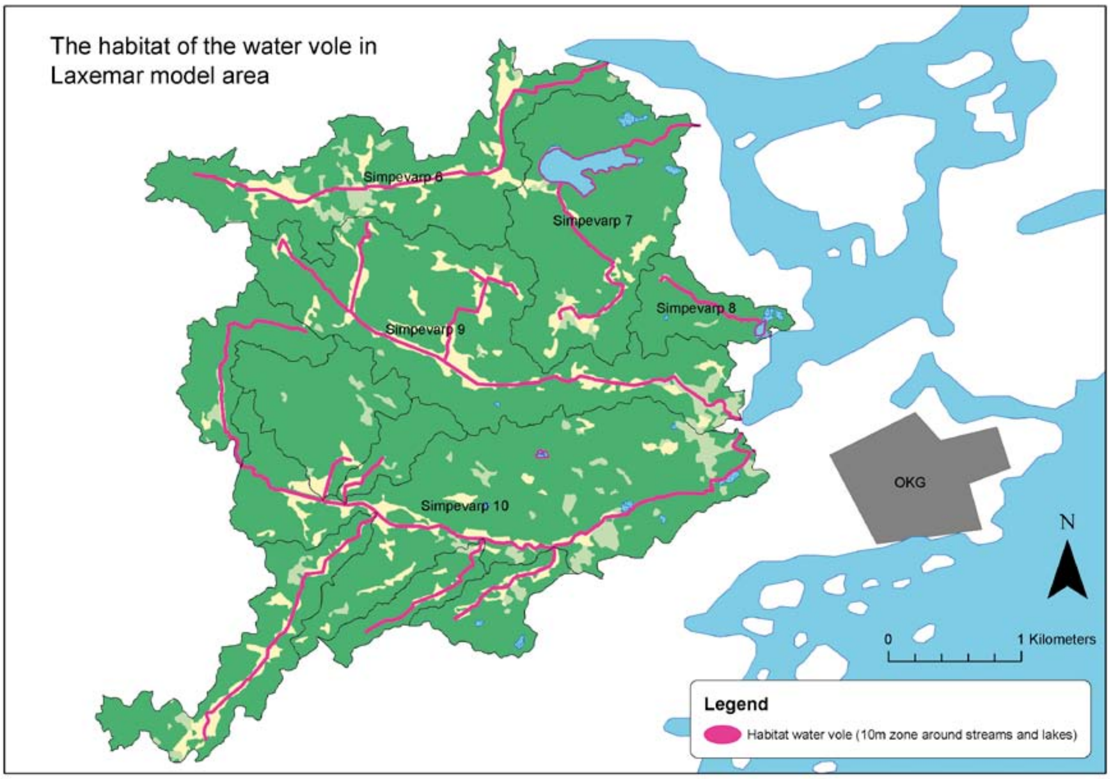


Figure 4-32. The water vole habitat in the Laxemar-Simpevarp area, calculated and illustrated in ArcGIS using the hydrographical data in the topographic map.

Marten

In the Forsmark area, mean marten density was estimated to be 0.84 ind·km^{-2} using inventories from 2003 and 2007, but there was a large difference between the results for the two different years. In Hållnäs, the density estimates were very similar in 2003 and 2007, with a mean of 0.44 marten·km^{-2}. Snow tracks of marten were found in both the Laxemar-Simpevarp area (0.13 marten·km^{-2}) and Blankaholm (0.05) in 2003, but not in 2007. The density estimates are relatively uncertain (large confidence intervals), but seem quite reasonable /Cederlund et al. 2004/.

According to a study in Britain, the diet of martens is diverse, but consists mainly of mammals (47%) /Truvé and Cederlund 2005/ (Table 4-27).

Red fox

The high frequency of tracks, in combination with long distances between end points and highly irregular movement patterns, made it too difficult and time consuming to estimate the red fox density. There is therefore no site-specific density data for fox /Cederlund et al. 2004/. A generic density figure has been found on /Svenska Jägareförbundet 2004 /. According to this source, the density of red foxes in Sweden varies between 0.2 and 0.8 per km^2. The highest density is found in agricultural areas in the southern parts of Sweden. As forests dominate both in the Forsmark and the Laxemar-Simpevarp area, a density of 0.2 per km^2 has been applied to the areas.

Like the marten, the red fox has a mixed diet. Red foxes feed mainly on rodents (minimum 32%), hares (minimum 35%) and birds (minimum 18%) during the summer, but several other animals as well as plants are consumed /Truvé and Cederlund 2005/ (Table 4-28).

Table 4-27. Diet of martens in Britain from /Truvé and Cederlund 2005/.

Food item	%
Mammals	47
Birds and eggs	15
Invertebrates and other	24
Fruits and vegetables	10
Hepetofauna (amphibians and reptiles)	4
Sum	100

Table 4-28. Red fox summer diet in Finland /Truvé and Cederlund 2005/.

Food item	Frequency of occurrence (min. %)
Herbivores (rodents and hares)	70
Birds	18
Insects	5
Other plants	7
Sum	100

Lynx

Tracks were found in the Forsmark area in 2002 (0.02 ind·km^{-2}). In 2007 a few tracks crossed the line but they were hard to follow since they passed lakes and wetlands with thin ice. Consequently, it was not possible to estimate population density. However, the results of surveys conducted by the Uppsala County Administrative Board show that there is one family group in the Forsmark area and one in Hållnäs. A family consists on average of 5.5 individuals. As the Forsmark area is 110 km^2, this gives a density of 0.05 ind·km^{-2} /Truvé J 2006, pers. comm./. The mean density in the Forsmark area is therefore 0.035 lynx·km^{-2}. No tracks of lynx have been found in the Laxemar-Simpevarp area. However, since lynx move over large areas, it is reasonable to believe that they occasionally pass through the Laxemar-Simpevarp area.

Lynx mainly feed on hares and deer species, but also on rodents, grouse and fox /Truvé and Cederlund 2005/.

Wild boar

According to local game managers, the wild boar population is fairly new in the Forsmark and Laxemar-Simpevarp areas and they are still at a low density. However, a rapid increase is expected in both areas /Cederlund et al. 2004/. The population growth of wild boar is 13% in central Sweden, on a yearly basis /Lemel 1999/. In the Forsmark area, only occasional tracks and no pellets were found in 2003, and therefore it was impossible to make any density estimate. In 2007 the pellet counts showed a density of 0.04 boar·km^{-2}, which was twice as high as in Hållnäs (0.02 boar·km^{-2}). The mean density in the Laxemar-Simpevarp area was estimated to be 0.21 boar·km^{-2} and in Blankaholm 0.36 boar·km^{-2}. The boar density according to pellet counts was approx. 30% higher in 2007 than in 2003.

There are large differences in rates of change between the results from snow tracking and faecal counts of wild boar, but neither of the methods has been thoroughly evaluated, which makes it difficult to assign either of the methods any real credibility /Truvé 2007/.

A wild boar is 85% herbivorous (vegetation and mushrooms) and 15% carnivorous /Lemel 1999/.

Domestic animals

The stock of domestic animals in Forsmark parish and the Laxemar-Simpevarp area has been obtained from SCB and was compiled in /Miliander et al. 2004a, b/ together with the carcass weights of the domestic animals. As there is only one farm in the Forsmark area, no agricultural statistics have been accessible for reasons of confidentiality. Instead, the data for Forsmark parish has been applied to the Forsmark area. The Forsmark area and the Laxemar-Simpevarp area are defined in /Miliander et al. 2004a, b/.

The density was calculated as the number of animals divided by the area for fodder production and grazing (see Section 4.1.2). The cattle density is almost equal in the Forsmark and Laxemar-Simpevarp areas (66 and 62 cows per km^2, respectively). There are 31 sheep per km^2 in the Forsmark area, but only 7 ind·km^{-2} in the Laxemar-Simpevarp area. There are only pig farms in the Laxemar-Simpevarp area (36 ind·km^{-2}).

According to /Arnesson 2001/, 1.8–3.0 hectares is required to produce the fodder for one cow. That corresponds to a density of approximately 42 cows per km^2. According to statistics from SCB, the cow density in the Forsmark and Laxemar-Simpevarp areas is higher, which can be explained by the fact that only 63% of the cow fodder is self-produced by the farms and the rest is purchased /Swedish Dairy Association 2007/.

Bat

Seven species of bat were found in the Forsmark area by /de Jong and Gylje 2005/ (Table 4-29). Two additional species have been found in earlier surveys. Three of these nine species are red-listed. The most interesting observation is the colony of *Nathusius pipistrelle* found at Kallerö in the southernmost part of the study area. Most of the Forsmark area contains few species and low abundance. In these parts the Northern bat dominates. However in some other parts, especially Forsmarks bruk, Habbalsbo, Johannisfors, Kallerö and Storskäret, species richness and abundance is relatively high.

In the Laxemar-Simpevarp area, the inventory resulted in nine species being identified within the area of investigation /Ignell 2004/ (Table 4-29). Two different environments have been identified as especially valuable to bats within the area of investigation. These two areas are the near-mainland farms and wind-shielded sites in the archipelago. Two red-listed species were found in the investigation area. Two colonies were discovered, one colony of *Nathusius pipistrelle* in the house at Lilla Simpevarp and one of brown long-eared bat in one of the summerhouses at Mederhult.

In total, ten species were found in both areas, which is half of the number of species found in Sweden. Of the 18 species of bats found in the country, five are rare and only recorded in a few cases /Ahlén 2004/. /Ignell 2004/ did not consider the species richness in the Laxemar-Simpevarp area to be high, as 11 to 13 species can be found in the most species-rich areas in Sweden /Ahlén 2004/. /de Jong and Gylje 2005/, on the other hand, considered the number of bats in the Forsmark area to be high. The bat fauna is almost identical in the two areas, aside from the parti-coloured bat that was found only in the Laxemar-Simpevarp area.

Table 4-29. Species of bats found in the Forsmark /de Jong and Gylje 2005/ and Laxemar-Simpevarp areas /Ignell 2004/.

Species Latin name	English name	Swedish name	Forsmark area	Laxemar-Simpevarp area
Myotis daubentonii	Daubenton's bat	Vattenfladdermus	Yes	Yes
Myotis brandtii	Brandt's bat	Brandts fladdermus	Yes	Yes
Myotis mystacinus[1]	Whiskered bat	Mustasch- fladdermus	Yes	Cannot be excluded[3]
Myotis nattereri[1]	Natterer's bat	Fransfladdermus	Yes, but not in this survey	Yes
Vespertilio murinus	Parti-coloured bat	Gråskimlig fladdermus	No	Yes
Pipistrellus nathusii[2]	Nathusius pipistrelle	Trollfladdermus	Yes	Yes
Pipistrellus pygmaeus	Common pipistrelle	Dvärgfladdermus	Yes	Yes
Eptesicus nilssonii	Northern bat	Nordisk fladdermus	Yes	Yes
Nyctalus noctula	Noctule	Stor fladdermus	Yes	Yes
Plecotus auritus	Brown long-eared bat	Långörad fladdermus	Yes, but not in this survey	Yes

[1] Red listed, classified as vulnerable (VU).
[2] Red listed, classified as near threatened (NT).
[3] Whiskered bat and Brandt's bat cannot be distinguished in the field without being caught.

Food web properties

From knowledge of what species are present, what they eat and how abundant they are in the area, it is possible to construct a food web and calculate the fluxes of energy or carbon within this food web. The methodology and the results used to describe pools and fluxes of the mammals in the food web are presented below.

Calculation of properties

Free-living mammals

The biomass has been calculated based on the density estimates that are presented in the previous section. These densities were estimated after the hunting season for moose, roe deer and hare and were therefore adjusted by increasing the estimated density with a value corresponding to some of the loss (see below) from hunting in the area, using local hunting statistics presented in /Miliander et al. 2004a, b/. This was done in order to provide the ecosystem model with a more appropriate annual consumption estimate for these animals. 40% of the harvested moose are calves and 60% are adults according to /Miliander et al. 2004a, b/. A calf consumes vegetation for a period of almost three months (Aug–Oct) before the hunting season, while the harvested adults consume for ten months (Jan–Oct). On a yearly basis, 60% of the harvested moose live and consume throughout the year, as $0.6\cdot(10/12)+0.4\cdot(3/12) \approx 0.6$. 60% of the loss from hunting has therefore been added to the estimated density figures. The same procedure has been applied to roe deer and hare.

In calculating the standing stock of carbon for each species, the population density was multiplied by the body mass (g) given in /Truvé and Cederlund 2005/ and the carbon content. According to site-specific analysis of chemical composition in deposits and biota in the Forsmark and Laxemar-Simpevarp areas /Hannu and Karlsson 2006, Engdahl et al. 2006/, mammal muscles contain on average 11.7% carbon based on the fresh weight (44.9% based on the dry weight). This value is lower than the factors given in both /Emsley 1998/ and /Sterner and Elser 2002/, who state that the carbon content of mammals is 22.9% based on the fresh weight and 57% based on the dry weight. Despite the divergence from other references, the site-specific values are used.

The fluxes of matter – i.e. consumption, production, respiration and egestion – for each species have been calculated based on its field metabolic rate (FMR). FMR is the total rate of energy conversion for a wild animal, including the basal metabolic rate (BMR), thermoregulation, locomotion, feeding, predator avoidance, reproduction, growth and other energy consuming activities. When used to analyze energy budgets, FMR is the same as the assimilated energy (A) and is often broken down into rate of production (growth and reproduction) and respiration (metabolic heat loss), expressed as: FMR = A = P+R /Brown et al. 2004/. Like BMR, FMR is strongly correlated with body mass in eutherian mammals (mammals with a placenta).

The total energy budget for an organism is often expressed as /Baird and Ulanowicz 1989/:

C = P+R+E

C = consumption or total intake

P = production

R = respiration

E = egestion (faecal matter)

The calculations of carbon flows have been performed in the following order:

1. The field metabolic rate (FMR) in kJ day^{-1} was calculated for different species using the formula FMR = ax^b, where x is body mass, a and b are known parameters for carnivores, herbivores, omnivores, rodentia in general and mesic rodents (rodents in moderately moist environment, assumingly water vole) /Nagy et al. 1999/.
2. Production (P) and respiration (R) were estimated using the formula FMR = P+R. Production and respiration were distinguished by using an estimate of average production efficiency (P/A in %) for small mammals, other mammals and insectivores /Humphreys 1979/. The P/A-factor for the category "small mammals" was used for rodents, while the factor for the category "other mammals" was used for herbivores and carnivores, and the factor for the insectivores was used for common shrew.
3. Consumption (C) in kJ day^{-1} was calculated in two steps:

   First, the FMR (kJ day^{-1}) was divided by a conversion factor for the metabolizable energy available from a gram of dry matter (DM) in the animal diet, giving consumption (C) in g DM/day. The conversion factors for different mammal groups – mammalian carnivores, herbivores, omnivores and insectivores – are found in /Nagy et al. 1999/.

   Second, C (in g/day) was multiplied by the total energy content (kJ g dry matter) of different diets /Golley 1961/, giving consumption (C) in kJ day^{-1}.
4. Egestion (E) was calculated using the formula C = P+R+E.
5. The figures were finally converted to carbon content by equating 1 g carbon to 10.94 kcal = 45.8 kJ /Salonen et al. 1976, Humphreys 1979/.

Domestic mammals

According to the agricultural statistics there is one agricultural enterprise (farm) in use within the Forsmark area. It is known that this farm has beef cattle. For reasons of confidentiality, no data are available concerning the production at this farm. When calculating the production of animal products in the Forsmark area, the densities of domestic animals in Forsmark parish have been applied to the Forsmark area. Agricultural statistics for the Laxemar-Simpevarp area have been obtained from Statistics Sweden.

The carbon pool of domestic animals was estimated based on the density figures from /Miliander et al. 2004a, b/. The carcass weights are given in /Miliander et al. 2004a, b/. The conversion factors between live weight and carcass weight are shown in Table 4-30. The carbon content in domestic animals is assumed to be 11.7% of the fresh weight as for the wild mammals.

Table 4-30. Conversion factors for live weight to carcass weight for cattle, pig and lamb.

Figure	Value	Source
Live weight of a cow	The carcass weight is 55% of the live weight	Assumed to be the same as for the game meat, given by /Cederlund 2004, Cederlund G 2006, pers. comm./.
Live weight of a pig	The carcass weight is 75% of the live weight	A carcass weight of 85 kg for a pig is equivalent to a live weight of 114 kg according to /Persson and Mattsson 2002/
Live weight of a lamb	The carcass weight is 39% of the live weight	A carcass weight of 17.5 kg for a lamb is equivalent to a live weight of 45 kg according to /Edberg 2006/

The carbon flows for domestic animals were not estimated using the field metabolic rate, as that method is based on free-living animals. Dairy cows and porkers are intensively managed and are very productive with regard to meat production. Their consumption is therefore not comparable to that of wild herbivores. Consumption has instead been estimated based on literature data. If the previous approach using the FMR equations had been used instead, consumption for cattle would be half as large, which means smaller figures for production, respiration and egestion.

According to /Swedish Dairy Association 2007/, a dairy cow consumes approximately 18 kg day^{-1}, of which 9.6 kg is coarse fodder (grass and ensilage) and 8.4 kg is concentrated fodder. A sheep consumes approximately 584 kg dw y^{-1} (1.6 kg dw day^{-1}) of crop silage and grass silage /Löfquist 2005/. The pig diet consists mainly of seeds. At a weight of 105 kg, a sow consumes approximately 2.9 kg dw day^{-1} (1,060 kg dw y^{-1}) /Partanen et al. 2007/.The carbon content of the domestic animal diet is assumed to be 0.46 gC per g dw, the same as for the green field layer in /Fridriksson and Öhr 2003/.

Production (P) has been assumed to be equal to the live weight of the slaughtered animals. Calculation of faeces production (egestion, E) for the domestic animals, the proportion between E and R in the FMR-calculations for free-living animals was used, giving an E of 42.7% of the energy input (consumption, C). The respiration (R) was calculated by using the formula C = P+R+E. The calculations of cattle milk production are presented in Section 4.1.2.

Results

Figures describing density, biomass, production, consumption, egestion and respiration per unit area for the two sites are presented in Tables 4-31 and 4-32.

Table 4-31. General figures per unit area describing densities, biomass, production, consumption, egestion and respiration for the mammals in the Forsmark area.

Mammal species		Habitat	Density	Biomass (standing stock)		Production mgC m^{-2} y^{-1}	Consumption mgC m^{-2} y^{-1}	Egestion (Faeces) mgC m^{-2} y^{-1}	Respiration mgC m^{-2} y^{-1}
			Number per km^2	Body mass g·ind^{-1}	Biomass mgC m^{-2}				
Herbivores (Even-toed ungulates)	Moose	Forest+Field	1.0	300,000	36	7.0	397	174	216
	Roe deer	Forest+Field	7.3	25,000	21	10	574	251	312
Herbivores (Lagomorphs)	European hare	Field	0.7	3,800	0.3	0.3	16	7	9
	Mountain hare	Forest	1.1	3,000	0.4	0.4	22	9.6	12
Herbivores (domestic)	Cattle	Field area (grain area excluded)	66	527,000/ 200,000	3,443	1,160	199,857	85,339	106,016
	Cattle (milk prod.)					7,343			
	Sheep	Field area (grain area excluded)	31	66,000/ 46,000	203	79	8,480	3,621	4,780
Carnivores	Marten	Forest	0.84	1,250	0.12	0.20	8.3	1.83	6.2
	Red fox	Forest+Field	0.20	6,000	0.14	0.18	7.4	1.7	5.6
	Lynx	Forest	0.035	30,000	0.12	0.12	5.11	1.14	3.85
Omnivorous	Wild boar	Forest+Field	0.043	60,000	0.3	0.11	5	1.0	3.5
Rodents	Bank Vole	Forest	275	23	0.7	1.7	199	87	110
	Field vole	Field	25	30	0.1	0.2	22	10	12
	Field vole	Forest	10	30	0.04	0.07	9	3.8	5
	Mouse	Field	340	23	0.9	2.1	246	108	136
	Mouse	Forest	175	23	0.5	1.1	127	56	70
	Water vole	around water[1]	525	74	4.5	9.2	1,090	478	603
Insectivores	Common shrew	Forest+Field	145	8.5	0.14	0.25	35	5.9	29

Table 4-32. General figures per unit area describing densities, biomass, production, consumption, egestion and respiration for the mammals in the Laxemar-Simpevarp area.

Mammal species		Habitat	Density	Biomass (standing stock)		Production mgC m^{-2} y^{-1}	Consumption mgC m^{-2} y^{-1}	Egestion (Faeces) mgC m^{-2} y^{-1}	Respiration mgC m^{-2} y^{-1}
			Number per km^2	Body mass g·ind^{-1}	Biomass mgC m^{-2}				
Herbivores-(Even-toed ungulates)	Fallow deer	Forest+Field	0.04	70,000	0.3	0.1	5	2.4	3.0
	Moose	Forest+Field	1.07	300,000	37.5	7.3	415	182	226
	Red deer	Forest+Field	0.08	170,000	1.6	0.4	22	10	12
	Roe deer	Forest+Field	5.6	25,000	16.5	7.8	439	193	239
Herbivores (Lagomorphs)	European hare	Field	2.4	3,800	1.1	1.0	56	24	30
	Mountain hare	Forest	0.84	3,000	0.3	0.3	17	7	9
Herbivores-(Domestic)	Cattle	Field area (grain area excluded)	62	527,000/ 200,000	3,125	1,084	186,811	80,142	99,558
	Cattle (milk prod.)					6,027			
	Sheep	Field area (grain area excluded)	7	66,000/ 46,000	43.4	17	1,815	778	1,019
	Pigs	Field area (grain area excluded)	36	114,000	483	827	17,713	7,599	9,287
Carnivores	Marten	Forest	0.13	1,250	0.02	0.03	1.3	0.28	1.0
	Red fox	Forest+Field	0.20	6,000	0.14	0.18	7.4	1.7	5.6
Omnivorous	Wild boar	Forest+Field	0.21	60,000	1.5	0.56	22	5	17
Rodents	Field vole	Field	420	30	1.5	3.1	368	161	203
	Mouse	Field	640	23	1.7	3.9	464	203	257
	Field vole	Forest	30	30	0.11	0.22	26	11.5	15
	Mouse	Forest	685	23	1.8	4.2	496	218	275
	Bank Vole	Forest	445	23	1.2	2.7	323	141	178
	Water vole	around water[1]	570	74	4.9	10	1,183	518	655
Insectivores	Common shrew	Forest+Field	100	8.5	0.10	0.17	24	4.1	20

[1] A habitat zone of 10 m along each side of streams and lakes has been assumed.

Conclusions and comparison between the two sites

Density estimates

Comparing the density of species in 2007 relative to 2002/2003 reveals a number of changes within populations during this time. The underlying causes of such changes are often unknown, and may stem from several processes of a more or less complicated nature. Surveys conducted on two subsequent occasions are not sufficient to draw conclusions concerning long-term population trends /Truvé 2007/. Such conclusions require longer data series. For instance, a difference in population size between two subsequent surveys could either be the result of a long term trend, a fluctuating population size, with a normally distributed annual variation, or a difference originating from a more complicated density pattern.

In the Forsmark area, moose and roe deer populations have declined during the period of investigation (2002–2007), which seems to be a general trend in the whole county. The standing stock of moose is comparable in the Forsmark area and the Laxemar-Simpevarp area, while the roe deer biomass is somewhat larger in the Forsmark area. According to the National Association of Huntsmen (*Sw: Svenska Jägareförbundet*) the normal density of moose is 1–1.5 moose·km^{-2} /Svenska Jägareförbundet 2007 /. The figures from the Forsmark and Laxemar-Simpevarp areas are within this interval and can therefore be regarded as average figures. The density of roe deer can be up to 40 roe deer per km^2 in favourable areas in the south and middle of Sweden /Svenska Jägareförbundet 2007/. The much lower estimates from the sites are by no means exceptional according to /Cederlund G 2006, pers. comm./.

There is a recently established lynx population in the Forsmark area and a larger population of marten (six times the biomass in the Laxemar-Simpevarp area). This result corresponds to the large-scale species distribution in Sweden. Red deer, fallow deer and wild boar have recently become established in Laxemar-Simpevarp. These densities are increasing.

According to a study in northern parts of Sweden, the density of mountain hare can be 2–2.5 hares per km^2 in the forests of Norrland /Svenska Jägareförbundet 2007 /. Compared to that figure the density in the Forsmark and Laxemar-Simpevarp areas is half as large. Hare populations have high interannual variation and the results are within the limits of what can be expected.

Wild boars do exist in both the Forsmark and Laxemar-Simpevarp areas. Their occurrence is though not as high as it can be in other parts of Sweden, with a maximum density of 1 boar per km^2 /Svenska Jägareförbundet 2007/. The wild boar populations have increased at an amazing rate, a phenomenon the area shares with many other parts of the country.

The standing stock of small mammals is notably larger in the Laxemar-Simpevarp area than in the Forsmark area (all species together). In the field it is 3 times larger and in forest 2.5 times larger. This is probably due to habitats of better quality (higher abundance of food resources and/or better nutritional quality of food items). Rodents show large regional variations.

Domestic animals have a significantly higher biomass per unit area than free-living animals. Their spatial distribution is, however, very limited and concentrated to agricultural areas (area for grain production excluded), which are sparse in both the Forsmark and Laxemar-Simpevarp areas.

Spatial distribution

An effort has been made to distribute the two predominant herbivores, moose and roe deer, among habitats in the landscape.

/Nikula et al. 2004/ studied moose habitat use in central Finland 1993–1996 by comparing the habitat composition of 54 home ranges with the overall landscape, and by comparing the habitat composition of the home ranges with the composition around moose locations within their home range. According to the study, the younger successional stages, especially pine-dominated habitats, seem to determine habitat selection by moose at the home range level, i.e. the amount of young successional stages has to be high enough to provide a suitable environment for moose. Only when the proportion of younger successional stages is high enough at the home range level is the mixture of other habitat types important for selection of home range habitat. Moose home ranges are located in areas with significantly fewer human settlements and, in the winter, significantly fewer agricultural fields than the average landscape. /Fisher and Wilkinson 2005/ have studied moose abundance in four successional stages of the boreal forests of North America. Moose were most abundant in the two youngest stages: the initiation stage (0–10 years) and the establishment stage (11–25 years). Moose abundance decreases at the aggradation stage (26–75 years) (higher abundance in clear-cuts than in burns), while moose tend to avoid old/mature stands. Accordingly, moose seem to prefer young forests (mainly pine forests). Within the home range though, different habitats are used. They tend to avoid agricultural fields, especially in winter, and also to avoid old/mature forests (> 76 years). Even so, it seems like the moose is a habitat generalist, occurring more or less frequently in different habitats. Moose food selection also indicates that the moose is a habitat generalist, as its diet is diverse (see above). Accordingly, the moose has not been assigned specific habitats in our calculations.

/Hansson 2002/ has studied foraging and movement within two different habitats: isolated deciduous woods and extensive conifer forest. Roe deer trails were more common inside the deciduous woodlands, both in centres and at edges, than in neighbouring coniferous forest. When comparing abundance in coniferous forest adjoining deciduous woodlands with an extensive coniferous forest, roe deer did not show any clear differences. Roe deer seem to prefer deciduous woods, but they do inhabit coniferous forests and field areas. Food selection confirms this statement as the winter diet is diverse and the summer diet consists primarily of herbs (see above). Accordingly, the roe deer has not been assigned specific habitats in our calculations.

Consumption

The resulting consumption figures in Table 4-31 and 4-32 shows that the largest herbivores have the largest intake of carbon per area unit. The domestic herbivores do browse on a very concentrated area though, while the moose and roe deer use forest areas as well as field areas for consumption. The mammal species that consume most are the mammal species that are used as food sources for humans. Hence, there is a potential indirect pathway for radionuclides from vegetation to humans in the event of a radionucklide release from the planned deep repository.

4.2.2 Birds

Species

Monitoring of birds in the Forsmark and Laxemar-Simpevarp areas has been performed annually between 2002 and 2009, where one aim has been to investigate whether changes in numbers of breeding birds can be related to disturbances from the site investigations /Green 2008a/. Between 2002 and 2004, a combination of line transects and point counts were used to survey the breeding birds in the area /Green 2005a/. The most common bird species in the Forsmark and Laxemar-Simpevarp areas according to the breeding bird counts between 2002 and 2004 are listed in Tables 4-33 and 4-34. In 2005 to 2009 the monitoring was focused on selected listed species and the investigation was performed by surveys of known territories and/or suitable habitats (e.g. /Green 2006b, 2007, 2009, 2010/).

Table 4-33. The fifteen most common nesting species in the Forsmark area, presented as the total number of birds registered and the number of birds per km in transect surveys /Green 2005a/.

Species English (Swedish)	Latin	Total number (2004)	Abundance (n/km) 2004	Abundance (n/km) 2003	Abundance (n/km) 2002
Willow Warbler (Lövsångare)	*Phylloscopus trochilus*	460	10.22	8.62	11.31
Chaffinch (Bofink)	*Fringilla coelebs*	444	9.87	13.27	11.36
Robin (Rödhake)	*Erithacus rubecula*	206	4.58	4.04	3.54
Common gull (Fiskmås)	*Larus canus*	198	4.40	4.09	1.36
Greylag goose (Grågås)	*Anser anser*	116	2.58	2.95	2.65
Song Thrush (Taltrast)	*Turdus philomelos*	98	2.18	3.83	1.81
Blackbird (Koltrast)	*Turdus merula*	87	1.93	2.26	2.46
Siskin (Grönsiska)	*Carduelis spinus*	74	1.64	1.81	3.57
Wood Pigeon (Ringduva)	*Columba palumbus*	67	1.49	1.05	1.01
Great Tit (Talgoxe)	*Parus major*	58	1.29	1.33	1.27
Goldcrest (Kungsfågel)	*Regulus regulus*	56	1.24	2.09	0.54
Tree pipit (Trädpiplärka)	*Anthus trivialis*	37	0.82	0.56	0.87
Yellowhammer (Gulsparv)	*Emberiza citrinella*	37	0.82	1.51	1.57
Pied flycatcher (Svartvit flugsnappare)	*Ficedula hypoleuca*	35	0.78	0.67	0.92
Jackdaw (Kaja)	*Corvus monedula*	35	0.78	3.29	1.29

Table 4-34. The fifteen most common nesting species in the Laxemar-Simpevarp area, presented as the total number of birds registered and the number of birds per km in transect surveys /Green 2005b/.

Species English (Swedish)	Latin	Total number (2004)	Abundance (n/km) 2004	Abundance (n/km) 2003	Abundance (n/km) 2002
Chaffinch (Bofink)	*Fringilla coelebs*	700	10.06	10.84	7.10
Willow warbler (Lövsångare)	*Phylloscopus trochilus*	471	6.77	3.41	7.15
Robin (Rödhake)	*Erithacus rubecula*	388	5.57	7.42	2.22
Song thrush (Taltrast)	*Turdus philomelos*	252	3.62	3.68	1.89
Blackbird (Koltrast)	*Turdus merula*	224	3.22	5.44	2.24
Great tit (Talgoxe)	*Parus major*	192	2.76	7.77	1.55
Siskin (Grönsiska)	*Carduelis spinus*	170	2.44	1.89	0.81
Starling (Stare)	*Sturnus vulgaris*	163	2.34	0.40	0.49
Wood pigeon (Ringduva)	*Columba palumbus*	157	2.26	2.62	1.63
Goldcrest (Kungsfågel)	*Regulus regulus*	131	1.88	1.44	0.38
Yellowhammer (Gulsparv)	*Emberiza citrinella*	106	1.52	1.59	0.87
Green finch (Grönfink)	*Carduelis chloris*	89	1.28	0.98	0.29
Blue tit (Bålmes)	*Parus caeruleus*	86	1.24	4.71	0.58
Tree pipit (Trädpiplärka)	*Anthus trivialis*	80	1.15	0.37	1.71
Wren (Gärdsmyg)	*Troglodytes troglodytes*	72	1.03	0.42	0.67

Of the fifteen most frequent species in 2004 in the Forsmark and Laxemar-Simpevarp area, eleven species are the same in the two areas. In the Laxemar-Simpevarp area, there are no sea birds among the fifteen most common birds, while common gull (*Sw: Fiskmås*) and greylag goose (*Sw: Grågås*) are among the fifteen most common species in the Forsmark area.

More red-listed species (Swedish Red List 2005) were recorded in the Forsmark area than in the Laxemar-Simpevarp area. 29 possibly breeding red-listed species were recorded in the Forsmark area, of which lesser black-backed gull (*Sw: Silltrut*), red-backed shrike (*Sw: Törnskata*) and wryneck (*Sw: Göktyta*) are the three most common /Green 2007/. In the Laxemar-Simpevarp area, 20 red-listed species were recorded, of which marsh tit (*Sw: Entita*), red-backed shrike (*Sw: Törnskata*) and nightjar (*Sw: Nattskärra*) are the three most common species /Green 2006a/.

Food web properties

The continuous monitoring of the breeding bird fauna in the Forsmark and Laxemar-Simpevarp area makes it possible to utilize site data to estimate biomass and consumption by breeding birds in the regional model areas.

Methodology

Bird biomass per unit area was calculated using information from bird inventories and consumption of carbon was estimated using the field metabolic rate (FMR) /Nagy et al. 1999/ for each species. The FMR is the total rate of energy conversion for a wild animal including basal metabolic rate (BMR), thermoregulation, locomotion, feeding, predator avoidance, reproduction, growth and other energy consuming activities /Truvé and Cederlund 2005/. The FMR is then converted into carbon by a conversion factor provided by /Humphreys 1979/.

Bird species, total number of individuals, biomass and habitats

Estimates of the bird species and the number of territories for each species were based on inventories of the regional model area during the breeding season for the Forsmark area 2002–2004 and the Laxemar-Simpevarp area 2003 and 2004 /Green unpubl./. The total number of individuals of each species was calculated by assuming that there were two adults (male/female) in each territory, multiplied by the number of territories. The body mass of the species was mainly taken from /Green unpubl./, but in some cases body mass was taken from the Danish ornithological association website /DOF 2007 /. All biomasses are presented in Appendix 4. The biomass per unit area was calculated by multiplying the number of breeding individuals by the species-specific body mass. The fresh weight was convented to carbon mass using measurements of the carbon content in mammels from the site (11.7% carbon per unit fresh weight /Hannu and Karlsson 2006/).

The different bird species were divided into three groups depending on which habitat they mainly gather their food from: woodland, open land or water (Appendix 4). Territory abundance (territory m^{-2}) was calculated for each species by dividing the number of territories by their habitat area, i.e. the coverage of forest, open land (Table 4-35) or water area (Table 4-36) in the monitored area, instead of the total surface area of the regional model areas. The coverages of the two different land habitats were estimated from the digital vegetation map /Boresjö Bronge and Wester 2003/.The water area was divided into six categories according to the potential feeding preferences of different bird species (Table 4-36).

Food selection, breeding period, number of eggs and offspring

Food selection by different species was found on the website of the Swedish Ornithological Association /SOF 2007 / and the Danish Ornithological Association /DOF 2007/ and /Jonsson 1992/. The species were divided into five different functional groups according to their main food preference (Figure 4-33).

The breeding period in days was calculated based on the number of months (30 days for all months) given in /Jonsson 1992/ or on the website of the Swedish Ornithological Association. The breeding period varied between 120 days, for species migrating to the south of the Sahara or a similar distance, and 365 days for non-migratory bird species. The number of eggs laid were found on the website of the Danish Ornithological Association /DOF 2007 /. The number of offspring produced was estimated by assuming that 50% of the mean number of eggs laid for each species /DOF 2007/ would hatch and the offspring would survive and leave the nest /Reid et al. 2000/, and multiplying this number by the number of territories.

Table 4-35. The area (km^2) of woodland and open land in the Forsmark and Laxemar-Simpevarp areas /Boresjö Bronge and Wester 2003/.

		Woodland	Open land
Land (m^2)	*Forsmark*	36.0	14.5
	Simpevarp	13.6	22.0

Table 4-36. The area (km^2) of different potential feeding habitats in the Forsmark and Laxemar-Simpevarp areas. The sea area was categorized by depth, where sea 1 = 0–5 metres and sea 2 = 5–20 metres.

	Forsmark	Simpevarp
Lakes	3.3	3.2
Lakes+sea 1	23.0	24.0
Lakes+sea 1,2	86.0	92.0
Sea 1	20.0	21.0
Sea 1,2	83.0	89.0
Sea 2	63.0	68.0

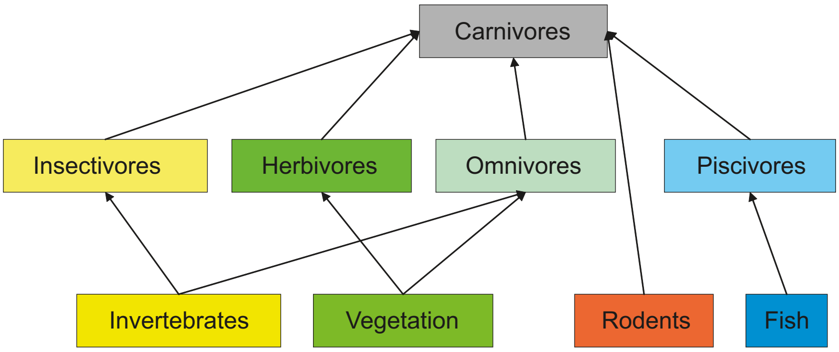


***Figure 4-33.** Schematic illustration of the food web categorization that was used to divide the bird species into five functional groups using their main food preference.*

Field metabolic rate calculations

The FMR estimations in kJ day^{-1} were calculated by using the equation by /Nagy et al. 1999/, which was based on adult and juvenile birds with the exception of nestlings. By utilizing the body mass it was possible to predict the daily food requirement of birds by using the equation:

$\text{FMR} = ax^b$

where x = body mass (g) and, a and b are known parameters /Nagy et al. 1999/ (a is the unconverted value of FMR (kJ day^{-1}) for a 1-g animal, and b is the slope of the log-log regression /Nagy 1987/). a and b were provided for the systematic/functional groups: passerines, Charadriiformes, Galliformes, marine birds, insectivores and omnivores and temperate forest birds. The group carnivores was assigned values representative for the category “All birds” in lieu of better estimates.

The annual food requirement for each bird species in the Forsmark and the Laxemar-Simpevarp areas was estimated by multiplying their daily FMR by the number of individuals and the breeding period in days. The same method for predicting the FMR was used for the offspring. Consumption for six months was calculated for offspring of bird species that remain over the winter, while consumption for only two months was calculated for offspring of migrating species. The FMR was then converted to total consumption of dry matter by dividing the FMR by the metabolizable energy in the specific food, which also includes the fraction that is egested (Table 4-37).

The carbon content of the food was then calculated using the total energy content of different food sources /Golley 1961/ presented in Table 7-5 in /Truvé and Cederlund 2005/ and then converted into gC by using the conversion factor 45.8 /Humphreys 1979/. These calculations assumed the carbon content of seeds for all herbivore food (0.46) and that the carbon content of diet for omnivores was the average of the carbon content of seeds and insects. By dividing the consumed carbon for each land and water type (Tables 4-18, 4-19), the consumption per square metre of woodland, open land and the six different water categories could be estimated.

Table 4-37. The metabolizable energy content of food for different functional bird groups from /Nagy et al. 1999/.

Functional group	Energy digestibility (kJ g^{-1} dry weight)
Carnivore*	16.2
Bird/reptile insectivore	18.0
Fish-eating bird	16.2
Herbivore	10
Omnivore	14

* Same values as for fish-eating birds.

Results

Biomass

The biomass estimates are representative for the beginning of the breeding season before the nestlings have left the nest and are presented in Table 4-38 for the Forsmark area and Table 4-39 for the Laxemar-Simpevarp area. Figures 4-34 and 4-35 are the resulting maps showing the bird biomass distributed in the landscape.

Consumption

Overall, consumption per unit area was higher in the Forsmark area compared with the Laxemar-Simpevarp area for all land categories except sea 1, which is the same, and open land, which is 50% lower in the Forsmark area (Tables 4-40, 4-41). The land class woodland has the highest consumption in both areas, but is more dominant in regard to both bird consumption per unit area and areal coverage. Figures 4-36 and 4-37 are the resulting maps showing the bird consumption distributed in the landscape. Even though this dataset only covers one year it will serve as an important input to ecosystem models, where fluxes of organic matter due to bird consumption can be evaluated in relation to other fluxes.

Table 4-38. The biomass of carnivorous, insectivorous, herbivorous, piscivorous and omnivorous birds in different habitats in the Forsmark area in gC m^{-2} based on the breeding period 2002–2004.

	Woodland	Open land	Water				
			Lakes	Lakes+Sea1	Lakes+Sea1,2	Sea1	Sea1,2
Carnivores	0.0002	0.0001	–	< 0.0001	–	–	–
Insectivores	0.0018	0.0006	–	0.0005	–	–	< 0.0001
Herbivores	0.0001	< 0.0001	–	0.0112	–	–	–
Piscivores	–	–	–	0.0065	0.0030	–	0.0010
Omnivores	0.0029	0.0024	< 0.0001	0.0026	–	0.0035	–
Total	0.0050	0.0031	< 0.0001	0.0210	0.0003	0.0035	0.0011

Table 4-39. The biomass of carnivorous, insectivorous, herbivorous, piscivorous and omnivorous birds in different habitats in the Laxemar-Simpevarp area in gC m^{-2} based on the breeding period 2003–2004.

	Woodland	Open land	Water				
			Lakes	Lakes+Sea1	Lakes+Sea1,2	Sea1	Sea1,2
Carnivores	0.0001	0.0003	–	< 0.0001	–	–	–
Insectivores	0.0012	0.0009	–	0.0003	–	–	< 0.0001
Herbivores	< 0.0001	0.0001	–	0.0116	–	–	–
Piscivores	–	–	–	0.0042	0.0001	–	0.0002
Omnivores	0.0023	0.0036	< 0.0001	0.0017	–	0.0035	–
Total	0.0037	0.0048	< 0.0001	0.0178	0.0001	0.0035	0.0002

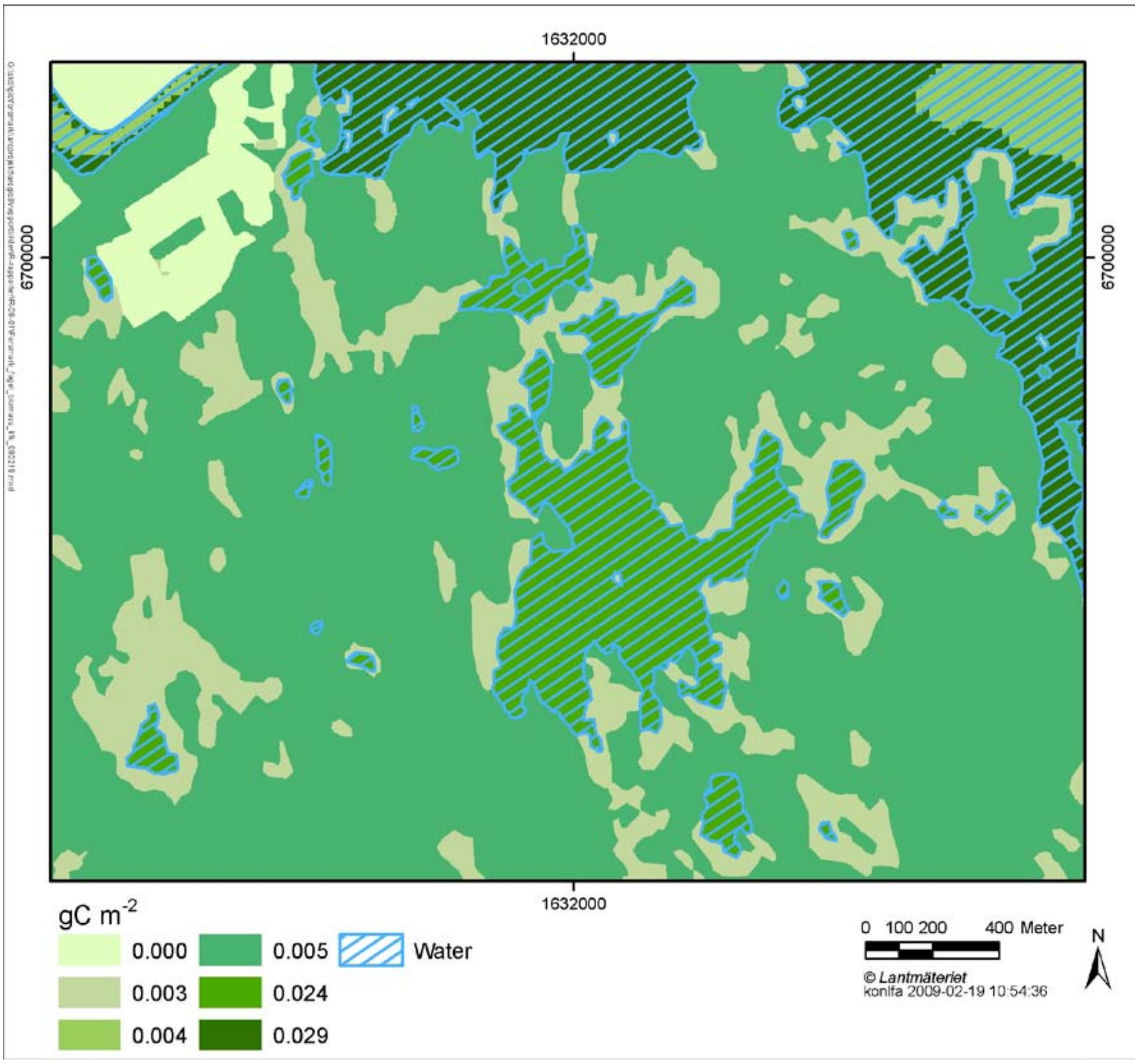


Figure 4-34. *An example from the Forsmark area, where the distribution of bird biomass as carbon is illustrated in one part of the regional model area. The areas with zero values are buildings or asphalt.*

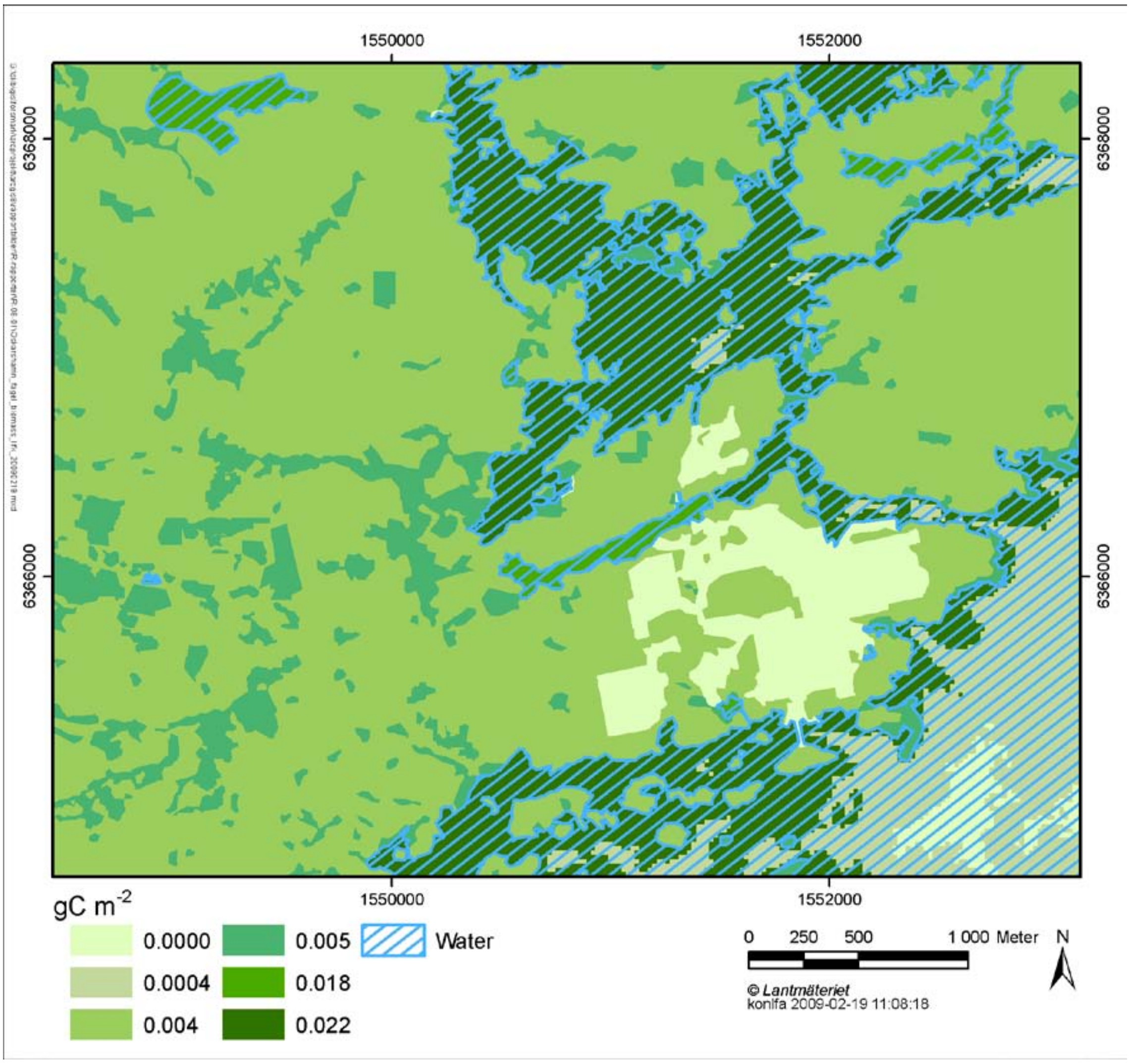


Figure 4-35. An example from the Laxemar-Simpevarp area, where the distribution of bird biomass as carbon is illustrated in one part of the regional model area. The areas with zero values are buildings or asphalt.

Table 4-40. The carbon consumption of carnivorous, insectivorous, herbivorous, piscivorous and omnivorous birds in different habitats in the Forsmark area in gC m^{-2} yr^{-1} based on bird densities in 2002–2004.

	Woodland	Open land	Water				
			Lakes	Lakes+Sea1	Lakes+Sea1.2	Sea1	Sea1.2
Carnivores	0.035	0.024	–	0.002	–	–	–
Insectivores	0.502	0.098	–	0.079	–	–	0.004
Herbivores	0.052	0.015	–	1.857	–	–	–
Piscivores	–	–	–	1.223	0.028	–	0.158
Omnivores	0.944	0.339	0.006	0.397	–	0.319	–
Total	1.53	0.48	0.01	3.56	0.03	0.32	0.16

Table 4-41. The carbon consumption of carnivorous, insectivorous, herbivorous, piscivorous and omnivorous birds in different habitats in the Laxemar-Simpevarp area in gC m^{-2} yr^{-1} based on bird densities in 2003–2004.

	Woodland	Open land	Water				
			Lakes	Lakes+Sea1	Lakes+Sea1.2	Sea1	Sea1.2
Carnivores	0.019	0.056	–	0.001	–	–	–
Insectivores	0.336	0.141	–	0.053	–	–	0.002
Herbivores	0.013	0.019	–	1.852	–	–	–
Piscivores	–	–	–	0.589	0.009	–	0.019
Omnivores	0.658	0.782	0.001	0.257	–	0.323	–
Total	1.03	1.00	0.001	2.75	0.01	0.32	0.02

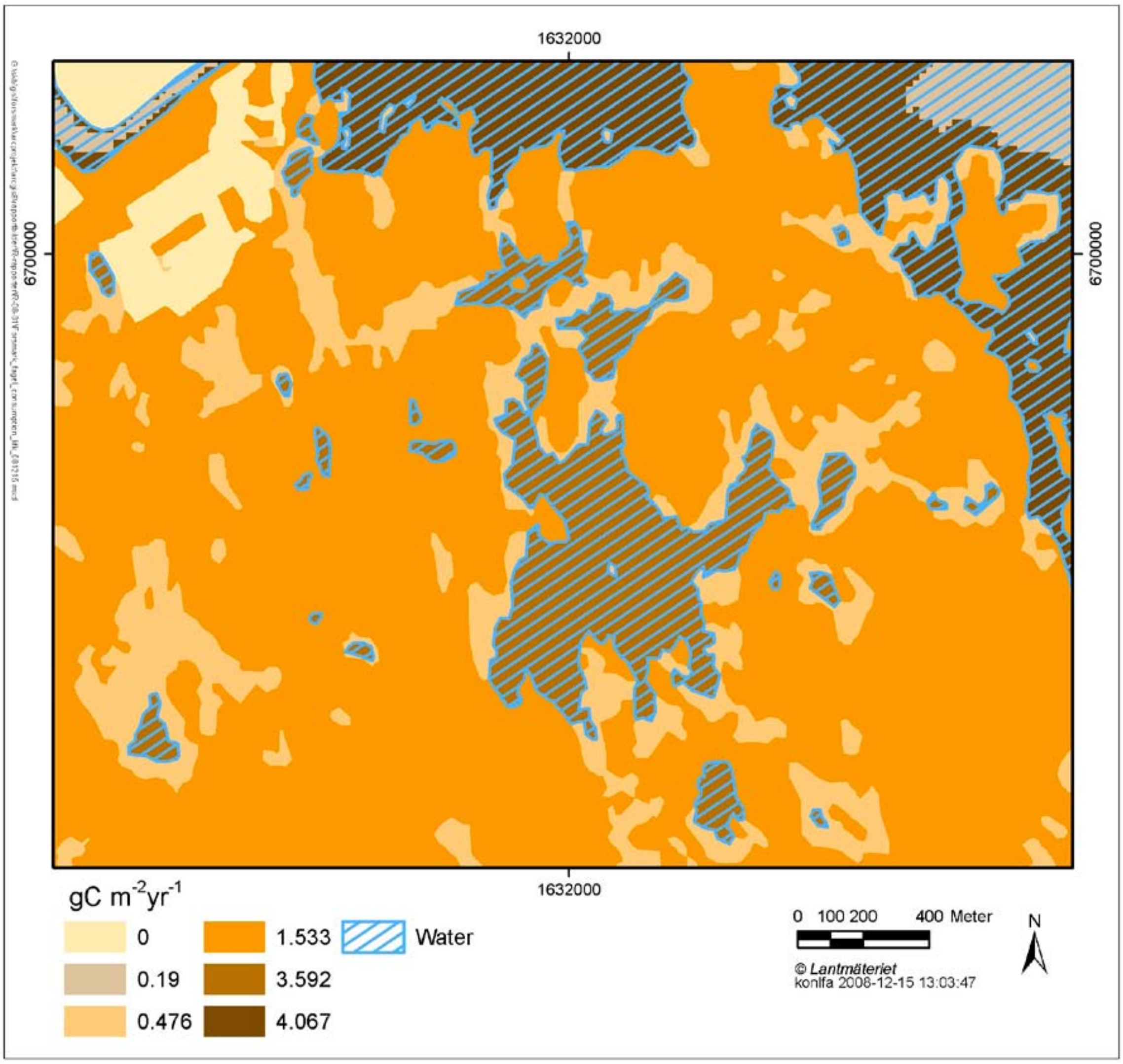


Figure 4-36. *Bird consumption of carbon illustrated in one part of the Forsmark area. The areas with zero values are buildings or asphalt.*

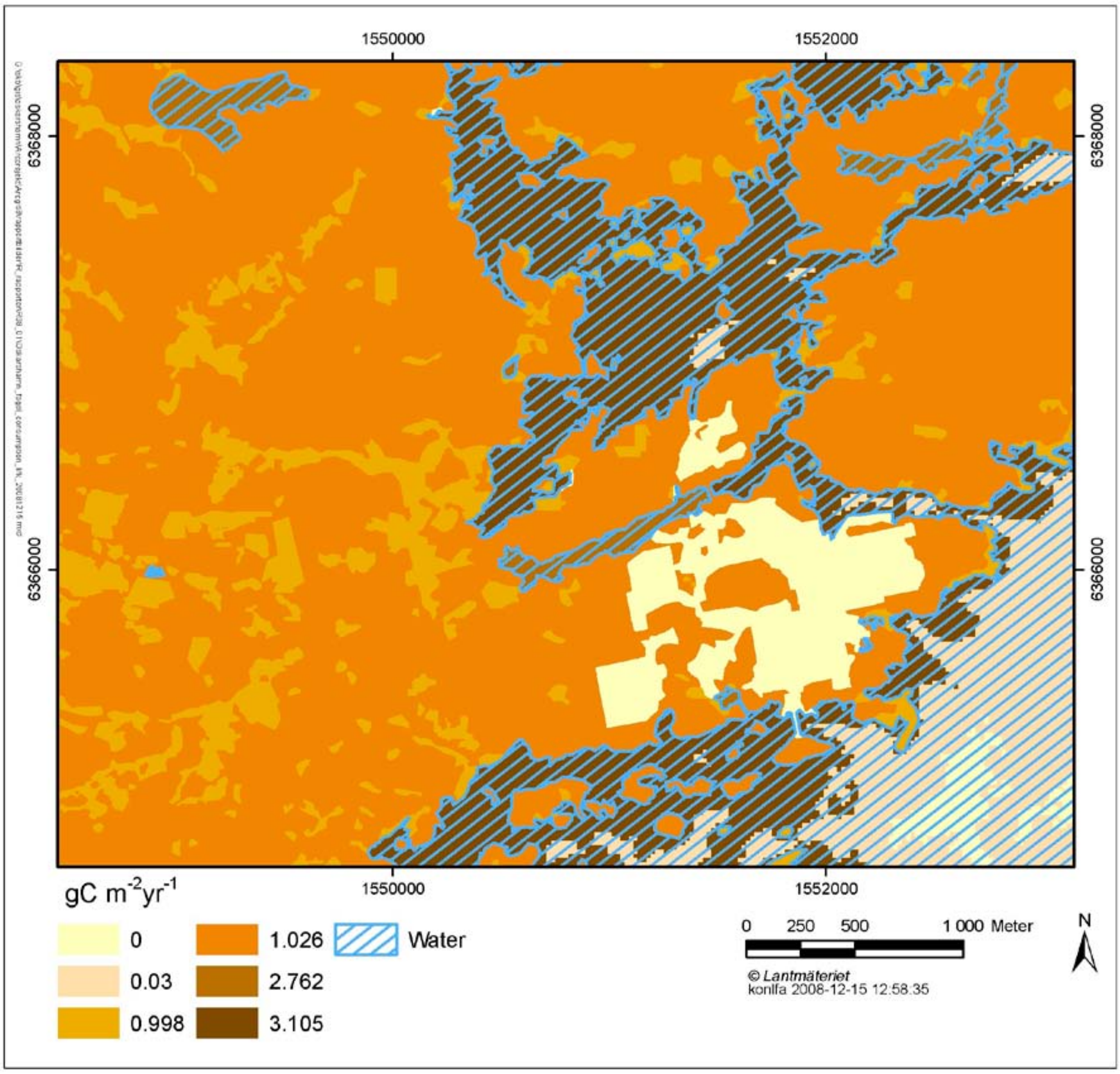


Figure 4-37. Bird consumption of carbon illustrated in one part of the Laxemar-Simpevarp regional model area. The areas with zero values are buildings or asphalt.

4.2.3 Amphibians and reptiles

Species and densities

For amphibians and reptiles, a short field study was performed primarily to verify the presence of suitable habitats for the Swedish species. It was carried out by following the smaller roads in the area and checking surrounding areas of special interest. The aim was to confirm the species that do occur in the Forsmark area and the Laxemar-Simpevarp area /Andrén 2004a, b/. The densities have been estimated based on the performed surveys and generic data (see Appendix 5). Information describing some ecological data for amphibians and reptiles is compiled in Table 4-42.

Common frog and pool frog were only found in the Forsmark area. Both species are well known not to occur in Kalmar County. The pool frog habitat is unique, as it is dependent on land uplift and the continuous emergence of new land. Only a few localities of sand lizard in Sweden are doing well, so the record of sand lizard in the Laxemar-Simpevarp area was of special interest. It indicates a probable colony within the area, although this could not be confirmed.

Table 4-42. Ecological data concerning amphibians and reptiles applicable to the Forsmark and Laxemar-Simpevarp areas (see Appendix 5).

Species English (Swedish)	Weight (g)	Density (ind per km^2)	Diet	Energy needs (g dry weight per year)	Reproduction
Adder (huggorm)	150	100	Primarily mice and voles	330	On average 5 young per year
Grass snake (vanlig snok)	175	100 (200 in wetlands)	Frogs and toads, fish, newts	350	Approx. 13 eggs per year
Smooth snake (hasselsnok)	70	20	Other reptiles such as slow worm	140	On average 6 young per year
Slow worm (kopparödla)	15	1,000	Earthworms and snails	60	8 young per year
Common lizard (skogsödla)	5	500	Spiders and insects	21	7 young per year
Sand lizard [1] (sandödla)	8	15	Spiders and insects	27	10 eggs per year
Common frog [2] (vanlig groda)	25	2,000 (0–100 metres from pond) 1,000 (100–300 metres from pond) 500 (300–500 metres from pond)	Spiders and insects	28	2,000 eggs per year
Pool frog [2] (Gölgroda)	20	50–100 per pond (Four ponds in the Forsmark area)	Spiders and insects	17	1,700 eggs per year
Moor frog (åkergroda)	20	3,000 (0–100 metres from pond) 1,000 (100–300 metres from pond) 100–500 (300–500 metres from pond)	Insects, spiders and worms	20	1,500 eggs per year
Common toad (vanlig padda)	60	4,000	Insects, spiders and worms	123	4,000 eggs per year
Smooth newt (mindre vattensalamander)	3	2 per m^2 water area, the population size can be up to 10,000 individuals. They stay within 300 metres from the pond.	Larger zooplankton, water insects, water spiders, earthworms, snails and larvae of insects		350 eggs per year
Great creasted newt (stor vattensalamander)	9	1 per m^2 water area, the population is never larger than a few thousand individuals.They stay within 500 metres from the pond.	Insects, earthworms, snails, water insects, water spiders, larvae of frog and smooth newt.	8	200 eggs per year

[1] Only recorded in Laxemar-Simpevarp.
[2] Only recorded in Forsmark.

Spatial distribution

To be able to calculate the total carbon pools and fluxes of moor frogs and common frogs, the habitat area was defined and calculated in ArcGIS. The moor frog lives near small lakes, creeks, ponds and fens with slow-moving water, and its density varies with distance from a pond (Table 4-43, Table 4-44). The frog habitats in the two investigation areas were calculated based on the lakes and open wetlands (fens or wetter wetlands) in the area, using the topographic map in Forsmark and the vegetation map /Boresjö Bronge and Wester 2003/ in Laxemar-Simpevarp. Buffer zones were created around the lakes and wetter wetlands, giving three habitat zones of 0 to 100 m, 100 to 300 m and 300 to 500 metres from a lake or wetter wetland. As the wetlands in Forsmark area are dominated by drier mires (only 7% of the mires are wetter mires), the frog habitats in Forsmark area were calculated based on the lakes solely. The moor frog and common frog habitats within the Forsmark area are illustrated in Figure 4-38, while the moor frog habitats in the Laxemar-Simpevarp area are illustrated in Figure 4-39.

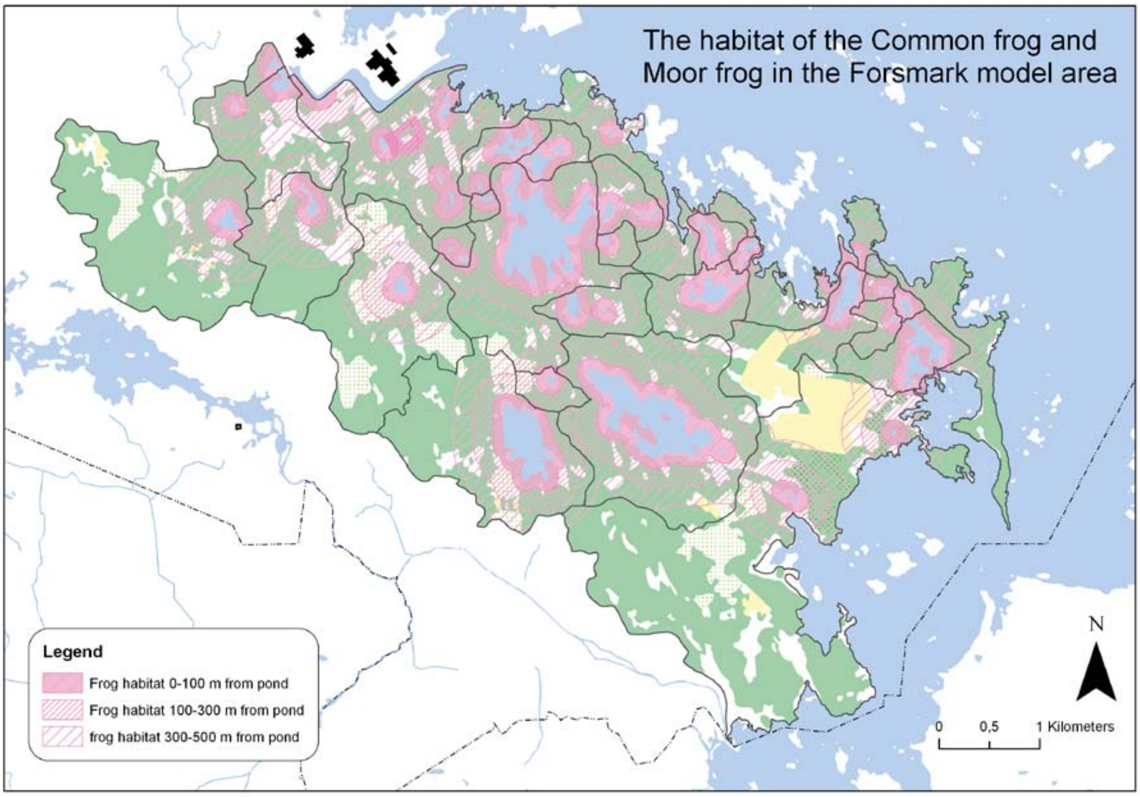


Figure 4-38. Distribution of Moor frog and common frog habitat in the Forsmark area.

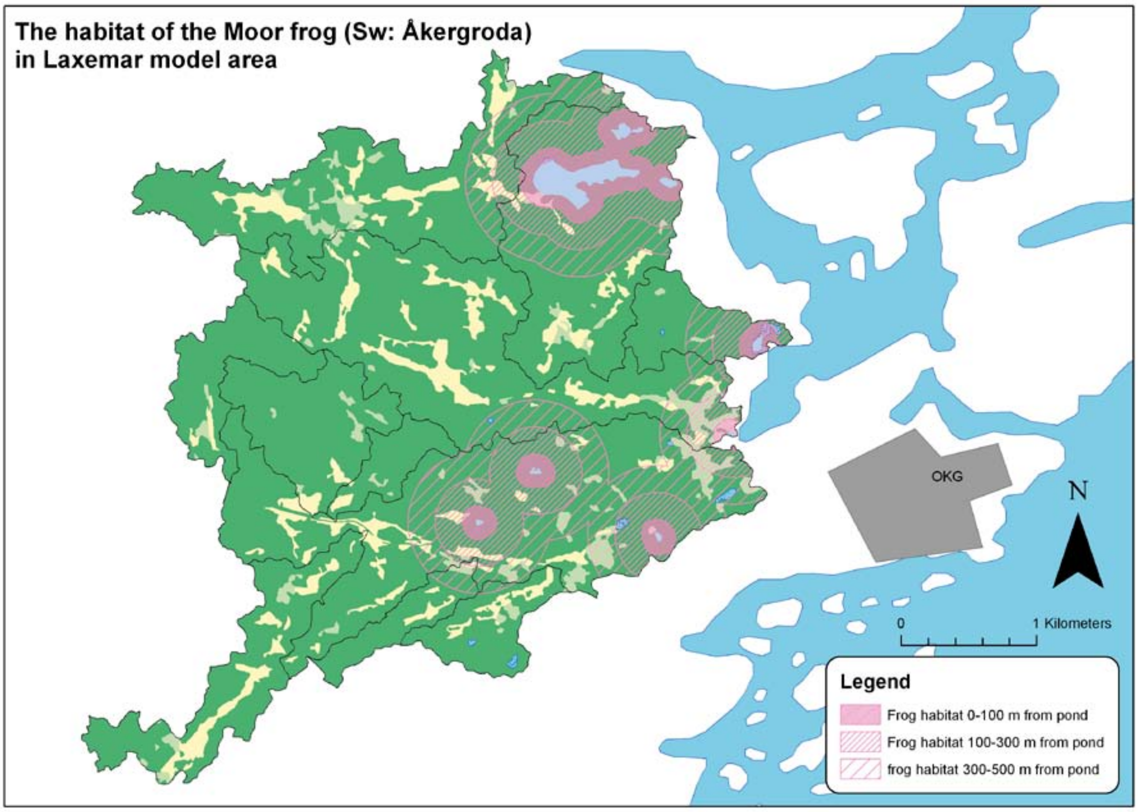


Figure 4-39. Distribution of Moor frog habitat in the Laxemar-Simpevarp area.

The habitat of the Common toad has been assumed to be equal to the land area, excluded the driest biotopes, i.e. pine forest, hard surfaces and coastal rocks These biotopes represent 35% of the land area in the Forsmark area and 34% in the Laxemar-Simpevarp area.

Food web properties

Generic densities for the species that occur in the Forsmark and Laxemar-Simpevarp areas have been estimated and are reported in Appendix 5. Average body mass as well as feeding habits and number of eggs/youngsters per individual are also included (see Table 4-22). No attempt has been made to calculate the production from the number of eggs/youngsters per female. Instead the production of the amphibians and the reptiles, as well as the egestion and respiration, have been calculated based on /Jerling et al. 2001, Table 2-4/, showing that the production of vertebrates (ectothermal, *Sw: växelvarma*) represent 8% of the energy input (consumption), while egestion represents 20% and respiration 72%.

The biomasses have been calculated with the assumption that the carbon content of amphibians and reptiles is 11.7% of the fresh weight (same as for mammals, Section 4.2.1). Reptiles are carnivores and their diet (small mammals, amphibians, other reptiles, insects and invertebrates) was assumed to contain 11.7% carbon (same as for mammals, see above). Amphibians eat insects and invertebrates.

The resultant annual pools and fluxes in the Forsmark and Laxemar-Simpevarp areas are presented in Tables 4-43 and 4-44.

Table 4-43. General figures per unit area for densities, biomass, production, consumption, egestion and respiration for the amphibians and reptiles in the Forsmark area. The column habitat shows the assigned habitats for the different species.

Species		Habitat	Density	Biomass (standing stock)		Production	Consumption	Egestion (Faeces)	Respiration
			Number per km^2	Body mass g ind^{-1}	Biomass mgC m^{-2}	mgC m^{-2} y^{-1}	mgC m^{-2} y^{-1}	mgC m^{-2} y^{-1}	mgC m^{-2} y^{-1}
Reptiles	Adder	Forest+Field	100	150	1.8	1.2	15	3.0	11
	Grass snake	Forest+Field	100	175	2.0	1.3	16	3.1	11
	Smooth snake	Forest+Field	20	70	0.2	0.1	1.3	0.3	0.9
	Slow worm	Forest+Field	1,000	15	1.8	2.2	27	5.4	19
	Common lizard	Forest+Field	500	5	0.3	0.4	4.7	0.9	3.4
Amphibians	Common toad	Found in all habitats below	4,000	60	28	18	221	44	159
	Moor frog	0–100 m from pond	3,000	20	7	2.2	27	5.4	19
		100–300 m from pond	1,000	20	2.3	0.7	9.0	1.8	6.5
		300–500 m from pond	300	20	0.7	0.2	3	0.5	2
	Pool frog	50–100 per pond (four in Forsmark)	75	20	0.2	0.05	0.7	0.1	0.5
	Common frog	0–100 m from pond	2,000	25	6	1.4	18	3.6	13
		100–300 m from pond	1,000	25	2.9	0.7	9.0	1.8	6.5
		300–500 m from pond	500	25	1.5	0.4	4	0.9	3

Table 4-44. General figures per unit area for densities, biomass, production, consumption, egestion and respiration for the amphibians and reptiles in the Laxemar-Simpevarp area.

Species		Habitat	Density	Biomass (standing stock)		Production	Consumption	Egestion (Faeces)	Respiration
			Number per km^2	Body mass g ind^{-1}	Biomass mgC m^{-2}	mgC m^{-2} y^{-1}	mgC m^{-2} y^{-1}	mgC m^{-2} y^{-1}	mgC m^{-2} y^{-1}
Reptiles	Adder	Forest+Field	100	150	1.8	1.5	19	3.8	14
	Grass snake	Forest+Field	100	175	2.0	1.6	20	4.0	14
	Smooth snake	Forest+Field	20	70	0.2	0.1	1.6	0.3	1.1
	Slow worm	Forest+Field	1,000	15	1.8	2.7	34	6.8	25
	Common lizard	Forest+Field	500	5	0.3	0.5	6.0	1.2	4.3
	Sand lizard	Forest+Field	15	8	0.01	0.02	0.2	0.05	0.2
Amphibians	Common toad	Habitat amphibians	4,000	60	28	22	281	56	202
	Moor frog	0–100 m from pond	3,000	20	7.0	2.7	34	6.8	25
		100–300 m from pond	1,000	20	2.3	0.9	11.4	2.3	8.2
		300–500 m from pond	300	20	0.7	0.3	3.4	0.7	2.5

4.2.4 Invertebrates

Invertebrates represent a major component of the biodiversity and function of ecosystems. They have often been neglected in ecosystem studies /Weisser and Siemann 2004/. In the site descriptions, effects of invertebrate activity has been estimated or included in the estimate for ecosystem functions such as bioturbation and detrivory. However, a number of mutualistic interactions, such as pollination, and food-web interactions, have not been assessed at the sites. Invertebrate herbivory that is regarded important for food web transfer have instead been discussed briefly based on literature. The studies related to invertebrates are briefly described below.

Soil fauna

Detrivory is generally practiced by the soil fauna, accounting for approximately 10% of the carbon turnover in soil, and the fungi and bacterial flora, accounting for approximately 90% /Persson T 2004, pers. comm./. The soil fauna is of greater importance to the soil structure and soil properties, e.g. bioturbation (see below). The main part of the soil fauna consists of microbivores (they consume microorganisms), while some species are primary decomposers /Persson T 2004, pers. comm./. According to /Jerling et al. 2001/, production by microbivores is 12% of the energy input (consumption), while respiration accounts for 18%. The rest leaves as faeces (70%).

Density and biomass may vary depending on habitat and Table 4-45 lists the occurrence of some important taxa. The biomass was approximately six times lower in the pine forest than in the deciduous forest, and the highest biomass was found in the grassland. In general, deciduous forests with moderately high to high pH have mull soils without a distinct humus layer. Typical mull soils indicate the presence of burrowing earthworms. Acid coniferous forests lack deep-burrowing earthworms, and these forests are characterized by a mor (raw humus) layer lying on top of the mineral soil. Some of the spruce forests in the Forsmark area had high pH and allowed deep-burrowing earthworms to mix the soil and form a mull-like soil. The abundance of medium-sized soil animals (mesofauna) is normally higher in coniferous than in deciduous forests (Table 4-45). These animals (springtails and oribatid mites) largely feed on fungal mycelia, which are the main decomposer organisms in coniferous forest soils, whereas bacterial decomposition is dominant in deciduous forest soils with high pH. Among the soil organisms, fungi probably have the greatest storage capacity for radionuclides /Persson T 2004, pers. comm./.

Table 4-45. Biomass and density in the soil fauna in three different biotopes /Lohm and Persson 1978/.

Species	**Deciduous forest (Uppland)**			**Pine forest (Gästrikland)**			**Grassland (Uppland)**		
English or Latin (Swedish)	**Number per m^2**	**Dry weight per m^2 (mg)**	**mgC per m^2**	**Number per m^2**	**Dry weight per m^2 (mg)**	**mgC per m^2**	**Number per m^2**	**Dry weight per m^2 (mg)**	**mgC per m^2**
Earthworms (daggmask)	180	6,100	3,050	< 1	17	8	130	5,900	2,950
Enchytraeidae (småringmask)	3,800	370	185	17,000	420	210	24,000	850	425
Wood lice (gråsuggor)	2	9	5	< 1	2	1	< 1	4	2
Centipede (tusenfotingar)	1,200	70	35	25	3	2	2	30	15
Springtails (hoppstjärtar)	66,000	110	55	65,000	100	50	110,000	140	70
Protura (trevfotingar)	3,800	2	1	1,000	1	1	40	1	0
Thrips (tripsar)	100	1	0	1,400	6	3	720	3	2
Homoptera (växtsugare)	70	2	1	270	11	6	70	1	1
Heteroptera (skinnbaggar)	10	7	4	190	10	5	10	3	2
Beetles (skalbaggar)	600	480	240	500	170	85	1,400	2,800	1,400
Hymenoptera (steklar)	50	50	25	40	15	8	110	3	2
Midge larvae (mygglarver)	1,300	50	25	700	20	10	4,400	320	160
Fly larvae (fluglarver)	30	80	40	70	9	5	1,100	330	165
Spiders (spindlar)	220	70	35	340	70	35	200	40	20
Mites (kvalster)	190,000	600	300	620,000	400	200	110,000	13	65
Sum	267,362	8,001	**4,000**	706,535	1,254	**627**	252,182	10,555	**5,277**

Bioturbation

/Persson et al. 2007/ studied the quantitative impact of earthworms and ants on bioturbation of soil in different ecosystems at a total of 10 localities in the Forsmark and Laxemar-Simpevarp area. Earthworms were sampled in four 20×20 cm sub-plots at each site and were determined, dried and weighed in the laboratory. Gut passage time and faeces production were determined in a laboratory experiment at constant temperature, and temperature dependence of earthworm growth was also studied. Ant species composition, ant nest density and nest volume were investigated in the field by using pitfall traps and a transect method to enumerate ant nests. Dry weights of ant nests were determined after weighing in the laboratory.

Earthworm bioturbation was found to be in the range 0.0003 to 25 kg dry weight m^{-2} y^{-1} among the ten localities. Ant bioturbation was markedly lower than earthworm bioturbation and was mainly caused by *Myrmica* species. Ant bioturbation varied between 0.004 and 0.5 kg dry weight m^{-2} y^{-1}. Thus, the ants generally contributed 0–2% of total bioturbation with the exception of an abandoned field in the Forsmark area (12%) and the acid spruce forests in the Laxemar-Simpevarp area (93%), which had low earthworm populations.

Earthworm abundances, biomasses and turnover of soil were markedly dependent on site characteristics, both in the Forsmark and the Laxemar-Simpevarp areas. There was a positive correlation between pH and abundance of earthworms in the Laxemar-Simpevarp area. In the Forsmark area, where the soils are generally rich in $CaCO_3$, soil pH was often close to 7 except for the litter and humus layers in some coniferous forests. Some of the localities in the Forsmark area had high groundwater tables, and this fact can explain reduced figures of earthworm bioturbation. No significant correlation was found between pH and abundance of ant nests. Total bioturbation estimated for earthworms and ants was between 0.3 (spruce forest on drained peatland) and 247 tonnes dry weight ha^{-1} y^{-1} (deciduous oak forest). /Persson et al. 2007/ concluded that bioturbation, especially by earthworms, can be remarkably high. A normal stone-free mull soil contains about 300 kg dry weight m^{-2} (3,000 tonnes ha^{-1}) in the top 30 cm. Earthworms and ants can thus turn over the topsoil in 12–20 years in suitable habitats.

Soil respiration

The flux of carbon (CO_2) from the soil, i.e. soil respiration, can be divided into autotrophic respiration (by roots) and heterotrophic respiration (by microbes, microfauna and fungi). It is the heterotrophic components that are responsible for decomposition. During decomposition of dead plant, animal and microbial material, the organic matter is converted into inorganic nutrients and CO_2. The balance between decomposition and NPP strongly influences the carbon cycle on both the ecosystem and global scales.

Methods

Soil respiration was measured in 2005 and 2006 in the Forsmark area /Heneryd 2007b/ and in 2004 /Tagesson 2006b, c/ and /Lundkvist 2006/ in the Laxemar-Simpevarp area for a number of different vegetation types (Table 4-46). The measurements were made over the space of a year to include the different seasons using permanent plots within each vegetation type. Measurements of the CO_2 flux from the ground were performed using a closed chamber technique, along with measurements of air and soil temperature /Tagesson 2006d/. Annual soil respiration was estimated using a regression approach, where the relationship between air temperature (logged every 30 minutes at the site) and soil temperature and measured soil respiration was used. Soil moisture was measured for 6 vegetation types in the Laxemar-Simpevarp area /Tagesson 2006b, c/, but was not included in the regression due to low explanatory power /Tagesson and Lindroth 2007/ and was not included in the calculations for the other vegetation types. The soil-temperature-modelled soil respiration generally showed higher values, which is probably an effect of a more fluctuating diurnal air temperature. The soil temperature is less prone to fluctuations due to the temperature-buffering capacity of the soil. The figures presented here describe only the soil-temperature-modelled soil respiration. The carbon flux measurements also made it possible to model GPP and calculate the net ecosystem exchange (NEE) from the soil and field layer, which is also presented below.

Results and discussion

Soil respiration

There was large seasonal variation in modelled soil respiration. Both air-temperature- and soil-temperature-based models peaked in July. The pastures and the semi-natural grassland show a very similar value for soil respiration, which is high compared with other studies, e.g. /Maljanen et al. 2001/, reported 760 gC m^{-2} y^{-1} for an organic field in eastern Finland. The highest value of the three estimates from different grasslands (1,150 gC m^{-2} y^{-1}) was found on a semi-natural grassland situated on peat soil that had been drained. Similarly, most agricultural land in Laxemar-Simpevarp area has peaty soils originating from an earlier stage as a wetland which start to oxidize when the water table is lowered.

The span of annual soil respiration for the coniferous forests (580–1,150 gC m^{-2} y^{-1}) is large where the low value is from an even-aged Norway spruce forest with a thin soil layer, whereas the high value is from a 100-year-old well-managed Scots pine forest on a deep soil layer. This span fits reasonably well the span from other investigations in the boreal region (see discussion in /Tagesson 2007/).

The range for deciduous forest (470–1,180 gC m^{-2} y^{-1}) embraces the mean for temperate forests of 650 gC m^{-2} reported by /Raisch and Schlesinger 1992/. The low value is from an open low-density forest subjected to regular grazing by cattle. Other studies have also reported high soil respiration for similar vegetation types, e.g. 820–1,210 gC m^{-2} y^{-1} /Bolstad et al. 2004/.

Clear-cuts or young coniferous forests are expected to have high soil respiration due to remaining woody debris, such as stumps and roots. /Kolari et al. 2004/ estimated total ecosystem respiration for differently aged stands and reported that soil carbon effluxes were largest for 12-year-old stands. Both estimates are in the upper range of the respective site values.

Wetland soil respiration is expected to be lower due to more or less anaerobic conditions /Heal et al. 1981/, but both estimates are rather high in comparison to estimates for a swampy mixed hardwood stand in the Harvard forest in Massachusetts of 140 gC m^{-2} y^{-1} /Davidson et al. 1998/. Others have found higher values, i.e. 396 gC m^{-2} y^{-1} from May to October 1996 for a boreal black spruce forest in Saskatchewan /Swanson and Flanagan 2001/. /Davidson et al. 1998/ explained their low values not only as caused by wetness, but also due to low input of C to the soil. In the Harvard stand in Massachusetts, trees are sparse so NPP is low as well, whereas in the Forsmark and Laxemar-Simpevarp areas trees are dense /Tagesson 2006a/, consisting of only deciduous trees and a high proportion of deciduous trees, respectively, and consequently a high C input to the soils.

The estimated soil respiration of the poor fen was somewhat larger than the range found in other studies done in mires and fens. In the Nordic countries, estimated values varied between 214 and 456 gC m^{-2} y^{-1}, where the low value was from Kaamanen in the northern subarctic regions of Finland /Lindroth et al. 2007/ and the high value was from Fäjemyren, close to Hässleholm in the southern parts of Sweden.

The standard deviations in Table 4-46 are large, reflecting the large spatial variation between the plots within each ecosystem. The three localities lacking a tree layer and having fairly uniform soil conditions (excluding the poor fen) all show a similar lower standard deviation.

GPP and NEE

GPP by the field and bottom layer vegetation in the poor fen (700 $gC{\cdot}m^{-2}y^{-1}$) is high compared with other fen studies in the Nordic countries with values between 250 and 480 $gC{\cdot}m^{-2}y^{-1}$ /Lindroth et al. 2007/. Some of these ecosystems were situated further north, and the lower GPP may reflect a shorter vegetation period. One of the study sites, Fäjemyren (480 $gC{\cdot}m^{-2}y^{-1}$), was at a similar latitude as the Laxemar-Simpevarp area, but other factors also influence GPP, such as nutrition, microclimate, biomass, species etc. GPP by ground vegetation in the agricultural field (dominated by grass and herbs, Table 4-46) (710 gC m^{-2} y^{-1}) is similar to that in other grassland studies with values between 270 and 1,210 gC m^{-2} y^{-1} /Flanagan et al. 2002, Suyker and Verma 2001, Suyker et al. 2003, Novick et al. 2004/.

Table 4-46. Annual soil respiration and standard deviation in kgC m^{-2} y^{-1} using soil-temperature-based models for the Forsmark and Laxemar-Simpevarp areas from /Tagesson 2006b, 2007/.

Site/Vegetation type	SKB ID Code	Year	Soil type /Lundin et al. 2004, 2005a/	Mean	SD
Forsmark area					
Pasture	AFM001257/AFM001081	2005/06	RG/GL-a	1.09	0.75
Norway spruce 1	AFM001258/AFM001068	2005/06	RG/GL	0.79	1.24
Norway spruce 2	AFM001259/AFM001247	2005/06	RG/GL / LP	0.58	0.25
Deciduous forest	AFM001260/AFM001071	2005/06	GL/CM	0.47	0.37
Clear-cut (20 y Scots pine)	AFM001261	2006	–	0.71	0.54
Forested wetland (Picea/Alnus)	AFM001263/AFM001076	2006	GL	0.45	0.38
Laxemar-Simpevarp area					
Semi-natural grassland	ASM001430	2004/05	UM/GL	1.15	0.71
Scots pine (deeper soil)	ASM001429	2004/05	PZ/RG	1.17	0.93
Lichen/outcrop (thin soil)	ASM000210	2004/05	LP	0.75	1.39
Norway spruce (drained peatland)	ASM001440	2004/05	HI-f	0.85	0.80
Pedunculate oak 1	ASM001426	2004/05	UM/RG	1.18	0.98
Pedunculate oak 2	ASM001427	2004/05	UM/RG	0.78	0.85
Poor Fen	ASM001443	2006	HI-f	0.99	1.84
Pasture	ASM000015	2006	UM/GL	1.08	0.56
Clear-cut (20–25 y Scots pine)	ASM000016	2006	PZ/RG	1.30	1.76
Forested wetland (Alnus)	ASM001434	2006	HI-f	0.73	0.62

NEE for the poor fen was between –290 and 320 gC m^{-2} y^{-1}, suggesting that there was no net carbon uptake or loss during the measured year. This is similar to other studies; in Fäjemyren there was a net uptake of 20 gC m^{-2} y^{-1} /Lund et al. 2007/. In Kaamanen, Siikaneva and Degerö, NEE was between 30 and 0 gC m^{-2} y^{-1} /Lindroth et al. 2007/. NEE in the agricultural areas indicate that there is net loss of carbon (on average –190 gC m^{-2} y^{-1}) to the atmosphere. Other studies have obtained a wide range of NEE estimates (–950 to 274 gC m^{-2} y^{-1}) /Suyker et al. 2003, Flanagan et al. 2002, Novick et al. 2004, Maljanen et al. 2001, Byrne et al. 2005, Soegaard et al. 2005, Hollinger et al. 2005/.

Table 4-47. Modelled GPP for the field layer using photosynthetically active radiation (PAR). Net ecosystem exchange (NEE) was calculated from the modelled soil respiration from three vegetation types in the Laxemar-Simpevarp area. From /Tagesson 2006b and 2007/.

Vegetation type	SKB ID Code	Year	GPP (kgC m^{-2} y^{-1})	NEE (+/– is gain/loss) (kgC m^{-2} y^{-1})
Seminatural grassland	ASM001430	2004/2005	0.54±0.36	–0.66 and –0.38
Pasture	ASM 000015	2006	0.71±0.27	–0.38 and 0.00
Poor Fen	ASM 001443	2006	0.70±0.17	–0.29 and 0.32

Herbivory

The total biomass of insects appears to be small compared to the plant biomass. For example, in an IBP study of a meadow-steppe in central Russian, above- and below-ground invertebrate biomass was equivalent to about 10% of the annual plant production (11–14 tons dw/ha) /Zlotin and Khodashova 1980/. More than 90% of the animal biomass was found below ground, and earthworms accounted for 94% of the soil animal biomass or 80–90% of total animal biomass. The biomass of above- and below-ground insects constituted less than 2% of the animal biomass or 0.2% of the plant production on the same meadow-steppe. Biomass does not generally entail a prominent role for insects in nutrient cycling (cf. /Petrusewicz 1967, Schowalter 2000/). This is a reason why insects are often not considered to be very important for nutrient cycling. A second reason is that the average proportion of net primary productivity (NPP) consumed by herbivorous insects is 10% or less, except in outbreak situations (e.g. /Detling 1988, Coupe and Cahill 2003/), while large mammalian herbivores, such as African mammals, are known to consume up to 90% of savannah NPP /Detling 1988/.

Direct effects of insects on ecosystem functioning include reduction of NPP by herbivores and breakdown of litter by detrivores. Perhaps one of the most important roles for the soil fauna is to physically break up organic matter in soil and make it accessible to fungi/bacteria. They thereby have a major impact on below-ground processes and nutrient cycling, usually by changing the soil structure and decomposition and mineralization rates /Jones and Bradford 2002/. Indirect effects include changes in matter fluxes due to changes in plants species composition that are mediated by insect herbivory.

Above ground

Herbivory by insects on Scots Pine (*Pinus sylvestris*) was estimated to be 0.7% of the total needle biomass and 2.5% of the total needle production during one year in central Sweden /Larsson and Tenow 1980/. A review of herbivory showed that herbivores generally consume less than 10% of NPP in forests, except during insect outbreaks, when herbivory can be up to 50% of NPP /Schowalter et al. 1986/. Another review came to the conclusion that on average, in terrestrial systems, only 18% of plant biomass is consumed by vertebrate and invertebrate herbivores /Cyr and Pace 1993/. /Mattson and Addy 1975/ tried to take a "forest-wide" perspective, taking several parameters into account. They estimated that insect herbivores consume on average around 10% of the total NPP in forests. The potential roles of insects in ecosystems are less well characterized above ground, but in some systems at least they may have dramatic, although often temporary, effects on primary production via intense grazing pressure /Schowalter et al. 1986, Dyer et al. 1993/.

Below ground

Root consumption by phytophagous nematodes was estimated to 0.3% of the annual production of fine roots in the Scots pine forest above /Magnusson and Sohlenius 1980/. In grassland systems, the plant production consumed by herbivores below ground may be between 3 and 7 times the amount consumed above ground /Scott et al. 1979/. Attempts to measure the impacts of herbivory on plant productivity are likely to be an underestimate because some of the effects of insect herbivores are relatively neglected /Hunter 2001/.

Root feeding limits plant uptake of water and nutrients, leading to a stress response being induced within the host plant. Such a response generally leads to the mobilization or translocation of soluble C and N to the foliage. Foliar herbivory generally leads to a reduction in root biomass (e.g. /Crawley 1983/), largely due to C reallocation to sustain growth. Soil nematodes can play a beneficial role in C cycling in grassland ecosystems. Nutrient leaching due to low levels of nematode root herbivory lead to enhanced microbial activity and microbial biomass and increase the allocation of photoassimilation to roots. If root herbivory can lead to a greater and more active soil microbial biota, then this in turn can lead to greater decomposition and mineralization, resulting in an increase in the availability of C and N for plant uptake. An alternative hypothesis is that a greater and more active soil biota, resulting from root herbivory, will lead to increased asymmetric competition between roots and microbes for nutrients (with microbes benefiting from the interaction).

4.2.5 Fungi

This section contains a brief description of fungi that have been found or been investigated at the sites. A more general discussion of mycorrhizas in an ecosystem perspective is found in Chapter 5, while estimates of the yield from edible fungi are presented in Section 4.3.2.

Species

/Abrahamsson 2003/ and /Andersson 2004a/ made a brief inventory of fungi in a few localities at both sites, mainly searching for red-listed species and species regarded as indicators of conservation values. The species lists are presented in Appendices 6 and 7.

/Johanson et al. 2004/ investigated element uptake by fungi in the Forsmark area and compared the element content for 20 elements in the soil, the mycelia and the fruiting bodies from a number of fungi species found at four forest localities dominated by conifers (Table 4-48).

Table 4-48. C and N content in fungi fruiting bodies (% of dry weight) of different species of fungi collected in the Forsmark area from /Johanson et al. 2004/.

Species	C	N
Lactarius deterrimus	46.1	2.7
Suillus granulatus	46.7	2.6
Lactarius scrobiculatus	45.6	3.4
Boletus edulis	47.0	4.6
Cortinarius odorifer	45.5	3.6
Sarcodon imbricatus	45.1	4.4
Cantharellus tubaeformis	46.3	3.3
Lactarius trivialis	45.7	3.0
Cortinarius armeniacus	46.4	4.1
Cortinarius sp.	44.8	3.9
*Hypholoma capnoides**	43.4	4.0
Tricholoma equestre	42.5	2.1
*Collybia peronata**	44.7	5.1
Suillus variagatus	47.8	3.7
Suillus variagatus	46.4	4.4
Suillus variagatus	44.2	4.7
Mean	45.5	3.7
Median	45.6	3.8
SD	1.4	0.8

* Saprophytes.

Mycorrhizas

Mycorrhizas are symbiotic relationships between plant roots and fungal hyphae. The plant obtains nutrients, mainly nitrogen and phosphorus, and in return the fungi are provided with carbohydrates, which is the major carbon source for these fungi. Data from diverse ecosystems indicate that more than 50% of the NPP is commonly allocated to below-ground plant parts. However, a significant proportion of carbon allocated below ground may be directed to mycorrhizal fungi /Read 1991/. The proportion of the total plant photosynthates that are allocated to ectomycorrhizal fungi has been reported to be 10–20% for arbuscular mycorrhizal fungi /Jakobsen and Rosendahl 1990/. Carbon transfer from vegetation through roots to fungi is of significant importance when describing the flow of carbon /Fitter et al. 2000/. Nutrient uptake by forest trees is greatly dependent on ectomycorrhizal (EM) fungi. Ectomycorrhizal fungi form an extensive mycelial network in the soil, which increases the absorbing surface area several-fold.

4.2.6 Confidence and uncertainties

Species inventories and population estimates

Intensive monitoring of the larger mammals and birds has resulted both in species lists and reliable population estimates from the sites. For other species, such as rodents and amphibians, there are estimates from the sites, but not covering the same temporal scale. Overall, these species lists and population estimates have to be regarded as unique and the best available to underpin further calculations of fluxes of matter in local food webs.

Consumption estimates

Studies of the field metabolic rates (FMRs) of free-living mammals and birds suggest that body mass is the primary determinant of energy and food requirements, which together with phylogeny accounts for 93–95% of the variation in log FMR /Nagy et al. 1999/. However, there is a considerable residual variation after antilog transformation that is expressed as a large confidence interval around FMRs predicted from body mass. The studies of FMR are based on doubly labelled water and are typically short-term studies, being sensitive to unusually energetic phases in an animal's life rather than being representative of a year. The FMRs that have been used to calculate the annual energy requirements of mammals and birds are the mean of a large number of studies, presented in /Nagy et al. 1999/. They are therefore considered to be fairly robust estimates.

Categorization of species according to food and habitat preferences

The categorization of species into functional groups according to their diet is in some cases difficult, since e.g. omnivores feed on a variety of different sources, although mainly insects and seeds. However, this categorization will reflect the major consumption and, accordingly, the major fluxes from the food sources to the different bird species, since it is based on their metabolic rate, so errors in the categorization of bird species into trophic levels will not cause an under- or overestimation of the actual consumption. The categorization of bird species into woodland and open land based on their feeding or nesting preferences is perhaps even more difficult, since some of the species feed in both forested and open habitats or feed in different habitats in the breeding and winter seasons. Classifying bird species as belonging to different habitats according to their food or nesting preferences is important to be able to determine whether some of the categories are more exposed to bioavailable contaminants, such as radionuclides, than others.

4.3 Land use

4.3.1 Land use classes at the landscape level

This is a general overview of different land uses at the two sites. Land use has been treated in greater detail within the descriptions of the vegetation types wetland, agricultural land and forests above.

The Forsmark area

Land use in the Forsmark area (area definition in /Miliander et al. 2004a/) differs from the average land use in Uppsala County (see Table 4-49). The agricultural area in the Forsmark area is only 4% of the total area, considerably lower than in Uppsala County, where it represents 25%. Furthermore, only 0.04% of the land area consists of urban areas (developed areas), compared with 4.9% in Uppsala County. On the other hand, there are far more forests, wetlands and lakes in the Forsmark area. The forest area represents as much as 72.5% of the land area.

The Laxemar-Simpevarp area

Land use in the Laxemar-Simpevarp area (area definition in Miliander et al. 2004b) differs from the average land use in Kalmar County (Table 4-50). The forest area is far more dominant in the Laxemar-Simpevarp area than in Kalmar County. The amount of arable land and other landscape types is considerably less in the Laxemar-Simpevarp area.

Table 4-49. Land use in Uppsala County and the Forsmark area /Miliander et al. 2004a/.

Type of land use	Uppsala county		Forsmark area	
	Area (hectares)	Percentage distribution (%)	Area (hectares)	Percentage distribution (%)
Agricultural land	179,940	25.1		
Arable land			34	1.7
Grazing land			50	2.6
Forest	401,500	55.9	1,411	72.5
Developed	34,900	4.9	0.7	0.04
Pits, mines etc	250	0	0	0
Wetlands -mire	17,000	2.4	206	10.6
Bare rocks, high mountains, other	65,320	9.1	67	3.4
Water	19,380	2.7	163	8.4
Unknown			14	0.7
Total	**718,290**	**100**	**1,946**	**100**

Source: Land area in Uppsala County from the report Markanvändning i Sverige, Table 5 /SCB 1998/. The agricultural area is not divided into arable and grazing area. Calculated: Land area in the Forsmark area from Vegetation Classification /Boresjö Bronge and Wester 2003/.

Table 4-50. Land use in Kalmar County and the Laxemar-Simpevarp area /Miliander et al. 2004b/.

Type of land use	Kalmar county		Laxemar-Simpevarp area	
	Area (hectares)	Percentage distribution (%)	Area (hectares)	Percentage distribution (%)
Arable land	134,878	12	556	4.4
Grazing land	53,007	4.5	465	3.7
Forest	728,605	62	11,251	89
Developed	18,551	1.6	125	1.0
Water	49,470	4.2	268	2.1
Other (wetlands bare rocks, pits etc)	182,049	16	41	0.3
Total	**1,166,560**	**100**	**12,706**	**100**

Source: Land area for Kalmar län from the report Markanvändningen i Sverige /SCB 1998, table B24/. Calculated: Land area for Laxemar-Simpevarp area from Vegetation Classification /Boresjö Bronge and Wester 2003/.

Conclusions and comparison

The two areas have a somewhat similar land use distribution. They are both dominated by commercial forestry, whereas agricultural activity is limited. However, agricultural activity is more prevalent in the Laxemar-Simpevarp area than in the Forsmark area. This difference is also noticeable in the population statistics. In Misterhult parish, 40% of the jobs are within agriculture, forestry, hunting and fishing, whereas this figure is 0% in Forsmark parish /Miliander et al. 2004a, b/.

The amount of lakes and wetlands is considerably greater in the Forsmark area (19% versus 2%).

4.3.2 Edible berries and fungi in the Forsmark and Laxemar-Simpevarp areas

Consumption of berries and fungi are two of several potential pathways for human exposure to radionuclides in the event of a radionuclide release. The potential radionuclide transfer to humans by consumption can be estimated by estimating the yield of berries and fungi /Löfgren et al. 2006/. Berry species that are common in Sweden are above all bilberry (*Vaccinium myrtillus* L), lingonberry (*V. vitis-idaea*), raspberry (*Rubus idaeus* L) /Eriksson et al. 1979/ and rosehip (*Rosa dumalis* Bechst.) /Mossberg and Stenberg 2003/, but also cloudberry (*Rubus chamaemorus* L) and cranberry (*V. oxycoccos* L) /Kardell and Carlsson 1982/. Bilberry, lingonberry and raspberry are common in the whole of Sweden. Raspberry has its highest abundance in the southern parts of the country, while in the north it is sparse to almost non-existent in the northernmost parts. Bilberry and lingonberry, on the other hand, have a higher degree of coverage in the more northern regions and are absent in parts of Skåne in southern Sweden /Eriksson et al. 1979/. Cloudberries and cranberries are two species mainly occurring in peatland areas. Cloudberry can be found all over Sweden except for some small areas in Skåne. Cranberry is rather common from the north to the southern parts of Dalarna, occurring more sporadically further south /Kardell and Carlsson 1982/. Bilberry and lingonberry produce the highest proportion of berries in the northern parts of Sweden /Eriksson et al. 1979, Kardell and Carlsson 1982/. Rosehip is common in grasslands and at the edge of the forest /Mossberg and Stenberg 2003/. Boletuses (*Boletus edulis*, 44%), russulas (*Russula paludosa*, 29%) and northern milk-caps (*Lactarius rufus/trivialis,* 20%) are fungus groups which are commonly found in Swedish forests. The different species of chanterelle (*Cantharellus cibarius*) are the most popular fungi in Sweden, representing c 1.2% of the edible species found. The abundance of edible species differs slightly depending on latitude /Kardell and Eriksson 1987/.

The berry yield may vary between years depending on frost, precipitation, temperature and pollination success /Wallenius 1999/. This variation is even more pronounced among fungi species, where the yield of fruiting bodies may be close to zero in certain years followed by years with high yields. This annual variation remains to be explained. Most fungus species are favoured by varied weather with periods of rain followed by periods of warm and dry weather. Many species are sensitive to frost and disappear in early autumn.

Neither berry nor fungus yield has been estimated by direct field surveys in the two areas. An attempt is made below to estimate the yield by using other site-specific information to infer berry production. Bilberry and lingonberry yields are estimated by using a model by /Ihalainen et al. 2003/. As the empirical model was developed for forest planning purposes in Finland, site and growing stock characteristics (fixed predictors) were the most reasonable known factors to use /Ihalainen et al. 2003/. The random part of the model accounts for the effect of plot, measurement year, and spatial clustering /Ihalainen et al. 2003/. According to /Ihalainen and Pukkala 2001/, sites of medium or rather poor fertility produce the highest bilberry yields. The bilberry yield is positively related to tree height, whereas the basal area of spruce and the proportion of deciduous trees are negatively related to the yield. On mineral soils, lingonberry yields are best on poor sites, and it was also found that a high proportion of Scots pine improves the lingonberry yield. The highest yields are found in open areas and in very young stands as well as in sparsely populated stands of large and old trees /Ihalainen and Pukkala 2001/. For other edible berries and fungi, literature values are used to estimate the yield in the two areas.

Method

Bilberry and lingonberry yield

The berry yield has been estimated using the model for *V. myrtillus* and *V. vitis-idaea* by /Ihalainen et al. 2003/. Site-specific soil fertility and tree stand data have been used for the Forsmark and Laxemar-Simpevarp areas in the model. Bilberry yield was predicted using stand age and forest type as fixed predictors in the model. Stand basal area, mean tree diameter and forest type, were used for lingonberry. The yield and carbon content was estimated in fresh weight.

Bilberry

The model describing the bilberry yield is as follows:

$y_b = \exp(0.0830+0.0103\ t_g+0.9904\ D_1+0.4997\ D_2)\times 2.4507-1$

where

y_b = bilberry yield in fresh weight (kg ha^{-1})

t_g = mean age of trees (year)

D_1 = site dummy: $D_1 = 1$, if the forest site type is medium, and $D_1 = 0$ otherwise

D_2 = site dummy: $D_2 = 1$, if the forest type is rather poor, and $D_2 = 0$ otherwise

Lingonberry

The model describing the lingonberry yield is as follows:

$y_b = \exp(1.0560+0.0005\ D_3\ d_g^2-0.1196\sqrt{G})\times 1.7713-1$

where

y_b = lingonberry yield in fresh weight (kg ha^{-1})

D_3 = site dummy: $D_3 = 1$, if the forest site type is rather poor or poor, and $D_3 = 0$ otherwise

d_g = mean diameter of trees (cm)

G = stand basal area ($m^2\ ha^{-1}$)

Classification of soil fertility

In the model by /Ihalainen et al. 2003/, three soils types (fertilities) were used: medium, rather poor and poor. The remaining soil types were grouped into one category, “other”. The soil types were classified by using the vegetation as an indicator of fertility grade (see /Ihalainen et al. 2003/). The soil types in the Forsmark and Laxemar-Simpevarp areas were classified by using the field layer vegetation map /Boresjö Bronge and Wester 2003/ over the areas where:

herb-heath type = medium

mesic bilberry heath type = rather poor

dry heath type, and mosaic of dry heath type = poor

and the remaining vegetation types were grouped into the “other” category.

Tree stand data

The characterization of the tree stands for both sites was done on the basis of information from the Swedish National Forest Inventory database (http://www-riksskogstaxeringen.slu.se/) for a regional area around the sites (SKB GIS database delivery id C169). A regional subset describing woodland was extracted from this database (Table 4-51). The data for the Forsmark area are from the plot inventory performed in 2005, while the data for the Laxemar-Simpevarp area are from the inventory performed in 2004 and 2005.

Table 4-51. Tree stand age, basal area and calibrated basal area diameter for the Forsmark (N=44) and Laxemar-Simpevarp areas (N=36) obtained from the Swedish National Forest Inventory database (SKB GIS database delivery id C169).

	Site	Mean	Min.	Max.
Tree stand age (yr)	Forsmark	74	22	147
	Laxemar-Simpevarp	61	17	135
Basal area (m^2 ha^{-1})	Forsmark	25	11	48
	Laxemar-Simpevarp	25	9	47
Calibrated basal area diameter (cm)	Forsmark	23	0	37
	Laxemar-Simpevarp	24	9	45

Berry yields for other edible species

The berry yields for other edible species are literature values.

Raspberry

The raspberry yield in Sweden was studied by /Eriksson et al. 1979/ in a three-year study between 1974 and 1977. The raspberry inventory was conducted each year starting in the middle of May or in the beginning of June and lasting until October. The inventory was carried out along transects covering the whole of Sweden, see /Eriksson et al. 1979/ for further details.

Rosehip

The rosehip yield in a five-year period was obtained from inventories conducted at a farm called Ekenäs gård in Södermanland in southern Sweden /Kardell 1993/. All rosehips were collected, without regard to degree of ripeness, in a 5 m^2 circle in 436 locations. The locations were inventoried twice a year in July and September /Kardell 1993/.

Cloudberry and cranberry

In order to estimate the annual Swedish berry yield of cloudberries and cranberries, /Kardell and Carlsson 1982/ used data obtained from 1,545 subplots distributed over 10 locations in the country collected by the Swedish National Forest Inventory 1978–1980.

Edible fungi

Edible fungi were defined as those species that, according to /Mossberg et al. 1979/, were edible with or without parboiling before consumption. The mean annual yield of edible fungi was estimated from a five-year period between 1977 and 1981. The fungi were collected in 23 different sampling plots measuring 30×30 or 50×50 metres 5–9 times each year. For further details see /Kardell and Eriksson 1987/.

Carbon content in berries and fungi

Carbon calculations

The carbon content was calculated using the same method as in /Lindborg 2006/, where the carbon in carbohydrates, lipids, and proteins was estimated /Altman and Dittmer 1964, Dyson 1978, Rouwenhorst et al. 1991/.

$CC_i = 0.53 \times Proteins_i + 0.44 \times Carbohydrates_i + 0.66 \times Lipids_i$

where,

CC_i is the carbon content in the i-th food type (kg C kg^{-1} fw),
$Proteins_i$ is the protein content in the i-th food type (kg kg^{-1} fw),
$Carbohydrates_i$ is the carbohydrate content in the i-th food type (kg kg^{-1} fw),
$Lipids_i$ is the lipids content in the i-th food type (kg kg^{-1} fw)

The amounts of the different components in berries and fungi were taken from the website of the /Fineli 2007/ (Tables 4-52 and 4-54).

The carbon content of berries ranges from 2.2 to 9.3% for the different species (Table 4-53). The carbon content was highest in rosehips, which differ from the other species. If rosehips are excluded, the mean carbon content of berries is 3.3% of the fresh weight.

The carbon content in different species of fungi on a fresh weight basis ranges from 1.4 to 3.3%. The mean value for fungi was 2.1% (Table 4-54). One survey of fungi has been performed in the Forsmark area, where the carbon and nitrogen content was estimated from dry matter (See Section 4.2.5).

Table 4-52. The energy, carbohydrate, lipid and protein content in 100 grams of berry /Fineli 2007/.

	Energy content (kJ)	Carbohydrates (g)	Lipids (g)	Proteins (g)
Bilberry	140	6.4	0.6	0.5
Lingonberry	142	6.8	0.5	0.4
Raspberry	142	4.1	0.8	1
Rosehip	392	16	0.5	3.6
Cloudberry	175	7.8	0.5	1.4
Cranberry	92	3.5	0.7	0.4

Table 4-53. The carbon content in different species of berries. Mean carbon content values are calculated with and without rosehip.

	Carbon content in % (fresh weight)
Bilberry	3.5
Lingonberry	3.5
Raspberry	2.9
Rosehip	9.3
Cloudberry	4.5
Cranberry	2.2
Mean (rosehip incl.)	4.3
Mean (rosehip excl.)	3.3

Table 4-54. The energy, carbohydrate, lipid and protein content per 100 grams of fungus /Fineli 2007/.

	Energy content (kJ)	Carbohydrates (g)	Lipids (g)	Proteins (g)
Champignon	55	0.3	0.3	2.1
Chantarelle	61	0.4	0.5	1.8
False morel	63	0.5	0.5	1.8
Boletus edible	127	2.9	0.5	3.2
Edible milk-caps	89	2.3	0.5	1.6
Boletus/Russula	104	2.9	0.5	1.8

Table 4-55. The carbon content of different species of fungus.

	Carbon content in % (fresh weight)
Champignon	1.4
Chantarelle	1.5
False morel	1.5
Boletus edible	3.3
Edible milk-caps	2.2
Boletus/Russula	2.6
Mean	2.1

The estimated carbon content of berries was lower than previously reported figures /Lindborg and Kautsky 2004, Lindborg 2006/. The method used to estimate the carbon content was the same as in /Lindborg 2006/, but the carbohydrate, lipid and protein contents of the berries differ. In /Lindborg 2006/, the three components for blueberry were found in the Nutrient Database from United States Department of Agriculture /USDA 2004/. However, the American blueberry is a larger species than the European bilberry /Naturhistoriska riksmuseet 1997 /. This may explain why the carbon content of blueberry is 7% of the fresh weight and only 3.5% in bilberry. The carbon contents of fungi were also somewhat lower than previously reported /Lindborg and Kautsky 2004, Lindborg 2006/. As in the case of berries, it probably has to do with what species were used for the calculations.

The carbon content of different types of food items is often unknown and it is therefore necessary to use some type of estimation/conversion. The carbon content can be estimated based on the composition of the food items, i.e. the amounts of carbohydrates, proteins and lipids. The carbon content differs relatively little in a comparison between the methodology used in /Holland et al. 1991/ and the method described in /Altman and Dittmer 1964, Dyson 1978, Rouwenhorst et al. 1991/. The carbon content of bilberry was c 8% lower when the /Holland et al. 1991/ methodology was used, which is equivalent to 0.27 grams of carbon per 100 grams of bilberry.

Results

Berry yield

The resulting yield estimates are presented in Table 4-56 and Figure 4-40 describes an example of how the total berry yield is distributed in the landscape.

Bilberry

The highest bilberry yield was found in areas with medium soil fertility. The increased tree stand heights positively affect the bilberry yield as well /Ihalainen and Pukkala 2001/. The bilberry yield might therefore be greater in the Forsmark area compared with the Laxemar-Simpevarp area (Table 4-56), since the tree stands were older in Forsmark and thereby might be taller as well. This does not necessarily mean that the bilberry yield for the whole site is higher in the Forsmark area than in the Laxemar-Simpevarp area.

Lingonberry

The lingonberry yield was slightly higher in areas with poor/rather poor soil in Laxemar-Simpevarp, where the calibrated mean tree diameter was somewhat higher (Table 4-56).

Raspberry

The raspberry reaches its maximum yield in areas that have recently been cleared. A cleared area is colonized by raspberries within three vegetative seasons /Kardell 1993/. The coverage of raspberry in young clear-cuts varies between 2 and 4%. As the forest gets older the raspberry yields declines, and after 20–30 years raspberry has totally disappeared /Eriksson et al. 1979/. No co-variance was found between the climate data and the raspberry yield. Nor was there a correlation between good bilberry and lingonberry yield on the one hand and good raspberry yield on the other. The mean raspberry yield was found to be 0.002 gC m^{-2} y^{-1} /Kardell 1993/ (see Table 4-56).

Rosehip

Rosehip is commonly found in grasslands and at the edge of the forest /Mossberg and Stenberg 2003/. The rosehip yield seems to be stable from year to year at approximately 0.062–0.093 gC m^{-2} y^{-1}, with a mean of 0.081 gC m^{-2} y^{-1} grassland, e.g. /Kardell 1993/ (see Table 4-56). The estimation of the yield variation was not done due to errors in measurements caused by grazing cows (see /Kardell 1993/).

Cloudberry

In Sweden, cloudberries are almost solely found on peatland. The mean yield on peatlands was estimated to be c 0.085 gC m^{-2} y^{-1}, while the mean yield on woodlands was 0.063 gC m^{-2} y^{-1} (see Table 4-56). In calculating the yield per hectare, the mountain areas were excluded /Kardell and Carlsson 1982/. The northern parts of Sweden have the highest cloudberry yields: 46% of the berries are produced in Norra Norrland, 28% in Södra Norrland, 22% in Svealand and 4% in Götaland /Kardell and Carlsson 1982/.

Cranberry

Cranberry was found to grow almost exclusively on peatland. Cranberry is rarely found in dense patches, and trees inhibit cranberry coverage. The mean yield of cranberry on peatland was 0.011 gC m^{-2} y^{-1} and on woodland 0.006 gC m^{-2} y^{-1} (see Table 4-56). As for cloudberry, the yield of cranberries in mountain areas was excluded when estimating the mean yield /Kardell and Carlsson 1982/.

When the Swedish cranberry yield was broken down into four different regions, the areal yield was found to be higher in the southern parts of Sweden for both peatlands and woodlands. The proportion of berries produced was however higher in the northern parts of Sweden (Norra Norrland 41%, Södra Norrland 22%, Svealand 27%, and Götaland 10%) /Kardell and Carlsson 1982/.

Table 4-56. Berry yield (mean, min, max and SD) is presented in gC m^{-2} yr^{-1} for the different species and landscape types. Bilberry and lingonberry mean, min. and max. were calculated using the estimates obtained from the model by /Ihalainen et al. 2003/, where the SD for the Forsmark and Laxemar-Simpevarp areas could not be estimated (see Section 4.1). The raspberry mean yields between 1975 and 1977 were used to estimate the min, max and SD /Eriksson et al. 1979/, while the mean yield between 1978 and 1980 was used for cloudberry and cranberry /Kardell and Carlsson 1982/. The rosehip yield was found in /Kardell 1993/, where the mean value was estimated and the min. and max. values were approximated. No estimates of the SD were available from that study.

				gC m^{-2} yr^{-1}			
Species	**Area**	**Landscape type**	**Category**	**Mean**	**Min.**	**Max.**	**SD**
Bilberry	Forsmark	Woodland	Medium	0.050	0.028	0.111	–
	Forsmark	Woodland	Rather poor	0.029	0.016	0.065	–
	Forsmark	Woodland	Otherwise	0.016	0.008	0.039	–
	Laxemar-Simpevarp	Woodland	Medium	0.043	0.026	0.097	–
	Laxemar-Simpevarp	Woodland	Rather poor	0.025	0.015	0.058	–
	Laxemar-Simpevarp	Woodland	Other	0.006	0.004	0.009	–
Lingonberry	Forsmark	Woodland	Rather poor/ Poor	0.009	0.008	0.012	–
	Forsmark	Woodland	Other	0.006	0.004	0.008	–
	Laxemar-Simpevarp	Woodland	Rather poor/ Poor	0.009	0.009	0.018	–
	Laxemar-Simpevarp	Woodland	Other	0.006	0.002	0.009	–
Raspberry	Sweden	Woodland	–	0.002	0.002	0.002	0.000
Rosehip	Sweden	Pastureland	–	0.081	0.062	0.093	–
Cloudberry	South of the Norrland border	Peatland	–	0.085	0.063	0.096	0.019
	South of the Norrland border	Woodland	–	0.063	0.046	0.079	0.017
Cranberry	South of the Norrland border	Peatland	–	0.011	0.007	0.013	0.003
	South of the Norrland border	Woodland	–	0.006	0.005	0.007	0.001

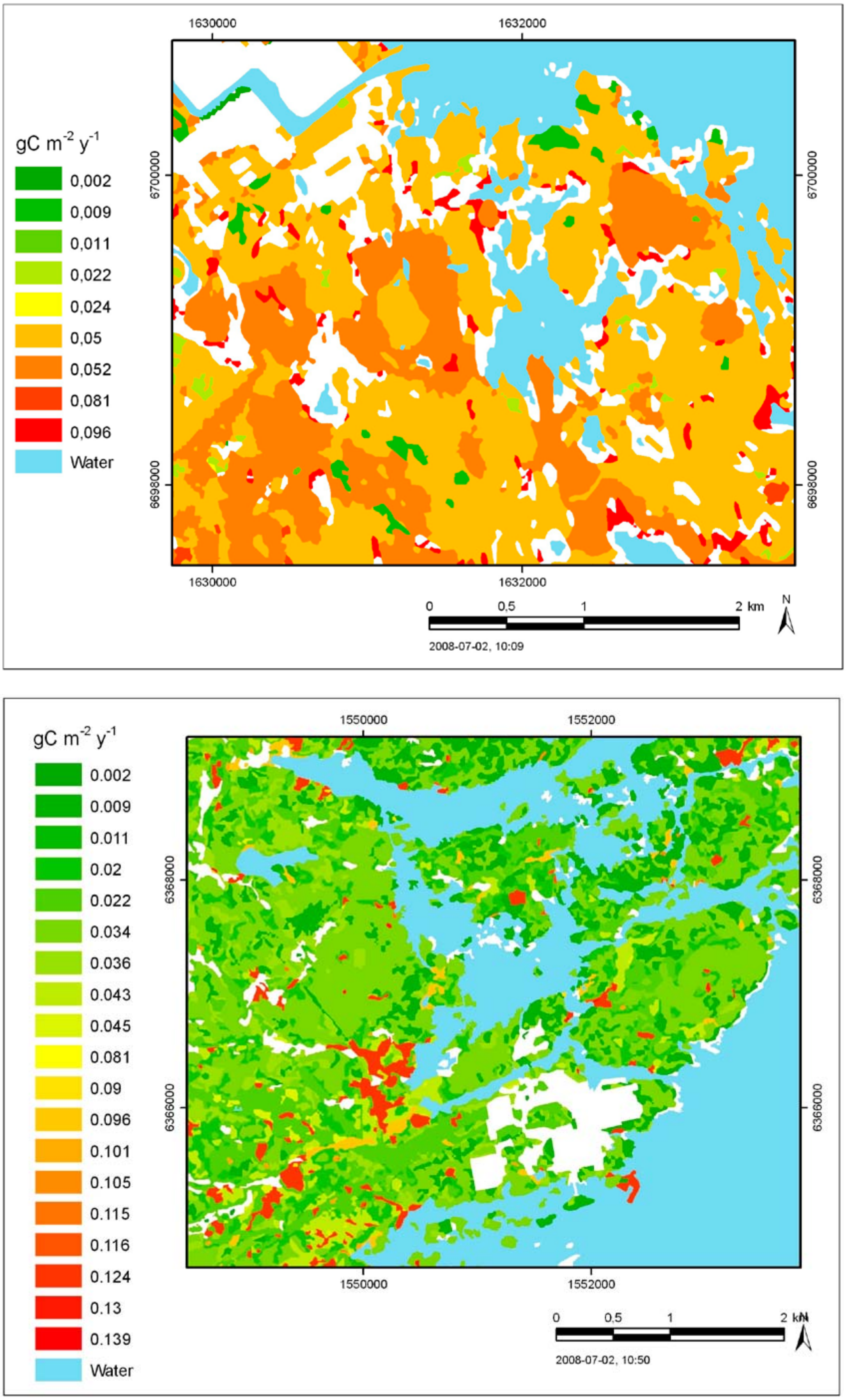


Figure 4-40. *Total berry yield from different species. The maps show a subset of the total area covered by the spatial models in a) Forsmark b) Laxemar-Simpevarp.*

Edible fungus yield

The mean yield of fungal fruiting bodies between 1977 and 1981 was found to be 0.091 gC m^{-2} y^{-1} for the whole of Sweden (Table 4-57). If the northernmost part of Sweden (north of the Limes Norrlandicus) is distinguished from the rest of Sweden, the annual yield for southern Sweden increases to 0.122 gC m^{-2} y^{-1}. The annual yield in the northern part of Sweden was estimated to be approximately 30% lower than in the southern part although the difference was not significant. The annual yield of the most popular species, i.e. the different species of chantarelle (*C. cibarius* and *C. tubaeformis*) and edible boletuses (*B. luteus* and *B. edulis*), was 0.003 gC m^{-2} y^{-1}, which represents barely 5% of the edible fungi /Kardell and Eriksson 1987/.

Discussion

Berry yield

Berry yield studies are generally rather small, local investigations typically consisting of only a few study plots, probably due to the laborious work involved in picking and measuring berry yields over large areas and for longer time periods /Wallenius 1999/.

The model used for estimating the berry yield for bilberry and lingonberry in the Forsmark and Laxemar-Simpevarp areas was based on a study performed in North Karelia. Forsmark (c. 60°) and Karelia (63–64°) are closer to each other in latitude than Laxemar-Simpevarp (c. 57°) and Karelia. This could mean that the estimated results reflect the Forsmark area better than the Laxemar-Simpevarp area. However, the model provides results similar to other studies performed in Sweden and Finland (Table 4-56). Most models used to predict berry yield do not consider actual conditions on the sites, which this model does. By utilizing the site-specific soil fertility and tree stand data, the model takes site characteristics into account. By means of this approach it was also possible to distinguish more or less productive areas.

In the study by /Ihalainen et al. 2003/, there is variation caused by a random part (effect of plot, measurement year and cluster) and a fixed part (site and growing stock characteristics) of the model. The fixed part of the model explains 6% of the total variance in the back-transformed bilberry yield (R^2=0.06) (RMSE), which is 0.077 gC m^{-2} y^{-1}. A major part of the residual variation (58%) was caused by the random sample plot effect. Within-sample-plot and within-year variation accounted for almost 40% of the variation, while the proportion explained by the year effect was only a few percentage points. In the lingonberry model, 3% of the variation is explained by the fixed part (R^2=0.03), which is 0.028 gC m^{-2} y^{-1}. The effect of the random components, except the year, was statistically significant. This suggests that, in a given year the level of lingonberry yields varied from cluster to cluster. In addition, variation occurred in lingonberry crops between different sample plots. Almost one-third of the variation consisted of random error. The variance in the random sample plot effect accounted for half of the total variance in the random effects. The proportions of year × cluster and year were 9% and 10%, respectively.

As shown in the study by /Kardell 1993/, the heterogeneity of the land greatly influences the berry yields (Table 4-59). This variation should be kept in mind when trying to predict the berry yield in an area.

Table 4-57. The mean, min, max and SD of edible fungi in Sweden in gC m^{-2} yr^{-1} based on the annual mean yield between 1977 and 1981 /Kardell and Eriksson 1987/.

			gC m^{-2} yr^{-1}			
Species	**Site**	**Landscape type**	**Mean**	**Min.**	**Max.**	**SD**
Edible fungi	Sweden	Coniferous forest	0.091	0.063	0.122	0.028

Table 4-58. Estimated mean yield for the three different soil fertilities (gC m^{-2} yr^{-1}) of bilberry and lingonberry in the Forsmark and Laxemar-Simpevarp area compared with results from field studies performed in Sweden and Finland.

Site	Reference	(gC m^{-2} yr^{-1}) Mean yield of bilberry	Mean yield of lingonberry
Sweden	Kardell 1980	0.031	0.019
Sweden (Ekenäs farm)	Kardell 1993	0.030	0.014
Finland	Ihalainen et al. 2003	0.046	0.011
Sweden (Forsmark)	Ihalainen et al. 2003	0.032	0.008
Sweden (Laxemar-Simpevarp)	Ihalainen et al. 2003	0.028	0.008

Table 4-59. Mean yield of berries on different landscape types at Ekenäs between 1981 and 1985 in gC fresh weight m^{-2} yr^{-1} /Kardell 1993/.

Landscape type	Bilberry	Lingonberry	Raspberry	Rosehip
	Fresh weight gC m^{-2} yr^{-1}			
Woodland				
-bare land	0.009	0.007	0.169	–
-young forest	0.009	0.059	0.023	0.013
-"thinning" forest	0.005	0.059	0.002	0.001
-older forest	0.085	0.000	0.000	–
Rock/waste land	0.012	0.001	0.000	–
Wetland	0.010	0.005	–	–
Pasture	–	–	0.011	0.076

Edible fungi yield

Fungal fruiting body production at the Ekenäs farm was estimated to be 0.042 gC m^{-2} y^{-1} (Table 4-60), which is considered to be a low figure. This could be explained by the character of the farm area, which was in general quite dry and consists primarily of rock/waste land /Kardell 1993/. Since the Ekenäs farm is not representative of the Forsmark and Laxemar-Simpevarp areas in terms of land characteristics, it can be assumed that fruiting body production is higher in the Forsmark and Laxemar-Simpevarp areas. The fungal fruiting body production estimates from the Swedish inventories between 1977 and 1981 are probably more representative when it comes to estimating the fungal yield in the two areas (0.090 gC m^{-2} y^{-1} for the whole of Sweden), but the estimated yield for the southern part of Sweden (below the Norrland border) should be even more appropriate (0.122 gC m^{-2} y^{-1}). The annual minimum yield of edible fungi in Finland was reported to be between 0.042 and 0.210 gC m^{-2} y^{-1}, where the variation was caused by the woodland type /Kardell and Eriksson 1987/. /Kardell and Eriksson 1987/ argue that the larger amount of edible fungi in Finland has to do with cultural differences. The people in Finland have been gathering fungi as a resource for a much longer time and are therefore able to find a larger quantity of edible species. The reported figures for edible fungi in Finland were in general higher than in Sweden. However, the yield in the northern parts of Finland was found to be considerably lower than in the south /Kardell and Eriksson 1987/. This suggests that the figure estimated for southern Sweden should be used to estimate the yield in the two areas instead of the total yield for the whole of Sweden. Furthermore, /Kardell and Eriksson 1987/ estimated that the collected amount of fungus represented approximately 70–80% of the total annual yield.

Table 4-60. Mean yield of edible fungi in gC m^{-2} yr^{-1} from three different field studies performed in Sweden and Finland.

Site	Time period	Landscape type	Fungal yield (gC m^{-2} yr^{-1})
Ekenäs*	1981–1985	Deciduous forest	0.042
Sweden**	1977–1981	Coniferous forest	0.090
Finland***	1944–1946	Coniferous forest	0.042 to- 0.210

*/Kardell 1993/.
**/Kardell and Eriksson 1987/.
***Minimum yield in /Kardell and Eriksson 1987/.

4.3.3 Game hunting

Introduction

The species that are mainly hunted for human consumption are moose, roe deer and hare. Hunting data for moose were obtained from the County administrative boards (*Sw: Länsstyrelserna*) covering five years (1999–2003), while hunting data for roe deer and hare were obtained from the National Association of Huntsmen (*Sw: Svenska Jägareförbundet*), also covering five years (1997–2001). The data were compiled, processed and analyzed in /Miliander et al. 2004a, b/. The data from the County administrative boards are reported for the parish as well as for the municipality and the County. The data from the National Association of Huntsmen are reported for the local hunting zone (Oskarshamns Norra jaktvårdskrets in Oskarshamn and Östhammars jaktvårdskrets in Forsmark).

The average harvest of moose in the parish and the average harvest of roe deer and hare in the local hunting zone reported in /Miliander et al. 2004a, b/ are applied to the Forsmark area and the Laxemar-Simpevarp area (Table 4-61 and 4-62).

The Forsmark area

According to the figures from the County Administrative Board in Uppsala, moose hunting is more extensive in Forsmark parish than in the municipality and county as a whole. The harvest has on average been greater in Forsmark parish than in Östhammar Municipality and Uppsala County during the entire dataset period (1997–2003). The number of harvested moose per km^2 reached a peak in 2000–2001. The number per km^2 decreased in 2002 and 2003.

Table 4-61. The harvest of free-living mammals in the Forsmark area, Östhammar Municipality and Uppsala County.

Game-hunting	Forsmark		Östhammar Municipality		Uppsala County	
	mean (ind·km^{-2})	SD	mean (ind·km^{-2})	SD	mean (ind·km^{-2})	SD
Moose[1]	0.53	0.08	0.42	0.05	0.39	0.04
Roe deer[2]	1.91	0.53				
European hare[2]	0.28	0.13				
Mountaine hare[2]	0.13	0.15				

[1] Statistics from The Administrative Board of Uppsala County for 1999–2003.
[2] Statistics from The National Association of Huntsmen (1997–2001), reported for the local hunting zone (Östhammars jaktvårdskrets).

Table 4-62. The harvest of free-living mammals in the Laxemar-Simpevarp area, Oskarshamn Municipality and Kalmar County.

Game-hunting	Laxemar-Simpevarp		Oskarshamn Municipality		Kalmar County	
	mean (ind·km^{-2})	SD	mean (ind·km^{-2})	SD	mean (ind·km^{-2})	SD
Moose[1]	0.49	0.10	0.43	0.10	0.29	0.05
Roe deer[2]	2.15	0.99				
European hare[2]	0.29	0.11				
Mountaine hare[2]	0.10	0.07				

[1] Statistics from The Administrative Board of Kalmar County for 1997–2003.
[2] Statistics from The National Association of Huntsmen (1997–2001), reported for the local hunting zone (Oskarshamns Norra jaktvårdskrets).

The Laxemar-Simpevarp area

According to the figures from the County Administrative Board in Kalmar County, moose hunting is more extensive in Misterhult parish than in the municipality and the county as a whole. The harvest has been greater in Misterhult parish than in Oskarshamn Municipality and Kalmar County during the entire dataset period (1997–2003). The number of harvested moose per km^2 reached a peak in 2000.

Discussion

The moose harvest is somewhat greater in Forsmark parish than in the Laxemar-Laxemar-Simpevarp area (Misterhult parish). The difference is very small, however (on average 0.53 moose·km^{-2} compared with 0.49), and it is not possible to draw any definite conclusions from the figures. The resemblance in hunting statistics is matched by the similarity in the density figures (1.0 moose·km^{-2} in the Forsmark area and 1.07 in the Laxemar-Simpevarp area).

Hunting of roe deer is also very similar at the two sites, even though the population density is greater in the Forsmark area. The average harvest of European hare and mountain hare has also been similar in the Forsmark area and Laxemar-Simpevarp area during the time period. However, the population of European hare, which inhabits fields, predominates in the Laxemar-Simpevarp area, whereas the forest species, mountain hare, is somewhat more frequent in the Forsmark area.

4.3.4 Recreation

The Forsmark area

The recreational value of the Forsmark area lies in its pristine nature with a wilderness character /Ottosson 2006b/. There is also a rich fauna of birds and game animals, which attracts bird watchers and hunters from far away.

During the period 2002–2007, Östhammar Municipality cooperated with other municipalities in Roslagen, Sweden and in Finland and Åland in a project called the Archipelago Route (*Sw: Skärgårdsleden*), aimed at marketing the recreational activities available in the area and developing tourism in a sustainable way /Ottosson 2006b/. The companies involved in the Archipelago Route can offer packages or single activities such as horseback riding, canoeing and biking. The Archipelago Route is promoted via the website *www.archipelagoroute.com*.

Aside from the Archipelago Route project, the municipality has no plans to expand recreational activities in the area around Forsmark /Ottosson 2006b/.

The Laxemar-Simpevarp area

There are primarily three areas that are used for recreation in the Laxemar-Simpevarp area /Ottosson 2006a/. These are Ostkustleden (the East Coast Trail), Kråkelund and Hamnefjärden, areas that are frequently used by both tourists and local inhabitants. A hike along Ostkustleden goes through forests and pastures and it is possible to sunbathe, fish and pick berries along the trail. Kråkelund, approx. 5 km northeast of the Oskarshamn nuclear power plant, attracts many bird watchers, but it is also a popular place for scuba divers. Hamnefjärden is a unique marine area since the water temperature can be up to ten degrees above the normal temperature due to the cooling water outlet. The water temperature attracts canoeists all year round and sunbathers until late autumn.

4.3.5 Confidence and uncertainties

Potential edible berry and fungus yield

The yield of berries has been estimated in some studies, but few have been able to relate these estimates to factors varying within a region. The regression approach using a number of forestry parameters has resulted in spatial descriptions of the lingonberry and bilberry yield within the sites that are close to the results of other studies.

In general, there are no long-term studies available that can be used to estimate the potential variation. Studies presented suggest a surprisingly low variation. The variation in yield is expected to be large, especially for fungi, due to large annual variation in e.g. precipitation. In a safety assessment, it is the long-term average that would be most appropriate to use, and in this sense there is nothing that suggests that the studies were made during years that would be considered extreme in any direction. However, another factor that may vary is the actual collection by humans. The cultural differences that have been used to explain a part of the difference in yield figures of edible fungi in Sweden and Finland is one example of that (in Finland more species are considered to be edible).

Wild-life hunting

For all four animals important for wildlife hunting (moose, roe deer, European and mountain hare) the hunting pressure is similar between the sites. During the rather short time period that the statistics were built upon (seven years for moose and five years for the others), the standard deviation was rather small, except for roe deer that also showed the largest populations at both sites. The large roe deer populations are expected to be sensitive to severe winters, which may explain a part of the large variation. Generally, there is a high hunting pressure and especially on moose /Cederlund 2008, Cederlund et al. 2004/. A much higher hunting pressure would probably not be sustainable. Recently, predators, such as lynx and red fox, have become more abundant and expanded their distribution, which implies negative effects on their prey populations and ultimately also on the wild-life hunting.

Recreation

Recreation covers a large number of potential activities and the overall extent of such activities has generally increased during the years. Sporadic or spontaneous activities are difficult to predict, and as long as no specific facilities aiming at recreation are planned, it is assumed that the recreation will continue to be sporadic.

5 A conceptual ecosystem model

This chapter contains a general description of processes important for transport and accumulation of elements in the terrestrial ecosystem. A conceptual ecosystem box model describes the biota, the physical environmental conditions and the transfer of matter or energy between these as well as interactions with water, solid matter (minerals), solutes and organic matter. The model is used in the following chapters to describe the fluxes and accumulation of carbon, a proxy for organic matter. This conceptual approach will also be an important input to the radionuclide models that will describe the fluxes and accumulation of radionuclides in different ecosystems.

Pools and fluxes of organic matter in ecosystems are of increasing interest to Environmental Impact Assessments, owing to their potential to describe and predict flow and accumulation of bioavailable contaminants, e.g. radionuclides, in a landscape context /Naito et al. 2002, Carrer et al. 2000/. The chemical behaviour of many bioavailable contaminants and radionuclides is similar to that of other elements, such as macronutrients or trace elements /Whicker and Schultz 1982, Sterner and Elser 2002/ and these analogues may thus be utilized for modelling purposes. Similarly, there are elements that are passively assimilated by plants and may therefore be better described by water flow through the plant, e.g. transpiration /Greger 2004/. However, in general, a multitude of bioavailable radionuclides with various behaviours assimilated into living tissue will ultimately follow the path of organic matter in the food web. A comprehensive descriptive ecosystem model, describing pools and fluxes of organic matter, may therefore be useful in describing and quantify the accumulation and transfer of radionuclides in general. Consequently, production of organic material, or net primary production (NPP), may serve as an upper limit to the incorporation of different elements in primary producers /Kumblad et al. 2006/. Fluxes to other trophic levels than vegetation, e.g. large herbivores, predators and humans, may be used to evaluate the potential exposure of these consumers from food intake.

Apart from the immediate transfer of elements via organic matter further up in the food chains, elements may also be accumulated or immobilized in the soil, either as ions (not incorporated into living tissue) or in organic material from litter production. Decomposition of organic matter originating from the vegetation leads to a release of elements into the upper part of the soil profile. Accumulation in the soil can be described by adsorption to mineral particles or organic material or by active discrimination of elements by plant roots. Such processes are important to describe in order to evaluate the potential of different elements to accumulate in the soil.

The specific configuration of an ecosystem model is determined by its purpose, e.g. to describe the emission of carbon to the atmosphere, and the spatial scale it will be used on, e.g. fluxes within a specific ecosystem or at the landscape level. Historically, this approach has been used since the 1950s in order to quantify pools and fluxes of organic matter e.g. /Odum and Odum 1955/. The approach emphasizes the general properties of the ecosystem without documenting all the underlying mechanisms and interactions. The resulting model may provide a mechanistic understanding of how matter or energy is distributed and how it flows, as well as important suggestions on how these pools and fluxes are regulated. In order to build an ecosystem model, the ecosystem must be divided into different functional components, which are connected to each other by fluxes of matter. This approach requires information on the biota, e.g. food webs, and abiotic conditions, e.g. soil descriptions, which makes it possible to describe the functional groups or compartments in the model. Moreover, a number of properties describing pools and fluxes of matter or energy have to be known or quantified by field measurements.

In brief, this chapter presents a conceptual model aimed at the following.

- Providing an understanding of pools and fluxes of carbon (used as a proxy or analogue for organic matter) in terrestrial environments. This knowledge underpins the fine- (Chapter 6) and coarse-resolution (Chapter 7, 8) descriptive ecosystem models describing pools and fluxes of organic matter in the terrestrial landscape of Forsmark and Laxemar-Simpevarp.
- Providing a basis for mass balance calculations of a large number of elements and isotopes (radionuclides) on the scale of the discharge areas (Chapter 9).
- Providing a basis for a conceptual understanding of transport and accumulation of other elements and thereby underpinning the radionuclide models describing radionuclide transfer and accumulation processes in terrestrial ecosystems at the site (e.g. Chapter 14).

5.1 Pools and fluxes in the conceptual ecosystem model

A conceptual ecosystem model for terrestrial systems was derived based on generic knowledge of important ecosystem processes and site-specific knowledge of the vegetation (Chapter 4), soil (Chapter 3 and 4 /Sohlenius and Hedenström 2008, Hedenström and Sohlenius 2008/) and food webs (Section 4.2). A comprehensive description of the pools and fluxes follows below, see Figure 5-1. The rationale for including, excluding or merging certain pools and fluxes is also discussed. Another aim is also to briefly describe internal processes within boxes that are of importance to element transport and accumulation in general. Some fluxes such as gas emission are not represented in Figure 5-1 (e.g. NH_3, N_2 or N_xO_x) but are discussed in the section describing heterotrophic soil respiration. As a rule, the conceptual model should be applicable to all the different ecosystems included in the terrestrial system. The wetland ecosystem differs in mainly two respects: it periodically has a high groundwater table and it receives runoff from the surrounding catchment, but all the pools and fluxes in Figure 5-1 should be applicable (see also Section 4.1.1).

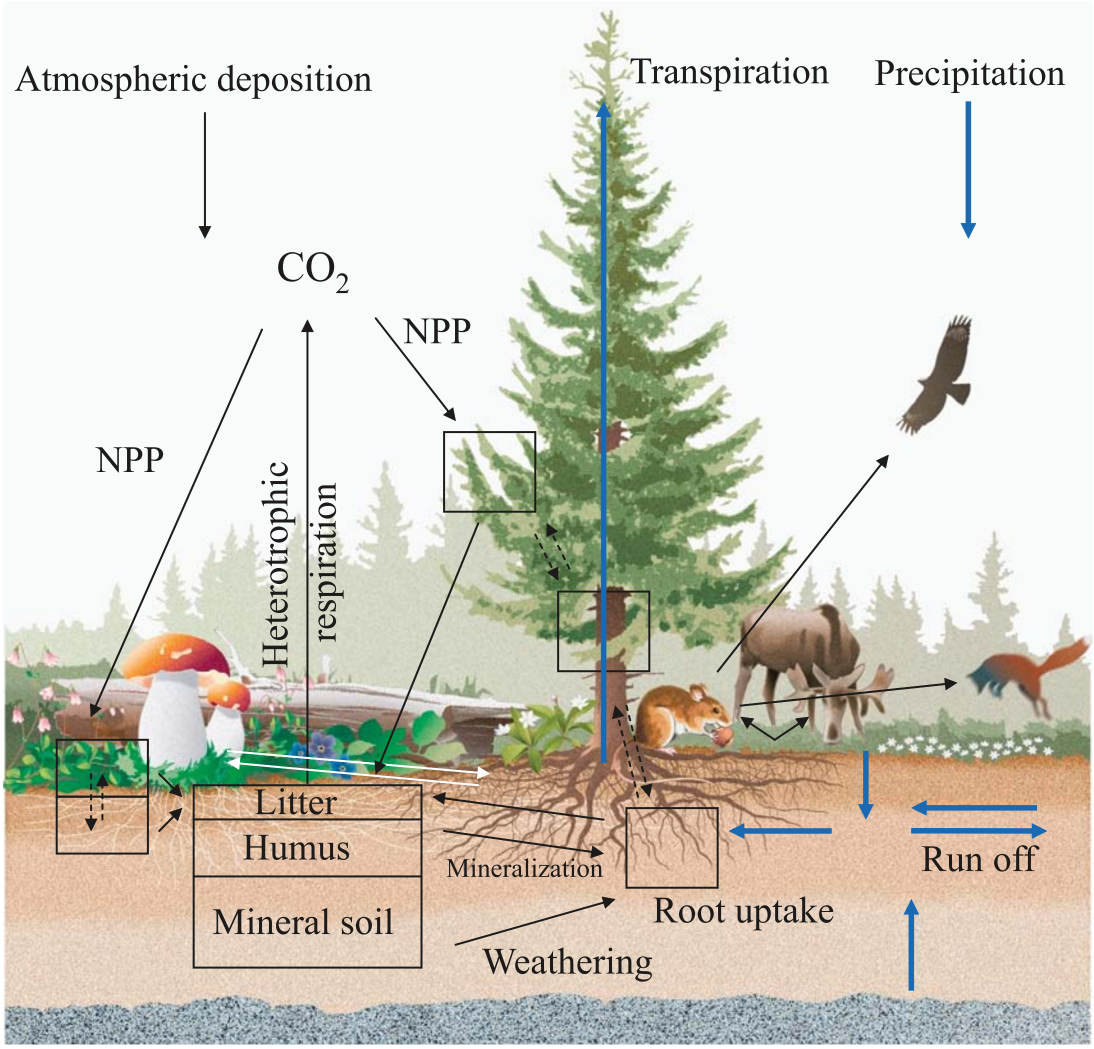


Figure 5-1. A conceptual terrestrial ecosystem model, where black boxes symbolize pools of carbon/organic matter/element, arrows symbolize carbon/organic matter/element fluxes and blue arrows symbolize water fluxes. The white arrows symbolize the mutualistic relationship between plants and ectomycorrhizal fungi. Broken arrows denote internal fluxes within plants.

5.1.1 Primary producers

The biomass in the terrestrial environment is strongly dominated by primary producers. The primary producers were divided into three functional groups: tree, field and bottom layers (Figure 5-1), based on differences in turnover and water and nutrient uptake (e.g. bryophytes lack roots). The tree and field layers were further subdivided into above-ground green biomass and woody biomass, comprising both above and below-ground coarse roots and fine root biomass, and corresponding to different allocation and turnover time patterns. The green tissue and fine roots are continuously replaced whereas the dead tissue, e.g. wood, will remain until the death of the entire tree. Trees are, when present, often the major component of the total biomass. The field layer consists of herbs, grasses and dwarf shrubs (e.g. *Vaccinium vitis-idaea*). The significance of this layer in relation to the total plant biomass varies between habitats, from being the major constituent in grassland to being of low importance in some types of wetlands and forests. The bottom layer includes all plants that are directly attached to the ground or litter, such as lichens and mosses. Lichens may be the dominant plant in dry Scots pine forests, while mosses may be of significance in moist Norway spruce forests and comprise the dominant plant group in mires.

Roots are often defined according to their function, where fine roots have the major function of absorbing water and nutrients from the surrounding soil, and coarse roots may have multiple functions, such as absorbing water and supporting the above-ground plant, with size often determining function /Persson 2002/. There is no conventional definition of fine roots, but many studies of forest biomass have defined fine roots as having a diameter less than 1–2 mm /Vogt and Persson 1991, Persson and Stadenberg 2007b/ and coarse roots having a diameter of more than 5 cm. In this report, fine roots are defined as < 2 mm (see also Chapter 6). However, this distinction is more or less arbitrary and is crudely related to their function (see Section 4.1.3).

Primary production

Photosynthesis provides the carbon and the energy that are essential for many important processes in the ecosystems. Photosynthesis directly supports plant growth and produces organic matter that is consumed by animals, humans and soil microbes. The photosynthesis at an ecosystem level is termed gross primary production (GPP). Approximately half of the GPP is respired by plants to provide the energy that supports the growth and maintenance of biomass /Chapin et al. 2002/. The net carbon gain is termed net primary production (NPP) and is the difference between GPP and plant respiration Figure 5-1. NPP is allocated among different plant functional components such as leaves, fine roots, stem and reproductive tissue, all with different biomass turnover times. NPP is regarded here as the sum of all materials that have been produced and are retained by live plants at the end of an interval and the amount of organic matter that was both produced and lost by the plants during the same interval /Clark et al. 2001/. NPP is restricted by light and the uptake of water, macro- and micronutrients from the soil.

Transpiration

An upward flow of water is driven by a combination of evaporation from the leaf/needle surface and transpiration from the vegetation. This is a passive process linking the water around roots with the water in the plants and the water in the atmosphere /Larcher 1995/. This process may be of importance for the upward transport of substances in the soil due to hydraulic lift /Caldwell et al. 1998/, but it is even more important for the active or passive transport of elements or substances dissolved in water into and in the plant. It is, however, of minor importance for transport of e.g. DOC.

Root uptake of mineral nutrients

Root uptake is a balance between demand by the vegetation and supply in the soil. Vegetation demand is determined by growth, and when nutrients are present in smaller amounts than required, growth is limited according to the Liebig's law of the minimum. Consequently, the plants preferentially invest most in absorption of the nutrient that most strongly limits growth /Chapin et al. 2002/. Roots may take nutrients from the soil in the following three ways: absorption of nutrient ions from the soil solution, exchange absorption of adsorbed nutrient ions by releasing H+, and mobilization of chemically bound nutrients by releasing organic compounds capable of forming soluble complexes with nutrients /Larcher 1995/. Nutrients in the soil solution are available to roots by diffusion and the mass flow of soil water to roots caused by the transpirational water loss by plants (see above). Nutrients are also made available by root activity, e.g. growth.

Translocation and retranslocation of mineral nutrients within plants

Mineral nutrients are rapidly translocated via the xylem, by the transpiration stream from the root to the shoot. The retranslocation of mineral substances incorporated into plant substances is mediated by the phloem, and there may be great variation in how easily they are redistributed /Larcher 1995/. Nutrients such as N, P and S have high concentrations in young leaves and are gradually moved with the ageing of the leaf. Heavy metals and alkaline earths, especially Ca, accumulate steadily in the leaves (the end of the xylem translocation route) /Greger 2004, Larcher 1995/.

Additional fluxes

There are a number of fluxes that may be considered less important in comparison with the size of the other internal ecosystem fluxes and could therefore be omitted. Studies concerning volatile and leachable components above ground suggest that these components constitute an insignificant loss of the forest NPP /Clark et al. 2001, Persson and Nilsson 2001/. Root exudation is the secretion of soluble organic compounds by roots into the soil. No estimates of root exudates are known at the forest stand level, and this flux is therefore left for further investigation. Ingrowth, which describes the continuous recruitment of new trees, has been disregarded because ingrowth is expected to have a low impact on the biomass and NPP estimations in managed forests. Roots may take up CO_2 in small amounts, but this is considered to be of less importance than the amount that is assimilated through the needles/leaves.

5.1.2 Consumers

The consumers may be divided in at least three functional groups: secondary producers, tertiary producers and humans. Furthermore, the secondary producers are divided into herbivores and mycorrhiza forming fungi. Terrestrial consumers normally consume a relatively small proportion of net primary production (NPP). /Cyr and Pace 1993/ conducted a review of 67 terrestrial ecosystem studies and concluded that the median removal of NPP by herbivores was 18% of the NPP. This flow of matter through individuals in the food web makes potential accumulation of substances incorporated into vegetation plausible. More productive ecosystems support higher levels of absolute consumption by herbivores and therefore maintain higher herbivore densities /Cyr and Pace 1993, Griffin et al. 1998/. This suggests that herbivory is dependent on the size of NPP. In general, the quantification of fluxes in the food web is based on the energy demand (field metabolic ratio) of the specific functional groups calculated from their density and body weight. The ability of functional group to assimilate the energy in their diet is discussed in Section 4.2.

Secondary producers I (herbivores)

Consumers in terrestrial environments, such as herbivores, are often of minor importance with regard to biomass, and their effects on the vegetation may be restricted to certain vegetation types, such as grasslands. Above-ground vertebrate herbivory, such as browsing, is easier to quantify, while invertebrate herbivory and specifically below-ground herbivory may generally be more difficult to estimate. A review of invertebrate herbivory showed that herbivores generally consume less than 10% of NPP in forests, except during insect outbreaks when their consumption can be up to 50% of NPP /Schowalter et al. 1986/. Herbivory by insects on Scots Pine (Pinus sylvestris) was estimated to be 0.7% of the total needle biomass and 2.5% of the total needle production during one year /Larsson and Tenow 1980/, while root consumption by phytophagous nematodes was estimated to be 0.3% of the annual production of fine roots /Magnusson and Sohlenius 1980/. In general, herbivory is excluded from the calculations of NPP, due to its low documented average impact on total NPP in boreal systems.

Secondary producers II (fungi)

Mycorrhiza is a symbiotic relationship between plant roots and fungal hyphae. The plant acquires nutrients, mainly nitrogen and phosphorus, from the mycorrhiza, and in return the fungus obtains carbohydrates, which is the major carbon source for these fungi. Carbon transfer from vegetation through roots to fungi is of significant importance when describing the flow of carbon /Fitter et al. 2000/. There are two main types of mycorrhizas: arbuscular mycorrhizas (AM) and ectomycorrhizas (EM). A third type, the ericoid mycorrhiza, is exclusively formed by plants of the order Ericales. In boreal forests and some temperate forests and in heathland ecosystems, EM associations dominate the root system of most plant species /Fitter et al. 2000, Read 1994/. Some studies indicate that the loss may be significant at the individual level, with up to 30% of NPP drained to the mycorrhizas /Chapin et al. 2002/. The fine roots of forest trees are almost always infected by mycorrhizal fungi /Persson 2002/. Their contribution to the total biomass is low (≈ 1% /Vogt et al. 1982/) and is often included in the quantification of fine root biomass or turnover (but see /Vogt et al. 1982/) because they are attached to the fine roots. Saprophytic fungi, which grow on dead organic material, are considered to be part of the soil community that, together with soil fauna and microbes, drives the heterotrophic soil respiration and are not considered separately.

Tertiary producers (carnivores and insectivores)

This group represents the predators above herbivores in the food web. They include carnivores and insectivores. Carnivores are mainly top predators such as mammals, e.g. lynx, or birds, e.g. sea eagle. Insectivores, which mainly include birds and amphibians, are often themselves part of the diet of carnivores.

Humans

Commercial forestry is the main factor structuring forests in southern Sweden (see Section 4.1). However, the impact of human management on different vegetation types is not conceptualized as such in the model. It will rather determine which vegetation type the model is applied to and how the vegetation type is parameterized.

Humans may utilize a number of resources in the landscape, such as crops, wild game, berries and fungi. Human consumption may either be quantified by estimating current consumption or be estimated as potential consumption, i.e. lingonberry production. The problem with describing actual consumption today is that it may vary over time. For example, utilization of berries and fungi was more intense in the past, whereas an estimate of the potential (maximum) consumption of e.g. lingonberry will set the upper limit on what is possible to consume. Traditionally, humans have created different types of land cover for food production. Land areas for haymaking and browsing were an important resource for supporting livestock. Such areas, including meadows (more or less wet, which were later transferred to arable land) and semi-natural grasslands, are today rare compared with their historical distribution.

5.1.3 Soil

The soil contains macro- and micronutrients, and water, which are important predictors for plant production /Larcher 1995/. Bulk density, hydraulic conductivity and field capacity are predictors for availability and/or presence of these predictors, as well as for elements in general. In boreal and hemiboreal forests the soil contains the largest pool of carbon and nitrogen (e.g. Chapin et al. 2002/). Most of the organic matter produced in the ecosystem enters this pool, where it is decomposed into inorganic nutrients, recalcitrant products and carbon dioxide.

Soil compartments

In a typical boreal forest the soil can be divided into the litter pool, the humus pool and the mineral soil pool. The litter pool, consisting of shed plant parts and fine and coarse woody debris such as standing dead trees and logs, is continuously being renewed due to incoming fluxes from the vegetation and outgoing fluxes in the form of decomposition (CO_2) and formation of less easily degradable fractions accumulated in the humus pool. The litter pool has the shortest turnover time of the three pools. The pool of coarse woody debris, which is a part of the litter pool, has a considerably longer turnover time, but is generally small in most well-managed forests today.

The humus layer, which consists of more or less decomposed organic and recalcitrant matter, constitutes a significant part of the soil organic matter (SOM) in some ecosystem types such as mires. Peat is the most extreme soil type, where little of the organic matter has been mineralized due to the anaerobic environment induced by a near-surface water table. Peat-forming wetlands are carbon sinks and a thick organic layer might be accumulated over time. A measure of the organic matter content of the humus layer is its thickness, and this layer may accumulate considerable amounts of carbon over time /Olsson et al. 2008/. High organic matter contents in the mineral soil layer are often an indication of well-drained nutrient-rich soils. These soil types often have a less distinct boundary between the humus and mineral soil layers. This is partly an effect of increased bioturbation, which is the movement of matter in the soil caused by soil fauna such as earthworms that occurs at great depths in well-drained and well-buffered soils /Persson et al. 2007/.

Most carbon mineralization occurs close to the surface and involves a wide array of different decomposers. They are small and numerous, and constitute a small but active part of the carbon pool in the soil. Saprophytic fungi are important decomposers but are mainly considered in the earlier part of the decomposition stage, e.g. litter, logs and branches. Another fraction of the soil organic matter is transported further down in the soil, either by bioturbation or by water movement (percolation). The dissolved organic carbon (DOC) is transported downward in the soil profile and becomes less mobile in lower soil horizons due to soil sorption processes /Neff and Ashner 2001, Berggren et al. 2003/. This fraction probably contains a substantial fraction of the carbon that is retained over time in woodland soils and is often referred to as the slow decomposing carbon pool, consisting of humins and humic acids /Schlesinger 1997/. Generally, the mineral soil has the largest carbon pool in a boreal forest /Olsson et al. 2008/.

Organic matter with assimilated radionuclides that is turned into litter would quickly be decomposed, creating an excess of radionuclides in comparison with carbon in the humus and upper mineral soil layer. The fate of these radionuclides would depend on the strength of their chemical interaction with the solid phases of the different soil horizons /Tipping 1996/. The resulting leaching or retention of radionuclides in soil can be further described as a function of precipitation, evapotranspiration and sorption in soil /Baes and Sharp 1983/.

Rhizosphere

Root uptake alters the chemical conditions around the roots, the rhizosphere, by reducing nutrient concentrations and by altering the pH due to an excretion of H+. The lowered pH also increases the accumulation of cations (see under section headed "Root uptake of mineral nutrients"). Moreover, carbon enters the rhizosphere both as fine root turnover and as labile carbon exudation from the fine roots. This carbon stimulates the growth of bacteria and can increase nutrient mineralization.

Weathering

Apart from the recirculation of mineral nutrients entering the soil from litter production (see below), mineral nutrients also enter the soil from a continuous weathering of the parent rock or soil material /Chapin et al. 2002, Sohlenius and Hedenström 2007/. This weathering is promoted by warm and wet conditions, but also by biological activity, and is particularly high in the rhizosphere /Chapin et al. 2002/. However, most of the macro- and micronutrients required by plants are supplied by mineralization of organic matter in the soil, but see discussion concerning phosphorus in Section 9.

Litter production

Litter production originates from both above- and below-ground components, where the largest annual inputs are from needles/leaves and fine roots /Chapin et al. 2002/. Below-ground litter production from roots and mycelia mainly enters the humus and the mineral soil layers and is roughly proportional to the root distribution in the soil. Litter production provides the soil compartment with organic material and is roughly proportional to the production of the ecosystem (see Chapter 6). Litter production is also affected by natural disasters, such as storms, which may cause a large increase in litter production, with regard to both more easily decomposed parts such as leaves and branches /Mjöfors et al. 2007/ but also less easily decomposed parts such as stems.

Heterotrophic soil respiration

The flux of carbon (CO_2) from the soil, i.e. soil respiration, can be divided into autotrophic respiration, by roots and mycorrhiza (carbon from autotrophs), and heterotrophic respiration, by microbes and soil fauna. Heterotrophic respiration is decomposition, where organic matter is converted into inorganic nutrients and CO_2. Biomass, with e.g. assimilated radionuclides, that is turned into litter is quickly decomposed and creates an excess of radionuclides in comparison with carbon in the humus and upper mineral soil layer. The fate of this enrichment depends on the strength of the chemical interaction with the solid phases of the different soil horizons (e.g. Tipping 1996). The balance between decomposition and NPP strongly influences the carbon cycle as well as other element cycles at both ecosystem and global scales.

Coarse woody debris is more slowly degraded than leaf and needle litter. The turnover rate of *Picea abies* logs was investigated by /Næsser 1999/ in southeastern Norway. He found that the decomposition of dead wood was significantly affected by cross-sectional diameter, ground contact, soil moisture and aspect. The overall average decomposition rate constant was 0.033 per year with a minimum of 0.017 and a maximum of 0.049 per year. The coarse woody debris pool, with a comparably longer turnover time than the litter pool, is generally small in most well-managed forests today.

In poorly inundated soils, such as wetlands, where oxygen is depleted by aerobic decomposition, methane is a second path of emission of carbon to the atmosphere. However, the magnitude of this emission is small compared with the emission of carbon as CO_2 and constitutes approximately 5 to 15% of the carbon emitted as CO_2 even in such soils. /Chapin et al. 2002/.

Other gases that may leave the soil compartment are NH_3, N_2 or N_xO_x. The NH_3 flux is low in most ecosystems but may be high where NH_4^+ accumulates due to nitrogen input from animals or human management, i.e. grass ecosystems or arable land /Chapin et al. 2002/. Nitrification and denitrification are associated with a loss of nitrogen. The loss during nitrification is more or less proportional to the rate of nitrification, where small amounts of nitrogen are lost as gas. Denitrification is typically high under conditions of low oxygen concentrations, high nitrate concentrations and a supply of organic carbon /Del Grosso et al. 2000/. Generally, the nitrogen loss from these fluxes is low and has a limited effect on the ecosystem pool of nitrogen. These fluxes may, however, be significant in some ecosystems under certain conditions or events, i.e. fires.

Atmospheric deposition

Another source of element input to the ecosystem, and eventually the soil compartment, is atmospheric deposition of e.g. nitrogen and sulphur deposition. Locally, this deposition may be high, due to aeolian deposition of soil, e.g. close to large areas of arable land. This deposition may be further augmented by deposition from sea spray, containing mainly cations such as I, Br, Cl and Na, in regions close to the sea.

Water fluxes

The downward flow of water in the soil profile (infiltration and percolation) results in a leaching of substances and a transport of e.g. humic acids downward in the soil profile. This vertical transfer of materials through soils generates distinctive profiles such as podzols. Soluble ions, originating from mineralization, weathering or atmospheric deposition, move downward. This downward movement of elements continues until the chemical environment causes them to become reactants in chemical processes that form compounds. With regard to DOC, leaching from the humus horizon was quantified at three localities as comprising between 6 and 19% of the total carbon input to the humus layer /Berggren Kleja et al. 2007/, but a major part is decomposed within a short time (e.g./ Cleveland et al. 2004/). The DOC becomes less mobile in lower soil horizons /Neff and Ashner 2001, Berggren et al. 2003/, where non-humic hydrophilic substances that are considered more easily biodegradable dominate the soil organic matter (SOM), while humic substances, also rich in N, are bound in soil sorption processes /Neff and Ashner 2001/. This fraction is probably a substantial part of the carbon that is retained over time in woodland soils. Other substances that are leached consist mainly of silicon, aluminium and iron ions that are bound as hydroxides and oxides in lower soil horizons.

5.2 Interactions with other ecosystems

The most important process for transport among terrestrial and aquatic ecosystems is the process mediated by water flow. Apart from water flow, few processes are available for transport across different terrestrial ecosystems. Wind transports small amounts of particles and deposits them as dry deposition, e.g. soil erosion and sea spray. The water-mediated transport from terrestrial systems to aquatic systems is seasonally highly variable, reaching a maximum in spring and autumn /Tröjbom et al. 2007, 2008/. Although the net transport of elements on a landscape scale is from terrestrial to aquatic systems, the reverse transport may be substantial on a local scale, e.g. deposition of organic material on sea shores.

5.2.1 Transport from terrestrial to aquatic ecosystems

The lateral flow of water (Figure 5-1) is large enough to transport substances. The water originates from precipitation that infiltrates through the surface and reaches the saturated zone and is further transported into streams and lakes. The unsaturated overland flow is assumed to be negligible in quantitative hydrological modelling /Bosson et al. 2008/, but may in extreme cases of downpour generate substantial transport of organic matter. Moreover, transport among terrestrial ecosystems (wetlands excluded) is considered to be of minor importance compared with the actual element fluxes within an ecosystem. However, transport to and from wetlands (here considered a terrestrial system) may be of significance for accumulation of allochtonous matter /Tröjbom et al. 2007, 2008/, where e.g. carbon is mainly transported as DOC but also as particulate organic carbon /Canham et al. 2004, Tröjbom et al. 2007, 2008/. Wetlands have been called the kidneys of the landscape because of their ability to filter and retain nutrients and contaminants /Mitsch and Gosselink 2000/. Similarly, a number of elements are transported from the land to the sea, where several factors – such as cation-anion exchange capacity, microbial mineralization and the amount of water flowing through the soil profile – influence this transport.

5.2.2 Transport from aquatic to terrestrial ecosystems

Transport of elements can occur from aquatic ecosystems to terrestrial ecosystems (mainly wetlands). Floodplains and riparian swamps and marshes are often inundated by rivers, streams or other water bodies and affected by overbank sedimentation. In this manner, elements associated with colloids and particles in the water are transported to the wetlands and retained. These wetlands can therefore function as sinks for nutrients and contaminants /Mitsch et al. 1979, Walling and Bradley 1988, Burrough et al. 1999, Stark et al. 2006/. Similarly, deposition of organic material from the sea, marine residues, may be substantial along shorelines.

Transport of materials and nutrients may also be mediated by biota. /Willson et al. 1998/ described this for the Pacific coastal region of North America, where anadromus fish such as salmon, char, and smelt travel every year from the ocean into freshwater streams to spawn. These fish provide an important resource for terrestrial predators like birds of prey and bears. A large amount of fish is consumed by terrestrial vertebrates and invertebrates, and /Willson et al. 1998/ estimated the potential input of P to the terrestrial ecosystems to be 6.7 kg/ha by this route.

5.3 Disturbances at the ecosystem level

Disturbances on large spatial scales, such as fire, affect the element pools and fluxes in the ecosystem. All above-ground biomass, litter and a major part of the humus layer can be removed in this way. Consequently, a severe fire may convert a large proportion of carbon and nitrogen into carbon dioxide and volatilized nitrogen. This means that the effect of a fire is a release of other elements now available to the next generation of biota or flushed away with the increased runoff, ending up in streams. A less drastic variant of this occurs after a clear-cut /Likens and Borman 1995/, where the effect on the litter and humus pool is less drastic. Most terrestrial ecosystems are affected by fire, although the fire interval may differ substantially, e.g. deciduous stands on south-facing slopes, *"lövbännor"*, moist Norway spruce forests and Norway spruce swamp forest (with decreasing fire interval).

A decreasing fire interval would generally suggest less time for accumulation of organic material, both in regard to biomass and SOM. The fire-adapted Scots pine forest on a shallow soil layer with a high fire frequency and the bog with a low fire frequency would be the two extremes on a continuous scale with regard to the potential release of radionuclides accumulated in organic material.

A heavy storm, where most of the biomass is left as organic material, would potentially prolong the time period for increased decomposition, but would not necessarily lead to an increased transport of elements to the surrounding streams as in the case of a severe fire.

5.4 Concluding remarks

The conceptual model makes it possible to identify pools of contaminants that are of potential interest to the risk assessment. These pools may have the potential of either becoming large and thereby comprising a potential sink for contaminants or becoming available to biota and being further transported up in the food web. Organic matter is accumulated mainly in the vegetation or in the soil. The allocation of organic matter in the vegetation is either to tissue with high turnover, such as leaves, needles or fine roots of which only a fraction is available to larger biota, or to tissue with a longer turnover time, such as woody debris whose turnover today is mainly controlled by humans through commercial forestry. The soil organic matter (SOM) also has pools with different turnover times, but may be accumulated over much longer time periods. The behaviour of both vegetation and SOM pools is typically determined by a number of fluxes, and the relationship between these regulates the size of the pools. Generally, NPP sets the upper limit to the potential input of organic material, whereas decomposition describes the major loss of organic material. By being able to describe these regulating fluxes, it is possible to understand how and under what circumstances pools may act as sinks or sources for organic matter, elements or radionuclides. A quantification of these pools and fluxes will further improve an understanding of accumulation and turnover. Such an understanding will be further enhanced in the following chapters by combining data from field investigations and dynamic modelling from the Forsmark and Laxemar-Simpevarp areas. This will also permit comparisons among alternative ways of describing pools and fluxes on different spatial and temporal scales.

6 Field-estimated pools and fluxes of carbon in various ecosystems

6.1 Introduction

Six ecosystems in Forsmark and Laxemar-Simpevarp were investigated with regard to pools and fluxes of carbon using field estimates. The investigated ecosystems represent vegetation types that have been considered to be important both with respect to area coverage and as potential sinks for organic matter. Accordingly, conifer forests and forested wetlands have been studied both in Forsmark and in Laxemar-Simpevarp. The aim was to quantify pools and fluxes, which will serve both as a way of describing these ecosystems more closely with regard to organic matter from a site-specific perspective, and also as a baseline for comparison with the modelling work presented in Chapter 7 and to compare these site-specific estimates with more general literature data that may be used to describe pools and fluxes in long-term perspectives in the safety analysis.

6.2 Methods and data

The ecosystems are illustrated by the pools and fluxes in Figure 5-1, and a description of these is found in the previous chapter (Chapter 5). In comparison with the previous chapter some fluxes have been omitted, but these changes are explained in the text below. In the following calculations we have omitted all fluxes assigned to consumers (presented in Section 4-2), which are introduced in the landscape scale budgets in Chapter 8. One reason for this is a combination of their mobility and a more coarse-grained resolution of data.

6.2.1 The ecosystems

The investigated ecosystems are presented in Table 6-1 and Figures 6-1a and b, and are further characterized in Table 6-2.

Table 6-1. The six investigated localities in the Forsmark and Laxemar-Simpevarp areas.

Site	Forest type	SKB ID code	Report code	X-coordinate	Y-coordinate
Forsmark	Norway spruce	AFM001247	B2a	6698733	1633420
	Norway spruce	AFM001068	FG1	6698152	1633558
	Alder swamp forest	AFM001076	SS1	6698060	1633495
Laxemar-Simpevarp	Oak forest	ASM001426	L1	6367828	1552003
	Norway spruce	ASM001440	G1	6369225	1547128
	Alder shore forest	ASM001434	S1	6367881	1551023

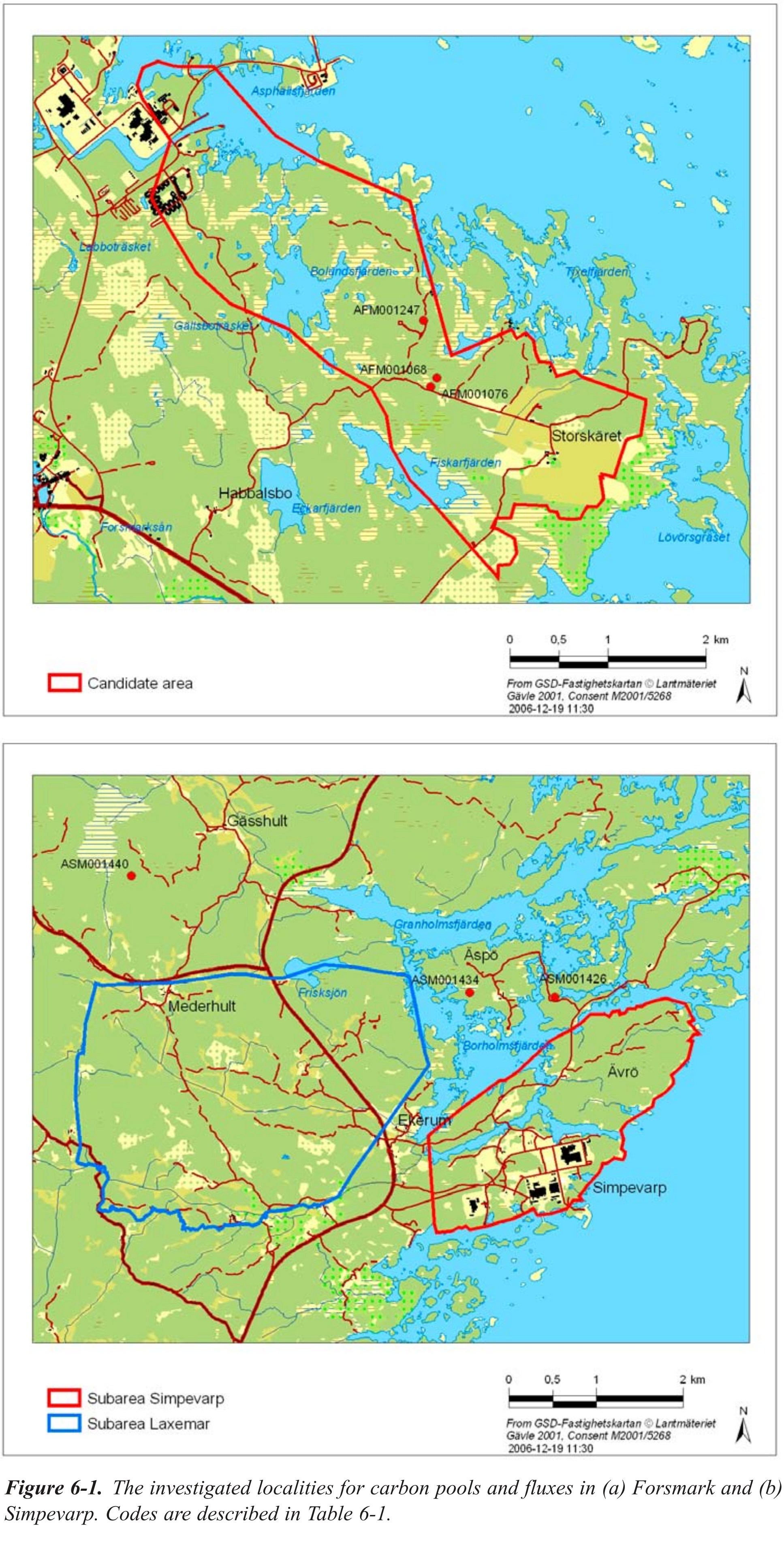


Figure 6-1. *The investigated localities for carbon pools and fluxes in (a) Forsmark and (b) Laxemar-Simpevarp. Codes are described in Table 6-1.*

Table 6-2. Characteristics of the investigated localities in the Forsmark and Laxemar-Simpevarp areas (see Table 6-1 and pictures in Appendix 8). Soil pH was measured dissolved in water and H is humus, whereas M is mineral soil. *The dominant height at 100 years indicates the productivity of the locality and is estimated according to /Hägglund 1973/, where G means Norway spruce and EK is oak, which would be the dominating tree at 100 years.

Properties	**Forsmark localities**			**Laxemar-Simpevarp localities**		
Report code	**B2a**	**FG1**	**SS1**	**L1**	**G1**	**S1**
Soil moisture class^1	Fresh	Fresh/moist	Moist	Fresh	Fresh	Moist
Soil pH (H_2O), H 0–0.3m^1	–	6.7	6.7	–	3.9	5.3
Soil pH (H_2O), M 0–0.1m^1	7.0*	7.2	7.1	5.3	–	–
Soil pH (H_2O), M 0.1–0.2m^1	7.0*	7.4	7.4	4.9	–	–
Soil pH (H_2O), M 0.55–0.65m^1	7.6*	7.9	7.7	5.2	–	–
Soil type^1	Leptosol	Regosol/Gleysol	Gleysol	Histosol/Gleysol	Histosol	Histosol
Stone/boulder volumetric content in M 0–30 (%)^1	62*	50	66	57	0	0
Number of trees/ha^2	1,340	780	3,340	200	400	1,600
Basal area (m^2/ha)^2 *Picea abies, Betula pendula, Alnus glutinosa, Pinus sylvestris, Quercus robur.*	22.5 (P. a.)	20.5 (P. a.), 6.5 (B. p.)	5.3 (B. p.), 7.33 (P.a.), 3.0 (A. g.), 2.3 (P. s.)	15.0 (Q. r.)	15.5 (P. a.)	17.5 (A. g.)
Tree age (2–3 trees)^2	69–70	90–98	97–108	107–136	57–67	44–55
Tree height (m)^2	16.3	19.8	18.1	17.1	21.0	11.6
Dominant height at 100 years /Hägglund 1973/.*	G 20	G 20	(G 18)	EK 18	G 28	–
Diameter at breast height (dbh in m)^2	0.21	0.26 (P. a.)	0.31 (P. a., n=5)	0.36	0.32	0.14
Veg. Types /Påhlsson 1998/	Coniferous, Calluna-Empetrum-type	Coniferous fern type	Alnus swamp herb type	Herb rich oak forest	Coniferous Vaccinium myrtillus type	Alnus shore forest type
Field-layer species^1	Low herbs without shrubs	Tall herbs without shrubs	Low herbs without shrubs	Broad leaved grass type	Bilberry type	Broad leaved grass type
Bottom-layer species^1	Mesic mosses type	Mesic mosses type	Mesic mosses type	Mesic mosses type	Mesic mosses type	–

*Measured 100 m from the locality 1) /Lundin et al. 2004, 2005a/ 2) /Tagesson 2006a/.

6.2.2 Estimation of pools and fluxes

A large number of different data sources have been used to put together the ecosystem descriptions. Generally, the aim was to use site-specific data whenever possible, but in some cases such data were lacking and regional or literature data were used instead.

Tree layer

Biomass

Tree layer data for the different localities were derived from tree height and breast height diameter measured for ten representative trees at each locality /Tagesson 2006a/. For conifer trees (*Picea abies* and *Pinus sylvestris*) and birch (*Betula* sp.), Marklund's equations were used to calculate fractions of green tissue, stem and living branches /Marklund 1988/. For alder (*Alnus glutinosa*), the equations presented in /Johansson 2000/ were used. The stump, coarse roots and fine roots down to Ø 5 mm and between 5 mm and 2 mm were calculated using functions presented in /Petersson and Ståhl 2006/, where birch root functions were also used for alder. Fine root biomass estimates for diameters < 2 mm were available for each locality /Persson and Stadenberg 2007a/ (see Section 4.1.3). These estimates were not corrected for stone and boulder content at the localities /Persson and Stadenberg 2007a/. Deciduous leaf biomass was estimated using a function derived from *Betula lenta* /Martin et al. 1998/. For oak (*Quercus robur*), equations presented in /Balboa 2005/ were used to describe the oak's above- and below-ground biomass. It was, however, unclear whether fine root biomass were included in derivation of the equations by /Balboa 2005/, and the field estimates of fine root biomass for roots with a diameter less than 2 mm were added to the calculated estimates.

Mean biomass and standard deviation were estimated for each tree compartment (Figure 5-1) using the sample trees. These derived average tree estimates were adjusted to the stand level of the locality by dividing by the average tree cross-sectional area (m^2) and multiplying by the average basal area ($m^2 \cdot ha^{-1}$), resulting in a basal-area-weighted mean and standard deviation /Tagesson 2006a/.

Net primary production

NPP is defined here as the sum of all materials that have been produced and are retained by live plants at the end of the interval and the amount of organic matter that was both produced and lost by the plants during the same interval /Clark et al. 2001/. The calculation of total NPP therefore includes estimates of biomass increment and biomass loss. Above-ground litterfall was estimated at five localities during two consecutive years /Mjöfors et al. 2007/. Litterfall at the sixth locality, the alder forest S1, was estimated from the average stand leaf biomass and by adding the branch and reproductive tissue fall from the mean fraction of leaf fall from three stands presented in /Raulo and Hokkanen 1989/. Fine root production and turnover were estimated at one locality, the Norway spruce stand FG1 in Forsmark, see Section 4.1.3 /Persson and Stadenberg 2007b/. They estimated the turnover for fine roots (diameter fractions less than 1 mm), which represent the fraction with the highest turnover /Persson and Stadenberg 2007b/, to be 0.6–0.7 y^{-1}. This estimate is regarded as conservative, due to the fact that only significant changes between four sampling occasions were used. They were not able to quantify a statistically significant turnover for larger diameter fractions (2 mm < Ø < 10 mm) /Persson and Stadenberg 2007b/.

A review of literature data from various forest stands, obtained by sequential coring, suggests annual turnover rates of 1–2 times the average fine root biomass. The mean for root diameters < 1 mm was 1.0 (min=0.1, excluded from the mean, and max=1.7) and the mean for root diameters < 2 mm was 1.5 (min=1.0 and max=2.4) /Persson and Stadenberg 2007b/). In the calculations, we assume that the fine root production at all six localities is 1.0 the biomass for the fraction < 2 mm. Turnover of larger root fractions was neglected, but by using a somewhat higher turnover rate than the estimated one this should partly be compensated for. Net stem increment was not measured at the localities, but was obtained from the Swedish National Forest Inventory database (http://www-riksskogstaxeringen.slu.se/) for a regional area around the sites (SKB GIS database delivery id C169). Stem increment data were extracted using a number of selection criteria fitted to each locality (Table 6-3), which resulted in a number of similar NFI sampling plots with estimated net stem increment. This increment was converted to dry matter per unit area using Table 6-4. Stem increment from each plot was the mean of five years, and a span of 6 to 16 plots was used to estimate the statistics for stem increment for each locality. The increment in branch and coarse root biomass was estimated using data from /Berggren et al. 2004/, where the mean ratio between branch/stem and root/stem increment was calculated from 18 plots. This ratio was applied to the stem increment estimates of the localities. The increment of leaf/needle and fine root biomass were assumed to be zero.

Table 6-3. Selection criteria that were used to extract data for stem increment for each of the six localities from data obtained from the Swedish National Forest Inventory database covering Forsmark and Laxemar-Simpevarp (SKB GIS database delivery id C169). Age (year) is based on tree rings at breast height.

Locality	Selection criteria	N	Year
B2a	age (60 < x < 80), mean height (140 < x < 180) and spruce proportion (0.6 < x)	9	1985–1993
FG1	age (85 < x < 105), mean height (180 < x < 220) and spruce proportion (0.5 < x < 0.9).	11	1985–2001
SS1	age (> 74 OCH < 130), mean height (> = 160 OCH < = 200) and "Wet -92|Moist 93-" (in Sw. "Blöt -92|Fuktig 93-").	9	1993–2005
L1	age (100 < x) and oak proportion (0.6 < x).	9	1985–2005
S1	age (39 < x), pine proportion (x=0) and "Wet -92|Moist 93-" (in Sw. "Blöt -92|Fuktig 93-").	6	1993–2005
G1	age (44 < x < 76), mean height (180 < x < 230) and spruce proportion (0.6 < x)	16	1983–2001

Table 6-4. Overview of studies providing data to this study.

Functional unit	Property	Part	Area (m²)	Time (y)	Year of data set	Reference
Tree layer	Biomass	Above-ground	400	1	2005	Partly in /Tagesson 2006a/
		Coarse root	400	1	2005	Partly in /Tagesson 2006a/
		Fine root < 2 mm	120	1	2004	/Persson and Stadenberg 2007a/
	NPP	Wood [1)]	150–300	5	1985–2005	Swedish National Forest Inventory database [2)]
	Litterfall		150	2	2004–2006	/Mjöfors et al. 2007/
	Root litter production < 2 mm		120	1	2004–2005	/Persson and Stadenberg 2007b/
Field and bottom layer	Biomass/NPP		120	1	2004	/Löfgren 2005/
Fungus mycelia	Biomass/NPP		120	1	2004	/Persson and Stadenberg 2007a/
SOM	Litter		120	1	2004	/Löfgren 2005/
	Humus/soil		225	1	2003–2004	/Lundin et al. 2004, 2005a/
	Woody debris		Tree stand	1	2004–2005	/Andersson 2004b, 2005/
Heterotrophic resp.			900	1	2004–2006	/Tagesson 2006b, 2007/

1) Not measured at the locality, but averaged for several similar localities.

2) SKB GIS database delivery id C169.

Field and bottom layers

The above-ground (AG) biomass for the field and bottom layers was investigated by collecting and measuring the biomass at the time of peak biomass. NPP for the field layer was estimated by assuming that all biomass, except perennial tissue, was produced during the year of the investigation. NPP for the bottom layer was estimated by measuring bryophyte shoot elongation at five plots on each locality in 2004 (bryophytes dominated the bottom layer) /Löfgren 2005/. AG biomass for the sixth locality, B2a, was estimated using a regression equation between AG and below-ground (BG) biomass (see below) for the other 5 localities (Spearman $r = 0.90$, $n = 5$, $p = 0.037$) and applying that equation to B2a using the BG biomass (below) as a predictor for the AG biomass. The standard deviation was calculated using the mean Coefficient of Variation for the five localities.

BG biomass of fine roots was estimated by /Persson and Stadenberg 2007a/ who distinguished between tree and field layer roots in their estimates. The same location of plots was used as in the study of the field layer, making it possible to directly relate measured above- and below-ground biomasses of the field layer.

Field layer litter production was assumed to be equal to the AG NPP plus the BG fine root fraction (Ø < 2 mm) that was assumed to be replaced during the year, and the bottom layer production. Consequently, it was assumed that the field and bottom layers had a negligible annual biomass accumulation in the six localities.

EM fungi

Estimates of biomass and NPP for ectomycorrhizal (EM) mycelia were based on a study by /Wallander et al. 2004/ in a Norway spruce forest in southern Sweden. The results of /Wallander et al. 2004/ suggested that the mean mycelia biomass was 53% of the total fine root biomass (mycorrhizal sheath excluded, here included in the fine root biomass) and the NPP was 8% of the fine root biomass. Their production estimate, mycelia growth into sand-filled mesh bags, was adjusted according to /Hendricks et al. 2006/ by multiplying the mycelia production in sand by three to adjust to mycelia production in soil. Turnover of mycelia was assumed to approximate the biomass/NPP ratio, indicating a steady state of mycelia biomass between years, and resulted in a turnover time of approximately 2 years. EM mycelia estimates were assigned to all six localities using the tree fine-root biomass, although the underlying investigation of mycelia may not be considered to represent the wetter sites such as the alder swamp forest and the alder shore forests.

Woody debris and litter

Coarse woody debris, such as standing and fallen logs, was quantified in volume by /Andersson 2004b, 2005/ in all vegetation types with a tree layer according to the vegetation map of both sites. Litter layer thickness was investigated in five out of six localities /Löfgren 2005/. It was therefore possible to obtain specific measurements for five of the localities. The sixth locality, B2a, was assigned the same value as FG1 due to their similarities.

Soil Organic Carbon (SOC) pool

The soil organic carbon (SOC) pool was estimated for each locality, making a total of eight lateral transects of one humus and three mineral soil samples down to approximately one metre below the surface in each replicate, using the same methodology as the National Forest Soil Inventory /Lundin et al. 2004, 2005a/. Soil microbes were not accounted for separately, but were included in the total carbon content of the soil. However, some generic data describing biomass for soil fauna are presented in Table 4-45.

C-mineralization

Soil respiration was measured during one year in 2004/2005 or 2005/2006 for Laxemar-Simpevarp and 2005/2006 for Forsmark in the different vegetation types, using a closed chamber technique, along with measurements of soil temperature and soil moisture (further described in Section 4.2.4) /Tagesson 2006b, 2007/. The annual soil respiration was estimated for each vegetation type using a regression between soil temperature and the measured soil respiration (Table 4-46). /Högberg et al. 2001/ presented data from a boreal forest (Pinus sylvestris) in northern Sweden, suggesting that the contribution of root-mycorrhizal respiration was between 52–56% of total soil respiration. They also showed that this relationship seemed to be fairly stable during the measurement period. Accordingly, 50% of the measured mean annual soil respiration was considered to be caused by C-mineralization across the vegetation types.

Omitted fluxes

Some fluxes have been omitted due to their low contribution to the overall budget. Studies of volatile and soluble components above ground suggest that these components constitute an insignificant loss of the forest NPP /Clark et al. 2001, Persson and Nilsson 2001/. No estimates of root exudates are known at the forest stand level, and this flux is therefore left for further investigations.

Ecosystem emergent properties

Changes in the total carbon stock of a forest stand, net ecosystem exchange (NEE), can be estimated by adding together the changes of the carbon stock in vegetation and soil. The change in carbon stock in the vegetation was calculated by adding biomass increase and litter production in the tree, field and bottom layers during a year. The change in the carbon stock in the soil was calculated as the difference between litter production (above- and below-ground) and heterotrophic respiration. It is assumed that import and export of carbon (e.g. dissolved organic carbon) is negligible (see Sections 5.2 and Table 8-7, 8-8).

The spatial and temporal extent of the different estimates

The site measurements were only conducted during a limited time period, in most cases one year. The calculated variation (standard deviation) therefore only represents the spatial variation during a particular year. For the estimate of the above-ground litterfall that covered two years, a mean of the standard deviation was calculated to represent the mean spatial variation within a year. The exception is the mean of the stem increment, which is based on the mean increment for five years from each locality. These localities were sampled in different years (Table 6-3). The spatial scale on which the measurements have been conducted is between 100 m^2 and 900 m^2 (Table 6-4).

Carbon concentrations and transformation factors

Carbon concentrations for different plant species and functional parts of species, i.e. wood and green tissue, were estimated in four studies. Three of these were conducted in Forsmark covering the field layer /Fridriksson and Öhr 2003/, fungal mycelia /Johanson et al. 2004, 44%/ and a more extensive study covering three vegetation types and a number of mammals /Hannu and Karlsson/. One was conducted in the Laxemar-Simpevarp area and was similar to the more extensive study conducted in Forsmark /Engdahl et al. 2006/. The results from /Hannu and Karlsson 2006/ and /Engdahl et al. 2006/ are presented in Table 6-5, which shows the results of merged data from both sites. Generally, woody compartments have a lower carbon content than leaves/needles and fine roots /Scarascia-Mugnozza et al. 2000, Skogsstyrelsen 2000/ (see Table 6-6). This was not found when using data from Table 6-6, probably due to the small sample sizes. However, in the calculations woody compartments were assigned a carbon content of 0.48 while green and fine root compartments were assigned a carbon content of 0.50 of the dry weight.

The average carbon content of fresh needle litter, obtained by gently shaking a number of branches at each locality, was 46.8% for the five different localities. This relative carbon content remained stable during two years of decomposition in litter bags on the ground /Mjöfors et al. 2007/. This figure was also in close agreement with the figure measured at one locality in Forsmark by /Fridriksson and Öhr 2003/ Table 6-7. Consequently, this figure was used to describe the carbon content of the litter pool and of woody debris.

Coarse woody debris volume was converted to dry weight using data from /Benediktsson et al. 2005/ (Table 6-8). Conversion of dry weight to carbon for decaying wood is dependent on the decay stage of the wood. Here the same conversion factor as for litter is used for the carbon concentration in the dead wood.

Table 6-5. Measured carbon concentrations (% of dry weight) from the Forsmark and Laxemar-Simpevarp areas sorted according to tree species and type of layer /Engdahl et al. 2006, Hannu and Karlsson 2006/.

Species/groups		mean	median	sd	N
Norway spruce	Green	52	53	2	4
	Wood	48	52	7	4
	root	55	57	7	10
Oak	Green	52	52	1	2
	Wood	41			1
	root	48	50	4	3
Alder	Green	49			1
	Wood	45			1
	root	44			2
Field layer	Green	46	46	0	7
Shrub layer	Green	53	51	5	5
Bottom layer	Bryophyte	50	49	3	7

Table 6-6. Carbon concentrations (% of dry weight) in some common tree species /Skogsstyrelsen 2000/. Carbon concentrations in roots are from /Alriksson and Eriksson 1998/.

Tree species	Stem	Branch	Needles	Root
Picea abies	48	59	49	48
Pinus sylvestris	49	51	51	48
Betula pendula	48	59	49	48
Other deciduous trees	49	49	49	*48

*Same value as *Betula pendula*.

Table 6-7. Mean carbon concentrations (% of dry weight) in plant materials in a Scots pine forest in Forsmark /Fridriksson and Öhr 2003/.

Component	N	Mean (SE), %
Field layer, green components	6	46.1 (0.2)
Field layer, brown components	6	45.7 (0.4)
Ground layer (Bryophytes)	6	43.9 (0.5)
Litter	6	46.2 (0.2)

Table 6-8. Biomass expansion factors for conversion from volume (m^3) to biomass (tonnes of dry matter /Benediktsson et al. 2005/). Stem biomass refers to stem and bark biomass above stump height. One m^3 of stem wood corresponds to the value in column 2 as tonnes of dry matter.

Species	Density
Pinus sylvestris	0.41
Picea abies	0.41
Broad-leaved	0.50
All trees	0.42
Dead trees	0.43

6.3 Results and discussion

The components of the ecosystem carbon model for the six localities are presented in Table 6-9.

6.3.1 The ecosystems

The pools and fluxes within the different ecosystems are discussed below.

The Norway spruce forest (B2a and FG1) in Forsmark

The younger stand (B2a) had a lower NPP than the older stand (FG1) but accumulation in biomass was higher, which means that the higher NPP is offset by higher litter production in the older stand. The denser young stand had much less biomass in the field layer than the older forest. The SOC pool was much smaller in the younger forest, which is largely attributable to a shallow soil layer with a high boulder frequency. Heterotrophic respiration was estimated to be 36% higher in the older stand, which also had a 37% higher litter production (47% and 52%, respectively, for G1 below). Both stands had a net change of the SOC pool that is close to zero.

The alder swamp forest in Forsmark (SS1)

The alder swamp stand in Forsmark had a higher carbon content in the humus layer compared with the two other stands in Forsmark. On the other hand, it had a low carbon content in the mineral soil, where it also had the highest stone/boulder content of all of the investigated localities. This locality had the highest allocation of organic matter to the soil, which should be expected due to the periodically water-logged conditions. The lack of peaty soil, the high input of litter during the measured years and low heterotrophic respiration suggest that this area may have a relatively short history of being a water-logged area and/or have large variation between years with regard to soil moisture, which is expected to limit heterotrophic respiration in this vegetation type.

Table 6-9. Mean carbon pools (±sd) for different components in the six investigated ecosystems at Forsmark and Laxemar-Simpevarp. The soil carbon pool is restricted to a depth of approximately 1 metre, except for B2a where there was only a shallow mineral layer on top of rock. The EM mycelia estimates are not included in the calculations of ecosystem emergent properties at the end of the table. Pools are in gC m^{-2} and fluxes are in gC m^{-2} y^{-1}.

			Forsmark			**Laxemar-Simpevarp**		
Functional groups and properties			**B2a**	**FG1**	**SS1**	**L1**	**S1**	**G1**
Tree layer	Biomass	Needles/leaves	677±263	593±453	326±305	233±87	97±56	421±116
		Wood	6,577±2,051	9,074±3,716	5,411±2,120	5,372±1,956	6,035±4,116	5,024±606
		Fine root < 2 mm	183±76	205±104	166±108	90±46	41±42	250±88
	Net acc	Branches	26±4	23±10	20±9	30±12	25±13	40±23
		Stems	114±19	99±41	88±41	129±52	107±57	172±100
		Coarse roots	29±5	25±10	22±10	32±13	27±14	43±25
	Litterfall		64±26	91±19	108±32	136±33	115±42	184±65
	Root litter production < 2 mm		183±76	205±104	166±108	90±49	41±42	250±88
Field and bottom layers	Biomass	Leaves	8±6	20±12	3±3	45±12	15±14	4±4
		Bryophytes	38±16	38±16	43±47	26±27	–	62±47
		Roots < 10 mm	29±35	98±115	22±47	137±121	38±53	9±26
	Litter prod. 1)		39±29	94±50	25±22	175±102	46±46	47±23
EM	Biomass		62	74	55	32	12	87
mycelia	Litter prod. 2)		28	33	25	14	5	39
SOC	Litter pool		544±228	544±228	383±130	294±79	507±116	746±507
	Humus		1,660	1,620	2,440	–	30,960 3)	59,700 3)
	Mineral soil		530	5,330	1,720	6,260	–	–
Heterotrophic respiration			290±125	395±620	225±190	590±490	365±310	425±400
Total	NPP		454±87	537±124	429±122	591±129	360±102	736±154
	Litter prod.		285±85	390±117	299±114	401±126	202±83	480±112
	Acc. soil		–5±151	–5±631	74±222	–189±506	–163±321	55±415
	Acc. veg		169±20	147±44	130±93	190±55	158±60	255±106
	NEP		164±153	142±632	204±226	1±507	–5±326	311±415

1) Includes field layer above-ground and below-ground, and bottom layer NPP.
2) Not included in properties under Total.
3) Peat soil.

The alder shore forest in Laxemar-Simpevarp (S1)

The alder shore forest is situated on histosol and is periodically water-inundated. It would therefore be expected to be a sink for carbon, contrary to the result. A low leaf biomass in comparison to the other localities is in agreement with a lower, independently sampled root biomass. /Raulo and Hokkanen 1989/ presented litterfall data for three alder stands in the interval 89–145 gC m^{-2} y^{-1}, which accords well with the estimate in Table 6-9. In comparison, the CoupModel arrived at a higher estimate of NPP and a much lower estimate of heterotrophic soil respiration (Table 6-10, see Section 4-3 for a presentation of this model). This locality is situated in a depression in close connection with a sea bay, and the water table in this forest is probably highly variable due to the surrounding hydrology as well as water level fluctuations in the sea. This suggests that soil respiration may fluctuate strongly, and thereby its potential of being a carbon sink or source. /Kutsch et al. 2001/ found unexpectedly high soil respiration in an alder stand during a period with a low water table. The net result during a somewhat longer time period should in any case be that the alder seashore is a sink for carbon until hydrological conditions cease being the main restrictor for heterotrophic respiration.

Table 6-10. The CoupModel was used to model two of the localities in Laxemar-Simpevarp, the alder shore forest and the Norway spruce forest (Fig 4-27b, d /Karlberg et al. 2006/). Input data from the localities were soil properties, soil carbon and nitrogen content. A negative sign indicates net emission. Fluxes in gC m^{-2} y^{-1}.

Property	Alder shore forest (S1)	Norway spruce forest (G1)
NPP tree layer	350	690
NPP field layer	180	160
NPP total	530	850
Heterotrophic soil respiration	300	930
Litter production	440	540
Net ecosystem exchange	230	–80

The oak forest (L1) in Laxemar-Simpevarp

The litterfall was estimated to be much less than the leaf biomass, which can partly be explained by the fact that broad-leaved trees become approximately 22% lighter in connection with senescence in the autumn /Viro 1955/. (This is, however, not applicable to alder). Another contributing factor to the missing leaves is that this locality is situated close to the sea, fairly exposed to wind, and might therefore export carbon as leaves to the sea during the stormy autumns. Another explanation could be that the biomass expansion factors for oak (from Spain by /Balboa 2005/) underestimate the leaf biomass under Nordic conditions in a fairly open habitat.

The SOC pool almost completely lacked a humus layer, although it had the second highest litter production of the six localities. This indicates high bioturbation, which was confirmed by /Persson et al. 2007/. This locality also had high soil respiration, which was greater than litter production, making the soil a large source of carbon. This could be explained by an underestimation of the autotrophic part of the soil respiration in this old stand, which can be much higher than the 50% assumed here. If heterotrophic respiration were to approximate litter production, heterotrophic respiration would constitute 34% of the total soil respiration. /Bolstad et al. 2004/ also found high soil respiration values for a deciduous tree stand (between 820 and 1,210 gC m^{-2} y^{-1}) in Northern Wisconsin, USA. The oak stand had the lowest tree density (Table 6-2) and consequently a large biomass in the field layer. This locality has a history as semi-natural grassland with large sparsely distributed oaks. From this perspective this locality is somewhat different from the other localities.

The Norway spruce forest in Laxemar-Simpevarp (G1)

During the measurements of litterfall in the Laxemar-Simpevarp area, this region was hit by the storm "Gudrun" in January 2005, which caused a somewhat higher litterfall for G1 during that year /Mjöfors et al. 2007/. The reason that G1 was more heavily affected than the oak locality was because "Gudrun" hit the region during the winter when the oaks were already defoliated. If the difference between the two years is adjusted using the average difference between year 1 and 2 from the three Forsmark localities /Mjöfors et al. 2007/, litterfall can be reduced by 48 gC m^{-2} y^{-1}. This would mean a somewhat reduced NPP and net accumulation in the soil that would be close to zero and similar to the other Norway spruce localities n Forsmark. The soil respiration measurements stopped in March 2005 and the increased litter production during January was probably not captured by the soil respiration measurements.

The NPP in the Norway spruce forest was high (689 gC m^{-2} y^{-1}), which was in accordance with the CoupModel estimate of the tree NPP for the same locality, Table 6-10 /Karlberg et al. 2006/. This is probably an effect of being a fairly young stand planted on drained peat soil. NPP in the field layer was however, greatly overestimated by the CoupModel. The estimated heterotrophic soil respiration was also of a similar magnitude, 850 gC m^{-2} y^{-1} and 930 gC m^{-2} y^{-1}, respectively, where the CoupModel estimated the heterotrophic respiration to be 45% of the soil respiration due to the high carbon content of the soil. The CoupModel was also able to show a net decrease in soil carbon, which would be expected as peat oxidizes under the aerobic conditions created after drainage (Table 6-10).

6.3.2 Ecosystem compartments and processes

This section compares and discusses pools and fluxes across the different ecosystems.

Tree layer

The tree layer carbon pool was sometimes larger than or similar in size to the SOC pool (see below). The tree layer contributed most to the ecosystem NPP and the tree trunks contained most of the carbon. Root turnover was only investigated at one locality, the Norway spruce forest (FG1), and this study was only able to detect a significant turnover of 0.7 y^{-1} of the fraction Ø < 1 mm. This is similar to what was presented by /Berggren Kleja et al. 2007/ for 40-year old Norway spruce stands (0.5–1). In this study, however, the turnover was adjusted to 1.0 y^{-1} and applied to < 2 mm. This was done in order to include litter production from the larger diameter fractions. No studies have been able to estimate this fraction of the litter production, and the assumption of a turnover of 1.0 y^{-1} might lead to an overestimation of the actual root litter production.

Field and bottom layers

The field and bottom layers were small in comparison with other carbon pools, but they were important with regard to NPP and contributed between 6% and 29% of the total NPP (Table 6-10). These layers generally have a low ability to accumulate large carbon pools but have high production, and it is mainly the field layer that is available for browsing animals and humans (e.g. berry picking). The distribution of field layer roots is somewhat shallower than the tree root distribution and is mainly confined to the humus layer /Persson and Stadenberg 2007a/.

Ectomycorrhizal fungi

EM mycelia have not been included in the calculation of NPP, and they have so far been excluded in similar attempts to make carbon budgets, e.g. /Berggren Kleja et al. 2007, Schulze 2000/. If it is assumed that secondary mycelial production requires photosynthates for production in a proportion similar to that for green plants (NPP approximately 50% of GPP), the corresponding GPP by the fungi (twice the secondary production) would constitute between 3 and 12% of the total ecosystem NPP. This fraction is commonly assumed to be a part of the vegetation GPP, or more specifically, the part of the soil respiration attributed to autotrophic and mycorrhizal respiration. Although few results are available, there is much to suggest that this carbon sink has generally been underestimated in other studies describing ecosystem budgets of carbon fluxes in forests or other ecosystems inhabited by mycorrhizal communities.

SOC

Swedish forests on Podzols under dry to slightly moist conditions have a mean SOC pool of 8,200 gC m^{-2} including the organic horizon (2,800 gC m^{-2}) and 0–0.5 m of the mineral soil /Olsson et al. 2008/. Similar figures were presented for two localities with Norway spruce forests with different soil moisture conditions, Knottåsen (organic horizon 1,270 gC m^{-2} and mineral soil 5,230 gC m^{-2}) and Asa (2,340 gC m^{-2} and 8,820 gC m^{-2}), at similar latitudes as Forsmark and Laxemar-Simpevarp, respectively /Berggren Kleja et al. 2007/. The localities were, however, located inland. The four localities lacking peat soils are all below the average for Sweden, which seems reasonable with regard to the fairly young soils at both sites /Hedenström and Sohlenius 2008, Sohlenius and Hedenström 2008/. Peatlands in Sweden have an average carbon content of 260,000 g m^{-2} /Olsson 2000a/. This value is higher than the values for the Norway spruce forest on drained peat soil and the alder shore forest located on peat soil in our study, and is probably more applicable to Sphagnum peat mires and bogs. Again, the accumulated peaty soils at the site are also expected to contain a smaller carbon pool than the average for Sweden due to the limited time for peat accumulation.

The flux of organic matter is highest to the humus pool (litterfall and fine root litter to the humus layer), whereas the largest carbon pool is generally found in the mineral soil /Olsson et al. 2008/. Estimates by /Bergren Kleja et al. 2007/ suggest that DOC originating from the humus layer and root litter in the mineral soil are of equal importance for the build-up of organic carbon in the mineral soil layer.

Heterotrophic respiration

The soil respiration fluxes for the oak forest and the Norway spruce forest in Laxemar-Simpevarp are large but not exceptional (see discussion in /Tagesson 2006b/). The high soil respiration in the Norway spruce forest is, however, caused by the underlying peaty soil, which is a remnant of an earlier drained peatland. Drainage and the growing forest have changed the conditions, leading to increased decomposition of the peat. A potential source of error is the generalization of how to divide soil respiration into heterotrophic respiration and root respiration. Estimates of the contribution of root respiration to total soil respiration vary from 10% to 90% /Hanson et al. 2000/. Here, the estimate of the heterotrophic fraction was based on a study by /Högberg et al. 2001/ of a boreal forest (*Pinus sylvestris*) in northern Sweden. They suggested that the contribution of root and mycorrhizal respiration to total soil respiration was 52–56%. For several reasons, this was also considered to be a conservative estimate. Accordingly, decomposition may be slightly overestimated in some localities but may also be underestimated in others, i.e. it is reasonable to assume that the heterotrophic component is underestimated in the Norway spruce forest standing on drained peatland, which would thereby constitute a source of carbon instead of a sink as shown in Table 6-9. This was confirmed in a simulation of the specific locality using the CoupModel, Table 6-10, /Karlberg et al. 2006/. Soil respiration is also discussed elsewhere (Section 4-3; /Tagesson 2006b, 2007, Tagesson and Lindroth 2007/), but the general conclusion is that the estimates are in good agreement with other studies in similar areas.

Ecosystem fluxes

/Högberg et al. 2001/ showed that the flux of photosynthates has a large impact on soil respiration, and Figure 6-2 shows a positive correlation between the independently estimated fluxes of ecosystem NPP and soil respiration.

NPP was estimated to be between 360 and 736 gC m^{-2} y^{-1} for the different forest types at the two sites, where the alder shore forest in the Laxemar-Simpevarp area had the lowest NPP and the Norway spruce forest on drained organic soils in the Laxemar-Simpevarp area had the highest NPP. This is within the estimates presented by /Gower et al. 2001/ for boreal ecosystems (52–868 C m^{-2} y^{-1}, mean 424 C m^{-2} y^{-1}). All sites seem to have been carbon sinks during the measurement period (142–311 C m^{-2} y^{-1}) except for the oak forest and the alder shore forest, which were close to zero. /Lindroth et al. 2007/ presented estimates of eddy flux measurements in Norway spruce stands in northern Sweden for two consecutive years that were validated by field estimates (107 and 98–108, respectively /Berggren Kleja et al. 2007/). At a site in south-western Sweden, NEP was estimated to be 350 gC m^{-2} y^{-1} (160 gC m^{-2} y^{-1} accumulated in the SOC pool and 190 gC m^{-2} y^{-1} accumulated in the vegetation) in a 30-year-old Norway spruce forest /Persson and Nilsson 2001/.

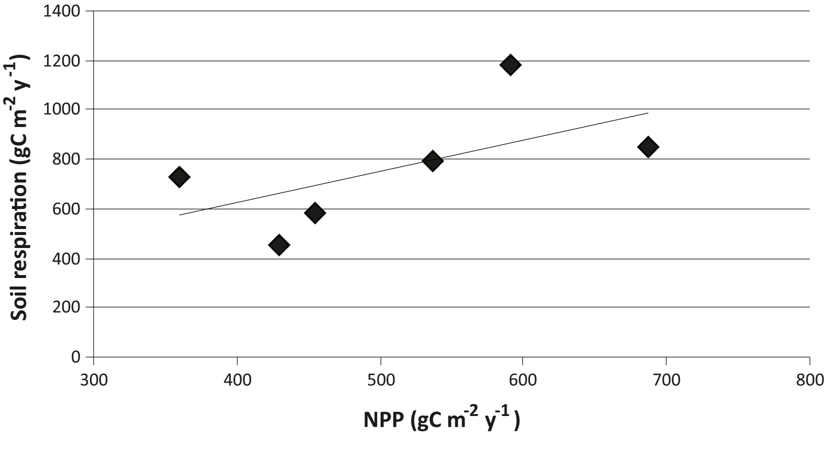


Figure 6-2. Soil respiration plotted against total NPP for the six localities. The NPP for locality G1 was adjusted by subtracting extra litter input due to a storm, see discussion above (Spearman r=0.77, p=0.07).

/Pregitzer and Euskirchen 2004/ presented a range of –360 to 260 gC m^{-2} y^{1} for five boreal coniferous forests. The CoupModel estimated the NEP to be 82 and 84 gC m^{-2} y^{-1} for an old conifer forest in the Forsmark and the Laxemar-Simpevarp regions, respectively /Gustafsson et al. 2006/. The field estimates therefore seem to be in agreement with other investigations, based both on field estimates and model simulations.

6.3.3 Confidence and uncertainties

Variation in estimates

The standard deviations that were estimated and propagated through the calculations mainly represent spatial variation (see Table 6-4), due to the short measurement period. The large variation found for a number of properties on this rather small spatial scale indicates that a number of factors influence these properties on a small scale, such as soil properties, topography, water availability etc. The large standard deviations of the NEP estimates mainly stem from the large standard deviations in the soil respiration estimates, which suggests a high spatial variation on the scale measured. Interestingly, the lowest variation was found in the most even-aged forest stands with relatively low litter production in combination with the smallest SOC pool on a shallow soil layer.

In addition to the spatial variation, there are differences between years caused by variations in climatic variables such as temperature and precipitation. These differences could be explored with the field data used in this chapter. The temporal variation is further explored using model simulations in Chapter 7.

Confidence

NEP is calculated as the difference between large flows of carbon, namely NPP and heterotrophic respiration, and the errors associated with the estimations of these large fluxes must be regarded as potentially large. The largest contributions to NPP are tree litter production above and below ground, which are based on measurements performed in 2004–2006 and 2005, respectively. The turnover rate of fine root biomass was, however, only estimated at one locality in Forsmark and then extrapolated to the other localities using their specific fine root biomass. Litterfall may be highly variable between years /Bray and Gorham 1964/, and the reliability of the methods for estimating root turnover have been discussed (e.g. /Matamala et al. 2003, Trumbore and Gaudinski 2003/) and large differences have been found /Gill and Jackson 2000, Persson and Stadenberg 2007b/. Furthermore, soil respiration was only measured during one year at the site (2004–2005 in Laxemar-Simpevarp and 2005 in Forsmark), and /Euskirchen et al. 2003/ found an overall difference of 37% between two consecutive years in soil respiration, which was associated with changes in soil temperature for six vegetation types. Nevertheless, the estimates presented here, both single estimates of pools and fluxes and ecosystem emergent properties, are well within expected ranges.

6.3.4 Concluding remarks

We have used a simplified approach to estimate the accumulation of carbon in the SOC pool: carbon output subtracted from carbon input. Nevertheless, organic matter, with assimilated radionuclides, that is turned into litter would quickly be decomposed, creating an excess of radionuclides in comparison with carbon in the humus and upper mineral soil layer. The fate of this enrichment would depend on the strength of the chemical interaction with the solid phases of the different soil horizons, e.g. /Tipping 1996/.

Generally, the estimated pools and fluxes from the six localities in Forsmark and Laxemar-Simpevarp were in agreement with those estimated in similar studies, where available. However, some discrepancies were discovered. A high net emission from the soil in two localities suggests that either the underlying assumptions are invalid or that there may be a large variation between years in this property for the two localities. For the oak forest, the underlying assumption that heterotrophic respiration is 50% of soil respiration seems to be invalid, while the water-inundated alder shore forest may have a potential high between-year variation in NEE due to the location of the water table.

Studies of boreal forest ecosystems are usually conducted in coniferous tree stands under dry to moist conditions. Here, data also included two different alder forest stands that are situated on water-logged soil during parts of the year. Few data for such vegetation types have been published previously. Overall, this exercise has generated a number of insights (discussed above) concerning the function of a subset of ecosystems at the two sites, even though the study only covers a short time period. Moreover, a site-specific database is now available for describing the pools and fluxes for a number of ecosystems that is further explored on the regional scale in the next chapter.

7 Describing regional carbon balances using a dynamic vegetation model

7.1 Introduction

Estimating carbon balances at a regional level is a challenge that requires an understanding of the factors affecting the carbon processes and the features to be investigated. Available methodologies can be grouped into field estimates, remote sensing and ecosystem modelling. In a landscape containing a number of different vegetation types, ground-based measurements are expensive and labour-intensive and some features are difficult to measure. However, in Sweden forest inventory data are available on above-ground biomass for the fraction that is of economic interest. To estimate whole-tree carbon, "biomass expansion factors" are therefore necessary. These vary between different regions and are not very well known /Nabuurs et al. 1997/.

In satellite-based remote sensing, the state and changes in the terrestrial biosphere are estimated by measuring reflected radiation in different electromagnetic bands. Several such products with estimates on different temporal and spatial scales are available and they are inexpensive compared to field measurements. Vegetation indices, such as ratios between different wavelength bands, are used in remote sensing for estimating, for example, leaf area index (LAI) or fraction of absorbed photosynthetically active radiation (FAPAR) /Chen and Cihlar 1995/. These characteristics can then be used to quantify and upscale physiological processes, such as photosynthesis, productivity and transpiration e.g. /Bonan 1993, Coble et al. 2001, Fassnach and Gower 1997, Jose and Gillespie 1997/. The complexity lies in the relationship between LAI or FAPAR and the carbon dynamics, since the relationship varies non-linearly due to differences in e.g. latitude, climate, biome, species and season.

Dynamic ecosystem models can be used to estimate carbon cycle balances based on different input parameters such as climate, vegetation characteristics and soil properties. A dynamic vegetation model describes both physiological processes and processes at the population and community level that affect vegetation dynamics. This approach also incorporates a temporal dimension, since carbon balances are highly influenced by stochastic disturbance regimes, climate changes and age of the stand. These influences are difficult, time-consuming and expensive to capture by field measurements and remote sensing. This chapter describes how the dynamic vegetation model, LPJ-GUESS, was used for estimating carbon balances for the two investigation areas. LPJ-GUESS has been subject to extensive validation against temporal and spatial variations in ecosystem carbon balances /Sitch et al. 2003, Heimann et al. 1998, Lucht et al. 2002, Morales et al. 2005/ and modelled species composition, biomass and species distributions /Badeck et al. 2001, Smith et al. 2001, Hickler et al. 2004/. In the Laxemar-Simpevarp investigation area, /Tagesson 2006c/ has also validated the model against soil respiration, tree biomass, net primary production (NPP) of grass ecosystems and the slow soil organic carbon (SOC) pool.

A new approach is to combine remote sensing with dynamic vegetation modelling. Satellite data show the spatial distribution of vegetation characteristics (e.g. LAI, FAPAR or vegetation structure), whereas the dynamic vegetation model estimates the relationship of these characters to physiological processes e.g. /Knorr et al. 2004/. The physiological processes can then be spatially extrapolated over the investigation areas.

In this chapter, the aim was to provide a regional description of carbon balances using results from LPJ-GUESS for a number of different vegetation types dominating the Forsmark and Laxemar-Simpevarp investigation areas. Some areas (sea shore, wetlands and forested wetlands) were not included due to the extensive work required to adapt the model to these vegetation types. For these vegetation types, field measurements as well as literature data are discussed in Chapter 4-1 and these vegetation types are parameterized for carbon balance calculations in Chapter 8. The model results cover the following vegetation types: young (25 y) and old (80 y) stands of Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), deciduous trees (oak (*Quercus robur*) and silver birch (*Betula pendula*)), mixed forests, dry pine on acid rocks, meadows and agricultural land.

The study was divided into four different parts. Firstly, the model was validated against field estimates to ensure that the parameterization of the model was suitable for the investigation areas and to confirm that estimated carbon balances are realistic in relation to measurements /Tagesson et al. 2009a/. Secondly, estimates of carbon balances for 2005 in the different vegetation types were made using the model. Thirdly, spatial variation in NPP was described by combining remote sensing and modelled NPP /Tagesson et al. 2009b/. And finally, temporal variation was described for a number of ecosystem properties for a 100-year forest cycle.

7.2 Materials and methods

7.2.1 Model description

LPJ (Lund Potsdam Jena)-GUESS (General Ecosystem Simulator) is a dynamic vegetation model that combines the dynamic ecological processes with the biogeochemical processes governing ecosystem carbon and water cycles /Sitch et al. 2003/. The biogeochemical processes include photosynthesis, respiration, tissue turnover and stomatal regulation, which control fluxes of C and H_2O between the different compartments of the ecosystem. The dynamic ecological processes are individual plant growth, plant resource competition, demographic processes and disturbances. A short description of the model is given here. For a more detailed account see /Sitch et al. 2003/ and /Smith et al. 2001/.

Dynamic vegetation models developed for simulations on a continental or global scale, so called DGVMs, use broadly defined plant functional types (PFTs) as basic biological units. Broadly defined, PFTs group the species within and among ecosystems with the same type of function and structure, and they have averaged parameters for the most part. These averaged parameters were based on the assumption of homogeneity in the vegetation and represent a necessary compromise between computational data and analytical demands for large-scale analyses of vegetation changes.

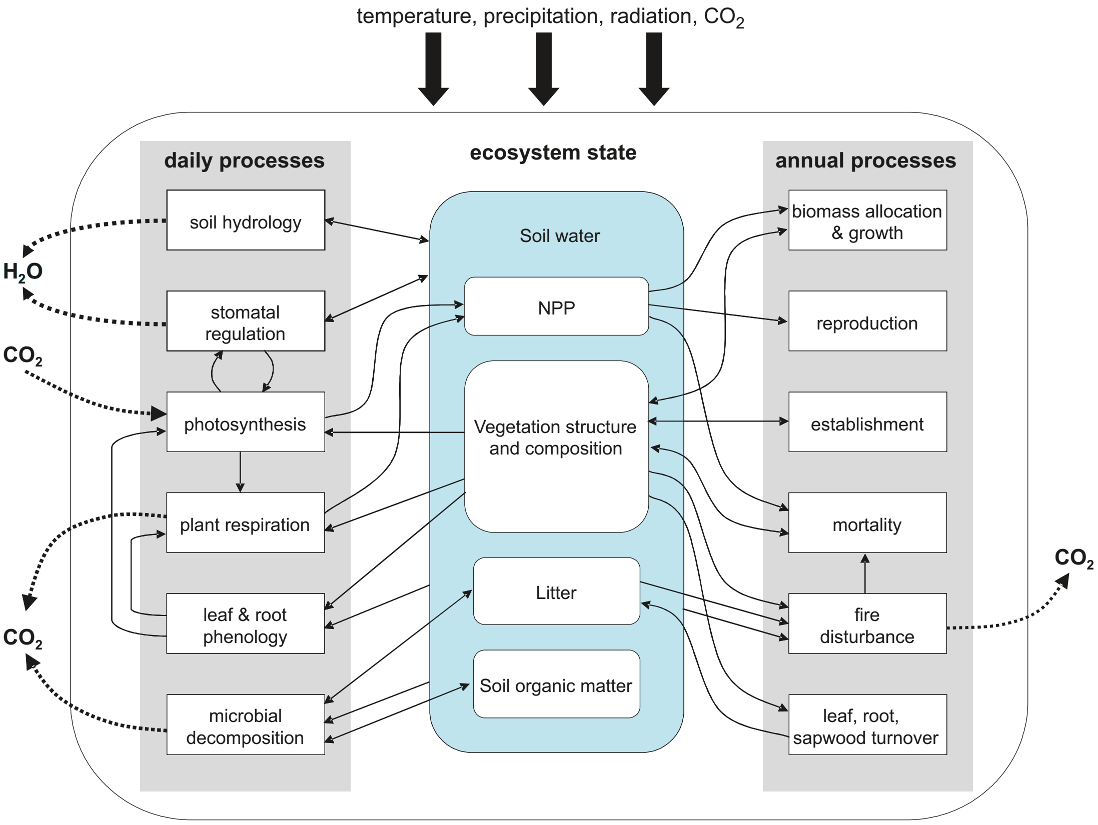


Figure 7-1. Flowchart describing the main processes and ecosystem state variables, and their interactions in the dynamic vegetation model LPJ-GUESS.

On a smaller spatial scale, such as the landscape of the present investigation, DGVMs are too generalized and their spatial scale is too coarse. In LPJ-GUESS, more narrowly defined PFTs, individual species or cohorts (age classes of the same species) can be used. Herbaceous plants were also represented but not on an individual species basis.

Abiotic parameters

The abiotic input parameters were latitude, soil texture, precipitation, temperature, insolation and atmospheric concentration of carbon dioxide. The ecosystem drivers – day length, growing season, photosynthetically active radiation (PAR), soil temperature, soil water, potential evapotranspiration, snow accumulation and snowmelt – were derived from these input parameters. The abiotic factors drove the model and thereby determined primary production, carbon cycling and vegetation dynamics.

Species properties

Each species simulated in the model has prescribed parameter values that govern its specific response to environmental variation and ecosystem changes. Tree individuals were characterized by their allocation of carbon to the stem, roots, branches and leaves. This allocation gives the individual its characteristics of height, crown area, bole height and leaf area index (LAI). Light absorption and thereby competition between the individuals for light capture is dependent on LAI and the structure of the plant canopies. The properties of the species also determine their establishment rate and their susceptibility to changes in climate factors. Herbaceous PFTs were simulated as one aggregated PFT at ground level.

Net primary production

Gross Primary Production (GPP) of ecosystems depends on the individual properties of the vegetation and the abiotic parameters that influence photosynthesis and stomatal conductance, which is in turn influenced by water uptake from the soil. Photosynthesis is dependent on the fraction of PAR assimilated by the woody individuals. Herbaceous PFTs assimilate the proportion of PAR that reaches ground level. Water balance is affected by evapotranspiration, soil hydrology and precipitation. Soil hydrology differs among 10 different soil texture types. Processes controlling evapotranspiration are dependent on the supply of soil water, water use by the plant and atmospheric water demand. Water supply can be a limiting factor for photosynthesis if atmospheric demand exceeds the water supply in the root zone of the plant.

Net Primary Production (NPP) is the proportion of GPP left for tissue production and reproduction after respiration resulting from plant use of carbohydrate energy (autotrophic respiration). Ten percent of the carbon from NPP is used for reproduction, while the rest is allocated to leaf, sapwood or root biomass. The tissue pools will be reduced due to mortality and tissue turnover.

Soil organic carbon and litter decomposition

Dead leaves, dead roots and all carbon from dead individuals were transferred to the above- and below-ground litter. The litter pool has a residence time of 2.86 years at 10ºC. When litter decomposes, seventy percent is respired to the atmosphere and the rest is transformed into soil organic carbon (SOC). Two SOC pools exist, a fast decomposing pool with a mean residence time of 33.3 years at 10ºC and a slowly decomposing pool with a mean residence time of 1,000 years at 10ºC. Abiotic factors that influence decomposition are soil and air temperature (exponential relationship) and soil moisture (linear relationship). Total heterotrophic respiration is the sum of respiration from the three pools.

Disturbances

Fire is the most important disturbance in forests and was the only disturbance modelled explicitly. The fire regime was set to be dependent on fire fuel and litter moisture in the ecosystems. Fire cannot spread below a minimum fuel load and above a threshold value of moisture content. Other disturbances, e.g. storms, droughts, pests, diseases and clear-cutting, can be set to have average return times. When there is a disturbance, all aboveground biomass in the ecosystem is fully consumed and released back to the atmosphere.

7.2.2 Input parameters

Model settings

The parameters of the model were chosen in order to correspond to the conditions at both sites. Following is a description of the parameterization of, and modifications made to, the model.

The model was set up to run in cohort mode, where age classes of the same species were distinguished. The Beer-Lambert coefficient was set at 0.45, estimated by /Lagergren et al. 2005/ for the Norunda research area not far from Forsmark. The proportion of PAR that is lost due to absorption by non-photosynthetic structures, such as stem and branches, was set at 0.4. Clear-cutting and re-establishment of a forest was prescribed in the same year as the forest was planted according to the forest management plan (cf. below). When the forests were clear-cut, it was assumed that 30% of the woody biomass entered the litter pool and the rest was removed as timber. All leaves and fine roots of the clear-cut forests were transferred to litter. The model had a spin-up period of 300 years to establish vegetation and soil carbon pools at equilibrium with the long-term climate. During this spin-up period, the first 30 years of the climate dataset and the first year of the carbon dioxide dataset were used.

The model was set to have a fire disturbance regime as well as general patch destroying disturbances with an average return time of 100 years, considering an average for natural disturbances in Sweden /Zackrisson 1977, Bradshaw and Zackrisson 1990/. Simulations were made for 100 patches with an area of 0.1 ha each. For the outputs, an average value of these 100 patches was calculated.

Output variables from the model were annual NPP, biomass and leaf area index both as ecosystem totals and for individual species. Ecosystem level output variables used were GPP, carbon fluxes to vegetation (NPP), soil respiration, Net Ecosystem Exchange (NEE, i.e. the sum of all above fluxes) and carbon fluxes caused by fire,. Additional ecosystem level output variables were FAPAR, autotrophic respiration by leaves, sapwood, roots, growth respiration, litter pools of root, leaf, wood and reproduction C and slow and fast SOC pools. Additional output variables (as ecosystem totals and for individual species) were stocks of leaves, sapwood, heartwood and fine roots.

Climate

Due to a lack of long time series from the specific sites, climate parameters were obtained from several different meteorological stations. Climate data were collected from NORDKLIM, NORDisk KLIMasamarbeid /SMHI 2003/, and the meteorological stations in Lövsta, Örskär, Oskarshamn, Gladhammar, Högmasten and Äspö /Johansson et al. 2005, Larsson-McCann et al. 2002a, Lärke et al. 2005/. The stations in the surroundings of Forsmark were Uppsala, Stockholm and Svenska högarna and the stations in the surroundings of Laxemar-Simpevarp were Krokshult, Växjö, Kalmar and the north cape of Öland /SMHI 2003/.

Temperature

Data recorded in Örskär situated in the Forsmark investigation area were used for the years 1961–2004 /Larsson-McCann et al. 2002b/. To get values between 1901 and 1960, a reference temperature was calculated with the dataset from Örskär and the NORDKLIM climate stations Uppsala, Stockholm and Svenska högarna /SMHI 2003/. Reference values (T_r) can be calculated by Alexandersson and Moberg 1997/:

$$T_r = \Sigma^k{}_{j=1} (\rho_j{}^2 (X_{ji} - X_{aj} + Y_a)) (\Sigma^k{}_{j=1} (\rho_j{}^2))^{-1} \qquad (7\text{-}1)$$

where ρ_j is the Pearson correlation coefficient between the climate station in Örskär and the other climate stations (*j*) during the period 1961–2000, X_{ji} is the temperature at the other climate station for the year and month (*i*), X_{aj} is the average temperature for each month 1961–2000 at the climate station *j* and Y_a is the average temperature for each month 1961–2000 at the climate station in Örskär. For 2005–2006 measurements from Högmasten situated in the Forsmark investigation area were used /Larsson-McCann et al. 2002b, SMHI 2003, Johansson et al. 2005/.

For Laxemar-Simpevarp, measurements from Oskarshamn situated 25 km south of the Laxemar-Simpevarp investigation area were used for the years 1961–2000. To get values between 1901 and 1960, a reference temperature (Equation 7-1) was calculated using the datasets from Oskarshamn, Växjö, north cape of Öland and Kalmar /SMHI 2003/. Measurements from the Äspö climate station were used for 2004 to 2006 /Lärke et al. 2005/.

Precipitation

Precipitation data from 1961 to 2004 were obtained from Lövsta /Larsson-McCann et al. 2002b/ for the Forsmark simulations. No data were available for 1901–1960, and reference values were therefore calculated for the period 1901–1960 with data from the surrounding NORDKLIM climate stations in Stockholm, Uppsala and Svenska högarna, where the precipitation was measured between 1890 and 2000 /SMHI 2003/. Reference values (P_r) for precipitation can be calculated by /Alexandersson and Moberg 1997/:

$$P_r = \Sigma^k_{j=1} (\rho_j{}^2 (X_{ji} Y_a X_{aj}^{-1})) (\Sigma^k_{j=1} (\rho_j{}^2))^{-1} \qquad (7\text{-}2)$$

where ρ_j is the Pearson correlation coefficient between the climate station in Lövsta and the other climate station (j) during the period 1960–2000, X_{ji} is precipitation at the other climate station for the year and month (i), X_{aj} is the average precipitation for each month 1960–2000 at the climate station j and Y_a is the average precipitation for each month 1960–2000 at the climate station in Lövsta.

Measurements of precipitation started at Högmasten in the Forsmark investigation area in September 2003 /Johansson et al. 2005/, and data from Högmasten in the Forsmark investigation area were used for the years 2005–2006. Measured precipitation is not true precipitation due to different factors such as wind, topography, evaporation and adhesion; all precipitation data were therefore corrected according /Alexandersson 2003/.

Precipitation data for the period 1912–2003 from Krokshult, situated about 25 kilometres west of Simpevarp were used for Laxemar-Simpevarp /SMHI 2003/. Reference precipitation was calculated with Equation 7-2 for 1901–1912 using the data from Krokshult and the surrounding climate stations in Växjö, Kalmar and the north cape of Öland /SMHI 2003/. For 2004 to 2006, data were taken from the Äspö climate station /Lärke et al. 2005/. All Laxemar-Simpevarp precipitation data were corrected according to /Alexandersson 2003/.

Solar radiation

For the Forsmark simulations, cloudiness from 1901–2001 was taken from the climate station in Stockholm /SMHI 2003/. For 2004–2006, solar radiation was measured in W m^{-2} at Högmasten in the Forsmark investigation area /Johansson et al. 2005/. Average monthly radiation was calculated using daytime data, i.e. radiation greater than 10 W m^{-2} /Smith 2006, pers. comm./. For 2002 and 2003, no measured data could be found in the surrounding areas and therefore linear regressions between cloudiness and precipitation 1901–2001 were used for each month. The regressions were used on the precipitation data set to estimate cloudiness for each month in 2002 and 2003.

Cloudiness data for 1901–2000 were taken from Växjö for the Laxemar-Simpevarp simulations /SMHI 2003/. Solar radiation was measured in W m^{-2} at the climate station in Gladhammar 2003 and at Äspö for the period 2004 to 2006 /Lärke et al. 2005/. Average monthly radiation was calculated using data greater than 10 W m^{-2} for 2003 to 2006. For 2001 and 2002, no measured data could be found and therefore linear regressions with cloudiness against precipitation 1901–2000 were done for each month. The regressions were used on the precipitation data set for each month of 2001 and 2002 to estimate cloudiness.

Carbon dioxide

An annual data set for the period from 1901 to 1998 for atmospheric concentration of carbon dioxide was taken from the Carbon Cycle Model Linkage Project /McGuire et al. 2001/. For the missing years 1999–2006, data were taken from a dataset from Mauna Loa /Tans 2006/.

Soil characteristics

Soils in the Forsmark investigation area are characterized by low-lying, young (less than 1,500 years) land formed by the sea /Lundin et al. 2004/. Sea waves have redistributed the material so that upland parts have coarser material, thin soils and bare bedrock, whereas the low-lying areas have a fairly high clay content in the sediments /Lundin et al. 2004/. Gleysol and Regosol are dominant soil types in the Forsmark area, which have coarse-textured till. These soils mainly have coniferous forests growing on them /Lundin et al. 2004/. Leptosols with shallow soil depths at upslope locations are also common /Lundin et al. 2004/. Pine and spruce forests dominate the tree layer. Regosol and Gleysol soil types dominate on arable land and pastures, and these soils can be found on clayey till. Two different soil types were chosen for Forsmark: medium-coarse soil types for the forest simulations and finer soil textures for the arable land and pastures. In the model, soil was divided into two different soil layers: an upper and a lower. Normally, the soil depth was 1,000 mm and the boundary between the layers was at a depth of 500 mm. For the Leptosol areas, the model was modified to have a soil depth of 250 mm and the boundary between the upper and lower soil layers was set at 125 mm.

The Laxemar-Simpevarp investigation area contains a wide variation of soil textures, mainly due to differing topography /Lundin et al. 2005a/. The most common soil type is Podzol/Regosol with quite a coarse-grained sandy and sandy-silty textured till and sorted sediments, and in these areas mainly forests occur /Lundin et al. 2005a/. At the most upslope locations, the commonest soil types are Leptosols, and in these areas the soil cover is rather thin (0.0–0.3 m). The soil texture again mainly consists of fairly coarse sandy and sandy silty till /Lundin et al. 2005a/. These areas are mainly covered by pine forest. In low-lying flat areas, the most frequent soil type is Umbrisol and the soil materials are mainly silt, clay and gyttja. These areas have been used as arable land and pastures /Lundin et al. 2005a/. The same soil types were chosen for Laxemar-Simpevarp as for Forsmark: medium-coarse soil types for the forest simulations and finer soil textures for the arable land and pastures. The soil depth was set at 1,000 mm and the boundary between the layers was at a depth of 500 mm. For the Leptosol areas, soil depth was set at 300 mm and the boundary between the layers was set at 150 mm.

Vegetation

A vegetation map derived from remote sensing of Forsmark and Laxemar-Simpevarp was used in order to identify the range of different vegetation types, (Figures 3-4 and 3-8 /Boresjö Bronge and Wester 2003/). A selection was made from this list of vegetation types in order to represent the most abundant and important vegetation types in terms of being potential sinks for organic matter (wetlands) and potential human food sources (arable land, pastures).

In the vegetation map, old and young conifer forests can be distinguished based on the spectral characteristics of a stand. These spectral characteristics were also related to site quality but seem to be equivalent to forest age when the stand is in the cutting class “thinning forest” or older /Boresjö 1989/ (3x and 4x in Table 7-1). The spectral characteristics obtained from the SPOT satellite were from 1999. The age distribution within cutting classes at the time of interpretation of the spectral characteristics (1999) was obtained from the forest management plan (In Swedish “Skogsbruksplanen”), which covers a substantial part of the regional model area of Forsmark. For Forsmark it is feasible to suggest that the median forest age for young forest in 2005 is approximately 25 years, see Table 7-1 (the median age at 1999 was 18 years and 7 years later it would be 25 years). If a similar approach was used to estimate the median age of old growth forest in 2005, the median age for old forest would be overestimated, since old forests are continuously being cut down, so their median age was set to 80 years. Deciduous forest age was estimated for the cutting class “thinning forest” or older separately, using 19 stands, which gave a similar age as for the older forest.

Data on cutting classes and ages in Laxemar-Simpevarp were not available. The forested area is divided up among a large number of private landowners, which makes it difficult to get an overall picture of this information. The management situation was assumed to be similar in Laxemar-Simpevarp as in Forsmark and the ages of the forests in the different thinning classes should consequently approximate those in Forsmark.

Table 7-1. The age of the cutting classes that correspond to young and old forest in the vegetation map of the Forsmark area. The statistics are taken from Sveaskog's management plan (in Swedish skogsbruksplan), which was updated in 1999–2000 and covers a substantial part of the regional model area.

Cutting class	Mean age	Median age	Min. age	Max. age
2x	19	18	6	37
3x and 4x	73	78	24	166

In the present study the model was configured to simulate major forest tree species, i.e. Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), silver birch (*Betula pendula*) and oak (*Quercus robur*). Parameters for C_3 grass were used for the field layer. Young stands were set to be clear-cut in 1980 and old stands were set to be clear-cut in 1925. The clear-cuts were set to be harvested in 2002 and clear-cuts with birch were harvested in 1990. The vegetation types and the species included in the simulations are presented in Table 7-2. Output data for 2005 were used as results.

The parameterization of the vegetation follows previous studies by /Hickler et al. 2004/ and /Koca et al. 2006/. Specific parameters for PFTs were used for the parameters concerning physiology and life history of the species, i.e. different values were given to trees versus grasses, angiosperms versus gymnosperms, boreal versus temperate, and to shade-tolerant versus intolerant species /Fulton 1991, Haxeltine and Prentice 1996, Vogt et al. 1996, Smith et al. 2001, Li et al. 2003, Sitch et al. 2003, Gerten et al. 2004, Hickler et al. 2004, Koca et al. 2006/. Longevity and bioclimatic limits for survival and establishment were given specific values for each species /Skre 1972, Prentice and Helmisaari 1991, Bugmann 1994, Sykes et al. 1996, Bradshaw et al. 2000, Koca et al. 2006/. All crop root biomass was transformed to root litter, since no roots survive until the next year because the fields are ploughed in the autumn. In the crop simulations, 66% of the leaf biomass was removed from the field and 33% remained as litter /Olsson 2006, HIR Malmöhus pers. comm./. It was also assumed that crop root biomass is 19% of the total biomass /Andrén et al. 1990/, and for the other parameters, crops had exactly the same values as grass. All parameters are given in Table 7-3.

Table 7-2. Major ecosystems in the investigation areas as identified in the vegetation map by /Boresjö Bronge and Wester 2003/, and the species included in the different simulations.

Ecosystem	Species included in simulations
Young Norway spruce	Norway spruce, grass
Old Norway spruce	Norway spruce, grass
Young Scots pine	Scots pine, grass
Old Scots pine	Scots pine, grass
Scots pine on bedrock	Scots pine, grass
Mixed forest	Norway spruce, Scots pine, Silver birch, oak, grass
Old deciduous forest	Silver birch, oak, grass
Clear cut	Silver birch, grass
Clear-cut with birch (young deciduous)	Silver birch, grass
Pasture	Grass
Arable land	Crop

Table 7-3. Species properties for the modelled vegetation types.

Parameters **Growth form**	**Details** **Tree**	 **Grass**	 **Crop**	
min. PAR flux for establishment (MJ m^{-2} day^{-1})	–	2.5	2.5	
fraction of roots in upper/lower soil layer	0.67/0.33	0.9/0.1	0.9/0.1	
fine root turnover (y^{-1})	0.7	0.7	1	
leaf/root	1	0.5	5.26	
Tree type	**Gymnosperms**	**Angiosperms**		
leaf phenology	Evergreen	Summergreen		
min. canopy conductance (mm s^{-1})	0.3	0.5		
leaf area/sapwood area (m^2 cm^{-2})	2	3		
leaf turnover (y^{-1})	0.33	1		
sapwood conversion (y^{-1})	0.05	0.1		
specific leaf area (cm^2 $(gC)^{-1}$)	220	410		
canopy interception parameter	0.06	0.02		
Climate zone	**Boreal**	**Temperate**		
optimal temperature range for photosynthesis	10–25	15–25		
Shade tolerance class	**Intolerant**	**Intermediate**	**Tolerant**	
growth efficiency threshold for stress mortality (kgC m^{-2} y^{-1})	0.12	0.1	0.0001	
max. establishment (saplings ha^{-1} y^{-1})	2,500	1,875	1,250	
recruitment shape parameter	10	6	3	
Tree taxon	**Spruce**	**Pine**	**Silver birch**	**Oak**
type	gymnosperm	gymnosperm	angiosperm	angiosperm
climate zone	boreal	boreal	boreal	temperate
shade tolerance	tolerant	intermediate	intolerant	intermediate
max. non-stressed longevity (y)	900	760	300	1,060
min. Tc for survival (°C)	–	–	–	–18
min. Tc for reproduction (°C)	–	–	–	–16
max. Tc for reproduction (°C)	–2	–1	–	–
min. GDD_5 for reproduction[1]	600	500	150	1,100

[1] Accumulated temperature for annual growing degree days on 5°C base; $GDD_5=\sum_d (T_d-5.0)$; T_d=mean temperature of Julian day.

7.2.3 Spatial variation in NPP

During 2005, LAI was estimated optically using LAI-2000, TRAC and the gap fraction method in representative forest stands at both Laxemar-Simpevarp and Forsmark. LAI was also extrapolated over both investigation areas based on normalized difference vegetation index (NDVI) images (see Section 4.1.3) /Tagesson 2006a/.

NPP was linked to LAI using the simple light use efficiency model /Ruimy et al. 1994/. The concept is to estimate NPP from FAPAR and a light use efficiency constant, ε

$$\text{NPP} = \varepsilon \text{ PAR FAPAR} \qquad (7\text{-}3)$$

where ε is the light use efficiency constant. FAPAR is highly linked to NPP since plants gain no benefit from harvesting more light than they have resources to use, and by combining this information with a variant of the Beer Lambert law (Equation 7-4), NPP can be estimated.

$$\text{FAPAR} = 1-\exp(-k \text{ LAI}) \qquad (7\text{-}4)$$

where FAPAR is the fraction of the PAR that is absorbed and *k* is the light extinction coefficient. The light extinction coefficient was estimated to be 0.45 for a mixed middle-aged coniferous forest in Norunda, not far from Forsmark /Lagergren et al. 2005/.

$$\mathrm{NPP} = (\varepsilon\ \mathrm{PAR}) - (\varepsilon\ \mathrm{PAR}) \exp(-0.45\ \mathrm{LAI}) \qquad (7\text{-}5)$$

ε PAR can be estimated from the model by dividing NPP by FAPAR. For each forest type in Table 7-2 identified in the vegetation map by /Boresjö Bronge and Wester 2003/, this fraction and Equation 7-5 were used on the LAI image to calculate NPP for both investigation areas. Average values and standard deviations of NPP were calculated for the different vegetation types (Table 7-2) in a GIS. This enabled us to describe the spatial variation in NPP caused by differences in nutrients, microclimate and other natural variation that exists within the investigation areas that it is not possible to estimate directly by means of a mechanistic model based on climatic variables and input parameters only. From now on, NPP estimated directly from the model will be referred to as “model-estimated NPP”, while the estimates based on the light-use efficiency model are referred to as “LAI-based NPP”.

7.2.4 Temporal variation of carbon balances during a forest cycle

For the forested areas, simulations were performed to describe variation in pools and fluxes during a 400-year period. Temporal variation in carbon balances is difficult to estimate in the field, due to the extensive work required for ground-based estimates. The main components investigated were NPP, litterfall, heterotrophic soil respiration and accumulation of carbon in the soil organic carbon pool. All species were included to estimate vegetation dynamics after a clear-cut. After the spin-up period, the forests were clear-cut in 1901 and the 100 years of climate data were repeated 4 times in order to cover the whole simulation period.

A forest cycle lasts on average 100 years /Sveaskog AB 2005, pers. comm./. The forests in the investigation areas are managed, and to get estimates for these forests, descriptive statistics were also calculated for the first 100-year period of the simulations. Maximum values were calculated from the 400-year perspective, approximating a long period of tree continuity without major disturbances.

7.2.5 Temporal variation in carbon balances for agricultural areas

NPP, crop yield and the accumulation of organic matter in soils are the most important factors in the agricultural areas for a risk assessment of the investigation areas. The harvested yield was assumed to be 0.66 of the leaf biomass /Olsson 2006, HIR Malmöhus pers. comm./, which was removed each year. In the simulations of the agricultural areas, the crop was the only species. Mean values and standard deviation of NPP, crop yield and the accumulation of organic matter were calculated for the period 1901–2000.

7.2.6 Evaluation of model results

Field-estimated data

LAI, soil respiration and stem increment were estimated in the field and compared with the model estimates. In 2005, LAI was estimated with LAI-2000, TRAC and the gap fraction method in representative forest stands in Laxemar-Simpevarp and Forsmark /Tagesson 2006a/. LAI was also extrapolated using NDVI images over both of the investigation areas /Tagesson 2006a/, see Section 4.1.3.

Soil respiration was estimated by means of the closed-chamber technique for six different ecosystems in Laxemar-Simpevarp in March 2004–March 2005 /Tagesson and Lindroth 2007/. In 2005 and 2006, it was also estimated in seven different ecosystems in Forsmark and four additional ecosystems in Laxemar-Simpevarp /Tagesson 2007/. See Section 4.2.4 and Table 4-46.

Site indices were estimated using the methods and height development curves in /Hägglund and Lundmark 1987a, b/ with age and height estimated in the field in representative forest stands in the investigation area /Tagesson 2006a/. The site characteristics were based on /Lundin et al. 2004, 2005a/ and /Löfgren 2005/. Site indices could not be estimated using the height development curves at two sites, containing deciduous forest, since the forest stands were not even-aged or homogeneous. The site characteristic tables for pine were then used to estimate site indices for these deciduous stands /Hägglund and Lundmark 1987a, b/, since no tables exist for deciduous stands and pine is a common vegetation type in the areas. Site indices were converted to site quality classes using tables in /Hägglund and Lundmark 1987a/. The site quality class of a site describes the potential stem increment of the trees averaged over a forest cycle.

Evaluation of model results

Model-estimated LAI 2005 was compared with both field-estimated LAI and average NDVI-estimated LAI for the different simulations. Linear regressions were calculated and the residuals were checked against a normal distribution using a Kolmogorov-Smirnov test. This was done with all datasets before performing Pearson correlations. All statistical analysis was done in SPSS 12.0.1, and results were regarded as significant if $p < 0.05$.

The same procedure was used for model-estimated soil respiration compared with ground-based-estimated soil respiration. The model-estimated soil respiration was compared with the ground-based estimates using the same year in the model output as with the field estimates. To get as close to field estimates of soil respiration as possible, estimates of heterotrophic respiration and root respiration were combined from model results. A problem was that respiration from the field layer and larger roots are not included in this estimate. For pastures and agricultural areas, soil respiration and total vegetation respiration were added. A Pearson correlation was performed between model-estimated and field-estimated soil respiration.

The stem increment was estimated in 2005 and compared with model-estimated and LAI-based NPP for the same years. To compare field-estimated stem increment with model-estimated NPP, NPP was converted to stem increment. The method using conversion factors from NPP to stem increment was taken from /Nabuurs et al. 2003/. The total standing tree volume 1996–2000 for Kronoberg County (coniferous 99,300,000 m^3, deciduous 19,200,000 m^3) and Uppsala County (coniferous 51,300,000 m^3, deciduous 11,300,000 m^3) obtained from /SLU 2001/ was divided into its different compartments stem, branches, roots and foliage in fractions of 0.55, 0.24, 0.17 and 0.04, respectively /Nabuurs et al. 2003/. The turnover rates were assumed to be 0.0024, 0.02, 0.03 and 0.5 per year, respectively, for the same compartments /Nabuurs et al. 2003/. Total litter production in the counties was estimated based on these parameters and the different tree biomass compartments. The mean stem volume increment for Kronoberg (coniferous 3,690,000 m^3y^{-1}; deciduous 760,000 m^3y^{-1}) and Uppsala (coniferous 1,900,000 m^3y^{-1}; deciduous 470,000 m^3y^-1) counties between 1996 and 2000 were provided by /SLU 2001/.

Total NPP for the counties was calculated by summing total litter production and stem increment. Average conversion factors for transferring NPP to stem increment were estimated for coniferous forests in both Kronoberg and Uppsala county (0.00176 $m^3\,kgC^{-1}$), and for deciduous forests of Kronoberg and Uppsala county (0.00183 $m^3\,kgC^{-1}$ and 0.00189 $m^3\,kgC^{-1}$), assuming a wood carbon density of 225 kgC m^{-3} /Jarvis et al. 2001/. Both model-estimated and LAI-based NPP were transformed to stem increment using these conversion factors and evaluated with a Pearson correlation against field-estimated stem increment.

7.3 Results

7.3.1 Evaluation of the dynamic vegetation model

Leaf Area Index

On average, the model-estimated LAIs were acceptable compared with field estimates. The average field-estimated LAI was 3.14±0.92, whereas for the same ecosystems the model estimated it at 3.07±0.43. The Pearson correlation between modelled LAI and field LAI for each stand was not significant. However, when the model was compared with NDVI-estimated LAI instead, there was a correlation (r=0.779, df=12 p=0.001). Average NDVI-estimated LAI was 3.54±0.84, whereas model-estimated LAI was 3.21±0.50. See Figure 7-2.

Soil respiration

Average model-estimated soil respiration was 534±137 gC m^{-2} y^{-1} whereas field estimates were 823±230 gC m^{-2} y^{-1}. The model was closer to the field estimates in Forsmark (model 543, field 657) than in Laxemar-Simpevarp, where the estimates were lower (model 529, field 928). There was no correlation between modelled and field estimates of soil respiration (Figure 7-3).

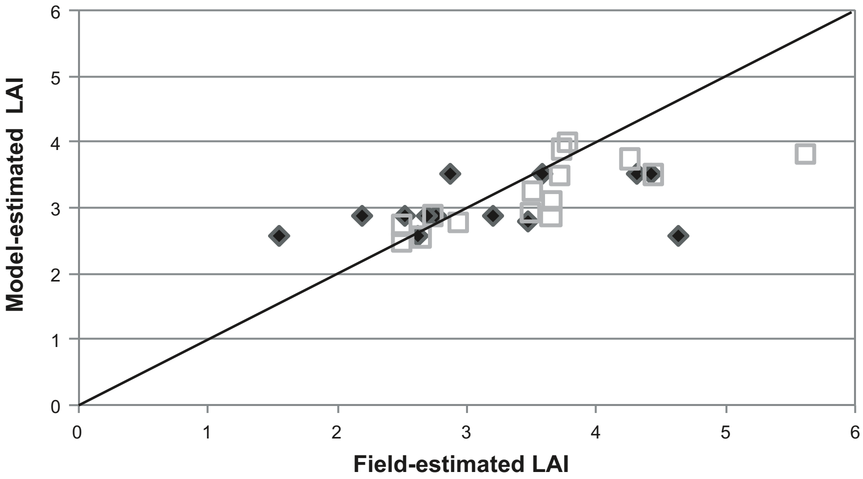


Figure 7-2. Model-estimated LAI compared with field-estimated LAI. Filled symbols are measured LAI values in local stands and open symbols are average NDVI-estimated LAI values for young and old pine, young and old spruce, old deciduous stands, old dry pine on acid rock, old mixed forest stands in both Forsmark and Laxemar-Simpevarp and clear-cut birch in Forsmark. The line shows the 1:1 relationship.

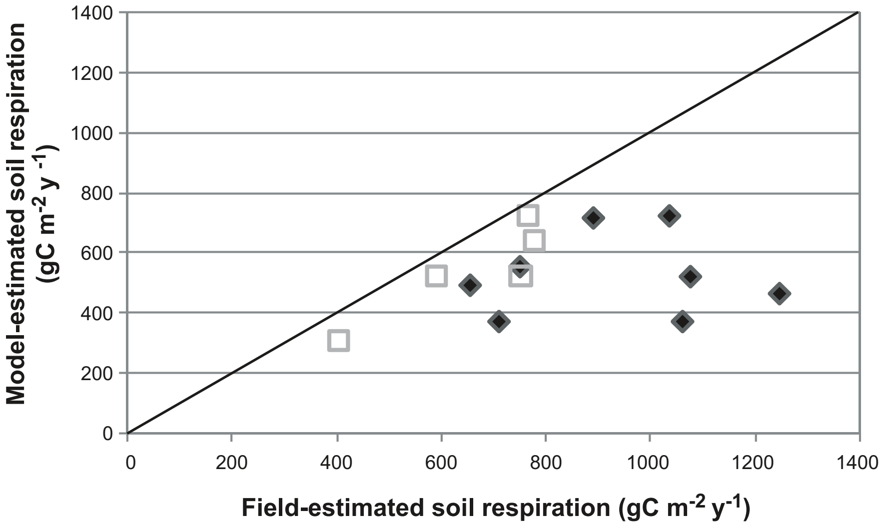


Figure 7-3. Modelled soil respiration for both Forsmark and Laxemar-Simpevarp versus field-estimated soil respiration for the local stands. Open symbols are Forsmark and filled symbols are Laxemar-Simpevarp. The line shows the 1:1 relationship.

NPP

The average stem increment in the field was estimated to be 5,911±2,986 m^3 ha^{-1} y^{-1} (120 gC m^{-2} y^{-1}) whereas model-estimated NPP converted to stem increment was 8,880±997 m^3 ha^{-1} y^{-1} (174 gC m^{-2} y^{-1}). LAI-based NPP converted to stem increment increased the average value to 9,597±1,034 m^3 ha^{-1} y^{-1}. There was no correlation between field-estimated and model-estimated stem increment, whereas there was a correlation between field-estimated and LAI-based stem increment (r=0.661, df=12, p=0.014) Figure 7-4.

Carbon balances of ecosystems in the Forsmark and Laxemar-Simpevarp investigation areas

Modelled carbon pools and fluxes for the different ecosystems in Table 7-2 are presented in Tables 7-4 and 7-5. The results show that all ecosystems in both Forsmark and Laxemar-Simpevarp were net sinks for carbon during 2005. Most carbon was accumulated in the vegetation, whereas the SOC pools were sources of carbon for most ecosystems in both Forsmark and Laxemar-Simpevarp.

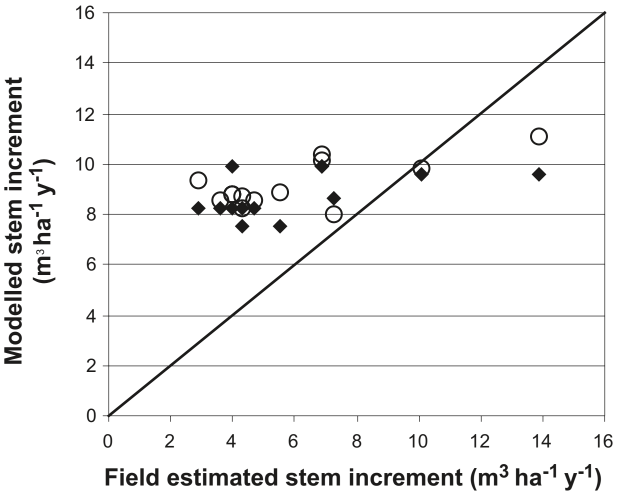


Figure 7-4. *Model-estimated stem increment versus field-estimated stem increment for the local stands in Forsmark and Laxemar-Simpevarp. Filled dots are model-estimated stem increment versus field-estimated, whereas the circles are LAI-based stem increment versus field-estimated. The line shows the 1:1 relationship.*

Table 7-4. Table of pools and fluxes predicted by LPJ-GUESS characterizing different vegetation types in Forsmark. Pools are in gC m^{-2} and fluxes are in gC m^{-2} y^{-1}. A positive value represents an accumulation of carbon in the soil whereas a negative value represents a loss of carbon to the atmosphere.

Func layer	Pools/fluxes		Spruce25	Spruce80	Pine25	Pine80	Dry pine	Deciduous	Mixed	Clear-cut	C-c birch	Pasture	Agri
Tree layer	biomass	Wood	3,997	8,702	4,201	8,201	8,458	6,379	7,017	87	1,821	–	–
		Green	222	194	216	173	181	61	128	9	67	–	–
		Fine roots	222	194	216	173	182	61	128	9	67	–	–
	NPP		628	564	617	570	586	456	505	70	497	–	–
Field layer	Biomass	Green	13	14	12	7	2	3	11	146	15	176	361
		Roots	26	28	25	15	4	6	22	291	29	353	69
	NPP		37	39	33	17	4	6	29	428	38	477	584
Soil	SOC	Litter pool	2,090	2,658	1,997	2,305	2,281	1,707	2,118	3,597	1,914	2,124	1,782
		SOC	11,840	11,397	11,373	11,254	11,040	7,923	1,836	12,211	11,516	9,097	7,055
	Heterotrophic soil respiration		–355	–404	–361	–398	–452	–298	–358	–571	–347	–327	–439
Total	NEE		280	230	276	190	140	165	183	–76	204	150	145
	GPP		1,396	1,304	1,330	1,225	1,248	856	1,077	866	969	916	942
	NPP tot		664	603	650	587	591	461	534	498	535	477	584
	Litter production		428	594	301	337	326	284	370	242	394	444	193
	Net accumulation veg		177	–7	306	246	261	172	158	245	134	33	0
	Net accumulation litter		133	238	7	54	–119	5	37	–385	110	117	0
	Net accumulation soil		–30	–1	–26	–6	–2	–2	–12	64	–40	0	0

Table 7-5. Table of pools and fluxes predicted by LPJ-GUESS characterizing different vegetation types in Laxemar-Simpevarp. Pools are in gC m^{-2} and fluxes are in gC m^{-2} y^{-1}. A positive value represents an accumulation of carbon in the soil whereas a negative value represents a loss of carbon to the atmosphere.

Func. layer	Pools/fluxes		Spruce25	Spruce80	Pine25	Pine80	Dry pine	Deciduous	Mixed	Clear-cut	C-c birch	Pasture	Agri
Tree layer	biomass	Wood	3,912	8,340	4,377	8,163	7,974	5,958	7,339	099	1,856	–	–
		Green	212	195	208	159	155	62	119	10	62	–	–
		Fine roots	213	196	208	160	157	63	120	10	62	–	–
	NPP		566	543	561	466	466	410	459	74	444	–	–
Field layer	Biomass	Green	10	9	8	9	8	8	7	120	8	288	288
		Roots	20	19	15	18	16	16	15	246	16	281	57
	NPP		25	25	25	25	19	25	25	25	25	371	446
Soil	SOC	Litter pool	1,923	2,344	1,826	2,954	2,566	1,884	2,286	3,825	1,699	2,102	1,754
		SOC	12,612	12,378	12,403	12,646	1,713	9,965	11,584	11,270	11,312	1,589	8,380
	Heterotrophic soil respiration		–297	–346	–281	–375	–459	–290	–320	–532	–275	–308	–389
Total	NEE		27	–194	318	100	43	39	32	–123	156	7	63
	GPP		1,271	1,263	1,277	1,153	175	855	1,033	792	70	773	750
	NPP tot		591	568	580	487	484	430	478	420	463	371	446
	Litter production		354	346	371	744	592	312	448	257	360	379	446
	Net accumulation veg		210	–193	196	–340	–119	10	–101	148	50	–8	0
	Net accumulation litter		102	8	163	452	160	41	146	–352	142	88	0
	Net accumulation soil		–35	–9	–41	–2	2	–12	–13	81	–36	–10	0

Spatial variation in NPP

NPP was on average 567±130 gC m^2 $y^{-1}$for the forested areas in Forsmark and 530±77 gC m^2 y^{-1} in Laxemar-Simpevarp 2005. NPP and LAI distribution in the different ecosystems is shown in Table 7-6 for Forsmark and Laxemar-Simpevarp, suggesting non-significant differences between the sites. The spatial distribution of NPP over the investigation areas can also be seen in Figure 7-5.

Figure 7-5. *Spatial distribution of NPP (kgC m^2 y^{-1}) in forested areas of a) Forsmark and b) Laxemar-Simpevarp.*

Table 7-6. Descriptive statistics of the spatial distribution of NPP (gC m^2 y^{-1}) and LAI for the different ecosystem types in Forsmark and Laxemar-Simpevarp.

Ecosystem	Forsmark NPP mean±sd	 max	Forsmark LAI mean±sd	Laxemar-Simpevarp NPP mean±sd	 max	Laxemar-Simpevarp LAI mean±sd
young spruce	627±130	710	3.72±0.92	659±20	706	5.61±0.70
old spruce	609±86	677	3.71±0.57	615±24	691	4.43±0.55
young pine	615±127	703	3.66±0.89	597±49	702	4.26±1.01
old pine	615±110	694	3.64±0.72	538±36	649	3.66±0.53
dry pine	582±138	683	3.42±0.88	492±38	645	2.93±0.45
deciduous	416±113	608	2.25±0.83	416±109	613	2.63±0.93
mixed	555±101	650	3.37±0.71	461±26	630	2.71±0.37
clear cut birch	457±77	668	2.15±0.59	–		–

7.3.2 Temporal variation in carbon balances

Temporal variation in a 400-year forest cycle

After a clear-cut, forests were dominated by pine and spruce in both Forsmark and Laxemar-Simpevarp. The pattern was more accentuated in Forsmark. The deciduous trees occurred early in the succession, but were later suppressed by the coniferous species. There was a larger fraction of deciduous trees in Laxemar-Simpevarp than in Forsmark. The field layer never became important with regard to biomass except for the first year, Figure 7-6. The total biomass continuously increased during the first 100–200 years and then levelled off.

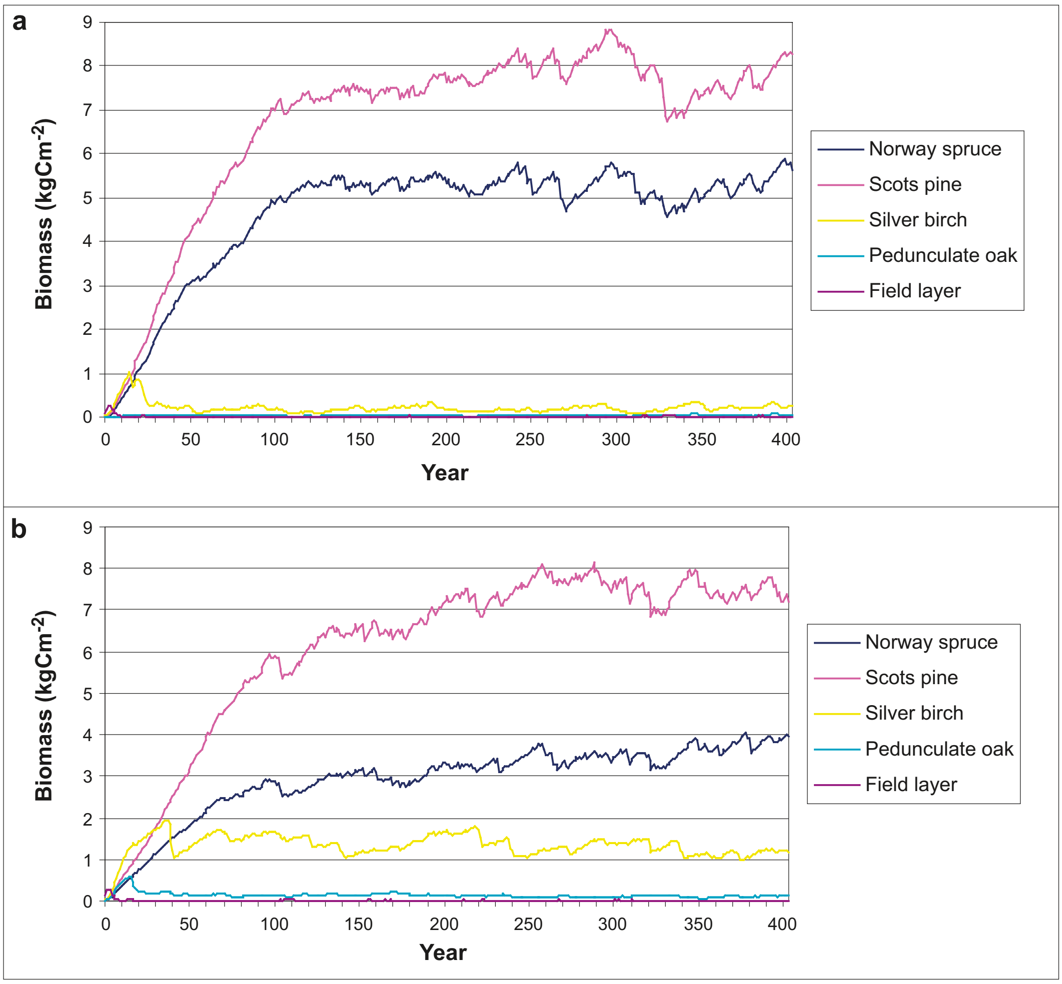


Figure 7-6. *Total biomass during the succession after clear-cut (year 0) in a forest in (a) Forsmark and (b) Laxemar-Simpevarp for four different tree species and the field layer during a 400-year period. The model was driven by climate data describing a 100-year period that was repeated. Values are given in kgC m^{-2} y^{-1}.*

NPP increased sharply during the first 50 years and reached its peak after about 100 years, after which it decreased slowly (for coniferous species), Figure 7-7. This slow decrease occurred at the same age as biomass levelled out (Figure 7-6).

Net ecosystem exchange of carbon was negative at the beginning of the forest cycle. More carbon was respired to the atmosphere than was photosynthesized by the growing vegetation, due to litter leftovers from clear-cutting of the forests. This relationship changed after 9 years in Forsmark and 6 years in Laxemar-Simpevarp. At this time, the emerging vegetation after clear-cut had increased its leaf biomass to the extent that photosynthesis and thereby carbon uptake balanced the heterotrophic respiration. Moreover, much of the litter from the clear-cut was already respired, Figure 7-8. After about 100 years, NEE levelled off at an average of 55 gC m^{-2} y^{-1} in both investigation areas. This occurred when biomass accumulation levelled off.

Immediately after the clear-cut the litter pool was large, but it decreased rapidly during the first 17 years in both Forsmark and Laxemar-Simpevarp. It subsequently increased slowly in Forsmark, reaching equilibrium after 175 years, whereas in Laxemar-Simpevarp the litter pool reached equilibrium after the initial substantial decrease. For the first 9 years the SOC pools increased as carbon from the litter pool was decomposed. During the following 100 years there was a slight decline in the SOC pools in both Forsmark and Laxemar-Simpevarp, which reached equilibrium with few changes for both investigation areas, Figure 7-9.

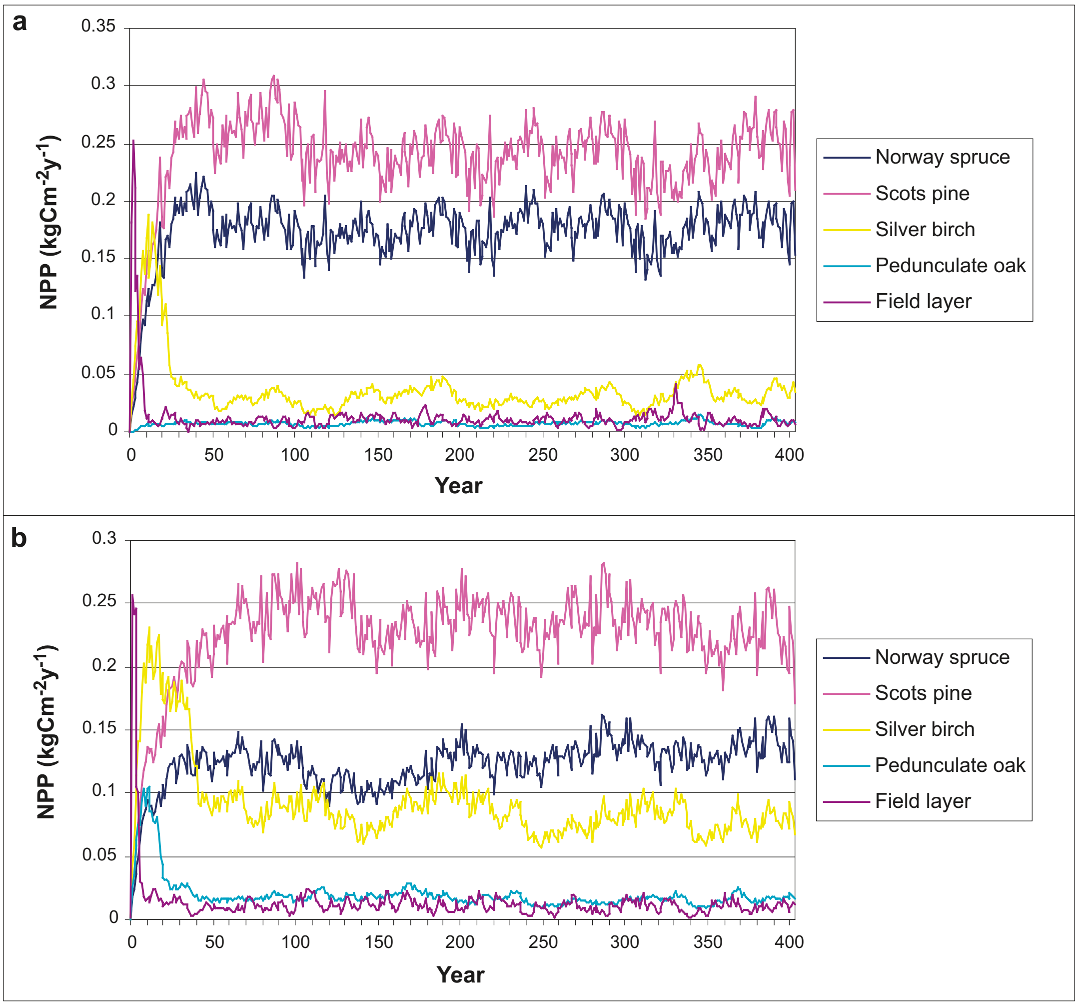


Figure 7-7. *Net primary production during the succession after clear-cut (year 0) in a forest in (a) Forsmark and (b) Laxemar-Simpevarp for four different tree species and the field layer during a 400-year period. The model was driven by climate data describing a 100-year period that was repeated. Values are given in kgC* m^{-2} y^{-1}.

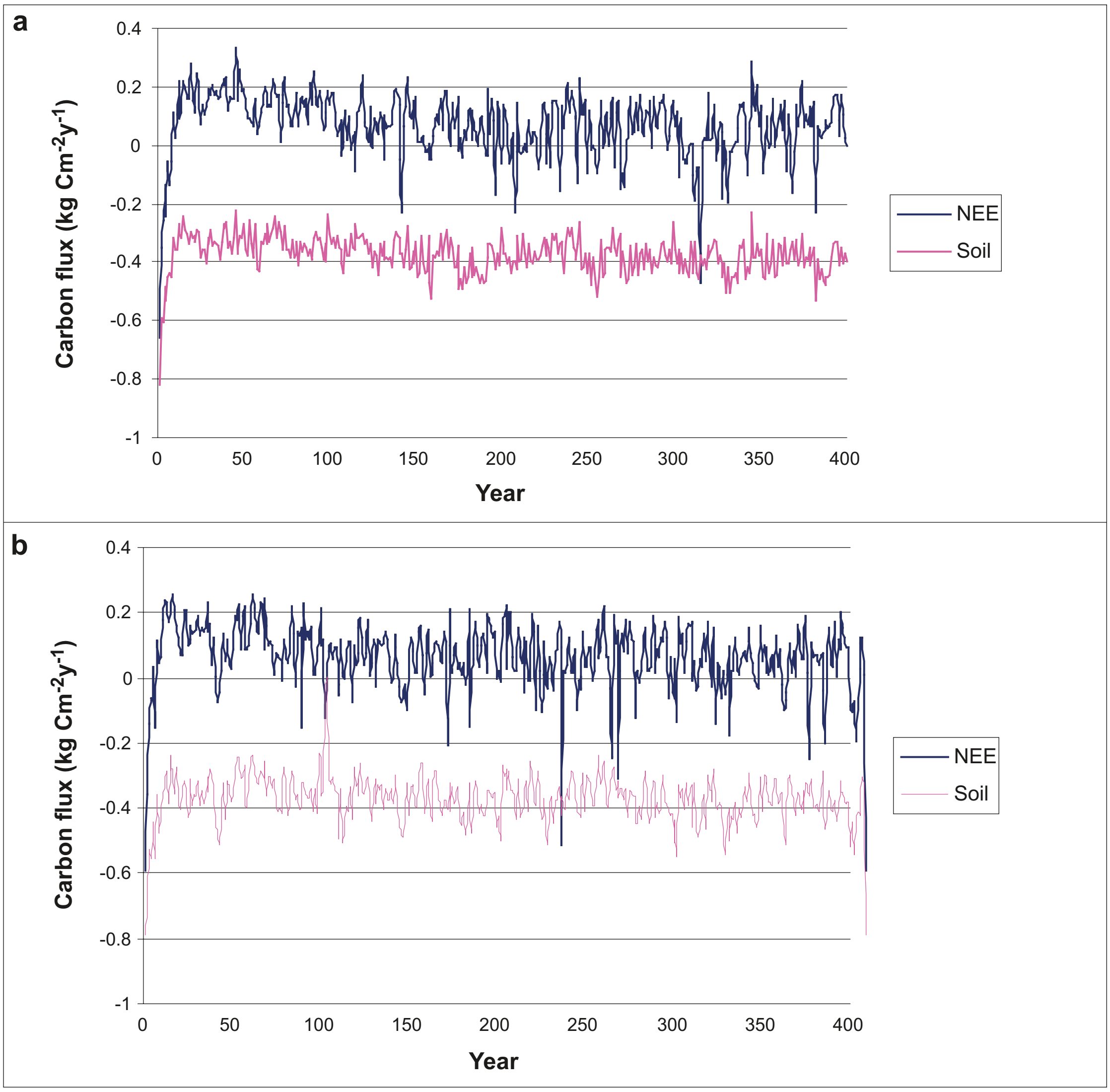


Figure 7-8. *Heterotrophic soil respiration in a forest during a period of 400 years starting after a clear-cut for (a) Forsmark and (b) Laxemar-Simpevarp. The model was driven by climate data describing a 100-year period that was repeated. Values are given in kgC* m^{-2} y^{-1}.

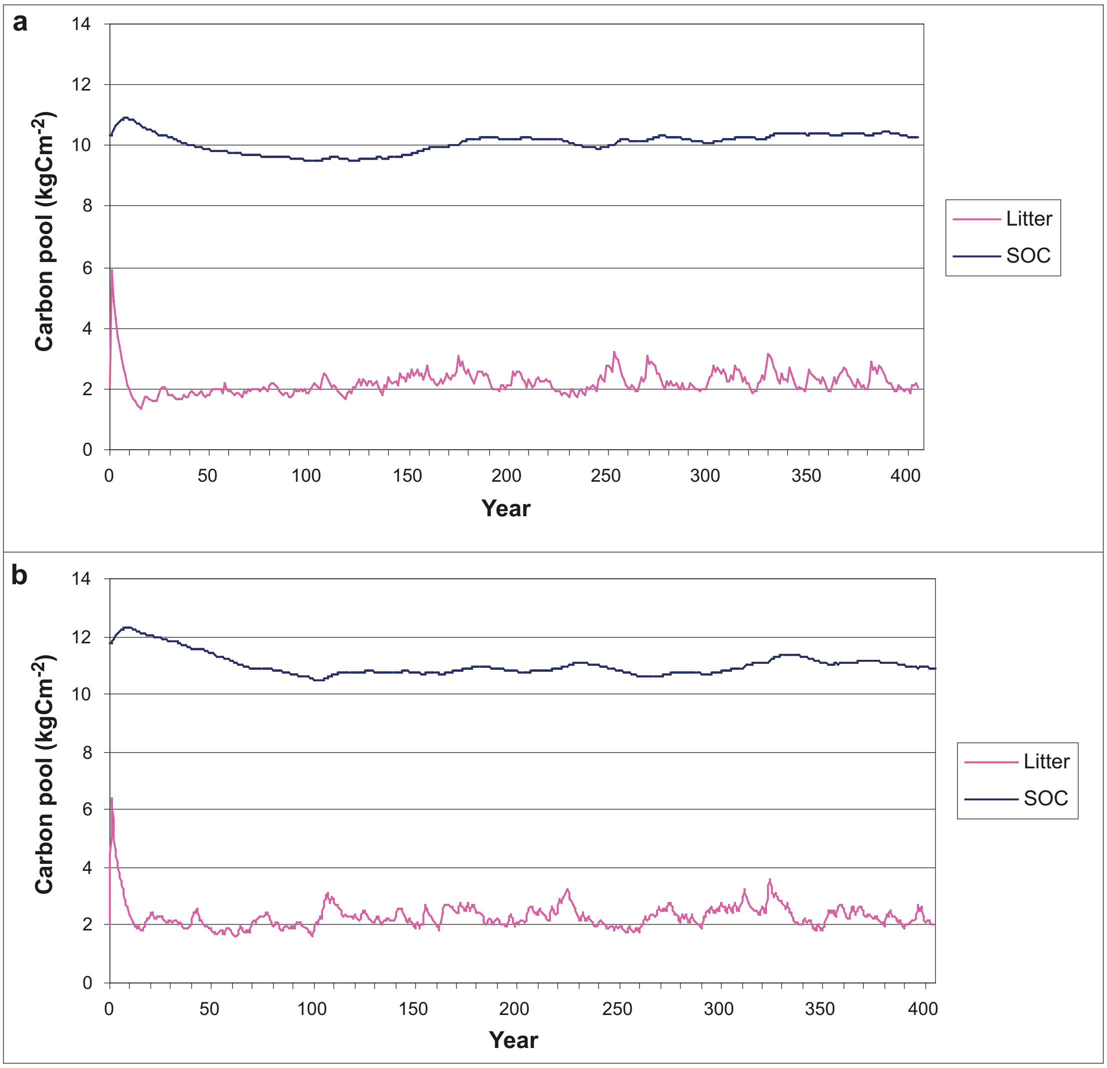


Figure 7-9. *Litter and soil organic carbon (SOC) pools in a forest during a period of 400 years starting after a clear-cut for (a) Forsmark and (b) Laxemar-Simpevarp. The model was driven by climate data describing a 100-year period that was repeated. Values are given in kgC* m^{-2} y^{-1}.

Temporal variation in a 100-year forest cycle

Average values of carbon balances during a 100-year forest cycle (after which period a commercially managed forest is felled) are illustrated in Figure 7-10. There was a positive uptake of carbon in both investigation areas, i.e. more carbon was added to the vegetation than was lost due to respiration. This can be explained by the fact that biomass was mainly accumulated during the first 100 years.

Descriptive statistics are shown in Table 7-7 and mean, standard deviation and median values are based upon the 100-year perspective. Maximum values were taken from the 400-year perspective since maximum values show the potential peak of the ecosystem property.

Temporal variation in carbon balances for arable land

Crop NPP (397 gC m^{-2} y^{-1}) and crop yield (182 gC m^{-2} y^{-1}) were rather similar in Forsmark and Laxemar-Simpevarp, Table 7-8. In the agricultural areas, there was a 6 gC m^{-2} y^{-1} net accumulation of SOC in Laxemar-Simpevarp, whereas 3 gC m^{-2} y^{-1} was accumulated in Forsmark. This accumulation was mainly caused by the large input of biomass that was left in the field after bringing in the yield.

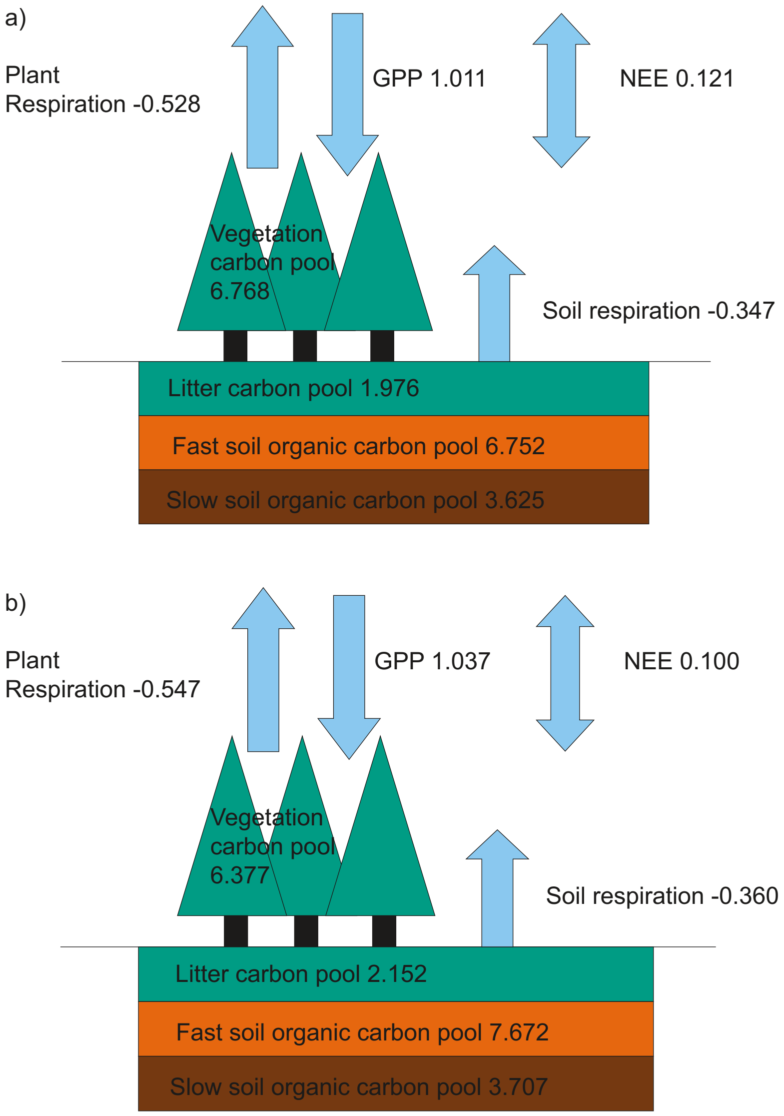


Figure 7-10. *Summary of the dominant carbon fluxes and carbon pools for a 100-year forest cycle until final felling in a) Forsmark and b) Laxemar-Simpevarp. Values are given in kgC* m^{-2} *for the carbon pools and kgC* m^{-2} y^{-1} *for the carbon fluxes.*

Table 7-7. Mean, standard deviation and median of the temporal variation in some ecosystem properties during the first 100 years and maximum values during the 400-year forest cycle for Forsmark and Laxemar-Simpevarp. Values are given in gC m^{-2} for the carbon pools and gC m^{-2} y^{-1} for the carbon fluxes.

Property	**Forsmark**			**Laxemar-Simpevarp**		
	mean±sd	**median**	**max**	**mean±sd**	**median**	**max**
LAI$_{\text{tree}}$	3.31±0.78	3.54	3.96	3.28±0.62	3.41	3.94
NPP$_{\text{tree}}$	459±103	482	736	464±84	479	562
NPP$_{\text{field}}$	19±40	9	252	20±43	11	257
Biomass$_{\text{tree}}$	6,403±3,433	7,099	14,524	6,052±2,868	6,041	12,986
Biomass$_{\text{treegreen}}$	170±47	189	210	148±32	158	172
Biomass$_{\text{treeroot}}$	171±47	189	212	151±33	160	193
Biomass$_{\text{treetotal}}$	6,744±3,536	7,509	14,896	6,351±2,945	6,353	13,325
Biomass$_{\text{field}}$	23±45	11	269	26±48	14	279
Litterfall	335±120	335	1,128	338±128	322	1,022
Respiration$_{\text{soil}}$	–347±80	–335	–819	–360±87	–350	–787
Litter	1,976±493	1,894	3,214	2,152±566	2,009	5,314
SOC	10,016±424	9,847	10,892	11,379±555	11,380	12,290
NEE	121±131	148	658	100±122	121	592

Table 7-8. Descriptive statistics of NPP, harvest of crop and accumulation of soil organic carbon (SOC) over 100 years in gC m^{-2} y^{-1}.

Property	Forsmark			Laxemar-Simpevarp		
	mean±sd	median	Min – max	mean±sd	median	Min. – max.
NPP	395±51	398	255–584	399±46	400	249–583
Yield*	185±22	186	125–241	178±22	178	123–271
SOC$_{\text{accumulation}}$	3±4	2	–4–16	6±6	6	–8–21

* 66% of aboveground biomass /Olsson 2006, HIR Malmöhus pers. comm./.

7.4 Discussion

7.4.1 Validation of the dynamic vegetation model

Unlike other more detailed models, LPJ-GUESS simulates carbon and vegetation dynamics directly on the basis of local climate, which makes the model very applicable. Several studies have compared the output of LPJ-GUESS and the closely related DGVM LPJ with the output of more detailed models, and even though they are driven by few parameters, robust results have been obtained for carbon balances and vegetation distribution /Bachelet et al. 2003, Cramer et al. 2001, Jung et al. 2007, Badeck et al. 2001/. The models have also been evaluated against field estimates of carbon, vegetation dynamics and water exchange across Europe /Sitch et al. 2003, Morales et al. 2005/. Along a European continental temperature gradient, LPJ predicts the general trends in LAI and GPP well in comparison with site data /Jung et al. 2007/. LPJ-simulated FAPAR was also comparable with remote-sensed estimates /McCloy and Lucht 2001/. LPJmL, a model developed for managed planetary land surface, was used to simulate the spatial distribution of sowing dates for temperate cereals, and the outputs were comparable with reported crop calendars /Bondeau et al. 2007/. Simulated yields for temperate cereals and maize were in good agreement with estimates from the FAO (Food and Agriculture Organization of the United Nations /Bondeau et al. 2007/). Fluxes of carbon over agricultural areas were also accurately described by the simulations /Bondeau et al. 2007/. In a study aiming at adapting LPJ-GUESS to African biomes, /Hély et al. 2006/ showed that model-estimated LAIs were in good agreement with remote-sensed estimates of LAI. For the same African biomes, the modelled vegetation composition agreed well with the vegetation cover obtained from a vegetation map and pollen data /Hély et al. 2006/.

Vegetation patterns, phenology and vegetation structure were accurately described by LPJ on a global basis /Sitch et al. 2003/. /Badeck et al. 2001/ showed that LPJ-GUESS correctly simulated the dominant plant functional types (PFTs) at five European pristine forest sites, and /Smith et al. 2001/ also correctly predicted the PFT composition of observed natural vegetation at various sites across Europe. LPJ-GUESS simulated vegetation dynamics, tree species composition and biomass accurately at three sites in the region of the great lakes, USA /Hickler et al. 2004/. LPJ also captured the broad patterns of vegetation distribution across the USA well /Bachelet et al. 2003/. The models have been used in several other applications such as palaeo-ecological changes and their link to climate dynamics /Ni et al. 2006, Lunt et al. 2007/, hydrological features e.g. evapotranspiration and runoff /Morales et al. 2005, Gerten et al. 2004/ and threshold responses of ecosystems to changing climates /Cowling and Shin 2006/.

7.4.2 Model limitations and parameter uncertainties

The development of process-based ecosystem models involves many assumptions and uncertainties. Inaccuracies mainly arise from the input data driving the simulation, the mathematical descriptions of the mechanisms behind the ecosystem processes and the parameters set in these functions to scale the mathematical estimates /Zaehle et al. 2005/. General considerations relevant to the LPJ-GUESS model involve the simplifications of the disturbance regime, the lack of anthropogenic influences, nutrition limitations and parameter uncertainties.

The disturbance regime in LPJ-GUESS was simplified to a mean disturbance interval of 100 years. This is the average return time for natural disturbances such as fire /Zackrisson 1977/. Climate changes influence the disturbance regime so that fires, diseases, pests and extreme weather events become increasingly common as the temperature increases. LPJ-GUESS is commonly used for predictions of vegetation dynamics under changing climate conditions, so changes in the disturbance regime should therefore be incorporated into the model. Nevertheless, under modern conditions 100 years is the average return time for natural disturbances /Zackrisson 1977/ and it has also been used in several earlier modelling studies /Koca et al. 2006/.

Another limitation of the model is that land-use practices and anthropogenic effects on vegetation dynamics were not included in the model. Both carbon and vegetation dynamics are highly influenced by both human management and unintentional human-induced effects. Forest management practices – for example soil scarification (chopping or ditching), thinning, competition control and fertilization – alter carbon and vegetation dynamics and should therefore be taken into account as well /Tyree et al. 2006/. No crop management was incorporated into the model, and the only factors that distinguished crops from C_3 grass were the root to leaf ratio and the fact that no roots survived the winter. An improvement would be to include management practices such as conventional tillage or no-till farming, crop rotation, leaving crop residue mulch and fertilization /West and Post 2002, Lal 2007/. Other factors that may be important to include are climate-dependent sowing and harvesting periods and more species-specific parameterization of the crops used in the investigation areas. Including anthropogenic influences is an important next step in future development of the model.

The model does not take into account the possible small-scale heterogeneity of environmental variables and the nutritional status of the soils. Small-scale heterogeneity can affect spatial variation in carbon balances as well as vegetation dynamics. Nitrogen can both be a limiting factor and a fertilizer of plant production. It could be important to include nitrogen constraints on NPP to limit NPP and to make sure that it is not overestimated. The net effect of nutrients on carbon balances is hard to predict, but several studies have shown that NPP is accurately predicted even if the model does not include a nutrient module e.g. /Koca et al. 2006, Bondeau et al. 2007, Cramer et al. 2001, Hickler et al. 2006/. A negative effect of including nutrient limitations is that parts of the generality and the simplicity of the model are lost when additional complex modules are included.

/Zaehle et al. 2005/ performed an uncertainty analysis of the parameters in LPJ to elucidate what the most important parameters are for controlling carbon balances. They came to the conclusion that the most important factor influencing NPP, heterotrophic respiration and vegetation carbon pools is the constant for intrinsic quantum efficiency (0.08 in this study). This is the constant that gives the intrinsic slope of the correlation between GPP and PAR, determining the amount of carbon taken up by photosynthesis per amount of solar radiation. The second most important factor for NPP and heterotrophic respiration is the constant determining the amount of PAR that is lost due to absorption of non-photosynthetic structures (0.4 in this study) such as stems and branches. These factors alter the uptake of solar radiation, leading to changed NPP and thereby changes in LAI and other carbon fluxes such as heterotrophic respiration. The second most important factor for the vegetation carbon pool was the turnover rate of sapwood (Table 7-3), while for the litter carbon pool it was the turnover rate of litter (Table 7-3). Other important factors are the shape parameter (0.7 in this study), describing the convex relationship between the GPP-PAR relationship and the light use efficiency constant /Zaehle et al. 2005/. There are also other species-specific parameters that alter the shape and allometry of the tree, naturally affecting LAI as well as the vegetation carbon pool and NPP. Wood density is another parameter, and with higher wood density less carbon can be allocated to, for example, leaves. Leaf longevity is an important parameter affecting the amount of leaves on the branches. Even though uncertain parameters can result in propagation errors, /Zaehle et al. 2005/ showed that the overall response of simulated carbon fluxes in LPJ to climate variation was relatively robust.

The model is adapted to global circumstances and not specifically Nordic environments. It has been shown in a comparison of the standard deviation of modelled results and measurements that uncertainties are higher at northern latitudes than in the more southern and tropical regions /Zaehle et al. 2005/. In particular, the parameters in the photosynthesis module are more sensitive at northern latitudes. /Zaehle et al. 2005/ showed that increasing the constant determining the amount of PAR that is lost due to absorption of non-photosynthetic structures and the intrinsic quantum efficiency increases the agreement between model and field estimates at northern latitudes. The parameters that contribute the most to uncertainties in LPJ, are, however, quite well known. The model has little sensitivity to the parameters that are more uncertain (for example descriptions of allometry, stand structure and fire dynamics) /Zaehle et al. 2005/.

7.4.3 Evaluation of the dynamic vegetation model

Leaf area index

Generally, the modelled LAI was acceptable and realistic compared with both field estimates and other studies, which have a range between 1.2 and 8.4 (average 3.6 of 54 studies)) /Chen et al. 1997, Fassnach and Gower 1997/. The direct correlation with field-estimated LAI was not significant, and the reason for this was one of the deciduous stands, a dense oak stand with very large LAI. If the dense oak stand is omitted, the correlation is significant (0.74, p-value 0.006). The model estimates more of an average value for the area, so these large values were not well simulated. This is the reason why the comparison with NDVI-estimated LAI (an average estimate for the investigation areas) was better correlated. For deciduous stands, the modelled LAI and the NDVI-estimated LAI were the same (2.50).

Soil respiration

The model underestimated soil respiration compared with measured values. One explanation could be that field estimates of soil respiration included all CO_2 respired from the ground, whereas model estimates did not include leaf respiration from the field layer and respiration from coarser roots was not included in root respiration but in sapwood respiration. However, the field layer should only have a minor effect, since only sparse field layers were seen in the forest stands where the measurements were performed /Tagesson and Lindroth 2007/. A large fraction of root respiration originates from fine roots, which was included in modelled soil carbon respiration /Pregitzer et al. 1998, Widén and Majdi 2001, Saiz et al. 2007/. Moreover, different studies have different boundaries between fine and coarse roots, e.g. /Widén and Majdi 2001/ and /Pregitzer et al. 1998/ adopted 5 mm whereas /Saiz et al. 2007/ adopted 3 mm as a boundary. In the model, the boundary was set at 2 mm /Matamala and Schlesinger 2000/, and a smaller fraction of total root respiration was included in fine root respiration, resulting in lower modelled soil respiration in comparison with field estimates.

Even though the model gave lower estimates than the field estimates, they were in the same range (between 281 and 459 gC m^{-2} y^{-1}) as literature values of field-estimated soil respiration. In a review by /Raisch and Schlesinger 1992/, the soil in boreal forests respires on average 324 gC m^{-2} y^{-1}. Similarly, soil respiration in the pasture, with an estimate of 308 and 327 gC m^{-2} y^{-1} for Laxemar-Simpevarp and Forsmark, respectively, was in the lower part of the observed range compared with field estimates of between 273 and 756 gC m^{-2} y^{-1} /Maljanen et al. 2001, Suyker and Verma 2001, Flanagan et al. 2002, Suyker et al. 2003/. /Tagesson and Lindroth 2007/ attributed their high field-estimated values either to errors in the estimation technique or the fact that several of the forest stands were managed. For example, one of the field estimates was from a spruce forest stand in Laxemar-Simpevarp on newly ditched peat. Site management alters primary production and this influences soil respiration. These factors were not included in the model.

Net primary production

Model-estimated Net Primary Production (NPP) was on average 514 gC m^{-2} y^{-1}, whereas LAI-estimated NPP was high at 540 gC m^{-2} y^{-1}compared with literature values. According to /Gower et al. 2001/, who used field measurements of stem increment, litterfall and root biomass, NPP values in Sweden and Finland for the boreal forests were between 210 and 460 gC m^{-2} y^{-1}. However, this was based on a few study sites. /Zheng et al. 2004/ combined remote-sensed data from the Advanced Very High Resolution Radiometer (AVHRR) and field estimates for spatial distribution of NPP over Sweden and Finland and showed that Forsmark and Laxemar-Simpevarp are in regions with high NPPs, which explains the higher values. Field estimates from two forests stands in Forsmark and two in Laxemar-Simpevarp were 454 gC m^{-2} y^{-1}, 537 gC m^{-2} y^{-1}, 591 gC m^{-2} y^{-1} and 736 gC m^{-2} y^{-1}, see Chapter 6. Other studies have also obtained large NPPs for these regions. For Norunda in the region of Forsmark, /Lagergren et al. 2005/ obtained NPP values between 710–940 gC m^{-2} y^{-1} with an average of 810 gC m^{-2} y^{-1}, and /Olofsson et al. 2006/ obtained values between 660 and 890 gC m^{-2} y^{-1}.

In the comparison with field estimates of stem increment, conversion factors for modelled NPP included several uncertainties. Smaller factors have been used in the past /Eriksson 1991, Nabuurs et al. 1997/, and if Eriksson's conversion factors were used instead, average model- and LAI-based NPP converted to stem increment would be 6.421 and 6.749 m^3 ha^{-1} y^{-1}, respectively, i.e. significantly closer to the field estimates of 5.911 m^3 ha^{-1} y^{-1}.

Forest net ecosystem exchange

A large range of NEE values are found for boreal forests, from a small loss of carbon at the Norunda site (52 gC m^{-2} y^{-1}) /Lagergren et al. 2008/ to a large gain of about 1,300 gC m^{-2} y^{-1} in an aspen forest in central Saskatchewan /Black et al. 1996/. Many different estimates have been recorded falling between these extremes e.g. /Goulden et al. 1997, Kolari et al. 2004, Lagergren et al. 2008/. Model-estimated NEEs (72±167 and 177±106 gC m^{-2} y^{-1} in Laxemar-Simpevarp and Forsmark, respectively) were in the intermediate range of most studies. One major outlier can be seen in Laxemar-Simpevarp: the old spruce forest with a loss of –194 gC m^{-2} y^{-1}, which was caused by the stochastic fire disturbance regime since as much as –415 gC m^{-2} y^{-1} was lost due to fire.

Crop and grass net ecosystem exchange

In the grasslands and agricultural areas in both Forsmark and Laxemar-Simpevarp, modelled NEE indicated that there was a net uptake of carbon (between 63 and 150 gC m^{-2} y^{-1}). In Laxemar-Simpevarp, field estimates of NEE suggested a net emission of between 0 and 380 gC m^{-2} y^{-1} for agricultural fields /Tagesson 2007/, whereas for grasslands the net emission of carbon was between 375 and 651 gC m^{-2} y^{-1} /Tagesson and Lindroth 2007/. /Tagesson and Lindroth 2007/ attributed the net emission to meadow drainage, a disturbance not included in the model. Other studies have obtained NEE values more similar to the model, and there is a wide range of NEE estimates from net emission to accumulation (–950 to 274 gC m^{-2} y^{-1}) /Suyker et al. 2003, Flanagan et al. 2002, Novick et al. 2004, Maljanen et al. 2001, Byrne et al. 2005, Soegaard et al. 2005, Hollinger et al. 2005/.

Crop and grass gross primary production

The only field estimates that could be compared to modelled GPPs were from a pasture and an agricultural field in Laxemar-Simpevarp. Model-estimated GPPs (773 gC m^{-2} y^{-1}) for pastures were higher than field estimates (540±360 gC m^{-2} y^{-1}, seminatural grassland in Table 4-47), even though the difference was not significant /Tagesson and Lindroth 2007/, whereas the agricultural areas were accurately simulated (field: 710±270 gC m^{-2} y^{-1}; model: 750 gC m^{-2} y^{-1}) /Tagesson 2007/. Modelled GPPs for the field layer in the pasture and the agricultural field were similar compared with a number of grassland studies in which the estimates varied between 270 and 1,210 gC m^{-2} y^{-1} /Flanagan et al. 2002, Suyker and Verma 2001, Suyker et al. 2003, Novick et al. 2004/.

Biomass

Field data were only available from four forest stands in a comparison with the model (Laxemar-Simpevarp: 1 old spruce, 1 deciduous; Forsmark: 2 old spruce). Nevertheless, data for the four forest types were checked for normal distribution by a Kolmogorov-Smirnov test and average values and standard deviations were calculated (Table 7-9).

Modelled tree wood biomass seemed to be slightly higher than the field estimate. Modelled biomass was high in a comparison with other studies as well. In a review by /Jarvis et al. 2001/, estimated total biomass for boreal forests ranged from 500 gC m^{-2} to 6,500 gC m^{-2}, with an average value for boreal forests in Western Europe of 5,100 gC m^{-2} y^{-1}. Biomass varied depending on ecosystem features such as species, age, climate, disturbance interval, latitude, soil character and nutrient availability, explaining the wide ranges of values /Jarvis et al. 2001, Giese et al. 2003/.

Modelled leaf carbon estimates were lower than field measurements (Table 7-9). The leaf carbon fraction of the total carbon pool was 0.02, which was half the fraction used by /Nabuurs et al. 2003/. The main parameter affecting leaf carbon mass is the leaf to root fraction. In the model, the maximum value of this parameter was set at one, but it was reduced due to water stress and was estimated to be 0.5–0.7. This is similar to values estimated in other field studies /Oleksyn et al. 1999/. According to field estimates from the investigation areas, this fraction should be as high as 2.91. Increasing the leaf to root fraction would also increase NPP in the upper part of its range.

Modelled field layer carbon estimates were less than the field estimates, probably due to the large estimated tree carbon pool. Uptake by trees represents a large fraction of incoming PAR and may therefore reduce the available light for the field layer.

Litterfall

Field measurements of annual input of above-ground litter from trees at three sites in Laxemar-Simpevarp and two sites in Forsmark were performed using circular litter traps with a nominal sampling area of 0.32 m^2 for 2004–2006 /Mjöfors et al. 2007/. Model-estimated total litter production was compared with field estimates of above-ground litterfall. Field estimates were available for 2004–2005 and for 2005–2006 /Mjöfors et al. 2007/. Average values of these two years were used for the model-estimated litter production and compared with the field estimates using a Pearson correlation. For all sites in both Forsmark and Laxemar-Simpevarp, average above-ground litterfall estimated in the field was 115±56 gC m^{-2} y^{-1}, whereas modelled total litter production was 504±23 gC m^{-2} y^{-1}. The Pearson correlation test indicated that there was no correlation between field-estimated above-ground litterfall and model-estimated total litter production (n=10, Pearson correlation 0.08, *p*-value 0.83). /Saarsalmi et al. 2007/ estimated about the same amount of litterfall (119 gC m^{-2} y^{-1}) as the field estimates for differently aged boreal forests over Finland 1961–2002. One reason for high model estimates of the litter production was that the modelled litterfall was all carbon moved from the vegetation pool to the litter pool, including both carbon moved from the living vegetation and mortality, whereas the field estimates comprised only above-ground litterfall from needles/leaves, twigs (Ø ≤ 5 mm), cones, seeds and flake bark from trees, omitting larger branches and roots.

Table 7-9. Mean biomass (±SD) of different components in four forest types as estimated by field studies and modelling. Values given in gC m^{-2}.

Property	Field	Model
Tree leaves	481±197	162±66
Tree wood	6,745±1,813	7,926±1,323
Tree fine roots1	166±52	162±66
Grass leaves	19±18	11±3
Grass roots	68±60	23±6

[1] Fine roots < 2 mm.

Soil organic matter

Field estimates for the investigation areas indicate an average of 6,340 gC m^{-2} for the SOC pool and 490 gC m^{-2} for the litter pool. This was much lower than the model estimates for the same ecosystem types, with 10,770 gC m^{-2} for the SOC pool and 2,390 gC m^{-2} for the litter pool. The field estimates were also lower than the mean for Sweden of 8,200 gC m^{-2} /Olsson et al. 2008/, which in turn was much lower than average estimates of SOC for boreal forests of, in general, around 15,000 gC m^{-2} /Schlesinger 1977, Pregitzer and Euskirchen 2004/. The latter figure was similar to the sum of the modelled litter, fast and slow SOC pools. An explanation of the discrepancy between field estimates and model estimates is that both Laxemar-Simpevarp and Forsmark are situated close to the coast, where the soils are young, resulting in a lower amount of SOC in comparison with average values for boreal forests /Lundin 2004, 2005a/. The high soil respiration estimated in the field could also be a result of easily decomposed litter, which would lead to a small amount of litter being present. Field estimates were very low in comparison with average values for boreal biomes, and the forests in Laxemar-Simpevarp and Forsmark do not have more litter than the average soils of grasslands /Schlesinger 1977/.

7.4.4 Spatial variation in net primary production

Previous studies have shown significant differences in NPP on different spatial scales. Climate is a major factor influencing NPP /Runyon et al. 1994/ and there are differences in climate within the investigated areas. It is wetter and warmer near the coast than further inland, even though the distance is only a couple of kilometres /Johansson et al. 2005, Larsson-McCann et al. 2002a, b/. Other properties that differ within the investigation area that affect NPP are species composition, age of forest, forest management, humus quality, sap conductivity, elevation, topographic gradients, soil properties, site water balance and nutrient availability /Burrows et al. 2003, Ahl et al. 2004, Albaugh et al. 2004, Fassnach and Gower 1997, Le Dantec et al. 2000, Samuelson et al. 2004/.

The estimates indicated much greater variation in NPP in Forsmark than in Laxemar-Simpevarp, (Table 7-6). The relationship between LAI and NPP is of an exponential character with a negative coefficient, i.e. at a certain level NPP reaches saturation and does not increase with LAI. LAI values for several ecosystem types are higher in Laxemar-Simpevarp than in Forsmark (Table 7-6), and NPP estimates are, therefore, closer to this saturation level, which gives lower variation. For the ecosystems with the same LAI or even lower LAI in Laxemar-Simpevarp, variation in NPP was still lower because NPPs for these ecosystem types are lower in Laxemar-Simpevarp (Table 7-6) and the saturation level was thereby reached at an earlier stage.

Today, data from land inventories, satellite imagery, research observations and dynamic vegetation modelling is often integrated to examine spatial and temporal patterns of ecosystem properties and processes e.g. /Liu et al. 1999, Knorr and Heimann 2001, Chen et al. 2003, Nemani et al. 2003, Knorr et al. 2004, Zheng et al.2004/. In an error analysis, /Knorr and Heimann 2001/ found that the sensitivity to the input parameters of the model was significantly reduced when satellite data were incorporated. In order to produce consistent results, dynamic vegetation models need correct input data. Remote sensing produces reliable input data on such factors as land use, soil quality and forest structure. /Smith et al. 2008/ performed an analysis of the accuracy of dynamic vegetation modelling alone and two different methods combining remote sensing with dynamic vegetation modelling. Their results suggest that the method using a model in combination with satellite data on vegetation structure gave the most accurate results.

In this study, we have quantified the spatial distribution of NPP, an important parameter in the quantification of carbon budgets. However, other parameters are equally important for a large-scale understanding of the spatial distribution of carbon balance. Thus, it is important to find ways of estimating other parts of carbon balance in the investigation areas. All ecosystem carbon pools and fluxes are estimated in dynamic vegetation models, and using this information to estimate key ecosystem responses to satellite-based information should be a straightforward method for completing the picture of the carbon balances of a region.

7.4.5 Temporal variation in carbon balances for forested areas

Generally, in a 400-year perspective, the forest stands reach an equilibrium with regard to carbon fluxes after between 150 and 200 years, Figures 7-6 to 7-9. A natural forest stand reaches a dynamic equilibrium after some time with a certain amount of young and old trees, due to disturbances and/or mortality. A general problem with the model is that it is designed for natural, not managed ecosystems. It is impossible to simulate stands containing only 400-year-old trees, since disturbances are included and the model is not local but regional. Average stand values are therefore simulated.

Vegetation dynamics

Generally, LPJ-GUESS simulated species composition and vegetation dynamics well (Figure 7-6). Boreal forests follow a common successional pattern after a major disturbance /Bergeron 2000/. In a young forest, sapling trees such as birch are common and hardwood plants dominate. Coniferous species begin growing among the hardwoods, but their growth is slow. In the second phase, as the stand matures and coniferous trees start to dominate, the hardwood species die off. Finally, in the climax state, the canopy is more open and coniferous trees are the most common. A few deciduous trees grow in the openings. The model follows these successional stages well. During the first few years silver birch dominated, then after about ten years coniferous and deciduous species were equally common and finally coniferous forests dominated. This tree-age dynamic was similar to the vegetation dynamics reported by /Bergeron 2000/.

In a comparison between modelled biomass (an as average for forests in equilibrium, i.e. the 300–400-year old forest) and an area occupied by the different species in the /Boresjö Bronge and Wester 2003/ vegetation map, species composition was simulated acceptably (Table 7-10). Pine was most common both in the field and in the simulations. In Forsmark, deciduous trees were more common in the field than in the model, whereas the model accurately approximated the situation in Laxemar-Simpevarp. Spruce trees were more common in the model than in the simulations for both investigation areas. The model is thought to simulate natural ecosystems well, whereas the situation is not so straightforward for both investigation areas as these are highly influenced by forest management.

Thus, although a comparison could be made between the modelled tree vegetation at the end of the time series and the vegetation map describing the forest composition today, it was not possible to determine whether the quantitative differences arose from limitations of the model or the effects of forest management.

Biomass

Generally, biomass increases until a certain age, at which the biomass accumulation levels off. The explanation is that NPP and maintenance respiration reach equilibrium and more biomass cannot be accumulated. /Pregitzer and Euskirschen 2004/ estimated this age to be between 120 and 200 years, which is roughly the same age as when carbon mass was saturated in the model (Figure 7-6).

Table 7-10. Species composition in Forsmark and Laxemar-Simpevarp as simulated by the model and as fractional area of the vegetation map by /Boresjö Bronge and Wester 2003/.

Vegetation type	Forsmark Field	Model	Laxemar-Simpevarp Field	Model
Norway spruce	0.25	0.40	0.09	0.29
Scots pine	0.49	0.58	0.82	0.60
Deciduous	0.27	0.02	0.09	0.11

Net primary production

Young stands have a high NPP. This is caused by increasing LAI with age so that more carbon can be accumulated. NPP reaches its peak at the maturity of the stands and then starts to decline with age (Figure 7-7). After between 150 and 200 years, NPP reaches equilibrium and it does not change at all. /Gower et al. 1996/ explained a decrease in above-ground NPP by decreasing soil nutrient availability and increasing hydraulic resistance in the stomata, which decreases water conductivity. /Binkley et al. 2002/ explain the decline in forest growth by competition-related changes in stand structure, where fewer large dominant trees sustain their resource efficiency at a cost of the resource efficiency of smaller non-dominant trees. /Smith and Long 2001/ have a similar explanation: the decline in forest growth is a result of canopy closure and interference between tree crowns. These factors affect production of foliage of the stands, resulting in a decrease in NPP with age /Smith and Long 2001, Binkley et al. 2002, Kashian et al. 2005/.

Net ecosystem exchange

/Kolari et al. 2004/ estimated NEE for four differently aged spruce stands in Finland. NEE changes with age, and they reported that 4 years after clear-cutting the forest stand acted as a source of carbon and 386 gC m^{-2} y^{-1} was lost to the atmosphere. In both Laxemar-Simpevarp and Forsmark the model estimate a loss of about 140 gC m^{-2} y^{-1} in 2005, but only the year before the loss was estimated to be 360 and 256 gC m^{-2}, respectively. In a 12-year old stand, /Kolari et al. 2004/ estimated NEE to be about 0 gC m^{-2} y^{-1}, whereas this was reached after 7 years in Laxemar-Simpevarp and 9 years in Forsmark. After that, forests generally start to be sinks of carbon and accumulate carbon in the vegetation and in the SOC pools. NEE of 40-year old stands in Finland was between 172 and 192 gC m^{-2} y^{-1}, which is similar to the model estimates at Forsmark and Laxemar-Simpevarp. In the Finnish study, the carbon sink increased with age, and at the age of 75 years stands had an NEE of 323 gC m^{-2} y^{-1}. In Laxemar-Simpevarp and Forsmark, however, it decreased slightly with forest age, and at the age of 70–79 years on average NEE was 121 gC m^{-2} y^{-1}. After that, the forest achieves equilibrium and for the 100 to 400-year old stands, NEE was on average 55 gC m^{-2} y^{-1}, i.e. a small sink of carbon is present (Figure 7-8).

Soil respiration

A pattern with high soil respiration in forest stands of medium age and lower in younger and older forests has been found in previous studies /Pregitzer and Euskirchen 2004/. The same tendency could also be seen in modelled soil respiration (Figure 7-8), although it was not very clear, especially in Laxemar-Simpevarp. According to /Janssens et al. 2001/and /Högberg et al. 2001/, NPP is the main factor determining soil respiration. A possible reason for the small differences in soil respiration at different ages for a forest stand in Laxemar-Simpevarp could be the small difference between peak NPP and NPP at equilibrium.

Litter and soil organic carbon pool

The large litter pool during the first year was a result of the large input directly after clear-cutting, and the subsequent decline in this pool was a result of heterotrophic decomposition. The litter pool was back at the same level as before clear-cutting after only 17 years. Several studies have shown that the SOC pool increases temporarily after harvesting /Black and Harden 1995, Pennock and van Knessel 1997, Johnson and Curtis 2001/, as was also seen during the first 9 years in the modelled output. After that, the 100-year continuous decline in SOC was probably an effect of a lower input of litter as a fraction of NPP, due to a high accumulation of biomass during these years. A general trend should be that the SOC pool reaches equilibrium after a while and returns to the same level as before the harvest /Johnson and Curtis 2001/. This was seen in Forsmark, whereas in Laxemar-Simpevarp the level was slightly lower than before clear-cutting. Several scenarios are widespread in the literature. /Black and Harden 1995/ hypothesized that the continuous decrease in the SOC pool for a forest in California was due to lower C/N ratios. In a review of world forests, /Pregitzer and Euskirschen 2004/ described a continuous increase in the SOC pool.

7.4.6 Temporal variation in carbon balances for agricultural areas

The simulations for the agricultural areas were simplified. Crop management was not included in the model, and the only factors that distinguished crops from C_3 grass were the root to leaf ratio and the fact that no roots survived the winter. An improvement would be to include crop management, climate-dependent sowing and harvesting periods and more species-specific parameterization for the crops used in the investigation areas.

Net primary production

Compared with a global NPP average of 344 gC m^{-2} y^{-1} for agricultural areas /Goudriaan et al. 2001/, NPP was accurately estimated by the model (395 gC m^{-2} y^{-1} in Forsmark and 399 gC m^{-2} y^{-1} in Laxemar-Simpevarp). Other studies have obtained similar values (375–425 gC m^{-2} y^{-1}) /Bolinder et al. 2007/. Several factors influence the variation in NPP. NPP is generally proportional to incoming radiation, but the relationship can be altered by factors such as temperature, limited water supply, pests and nutrients /Goudriaan et al. 2001/. The variations caused by climate factors and disturbances such as pests were included in the model estimates, whereas nutrient limitations were not. Shortage of nutrients, however, is very rare since fertilization is common practice in agricultural areas.

Yield

The yield estimates (185 gC m^{-2} y^{-1} for Forsmark and 178 gC m^{-2} y^{-1} for Laxemar-Simpevarp) were somewhat lower than in regional statistics for the period 1966–1996, which were 242±110 gC m^{-2} y^{-1} in Forsmark (Uppsala County) and 207±101 gC m^{-2} y^{-1} in Laxemar-Simpevarp (Kalmar County) (Data from *www.scb.se*, corrected by adding threshing loss and straw yield, see Section 4.1.2, and averaged for five different crops). However, not statistically significant. The assumption of a 66% removal of total biomass as yield may be too low and more should be allocated to harvest. The standard deviation for the yield statistics was much higher (a factor of 4), probably because the statistics were based on five different crops.

Soil organic carbon

The SOC pool is strongly dependent on agricultural management and type of crop grown /West and Post 2002, Baker et al. 2007/. Most agricultural soil contains less SOC than its ecological potential, and SOC pools are depleted and not accumulated as in the model results /Lal 2007/. Accumulation or depletion of the soil is strongly dependent on management practices, such as conventional tillage or no-till farming, crop rotation, leaving crop residue mulch and fertilization /West and Post 2002, Lal 2007/. 33% of the biomass was left as crop residue mulch in the model, whereas the rest was removed as yield, explaining the accumulation of carbon in the SOC pool.

7.4.7 Conclusions

Unlike many other detailed models, requiring many input parameters, LPJ-GUESS simulates carbon and vegetation dynamics based on the local climate. Generally the model-simulated carbon balances acceptably well. Values were in the upper range for boreal forests but not unrealistic in comparison with field data and literature values. Temporal variation in carbon balances was also estimated and was fairly similar to literature estimates. The model has a couple of limitations, and the limitation that probably had the greatest influence on the results for the investigation areas was that anthropogenic influences were not included. The investigation areas consist of managed forests, and sites are prepared by for example chopping, ditching, thinning, competition control and fertilization. These factors should be included in the future development of the model. The SOC pool may also be greatly overestimated due to the young soils at both sites. Remote sensing and dynamic vegetation modelling were combined to estimate spatial variation in NPP. Further improvements in this technique could be used to refine the input by including more spatial information, such as soil character, forest structure and land use. Nevertheless, the model has provided a good description of carbon balances in both investigated areas, and carbon balances were estimated realistically in comparison with field estimates and the literature.

8 Pools and fluxes of matter on the catchment scale

8.1 Introduction

Descriptions of pools and fluxes of matter in a catchment are of increasing interest in Environmental Impact Assessments describing flows and accumulations of bioavailable contaminants such as radionuclides /Kumblad 2004, Lindborg and Löfgren 2005, Naito et al. 2002/. The rationale for using the catchment scale is that transport of elements is mediated by water and the catchment will set the boundary for further transport and accumulation. Within the catchment biotic process will set boundaries to what is available for further transport up in the food web and accumulation in vegetation or soil. In this chapter, carbon estimates are presented across a landscape mosaic of different vegetation types and management regimes using a geographical information system (GIS). This approach has also been presented for Laxemar-Simpevarp in an earlier publication /Löfgren et al. 2006/, but is here made with more site-specific data and with a more comprehensive description of alternative human land use. The carbon estimates were based on a combination of field and model estimates of pools and fluxes previously described in Chapters 4, 6 and 7. Pools and fluxes of consumers, such as animals, birds, amphibians and reptiles were included, as well as fluxes to humans. Human use of the landscape was described and analyzed in three different ways: a regional generic case, a self-sustainable case and a case in which all potential arable land was used as such.

A large data set is presented in this chapter for the purpose of supporting further calculations and discussions in the safety analysis of the two sites. Many of the data are therefore onl presented in tables and not further discussed in this chapter. The descriptions applicable to carbon also underpin the mass balance calculations for a large number of other elements that are presented in Chapter 9.

8.2 The conceptual model describing pools and fluxes of organic matter on the catchment scale

The definition of and the rationale for the use of the different ecosystem compartments and fluxes of carbon follows the description presented in Chapter 5, but a number of pools and fluxes have been aggregated here in order to present an overview of pools and fluxes on the catchment scale (Figure 8-1). Net primary production (NPP) is treated as the sum of all vegetation production. The biomass of the tree layer is divided into a green and a woody compartment. The field layer consists of both the field layer and the bottom layer, whereas the root compartment consists of both tree and field layer fine roots (Ø < 2 mm for trees and < 10 mm for herbs and grasses). The regolith is divided into a humus and a mineral soil compartment. The humus compartment consists of both litter and humus layers. Heterotrophic respiration is soil respiration minus autotrophic root respiration. Litter production is the combined fluxes from litterfall and root litter production. Horizontal transport is the water-mediated transport of mainly dissolved organic carbon to streams and lakes.

8.3 Data and methods

8.3.1 The catchments

The catchments that were modelled in Forsmark and Laxemar-Simpevarp are shown in Figures 8-2 and 8-3 with regard to their spatial distribution. Tables 8-1 and 8-2 are included to show differences between the areas with regard to major land use classes.

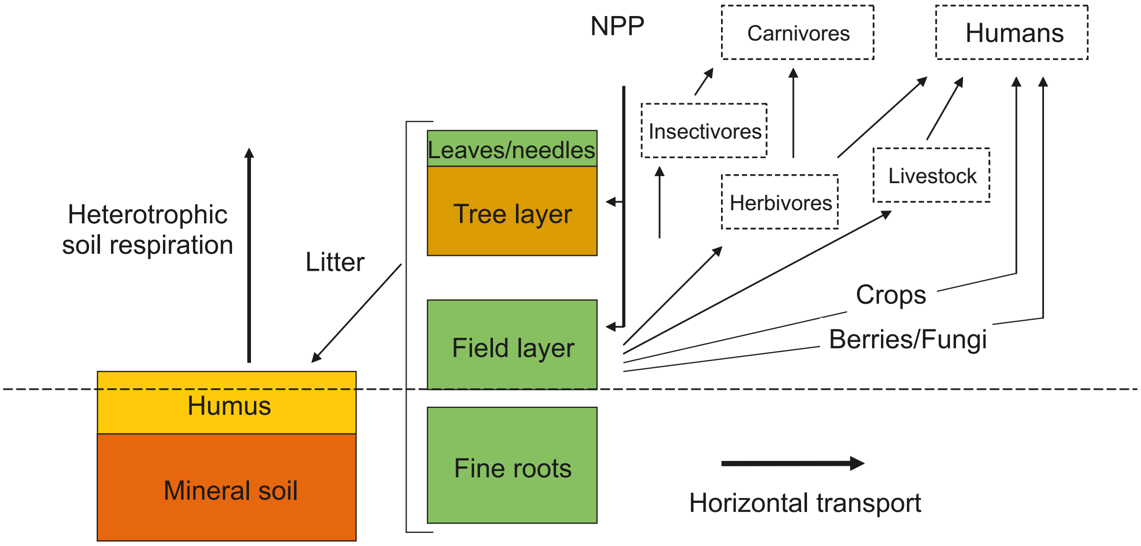


***Figure 8-1.** The different pools and fluxes describing the carbon balance on the catchment scale. Coloured boxes symbolize pools and arrows fluxes, whereas non-coloured boxes represent the consumers.*

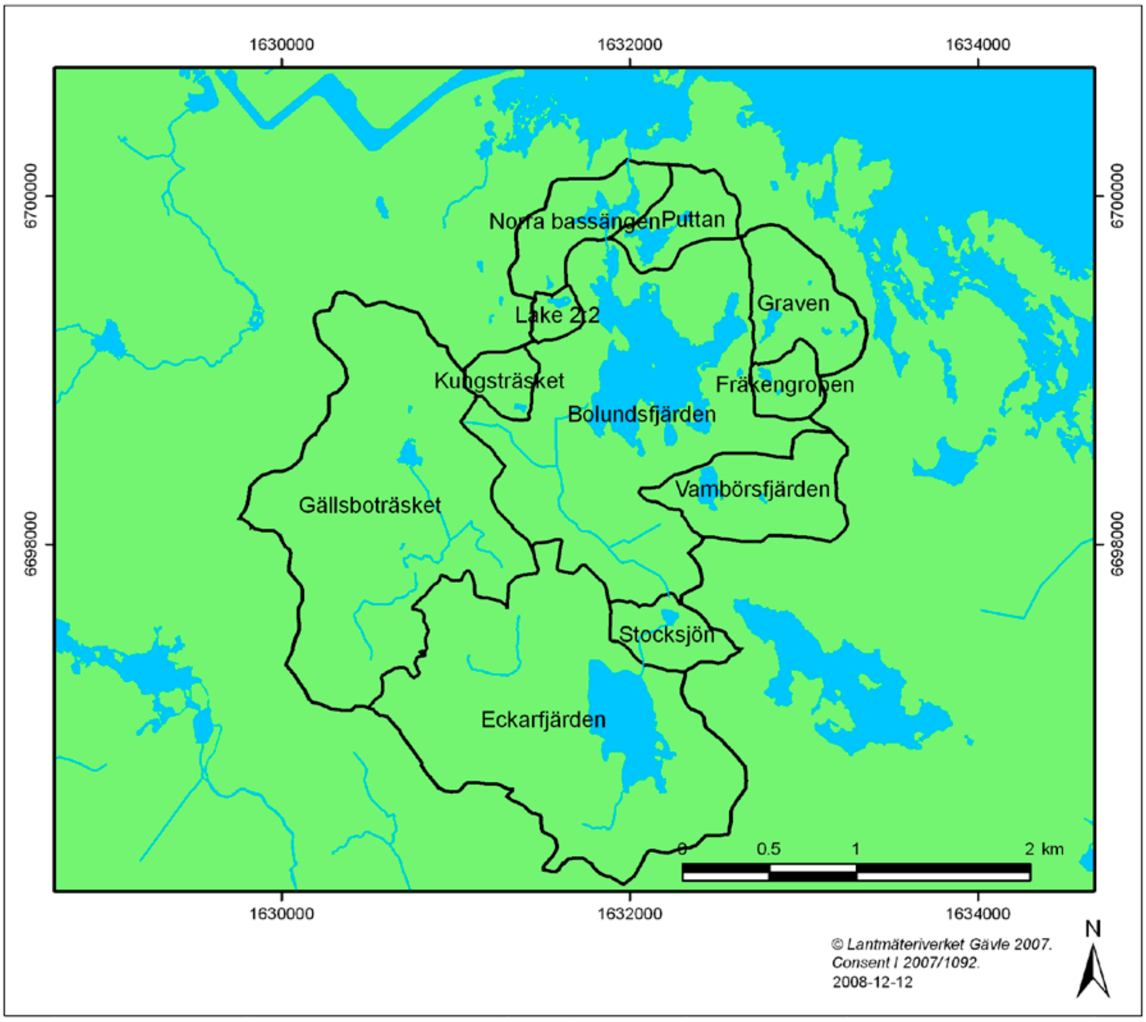
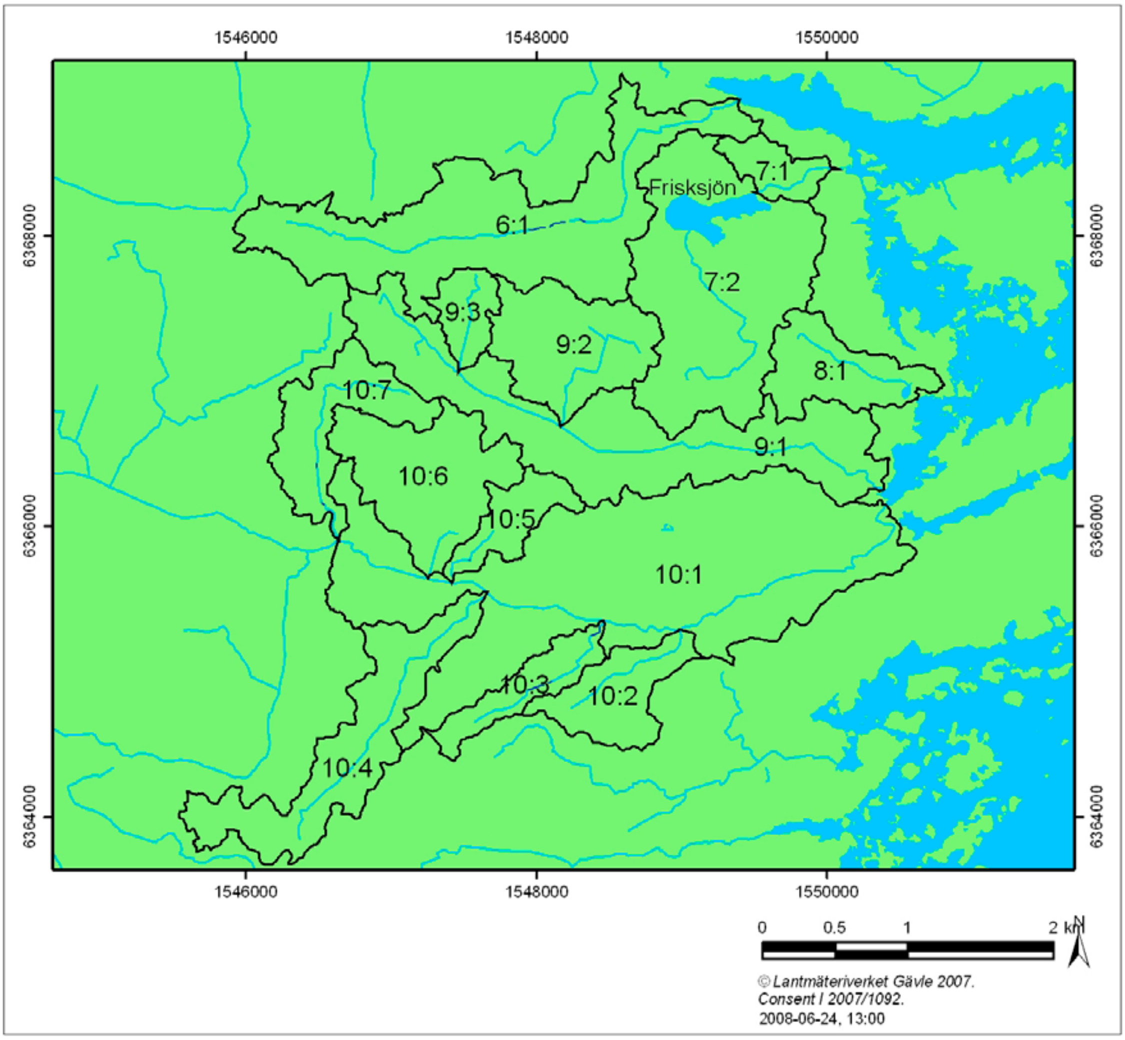


***Figure 8-2.** Forsmark with all 11 sub-catchments shown.*



© Lantmäteriverket Gävle 2007.
Consent I 2007/1092.
2008-06-24, 13:00

Figure 8-3. *The 11 sub-catchments modelled in the Laxemar-Simpevarp area. Catchment 10:1 continues to the left, but only the downstream area shown in the figure was modelled.*

Table 8-1. The total areas of the catchments and the relative distributions (%) of some vegetation types in the modelled Forsmark catchments.

Catchment	Basin nr	Area (km^2)	Forest	Forested wetland	Wetland	Arable land	Pasture	Clear-cut
Bolundsfjärden	136	1.84	69.6	2.2	17.9	0.0	0.0	10.3
Eckarfjärden	149	2.08	64.4	0.0	7.7	0.5	4.8	22.6
Fräkengropen	133	0.14	78.6	0.0	21.4	0.0	0.0	0.0
Gällsboträsk	142	2.13	40.8	0.5	11.3	0.0	0.5	46.9
Graven	127	0.38	63.2	0.8	26.3	0.0	0.0	7.9
Kungsträsket	131	0.12	58.3	0.0	5.0	0.0	0.0	33.3
Lake 2:2	128	0.07	71.4	0.0	7.1	0.0	0.0	28.6
Norra Bassängen	125	0.32	68.8	1.9	28.1	0.0	0.0	0.3
Puttan	124	0.22	59.1	0.0	36.4	0.0	0.0	2.3
Stocksjön	147	0.21	76.2	0.0	19.0	0.0	1.4	1.4
Varmbörsfjärden	141	0.46	78.3	2.2	19.6	0.0	0.0	2.2
Total		8.0	60.6	0.9	14.7	0.1	1.4	22.2

Table 8-2. The total areas of the catchments and the relative distributions (%) of some vegetation types in the modelled Laxemar-Simpevarp catchments.

Catchment	Basin nr	Area (km^2)	Forest	Forested wetland	Wetland	Arable land	Pasture	Clear-cut
6:1	502	2.00	75.5	0.1	0.0	12.0	5.0	7.5
7:1	502	0.21	85.7	0.0	5.7	0.0	0.0	11.4
7:2	507	1.74	84.5	0.3	1.2	6.3	2.1	6.3
8:1	508	0.50	90.0	0.0	3.2	0.0	1.4	3.6
9:1	508	1.85	69.7	0.0	0.2	10.8	5.9	13.0
9:2	508	0.77	71.4	0.0	0.0	14.3	0.3	13.0
9:3	508	0.22	63.6	0.0	0.0	17.3	3.2	18.2
10:1	508	3.44	65.4	1.3	0.5	6.4	6.7	19.5
10:2	508	0.46	69.6	0.0	1.3	11.1	3.5	14.3
10:3	508	0.32	84.4	0.0	0.0	7.5	2.5	6.3
10:4	508	1.00	73.0	0.7	0.0	15.0	3.9	8.3
10:5	508	0.29	48.3	1.4	0.0	4.5	2.1	41.4
10:6	508	0.89	76.4	0.3	0.0	3.6	3.1	16.9
10:7	508	0.61	86.9	0.0	0.0	3.0	2.5	8.2
Total		14.3	73.5	0.5	0.6	8.5	4.2	12.9

8.3.2 Description of vegetation types

Spatial delimitation of vegetation types

The vegetation types in the vegetation maps were re-classified into a more coarse-grained classification by merging grid code classes into new classes (Tables 8-3 and 8-4). Hard surfaces, mainly coastal rocks, were not assigned any values, due to low or absent biomass and NPP. There were no sea shores in the modelled catchments at the Forsmark and Laxemar-Simpevarp sites.

Identification and classification of wetlands in the interface zone between the terrestrial and aquatic environments

Near-shore areas identified as wetlands in the vegetation map (satellite images 25×25m resp. 30×30m, /Boresjö-Bronge and Wester 2003/) were overlain with the zero-DEM isoclines, showing the sea level, to distinguish between wetland habitats and the sea basin. Wetland parts falling below the zero-DEM isocline were included in the sea basin element budget. However, no sea shore wetlands were found within the modelled terrestrial catchments of Forsmark and Laxemar-Simpevarp.

The wetlands situated close to lakes were identified with the vegetation map. Lakes have been described in earlier work /Brunberg et al. 2004a, b/, where the highest high water level was used to identify different kinds of habitats within the lake. One of these, called Littoral I, is defined as an area "with emergent and free-floating macrophytes, which is developed in shallow wind-sheltered areas with soft substrate". For the lakes in Forsmark, these areas were dominated by reed (*Phragmites australis*) and were classified as "open wetlands to lake". This also applied to Frisksjön in Laxemar-Simpevarp, which was the only lake within the modelled catchments.

Concerning accumulation and transport of radionuclides, an assumption of zero exchange between a wetland (reed belt) and the lake/sea has to be regarded as conservative as long as the wetland area is smaller than the lake area, since it concentrates the radionuclides into an area (the reed belt) smaller than the area of accumulation bottoms in adjacent sea basins. The potentially most important input of high-concentration contamination is contaminated groundwater discharging into the interface between land and lake/sea, or discharging higher up in the drainage areas, rather than directly into the sea water. This may, however, not be applicable to a wetland–lake interface, since radionuclides can reach much higher concentrations in the lake water than in the sea due to the generally smaller water volumes and longer water retention times in lakes.

Parameterization of the vegetation types

The identified vegetation types were parameterized using data from the LPJ-GUESS modelling (Tables 7-4 and 7-5). Wetlands were, however, difficult to model with LPJ-GUESS and therefore other sources of information had to be used in order to present carbon budgets for those ecosystems. In Forsmark, one Norway spruce wetland with alder was studied, whereas one alder near-shore wetland was studied in Laxemar-Simpevarp (see Section 6, SS1 and S1 in Table 6-10). These were used to describe the forested wetlands in both Forsmark and Laxemar-Simpevarp. The conifer wetland in Laxemar-Simpevarp is, however, dominated by Scots pine, but due to the small total area of this wetland type in Laxemar-Simpevarp, the Norway spruce wetland from Forsmark was used instead.

For the non-forested wetland types, mires and wetlands in connection with lakes, a number of sources were used including local measurements as well as literature data. Site-specific data describing biomass and NPP for both Forsmark and Laxemar-Simpevarp were available for the mires /Löfgren 2005/. Similarly, /Hedenström and Sohlenius 2008, Sohlenius and Hedenström 2008/ presented estimates of the soil carbon pools (see Tables 8-3 and 8-4). Accumulation in the SOC pool for mires was assumed to approximate the long-term accumulation in mires estimated by /Sternbeck et al. 2006/. Accordingly, heterotrophic respiration was calculated by substituting accumulation in the SOC from litter production. The reason for not using the estimated soil respiration from a mire in Laxemar-Simpevarp by /Tagesson 2007/ was because of difficulties in separating the soil respiration into its autotrophic and heterotrophic components. The vegetation type “wetland to lake”, which is a reed-dominated ecosystem, was assigned the biomass and above-ground (AG) NPP estimates from the sites (Table 4-6) /Andersson et al. 2003, Andersson et al. 2006/. Below-ground (BG) production was assumed to be 77% of the AG production /Asaeda and Karunaratne 2000/. By assuming that the annual root mortality was 7.5% /Asaeda and Karunaratne 2000/, AG mortality was 100%, 41% of the litter production was respired regardless whether it was produced AG or BG /Asaeda and Karunaratne 2000/ and the rest was transferred to the SOC pool, all fluxes could be calculated.

In the evaluation of the LPJ-GUESS results, the SOC was consistently found to be overestimated by the model. Site estimates of the litter pool were also added /Löfgren 2005/ and the calculations are described in Section 6.2.2. The humus and mineral soil carbon pools were from /Lundin et al. 2004, 2005a/, which have partly been recalcultated, see /Hedenström and Sohlenius 2008, Table 6-32 Sohlenius and Hedenström 2008/. The conifer wetland was parameterized with a SOC pool from Forsmark when used for Forsmark and with a pool from Laxemar-Simpevarp when used for Laxemar-Simpevarp. The LPJ-GUESS estimates lacked a bottom layer, which may be rather significant in terms of biomass and NPP in boreal environments. A bottom layer were therefore added with regard to biomass /Löfgren 2005/. NPP for this layer was, however, not added to avoid interference with the climate-based descriptions of the fluxes. The resulting parameterization is presented in Table 8-3 for Forsmark and Table 8-4 for Laxemar-Simpevarp.

Implementation in a GIS

The ecosystems and their properties (Tables 8-3 and 8-4) were assigned grid codes in the vegetation map (column 2). This resulted in a map describing the spatial extent of each ecosystem and their different ecosystem properties. The catchments were individually cut out and the area of each vegetation type was multiplied by the area-specific property in Tables 8-3 and 8-4 and added to the result for each vegetation type and pool/flux within the catchment to generate an estimate for the whole catchment.

Table 8-3. Ecosystem properties for the vegetation types used to describe the terrestrial landscape in Forsmark in the GIS model. The grid codes in column 2 are defined in /Boresjö Bronge and Wester 2003/. Pools are in gC m^{-2} and fluxes are in gC m^{-2} y^{-1}.

Vegetation types	Grid code in Veg. map	Source	Tree layer				Field and bottom layer				SOC pool					Accumulation	
			Wood	Green	Roots	NPP	Green	Roots	Bottom layer	NPP	Litter	Humus	Min. soil	Het._ resp	Lit. prod.	Acc._veg.	Acc._SOC
Young Norway spruce	12,41,43	Spruce25[1]	3,997	222	222	628	13	26	62	37	544	2,921	4,586	355	428	177	103
Old Norway spruce	11	Spruce80[1]	8,702	194	194	564	14	28	62	39	544	2,921	4,586	404	594	–7	237
Young Scots pine	14,42	Pine25[1]	4,201	216	216	617	12	25	62	33	544	2,921	4,586	361	301	306	–19
Old Scots pine	13	Pine80[1]	8,201	173	173	570	7	15	62	17	544	2,921	4,586	398	337	246	48
Scots pine on bedrock	15	Dry pine[1]	8,458	181	182	586	2	4	213	4	544	831	732	452	326	261	–121
Old deciduous forest	21,23,26	Deciduous[1]	6,379	61	61	456	3	6	26	6	506	0	13,554	298	284	172	3
Mixed forest	30	Mixed[1]	7,017	128	128	505	11	22	26	29	506	0	13,554	358	370	158	25
Clear cut	46,50,64	Clear-cut[1]	87	9	9	70	146	291	62	428	544	2,921	4,586	571	242	245	–321
Clear-cut with birch (young deciduous)	44,45,31	C-c birch[1]	1,821	67	67	497	15	29	62	38	544	2,921	4,586	347	394	134	70
Pasture	82	Pasture[1]	0	0	0	0	176	353	23	477	459	0	13,884	327	444	33	117
Arable land	81	Agri[1]	0	0	0	0	361	69	0	584	0	0	13,884	439	584	0	0
Forested wetland, conifers	61, 62	SS1 (Fm)[2]	5,411	326	166	404	46	22	0	25	383	2,594	3,367	225	299	130	74
Forested wetland, deciduous	63	S1 (Sm)[2]	6,035	97	41	314	15	38	0	46	507	2,594	3,367	365	202	158	–163
Open wetland	64, 72, 74–79	Mire[3]	0	0	0	0	399	1,787	0	253	252	43,282	0	215	253	0	38
Open wetland to lake	See text	Lake shore[3]	0	0	0	0	187	623	0	331	252	43,282	0	81	198	133	117

1) LPJ-GUESS data from Section 7.2) Field-estimated data from Section 6.3) Field-estimated data from Section 4.4) Is not found among the catchments that are described below.

Table 8-4. Ecosystem properties for the vegetation types used to describe the terrestrial landscape in Laxemar-Simpevarp in the GIS model. The grid codes in column 2 are defined in /Boresjö Bronge and Wester 2003/. Pools are in gC m^{-2} and fluxes are in gC m^{-2} y^{-1}.

Vegetation types	Grid code in Veg. map	Source	Tree layer				Field and bottom layer				SOC pool					Accumulation	
			Wood	Green	Roots	NPP	Green	Roots	Bottom layer	NPP	Litter	Humus	Min. soil	Het._ resp	Lit._prod	Acc._veg.	Acc._SOC
Young Norway spruce	12,41,43	Spruce25[1]	3,912	212	213	566	10	20	62	25	775	4,820	3,420	297	354	210	67
Old Norway spruce	11	Spruce80[1]	8,340	195	196	543	9	19	62	25	775	4,820	3,420	346	346	–193	–1
Young Scots pine	14,42	Pine25[1]	4,377	208	208	561	8	15	62	25	775	4,820	3,420	281	371	196	122
Old Scots pine	13	Pine80[1]	8,163	159	160	466	9	18	62	25	775	4,820	3,420	375	744	–340	450
Scots pine on bedrock	15	Dry pine[1]	7,974	155	157	466	8	16	213	19	591	2,410	340	459	592	–119	162
Old deciduous forest	24,25	Deciduous[1]	5,958	62	63	410	8	16	26	25	238	0	9,540	290	312	10	29
Mixed forest	30	Mixed[1]	7,339	119	120	459	7	15	26	25	238	0	9,540	320	448	–101	133
Clear cut	50	Clear-cut[1]	99	10	10	74	120	246	62	25	775	4,820	3,420	532	257	148	–271
Clear-cut with birch (young deciduous)	23,44,45	C-c birch[1]	1,856	62	62	444	8	16	62	25	775	4,820	3,420	275	360	50	106
Pasture	82	Pasture[1]	–	–	–	–	288	281	23	371	236	0	27,600	308	379	–8	88
Arable land	81	Agri[1]	–	–	–	–	288	57	0	446	0	0	20,460	389	446	0	0
Forested wetland, conifers	62	SS1 (Fm)[2]	5,411	326	166	404	3	22	43	25	383	34,180	0	225	299	130	74
Forested wetland, deciduous	63	S1 (Sm) [2]	6,035	97	41	314	15	38	0	46	507	34,180	0	365	202	158	1
Open wetland	71–77, 79,80	Mire[3]	0	0	0	0	190	1,142	110	342	136	1,564	0	313	342	0	29
Open wetland to lake	78, littoral 1	Lake shore[3]	0	0	0	0	275	917	0	487	136	1,564	0	119	291	196	172

1) LPJ-GUESS data from Chapter 7. 2) Field-estimated data from Chapter 6. 3) Field-estimated data from Chapter 4. 4) Is not found among the catchments that are described below.

Export of carbon

The transport of total organic carbon in surface water was estimated from concomitant measurements of concentrations and discharges in streams of Forsmark, Appendix F in /Tröjbom et al. 2007/ and Laxemar-Simpevarp, Appendix C in /Tröjbom et al. 2008/.

Fungi and berry yield

The yield of fungi was assumed to be 0.122 gC m^{-2} y^{-1} (Table 4.56, see discussion in Section 4.3.2) in both Forsmark and Laxemar-Simpevarp. This yield was assigned to all forest types, clear-cuts and grasslands, excluding open wetlands and arable land.

Berry yield was estimated using the information presented in Section 4.3.2 and comprises the following species: bilberry, lingonberry, raspberry, rosehip, cloudberry and cranberry.

8.3.3 Description of consumers

The description of the food web is similar to the one in Sections 4.2.1 to 4.2.3 and is based on the food web illustrated in Figure 4-29. The carbon pools and fluxes were calculated for four functional groups – herbivores, insectivores, carnivores and livestock – in 11 drainage areas in Forsmark and 14 in Laxemar-Simpevarp. The spatial distribution of mammals, birds, amphibians and reptiles followed the distributions presented in Sections 4.2.1–4.2.3. The calculations were based on the general figures per unit area and the habitat selection for each species given in Tables 4-31, 4-32, 4-38 and 4-41 and 4-43, 4-44 and the land use distribution within each site obtained from the vegetation map (see Sections 3.1.2 and 3.2.2).

Distribution of livestock in the landscape

The domestic animals in Forsmark are cattle and sheep, whereas there are cattle, sheep and pigs in Laxemar-Simpevarp. Two different cases were calculated concerning livestock density and production of beef and milk. Firstly, a regional generic case was calculated based on meat production in Forsmark parish and the Laxemar-Simpevarp area, assuming a certain amount of imported fodder (Table 4-31 and 4-32). Secondly, a potential self-sustainable case was calculated where the livestock density was set by the potential area that can sustain the livestock with fodder production and grazing.

Potential self-sustainable case

To calculate the self-sustainable case some assumptions have to be made. Available agricultural land includes both arable land (crop land) and grazed pastures (grazing land). The agricultural land, directly used for agricultural production, is also referred to as direct land area. In order for the food production system to work, more agricultural area is needed than the actual agricultural land where the food is produced. This agricultural land that is not directly used for agricultural production is called semi-direct area /Johansson 2005/.

/Johansson 2005/ has calculated the direct area (DA) for producing food consumed in Sweden for the period 1997–2000 using the following equation: DA = D+I–E, where D is the domestic area, I is the imported area and E is the exported area. The domestic area (D) producing food was 2.67 million ha in Sweden for the period 1997–2000. The imported area (I) was 1.86 million ha. The exported area (E), which to some extent is related to the imported area, e.g. the area for coffee and oil-bearing crops that are imported and then re-exported, was 0.79 million ha. This gives a DA of 3.74 million ha. Together with the semi-direct land, estimated to be 261,744 ha in /Johansson 2005/, the total agricultural area comprises 4 million ha, or 0.44 ha per capita. The most dominant food area was that of fodder production, corresponding to 74% of Swedish DA. When calculating the potential production of crop and meat in the future, 74% of the agricultural area is assumed to be used for fodder production and grazing and 26% for crop production for human consumption. It is possible to estimate a potential self-sustainable case for each drainage area, based on the assumption that 74% of the agricultural area is used for fodder production and grazing and 26% for crop production for human consumption.

According to /Arnesson 2001/ a cow needs approximately 2.4 hectares for fodder production and grazing for its survival. This gives a density of 41.7 cows per km^2. One dairy cow can produce 7,735 kg of milk per year (2002). The cow gives birth to her first calf at the age of two years. Thereafter she has a calf each year and gives milk for ten months a year. An average dairy cow is slaughtered at the age of five years after she has given birth to three calves /Miliander et al. 2004a, b/. Accordingly, five cows, 0–5 years old, can together produce three calves per year. Hence, three cows of five can produce milk. The milk production per unit area has been estimated using the following formula:

$Pmilk = \rho \times 3/5 \times 7,735$

where ρ is the cattle density of 41.7 cows per km^2 and Pmilk is the production rate of milk in kg per km^2 per year.

The total milk production in each catchment can be estimated based on the agricultural area. A steady population of five cows, 0–5 years old, which produces three calves per year, would have to keep one calf per year for breeding, which leaves two for slaughter together with the oldest cow. When calculating the theoretical total meat production per unit area the following formula has been used:

$Pmeat = 1/5 \times \rho \times Xcow + 2/5 \times \rho \times Xcalf$

where X is the biomass (live weight) and ρ is the cattle density of 41.7 cows per km^2.

The theoretical total meat production per unit area has to be converted to the utilized carcass, which is calculated to 57% of the live weight /Miliander et al. 2004a, b/. The average weight of slaughtered cows and calves is presented in /Miliander et al. 2004a, b/. The carbon content of milk can be estimated from the content of proteins, carbohydrates and lipids /Altman and Dittmer 1964, Dyson 1978, Rouwenhorst et al. 1991/ (see Section 4.1.2).

Human consumption

The human consumption of crops (barley) and animal products (beef, milk and game meat) originating from the 11 catchment areas in Forsmark and 14 in Laxemar-Simpevarp was calculated using three different cases regarding consumption of agricultural products: a regional generic case, a potential self-sustainable case and crop production alone.

Human consumption of crops

Barley is the dominant crop in Forsmark and Misterhult parish /Miliander et al. 2004a, b/ and human consumption is assumed to be equal to the standard yield of barley in the yield survey district (SKO area 0322 for Forsmark and SKO area 0814 for Laxemar-Simpevarp, Table 4-11). The standard yield is the yield of crops that are gathered during the harvest (straw yield and threshing loss excluded).

Production in each drainage area has been estimated by multiplying the standard yield by the estimated area for crop production.

According to Table 4-9, only 16% of the arable land in the Forsmark parish is used for production of crops for human consumption. This figure has been applied to the catchment areas in the regional generic case. Only one catchment area (Eckarfjärden) contained some arable land. According to Table 4-10, 21% of the arable land in Laxemar-Simpevarp is used for production of crops for human consumption.

In the self-sustainable case, 26% of the agricultural area is used for crop production, and in the third case, 100% of the agricultural area is used for crop production.

The amount of carbon in barley is estimated to be 0.46 $gC\ gdw^{-1}$, the same as for the field layer in /Fridriksson and Öhr 2003/. The dry weight is 86% of the fresh weight /SCB 2000b/.

Human consumption of domestic meat

Consumption of beef has been estimated for each catchment area based on the meat production in Forsmark parish and the Laxemar-Simpevarp area (Tables 4-12 and 4-13) and the area for fodder production and grazing in each catchment area. For the regional generic case, the area corresponds to 93.3% of the field area in Forsmark and 86.5% in Laxemar-Simpevarp (see Section 4.1.2). In the self-sustainable case, 74% of the field area is used for fodder production and grazing.

Human consumption of game meat

The species hunted for consumption are moose, roe deer and hare. The average harvests of these species in the local hunting zones of Forsmark and Misterhult parish /Miliander et al. 2004a, b/ were applied to the catchment areas of Forsmark and Laxemar-Simpevarp (Tables 8-6 and 8-7). Human consumption (utilized part of carcass weight) is assumed to be 80% of the carcass weight, and the carcass weight is assumed to be 55% of the live weight /Cederlund G 2004, pers. comm./. The local carcass weights for moose are given in /Cederlund and Lemel 2007a, b/, which give carcass weights for 2002–2006. The live weight of roe deer and hare are obtained from /Truvé and Cederlund 2005/.

Table 8-5. Hunting statistics describing the carbon flux from wildlife to humans in Forsmark.

Harvested species	Habitat	Harvest ind*km^{-2} (mean ± SD)	Biomass mgC m^{-2} y^{-1} (mean ± SD)	Carcass biomass mgC m^{-2} y^{-1} (mean ± SD)	Utilized biomass mgC m^{-2} y^{-1} (mean ± SD)
Moose[1]	Field +Forest	0.53 (± 0.08)	13.5 (± 1.97)	7.4 (± 1.09)	5.9 (± 0.87)
Roe deer[2]	Field +Forest	1.91 (± 0.53)	5.6 (± 1.54)	3.1 (± 0.85)	2.5 (± 0.68)
European hare[2]	Field	0.28 (± 0.13)	0.13 (± 0.06)	0.069 (± 0.03)	0.055 (± 0.02)
Mountaine hare[2]	Forest	0.13 (± 0.15)	0.05 (± 0.05)	0.02 (± 0.03)	0.02 (± 0.02)

[1] Harvest data for 1999-2003, from the County administrative board

[2] Harvest data for 1997-2001, from the National Association of Huntsmen

Table 8-6. Hunting statistics describing carbon flux from wildlife to humans in Laxemar-Simpevarp.

Harvested species	Habitat	Harvest ind*km^{-2} (mean ± SD)	Biomass mgC m^{-2} y^{-1} (mean ± SD)	Carcass biomass mgC m^{-2} y^{-1} (mean ± SD)	Utilized biomass mgC m^{-2} y^{-1} (mean ± SD)
Moose[1]	Field +Forest	0.48 (± 0.10)	11.5 (± 2.5)	6.3 (± 1.4)	5.1 (± 1.1)
Roe deer[2]	Field +Forest	2.15 (± 0.99)	6.3 (± 2.9)	3.5 (± 1.6)	2.8 (± 1.3)
European hare[2]	Field	0.29 (± 0.11)	0.13 (± 0.05)	0.07 (± 0.03)	0.06 (± 0.02)
Mountain hare[2]	Forest	0.1 (± 0.07)	0.04 (± 0.03)	0.02 (± 0.01)	0.02 (± 0.01)

[1] Harvest data for 1997-2003, from the County administrative board

[2] Harvest data for 1997-2001, from the National Association of Huntsmen

8.4 Results

8.4.1 Vegetation and regolith

The calculated pools and fluxes for the vegetation and regolith pools are presented in Tables 8-7 and 8-8.

8.4.2 Food web

The calculated pools and fluxes within the food web at both sites are presented in Tables 8-9 and 8-10. Birds are shown separately and contribute significantly to both biomass and consumption in all catchments (Tables 8-11, 8-12), where the ratio between birds and other animals (excluding livestock) in Forsmark was 5% and 81% for biomass and consumption, respectively. The corresponding figures for Laxemar-Simpevarp were 4% and 48%. Pools and fluxes for domestic animals are presented in Tables 8-13 and 8-14 for a generic and a self-sustainable case.

Tabell 8-7. Pools and fluxes for vegetation and soil in Forsmark. Pools are in gC and fluxes gC y^{-1}.

		Bolundsfjärden	Eckarfjärden	Fräkengropen	Gällsboträsk	Graven	Kungsträsket	Lake 2:2	Norra Bassängen	Puttan	Stocksjön	Varmbörsfjärden
Tree layer	WOOD	9.76E+09	1.06E+10	9.22E+08	7.47E+09	1.56E+09	5.52E+08	3.37E+08	1.45E+09	1.04E+09	1.26E+09	2.58E+09
	GREEN	2.64E+08	2.72E+08	2.04E+07	2.31E+08	5.12E+07	1.69E+07	1.04E+07	4.19E+07	2.51E+07	2.84E+07	7.34E+07
	ROOTS	2.58E+08	2.68E+08	2.04E+07	2.29E+08	5.07E+07	1.69E+07	1.04E+07	3.94E+07	2.51E+07	2.84E+07	7.14E+07
Field layer	F_GREEN	7.48E+07	8.18E+07	5.37E+06	8.06E+07	1.81E+07	2.46E+06	1.76E+06	1.48E+07	1.45E+07	8.65E+06	1.67E+07
	F_ROOTS	4.02E+08	2.71E+08	2.93E+07	2.97E+08	1.43E+08	8.62E+06	4.80E+06	1.10E+08	8.11E+07	3.99E+07	1.30E+08
	Bottom layer	1.02E+08	1.19E+08	6.85E+06	1.01E+08	2.77E+07	5.62E+06	2.84E+06	2.47E+07	1.37E+07	1.03E+07	3.11E+07
Total biomass pool		1.09E+10	1.16E+10	1.00E+09	8.41E+09	1.85E+09	6.03E+08	3.67E+08	1.69E+09	1.20E+09	1.37E+09	2.90E+09
Soil organic carbon pool	SOC humus	1.93E+10	1.25E+10	1.47E+09	1.66E+10	5.38E+09	6.62E+08	4.31E+08	4.52E+09	3.90E+09	2.26E+09	4.96E+09
	SOCmin	7.62E+09	1.09E+10	6.23E+08	9.10E+09	1.34E+09	5.36E+08	2.71E+08	1.53E+09	7.94E+08	8.81E+08	1.88E+09
	Litter prod	7.35E+08	7.93E+08	6.34E+07	7.90E+08	1.50E+08	4.82E+07	2.94E+07	1.15E+08	8.57E+07	7.38E+07	1.93E+08
	Resp.	6.26E+08	7.65E+08	4.73E+07	7.42E+08	1.21E+08	4.35E+07	2.35E+07	9.61E+07	6.38E+07	6.90E+07	1.61E+08
NPP	Total	9.92E+08	1.15E+09	7.39E+07	1.15E+09	1.99E+08	6.97E+07	3.87E+07	1.61E+08	1.07E+0.8	1.09E+08	2.53E+08
NEP		4.09E+08	4.47E+08	3.08E+07	4.50E+08	7.96E+07	2.91E+07	1.59E+07	6.78E+07	4.69E+07	5.10E+07	1.02E+08
	Acc. veg.	2.28E+08	3.25E+08	8.92E+06	3.32E+08	4.03E+07	1.93E+07	7.71E+06	4.02E+07	1.91E+07	3.39E+07	5.10E+07
	Acc. SOC	1.82E+08	1.22E+08	2.19E+07	1.19E+08	3.93E+07	9.74E+06	8.20E+06	2.77E+07	2.78E+07	1.71E+07	5.05E+07
Export	TOC*	5.56E+06	5.06E+06	4.12E+05	5.91E+06	1.33E+06	2.92E+05	1.43E+05	1.07E+05	7.74E+05	6.50E+05	1.47E+06

*Diffuse transport per catchment from /Tröjbom et al. 2007/.

Table 8-8. Pools and fluxes for vegetation and soil in Laxemar-Simpevarp. Pools are in gC and fluxes gC y^{-1}.

		6:1	7:1	7:2	8:1	9:1	9:2	9:3	10:1	10:2	10:3	10:4	10:5	10:6	10:7
Tree layer	WOOD	1.06E+10	1.02E+09	1.02E+10	3.53E+09	9.37E+09	3.88E+09	1.03E+09	2.50E+10	2.32E+09	2.00E+09	5.25E+09	1.02E+09	4.67E+09	3.64E+09
	GREEN	2.66E+08	3.46E+07	2.53E+08	7.34E+07	2.17E+08	9.83E+07	2.27E+07	3.87E+08	5.57E+07	4.39E+07	1.20E+08	3.21E+07	1.20E+08	9.11E+07
	T_ROOTS	2.67E+08	3.46E+07	2.54E+08	7.39E+07	2.19E+08	9.89E+07	2.28E+07	3.86E+08	5.60E+07	4.41E+07	1.20E+08	3.20E+07	1.20E+08	9.16E+07
Field layer	F_GREEN	1.14E+08	4.06E+06	6.44E+07	1.10E+07	1.12E+08	4.16E+07	1.86E+07	1.80E+08	2.38E+07	1.20E+07	6.43E+07	9.19E+06	2.66E+07	1.43E+07
	F_ROOTS	7.52E+07	1.72E+07	7.29E+07	3.24E+07	9.05E+07	2.48E+07	1.54E+07	1.93E+08	2.11E+07	9.52E+06	4.16E+07	1.00E+07	2.86E+07	1.49E+07
	Bottom layer	1.19E+08	1.51E+07	1.20E+08	3.87E+07	1.07E+08	5.13E+07	1.29E+07	1.68E+08	2.69E+07	1.85E+07	5.43E+07	1.53E+07	4.96E+07	4.18E+07
Total biomass pool		1.14E+10	1.13E+09	1.10E+10	3.76E+09	1.01E+10	4.19E+09	1.12E+09	2.63E+10	2.50E+09	2.13E+09	5.65E+09	1.12E+09	5.02E+09	3.89E+09
Soil organic carbon pool	SOC humus	7.81E+09	1.08E+09	7.55E+09	2.40E+09	6.76E+09	3.08E+09	8.37E+08	1.33E+10	1.80E+09	1.60E+09	5.17E+09	1.66E+09	4.84E+09	2.63E+09
	SOCmin	1.43E+10	7.62E+08	9.07E+09	1.77E+09	1.37E+10	4.70E+09	1.65E+09	2.58E+10	3.08E+09	1.97E+09	7.75E+09	1.60E+09	5.24E+09	3.07E+09
	Litter prod.	9.96E+08	9.08E+07	9.32E+08	3.19E+08	9.34E+08	3.90E+08	1.14E+08	1.49E+09	2.34E+08	1.77E+08	5.11E+08	1.13E+08	4.19E+08	3.17E+08
	Resp.	6.92E+08	5.90E+07	6.03E+08	1.76E+08	6.51E+08	2.75E+08	8.70E+07	1.11E+09	1.52E+08	1.13E+08	3.52E+08	8.72E+07	2.92E+08	2.07E+08
NPP	Total	1.00E+09	1.14E+08	8.68E+08	2.37E+08	8.73E+08	3.75E+08	9.43E+07	1.62E+09	2.26E+08	1.58E+08	4.78E+08	1.40E+08	4.42E+08	3.11E+08
NEP		2.02E+08	4.00E+07	2.28E+08	5.10E+07	1.77E+08	8.23E+07	1.17E+07	3.44E+08	5.46E+07	2.82E+07	8.87E+07	4.33E+07	1.09E+08	8.22E+07
	Acc. veg.	-1.48E+08	1.16E+07	-1.56E+08	-1.12E+08	-1.54E+08	-5.06E+07	-2.06E+07	-6.01E+07	-3.69E+07	-4.74E+07	-9.08E+07	1.52E+07	-4.01E+07	-4.97E+07
	Acc. SOC	3.50E+08	2.84E+07	3.83E+08	1.63E+08	3.31E+08	1.33E+08	3.22E+07	4.04E+08	9.15E+07	7.55E+07	1.79E+08	2.81E+07	1.49E+08	1.32E+08
Export	Export TOC 1)	9.58E+06	1.02E+06	8.27E+06	2.37E+06	8.82E+06	3.67E+06	1.06E+06	1.64E+07 2)	2.20E+06	1.53E+06	4.78E+06	1.39E+06	4.25E+06	2.91E+06

1) Diffuse transport per catchment from /Tröjbom et al. 2008/; 2) The export amount was calculated using the figure 4,770 gC km^{-2} obtained from /Tröjbom et al. 2008/ and the size of the cut out 10_1.

Table 8-9. Carbon pools and fluxes in a regional generic case for the functional groups herbivores, insectivores and carnivores in 11 catchment areas in Forsmark. Biomasses are in gC and, consumption and production are in gC y^{-1}.

Total gC y^{-1} **“Regional generic case”**		**Vambors-fjärden**	**Fräkengropen**	**Stocksjön**	**Bolunds-fjärden**	**Gällsbo-träsket**	**Eckarfjärden**	**Lake 2:2**	**Kungsträsket**	**Norra Bassängen**	**Graven**	**Puttan**
Herbivores	Biomass	27,531	8,121	12,145	109,339	126,541	123,146	3,952	7,237	18,817	22,445	12,990
	Consumption	623,091	184,347	278,837	2,564,668	2,878,393	2,780,726	92,108	166,302	435,881	509,360	300,066
	Production	9,537	2,818	4,238	38,578	43,957	42,617	1,390	2,527	6,595	7,785	4,545
Domestic animals	Biomass	0	0	11,047	0	46,675	404,796	0	0	0	0	0
(Cattle + sheep)	Consumption	0	0	407,260	0	1,720,694	14,923,104	0	0	0	0	0
	Production	0	0	3,753	0	15,855	137,508	0	0	0	0	0
Carnivores	Biomass	2,815	830	1,239	11,140	12,969	12,624	767	743	1,912	2,287	1,316
	Consumption	35,791	10,546	15,691	141,670	166,337	161,648	5,216	9,607	24,003	28,735	16,317
	Production	2,390	705	1,051	9,457	11,026	10,729	344	632	1,620	1,937	1,112
Insectivores	Biomass	11,890	3,599	5,363	47,330	45,030	46,837	1,899	3,414	8,974	10,208	6,063
	Consumption	96,862	28,888	43,102	384,328	411,738	411,355	14,557	26,453	69,106	80,768	47,251
	Production	6,566	1,962	2,927	26,066	27,504	27,616	995	1,806	4,722	5,497	3,223

Table 8-10. Carbon pools and fluxes in a regional generic case for the functional groups herbivores, insectivores and carnivores in 14 catchment areas in Laxemar-Simpevarp. Biomasses are in gC and, consumption and production are in gC y^{-1}.

Total gC/y "Regional generic case"		Area 6:1	Area 7:1	Area 7:2	Area 8:1	Area 9:1	Area 9:2	Area 9:3	Area 10:1	Area 10:2	Area 10:3	Area 10:4	Area 10:5	Area 10:6	Area 10:7
Herbivores	Biomass	122,428	13,035	106,240	30,215	112,823	46,854	13,599	209,975	28,125	19,569	61,231	17,707	54,155	37,220
	Consumption	3,641,450	392,345	3,148,893	901,305	3,367,964	1,388,500	410,633	6,207,004	838,844	596,594	1,828,712	526,541	1,582,897	1,120,188
	Production	48,232	5,166	41,736	11,909	44,543	18,415	5,407	82,394	11,097	7,818	24,185	6,968	21,095	14,749
Domestic animals (Cattle, sheep, pig)	Biomass	1,054,175	0	433,646	26,022	978,416	329,756	136,105	1,471,229	205,745	97,930	564,328	59,589	194,525	105,717
	Consumption	59,566,585	0	24,503,350	1,470,367	55,285,811	18,633,011	7,690,657	83,132,375	11,625,709	5,533,552	31,887,563	3,367,094	10,991,735	5,973,554
	Production	556,486	0	228,916	13,737	516,494	174,074	71,848	776,643	108,610	51,696	297,902	31,456	102,688	55,806
Carnivores	Biomass	11,775	1,254	10,236	2,911	10,845	4,510	1,304	20,223	2,704	1,878	5,884	1,706	5,230	3,581
	Consumption	166,378	17,742	144,768	41,188	153,245	63,745	18,422	285,878	38,217	26,553	83,125	24,137	73,993	50,664
	Production	12,364	1,317	10,750	3,057	11,388	4,736	1,370	21,238	2,840	1,972	6,178	1,792	5,493	3,761
Insectivores	Biomass	37,836	4,912	35,583	9,838	35,045	14,316	4,141	67,826	8,594	6,002	18,679	5,414	16,597	11,362
	Consumption	428,773	49,951	385,798	108,332	395,879	163,370	47,254	750,229	98,010	68,209	213,159	61,782	189,398	129,657
	Production	30,782	3,621	27,805	7,797	28,429	11,722	3,390	53,974	7,032	4,896	15,294	4,433	13,589	9,303

Table 8-11. Carbon pools and fluxes for birds for the 11 catchment areas in Forsmark in gC for biomass and in gC y^{-1} for consumption.

Birds		Vamborsfjärden	Fräkengropen	Stocksjön	Bolundsfjärden	Gällsboträsket	Eckarfjärden	Lake 2:2	Kungsträsket	Norra Bassängen	Graven	Puttan
Herbivores+omnivores	Biomass	1.16E+04	3.41E+03	5.06E+03	4.58E+04	5.40E+04	5.24E+04	1.70E+03	3.13E+03	7.70E+03	9.23E+03	5.20E+03
	Consumption	4.08E+05	1.20E+05	1.76E+05	1.62E+06	1.97E+06	1.90E+06	6.29E+04	1.17E+05	2.59E+05	3.11E+05	1.66E+05
Insectivores	Biomass	6.11E+03	1.80E+03	2.64E+03	2.42E+04	2.95E+04	2.85E+04	9.45E+02	1.76E+03	3.87E+03	4.66E+03	2.48E+03
	Consumption	1.99E+05	5.83E+04	8.52E+04	7.87E+05	9.70E+05	9.34E+05	3.13E+04	5.86E+04	1.23E+05	1.49E+05	7.73E+04
Carnivores	Biomass	8.43E+02	2.48E+02	3.66E+02	3.34E+03	4.02E+03	3.89E+03	1.28E+02	2.37E+02	5.45E+02	6.55E+02	3.57E+02
	Consumption	1.53E+04	4.51E+03	6.69E+03	6.06E+04	7.19E+04	6.97E+04	2.27E+03	4.19E+03	1.01E+04	1.21E+04	6.78E+03

Table 8-12. Carbon pools and fluxes for birds for the 14 catchment areas in Laxemar-Simpevarp in gC for biomass and in gC y^{-1} for consumption.

Birds		Area 6:1	Area 7:1	Area 7:2	Area 8:1	Area 9:1	Area 9:2	Area 9:3	Area 10:1	Area 10:2	Area 10:3	Area 10:4	Area 10:5	Area 10:6	Area 10:7
Herbivores + omnivores	Biomass	4.41E+04	4.41E+03	3.68E+04	1.02E+04	4.07E+04	1.67E+04	4.98E+03	7.44E+04	1.01E+04	6.77E+03	2.22E+04	6.03E+03	1.85E+04	1.26E+04
	Consumption	1.39E+06	1.45E+05	1.19E+06	3.35E+05	1.28E+06	5.30E+05	1.55E+05	2.37E+06	3.18E+05	2.18E+05	6.96E+05	1.97E+05	6.05E+05	4.13E+05
Insectivores	Biomass	1.90E+04	2.10E+03	1.69E+04	4.88E+03	1.75E+04	7.33E+03	2.08E+03	3.30E+04	4.38E+03	3.10E+03	9.46E+03	2.84E+03	8.72E+03	5.99E+03
	Consumption	6.07E+05	6.93E+04	5.53E+05	1.62E+05	5.59E+05	2.36E+05	6.57E+04	1.07E+06	1.40E+05	1.01E+05	3.00E+05	9.38E+04	2.87E+05	1.98E+05
Carnivores	Biomass	2.34E+03	2.25E+02	1.90E+03	5.18E+02	2.16E+03	8.81E+02	2.67E+02	3.91E+03	5.34E+02	3.51E+02	1.19E+03	3.09E+02	9.49E+02	6.42E+02
	Consumption	5.06E+04	4.49E+03	3.91E+04	1.03E+04	4.66E+04	1.88E+04	5.89E+03	8.26E+04	1.15E+04	7.24E+03	2.59E+04	6.22E+03	1.91E+04	1.28E+04

Table 8-13. Carbon pools and fluxes calculated for two cases: a regional generic and a potential self-sustainable case for the functional group “Domestic animals” in 11 catchment areas in Forsmark. Biomass in gC and, consumption and production in gC y^{-1}.

“Regional generic case”		Vamborsfjärden	Fräken-gropen	Stocksjön	Bolunds-fjärden	Gällsbo-träsket	Eckarfjärden	Lake 2:2	Kungs-träsket	Norra Bassängen	Graven	Puttan
Livestock	Biomass	0	0	11,047	0	46,675	404 796	0	0	0	0	0
	Consumption	0	0	407,260	0	1,720,694	14 923 104	0	0	0	0	0
	Production	0	0	3,753	0	15 855	137 508	0	0	0	0	0
“Self-sustainable case”												
Livestock	Biomass	138,306	41,890	70,019	539,212	402,538	434,539	8,338	10,296	142,758	165,546	129,964
	Consumption	7,982,489	2,417,713	4,041,235	31,121,333	23,233,005	25,080,010	481,262	594,227	8,239,452	9,554,730	7,501,067
	Production	57,170	17,315	28,943	222,888	166,393	179,621	3,447	4,256	59,010	68,430	53,722

Table 8-14. Carbon pools and fluxes calculated for two cases: a regional generic and a potential self-sustainable case for the functional group “Domestic animals” in 14 catchment areas in Laxemar-Simpevarp. Biomass in gC and, consumption and production in gC y^{-1}.

“Regional generic case”		**Area 6:1**	**Area 7:1**	**Area 7:2**	**Area 8:1**	**Area 9:1**	**Area 9:2**	**Area 9:3**	**Area 10:1**	**Area 10:2**	**Area 10:3**	**Area 10:4**	**Area 10:5**	**Area 10:6**	**Area10:7**
Livestock	Biomass	1,097,948	0	452,842	26,022	1,014,827	350,155	143,064	1,512,029	215,106	102,223	591,070	61,924	200,335	108,972
	Consumption	62,039,994	0	25,588,040	1,470,367	57,343,221	19,785,648	8,083,876	85,437,794	12,154,627	5,776,154	33,398,641	3,499,037	11,319,988	6,157,525
	Production	579,593	0	239,050	13,737	535,715	184,842	75,522	798,181	113,552	53,962	312,018	32,689	105,754	57,525
“Self-sustainable case”															
Livestock	Biomass	528,989	18,593	252,723	36,522	487,374	177,508	70,644	727,574	114,556	49,549	289,121	29,652	93,543	51,014
	Consumption	31,686,349	1,113,691	15,138,099	2,187,660	29,193,630	10,632,680	4,231,576	43,581,604	6,861,871	2,967,972	17,318,282	1,776,148	5,603,221	3,055,733
	Production	226,935	7,976	108,418	15,668	209,082	76,150	30,306	312,128	49,144	21,256	124,032	12,721	40,130	21,885

8.4.3 Human consumption

Human consumption of game meat and the three different cases describing the use of the agricultural land – the regional generic case, the self-sustainable case and 100% crop cultivation – are presented in tables 8-15 to 8-18.

8.4.4 Berry and fungi

Fungi and berry yields are presented in Tables 8-19 and 8-20. These yields have to be considered as the potential maximum yield, of which only a small fraction is utilized by humans. The fungi yield was consistently higher than the estimated berry yield for all catchments.

8.4.5 Summarizing models for the two sites

Figure 8-4 summarizes the above estimated and tabulated values for the modelled areas in Forsmark and Laxemar-Simpevarp.

8.5 Discussion

8.5.1 Vegetation and regolith

The range in the estimates of different properties is dependent on the size of the catchments and the spatial distribution of the different vegetation types, which in this landscape mainly consists of conifer forests. NPP is allocated among the different functional compartments of the autotrophic organisms, where a minor fraction is incorporated into perennial woody tissues, such as the stem in trees, and a large fraction enters the soil organic matter pool as litter within a year (e.g. Figure 8-4a). Interestingly, this allocation of carbon to different compartments differed somewhat between the sites for the year 2005. In Laxemar-Simpevarp where the LPJ-GUESS-modelled litter production was large for this year (Figure 8-4b) it exceeded heterotrophic soil respiration and resulted in a net loss of biomass (66 gC m^{-2} y^{-1}) and a net accumulation of carbon (174 gC m^{-2} y^{-1}) in the SOC pool summed over all catchments. The corresponding figures for Forsmark were a net gain in biomass of 139 gC m^{-2} y^{-1} and a net accumulation of carbon in the SOC pool of 79 gC m^{-2} y^{-1}. The net loss of biomass in Laxemar-Simpevarp is mainly explained by the low precipitation during 2005 in comparison to longer time-series (Figure 2-11 /Werner et al. 2009/). A dry year increases both loss of biomass caused by litterfall and fire. Litterfall may be highly variable between years /Bray and Gorham 1964/ and a similar peak in field-estimated litter production was recorded in Laxemar-Simpevarp during the storm "Gudrun" in 2005 /Mjöfors et al. 2007/. However, wind is not a parameter included in the LPJ-GUESS model. Similarly, the higher fire frequency also increases the loss of biomass for this dry year. However, loss due to fire is not illustrated as a separate flux, but is uncluded in the estimate of net change in the vegatation pool. Accumulation in living tissue is normally the dominant sink for carbon, which was also the case for Forsmark.

Some vegetation types are considered to be more important for long-term accumulation of matter. For example, vegetation types periodically inundated by water have a higher accumulation of matter, forming peat, than other terrestrial vegetation types /Borgmark 2005a/. These cover a relatively larger area in Forsmark than in Laxemar-Simpevarp (Tables 8-1 and 8-2). Similarly, some catchments are more important than others with regard to accumulation of organic matter, depending on their constitution. Catchments dominated by younger forests have a higher potential for assimilating bioavailable radionuclides today than catchments with a large proportion of clear-cuts, e.g. Gällsboträsk and 10:5. However, the opposite may be true in a long-term perspective, e.g. 100 years.

The estimated accumulation of carbon in Forsmark may be considered large in a long-term perspective, but is plausible for specific years, due to high sensitivity to temperature /Lindroth et al. 1998/. The variation between years is further reinforced by the example from Laxemar-Simpevarp, which had a large litter production in the modelled year 2005, resulting in nearly twice as high accumulation in the SOC pool compared to Forsmark. This does not necessarily mean that long-term accumulation increases, since this is compensated by a higher heterotrophic soil respiration in the following years. This indicates that the variation in fluxes between years may be considerable. However, in comparison with other studies, the input data for the different vegetation types has to be regarded as plausible and realistic in a short-term perspective (years).

Table 8-15. Human harvest and consumption of game meat, domestic animals and crops according to the "Regional generic case" in Forsmark.

Human harvest and consumption per year (gC y^{-1})		Vambors-fjärden		Subarea: Fräken-gropen		Subarea: Stocksjön		Subarea: Bolundsfjärden		Gällsboträsket		Eckarfjärden		Lake 2:2		Kungsträsket		Subarea: Norra Bassängen		Subarea: Graven		Puttan	
"Regional generic case"		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD	
Hunting of moose	Harvest[1]	6,271	917	1,849	270	2,762	404	24,811	3,628	28,809	4,212	28,233	4,128	897	131	1,646	241	4,276	625	5,111	747	2,953	432
	Consumption[2]	2,759	403	814	119	1,215	178	10,917	1,596	12,676	1,853	12,423	1,816	395	58	724	106	1,881	275	2,249	329	1,299	190
Hunting of roe deer	Harvest[1]	2,589	714	764	210	1,140	314	10,243	2,824	11,893	3,278	11,656	3,213	370	102	679	187	1,765	487	2,110	582	1,219	336
	Consumption[2]	1,139	314	336	93	502	138	4,507	1,242	5,233	1,443	5,129	1,414	163	45	299	82	777	214	928	256	536	148
Hunting of European hare	Harvest[1]	11	4.8	3.2	1.5	5.4	2.4	41.8	18.7	31.2	14.0	33.7	15.1	1	0	0.8	0.4	11.1	5.0	12.8	5.8	10.1	4.5
	Consumption[2]	4.7	2.1	1.4	0.6	2.4	1.1	18.4	8.2	13.7	6.2	14.8	6.6	0	0	0.4	0.2	4.9	2.2	5.7	2.5	4.4	2.0
Hunting of mountain hare	Harvest[1]	17	20	5.0	6.0	7.3	8.7	68	81	85	102	82	98	2.8	3.3	5.2	6.2	10	12	12	15	6.3	7
	Consumption[2]	7.5	9	2.2	2.6	3.2	3.8	30	36	38	45	36	43	1.2	1.5	2.3	2.7	4.5	5.4	5.5	6.6	2.8	3.3
Domestic animals (cattle + sheep)	Harvest[1]	0		0		3,753		0		15,855		137,508		0		0		0		0		0	
	Consumption[2]	0		0		1,163		0		4,915		42,627		0		0		0		0		0	
Milk	Production and consumption	0		0		22,252		0		94,017		815,387		0		0		0		0		0	
Crop	Production and consumption	0		0		0		0		0		243,961	6,420	0		0		0		0		0	

[1] Live biomass.

[2] Utilized carcass weight.

Table 8-16. Human harvest and consumption of game meat, domestic animals and crop according to the "Regional generic case" in Laxemar-Simpevarp.

Human harvest and consumption per year (gC y^{-1})		Area 6:1		Area 7:1		Area 7:2		Area 8:1		Area 9:1		Area 9:2		Area 9:3		Area 10:1	
"Regional generic case"		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD	
Hunting of moose	Harvest[1]	23,117	4,975	2,461	530	20,091	4,324	5,712	1,229	21,292	4,583	8,854	1,906	2,561	551	39,700	8,544
	Consumption[2]	10,171	2,189	1,083	233	8,840	1,903	2,513	541	9,369	2,016	3,896	838	1,127	243	17,468	3,760
Hunting of roe deer	Harvest[1]	12,582	5,828	1,339	620	10,935	5,065	3,109	1,440	11,589	5,368	4,819	2,232	1,394	646	21,608	10,008
	Consumption[2]	5,536	2,564	589	273	4,811	2,228	1,368	634	5,099	2,362	2,120	982	613	284	9,507	4,404
Hunting of European hare	Harvest[1]	43	17	1.5	0.6	21	8	3.0	1.2	40	16	14.5	5.7	5.8	2.3	59	23
	Consumption[2]	19	7.4	0.7	0.3	9	3.6	1.3	0.5	17	6.9	6.4	2.5	2.5	1.0	26	10
Hunting of Mountain hare	Harvest[1]	59	43	7.2	5.2	56	40	17	12	55	39	23	17	6.3	4.5	106	76
	Consumption[2]	26	19	3.2	2.3	25	18	7.4	5.3	24	17	10	7.4	2.8	2.0	47	34
Domestic animals	Harvest[1]	556,486		0		228,916		13,737		516,494		174,074		71,848		776,643	
	Consumption[2]	201,716		0		82,978		4,979		187,220		63,099		26,044		281,519	
Milk	Production and consumption	1.7E+06		0		7.2E+05		4.3E+04		1.6E+06		5.4E+05		2.2E+05		2.4E+06	
Crop	Production and consumption	6.5E+06	3.2E+05	0	0	2.9E+06	1.4E+05	0	0	5.4E+06	2.6E+05	3.0E+06	1.5E+05	1.0E+06	5.1E+04	6.1E+06	3.0E+05

[1] Live biomass.

[2] Utilized carcass weight.

Table 8-16. (Continued from previous page.)

Human harvest and consumption per year (gC y^{-1})		Area 10:2		Area 10:3		Area 10:4		Area 10:5		Area 10:6		Area 10:7	
"Regional generic case"		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD		mean±SD	
Hunting of moose	Harvest[1]	5,309	1,143	3,685	793	11,552	2,486	3,348	721	10,265	2,209	7,027	1,512
	Consumption[2]	2,336	503	1,622	349	5,083	1,094	1,473	317	4,516	972	3,092	665
Hunting of roe deer	Harvest[1]	2,890	1,338	2,006	929	6,288	2,912	1,822	844	5,587	2,588	3,825	1,771
	Consumption[2]	1,271	589	883	409	2,767	1,281	802	371	2,458	1,139	1,683	779
Hunting of European hare	Harvest[1]	9.3	3.7	4.0	1.6	24	9.2	2.4	0.9	7.6	3.0	4.2	1.6
	Consumption[2]	4.1	1.6	1.8	0.7	10	4.1	1.1	0.4	3.4	1.3	1.8	0.7
Hunting of Mountain hare	Harvest[1]	14	9.9	10	7.4	29	21	10	6.9	30	21	21	15
	Consumption[2]	6.1	4.4	4.5	3.2	13	9.2	4.3	3.1	13	9.4	9.0	6.5
Domestic animals	Harvest[1]	108,610		51,696		297,902		31,456		102,688		55 806	
	Consumption[2]	39,369		18 739		107,984		11,402		37,222		20,229	
Milk	Production and consumption	3.4E+05		1.6E+05		9.3E+05		9.8E+04		3.2E+05		1.7E+05	
Crop	Production and consumption	1.4E+06	6.8E+04	6.4E+05	3.1E+04	4.0E+06	1.9E+05	3.5E+05	1.7E+04	8.6E+05	4.2E+04	4.8E+05	2.4E+04

[1] Live biomass.
[2] Utilized carcass weight.

Table 8-17. Human harvest and consumption of domestic animals and crops according to the “Potential self-sustainable case” and “case 100% crop” in Forsmark. Consumption via hunting is the same as in the regional case in Table 8-17.

Harvest and human consumption per year (gC y^{-1})		Vamborsfjärden	Subarea: Fräkengropen	Subarea: Stocksjön	Subarea: Bolundsfjärden	Gällsboträsket	Eckarfjärden	Lake 2:2	Kungsträsket	Subarea: Norra Bassängen	Subarea: Graven	Puttan
“Self sustainable case”												
Domestic animals	Harvest	5,7E+04	1,7E+04	2,9E+04	2,2E+05	1,7E+05	1,8E+05	3,4E+03	4,3E+03	5,9E+04	6,8E+04	5,4E+04
(Cattle)	Consumption	1,8E+04	5,4E+03	9,1E+03	7,0E+04	5,2E+04	5,6E+04	1,1E+03	1,3E+03	1,8E+04	2,1E+04	1,7E+04
Milk	Production and consumption	6,2E+05	1,9E+05	3,2E+05	2,4E+06	1,8E+06	2,0E+06	3,8E+04	4,6E+04	6,4E+05	7,5E+05	5,9E+05
Crop	Production and consumption	2,5E+06	7,7E+05	1,3E+06	9,9E+06	7,4E+06	8,0E+06	1,5E+05	1,9E+05	2,6E+06	3,0E+06	2,4E+06
“Case 100% crop”												
Crop	Production and consumption	9,7E+06	2,9E+06	4,9E+06	3,8E+07	2,8E+07	3,1E+07	5,9E+05	7,2E+05	1,0E+07	1,2E+07	9,1E+06

Table 8-18. Human harvest and consumption of domestic animals and crops according the “Potential self-sustainable case” and “case 100% crop” in Laxemar-Simpevarp. Consumption via hunting is the same as in the regional case in Table 8-18.

Harvest and human consumption per year (gC y^{-1})		Area 6:1 mean	Area 7:1 mean	Area 7:2 mean	Area 8:1 mean	Area 9:1 mean	Area 9:2 mean	Area 9:3 mean	Area 10:1 mean	Area 10:2 mean	Area 10:3 mean	Area 10:4 mean	Area 10:5 mean	Area 10:6 mean	Area 10:7 mean
“Self-sustainable case”															
Domestic animal	Harvest[1]	2,3E+05	8,0E+03	1,1E+05	1,6E+04	2,1E+05	7,6E+04	3,0E+04	3,1E+05	4,9E+04	2,1E+04	1,2E+05	1,3E+04	4,0E+04	2,2E+04
(cattle)	Consumption[2]	7,1E+04	2,5E+03	3,4E+04	4,9E+03	6,6E+04	2,4E+04	9,5E+03	9,8E+04	1,5E+04	6,7E+03	3,9E+04	4,0E+03	1,3E+04	6,9E+03
Mil^{k}	Production and consumption	2,5E+06	8,7E+04	1,2E+06	1,7E+05	2,3E+06	8,3E+05	3,3E+05	3,4E+06	5,4E+05	2,3E+05	1,4E+06	1,4E+05	4,4E+05	2,4E+05
Crop	Production and consumption	1,1E+07	4,0E+05	5,4E+06	7,9E+05	1,0E+07	3,8E+06	1,5E+06	1,6E+07	2,5E+06	1,1E+06	6,2E+06	6,4E+05	2,0E+06	1,1E+06
“Case 100% crop”															
Crop	Production and consumption	4,4E+07	1,5E+06	2,1E+07	3,0E+06	4,0E+07	1,5E+07	5,8E+06	6,0E+07	9,5E+06	4,1E+06	2,4E+07	2,5E+06	7,7E+06	4,2E+06

[1] Live biomass.

[2] Utilized carcass weight.

Table 8-19. Fungi and berry potential maximum yield for each of the 11 modelled catchments in Forsmark.

Catchment	Fungi yield (gC y^{-1})	Berry yield (gC y^{-1})
Bolundsfjärden	1.84E+05	7.96E+04
Eckarfjärden	2.33E+05	9.93E+04
Fräkengropen	1.36E+04	5.62E+03
Gällsboträsk	2.32E+05	9.78E+04
Graven	3.37E+04	1.51E+04
Kungsträsket	1.41E+04	6.02E+03
Lake 2:2	7.48E+03	3.33E+03
Norra Bassängen	2.79E+04	1.24E+04
Puttan	1.69E+04	7.78E+03
Stocksjön	2.01E+04	8.51E+03
Varmbörsfjärden	4.62E+04	2.02E+04

Table 8-20. Fungi and berry potential maximum yield for each of the 14 modelled catchments in Laxemar-Simpevarp.

Catchment	Fungi yield (gC y^{-1})	Berry yield (gC y^{-1})
6:1	2.15E+05	6.02E+04
7:1	2.46E+04	5.39E+03
7:2	1.97E+05	5.39E+03
8:1	5.84E+04	1.68E+04
9:1	2.00E+05	5.74E+04
9:2	8.00E+04	1.80E+04
9:3	2.24E+04	6.07E+03
10:1	3.90E+05	1.16E+05
10:2	4.91E+04	1.38E+04
10:3	3.61E+04	9.66E+03
10:4	1.04E+05	2.88E+04
10:5	3.38E+04	8.66E+03
10:6	1.05E+05	2.72E+04
10:7	7.21E+04	1.82E+04

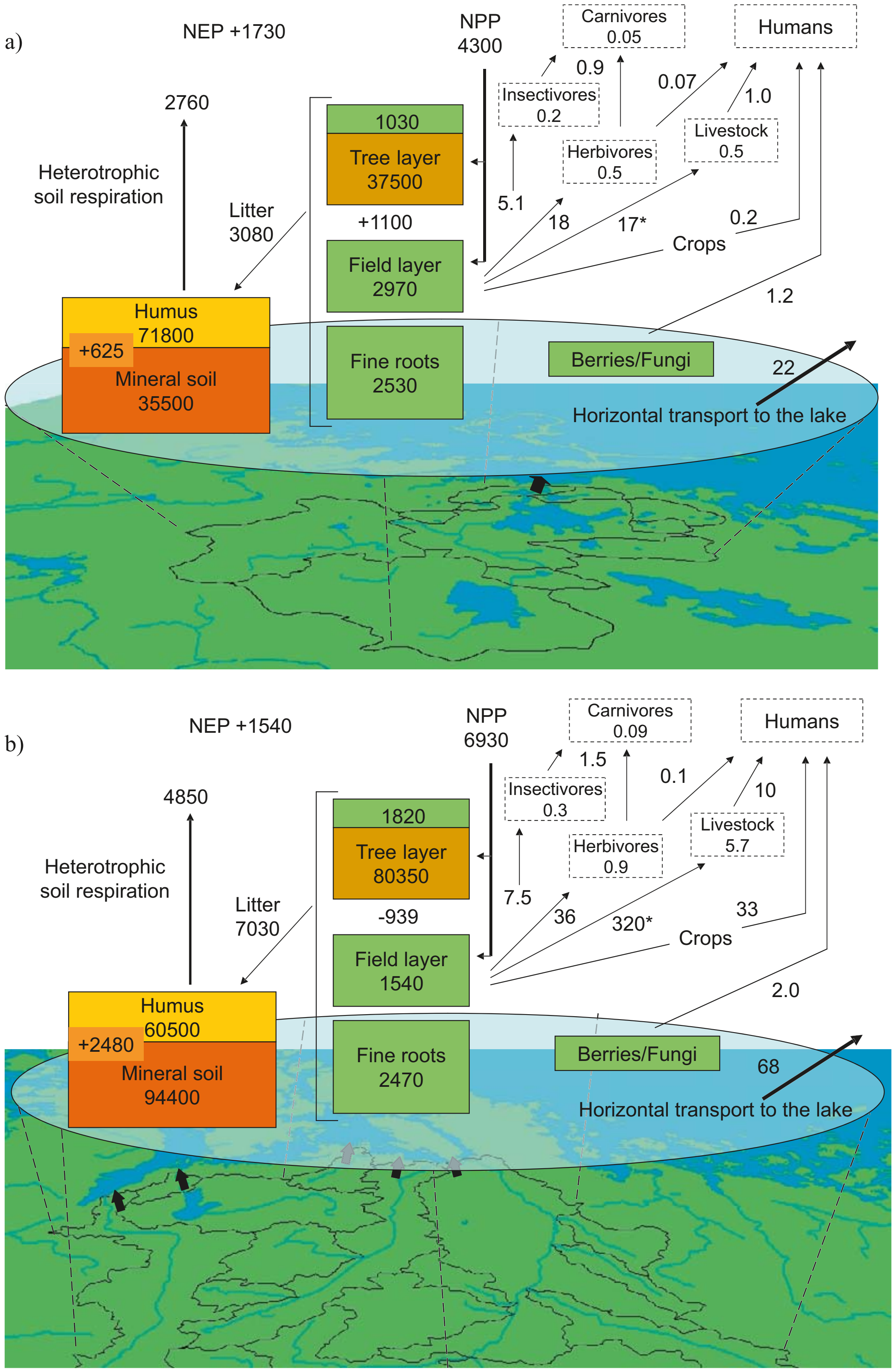


Figure 8-4. *Descriptive models of the total carbon balance in all the investigated catchment areas in a) Forsmark and b) Laxemar-Simpevarp, where modelled pools and fluxes for all vegetation types have been added together. Production of berries/fungi is the potential harvest available to biota. The black arrows on the map indicate discharge into the Baltic Sea. All pools (boxes) are in 1×10*^{6} *gC and fluxes (arrows) are in 1×10*^{6} *gC y*$^{-1}$*. Changes in the soil organic carbon pool and the vegetation pool are indicated by a +/– before the figure. *Livestock consumption includes both locally produced and imported fodder. Animal consumption has not been subtracted from the net ecosystem production (NEP).*

8.5.2 Food web

The flux of carbon from autotrophic production to herbivores is close to 1% of the NPP in Forsmark but almost 5% in Laxemar-Simpevarp. This difference is due to the higher abundance of livestock in Laxemar-Simpevarp, and if that is excluded, consumption is close to 0.5% at both sites. However, a portion of the NPP is confined to wood, a poor quality food largely unavailable to most herbivores. Herbivore consumption efficiency is normally 1–40% of NPP and is usually low in woods but reaches higher values in grasslands /Chapin et al. 2002/. The most important herbivore with regard to consumption and production (except for livestock) in Forsmark is roe deer, closely followed by moose, whereas the opposite is true in Laxemar-Simpevarp. Livestock consumption is the largest flux of carbon from the vegetation, but there is a greater difference between livestock and wild game consumption in Laxemar-Simpevarp than in Forsmark, due to higher abundances of livestock in Laxemar-Simpevarp. In some catchments where livestock was absent the consumption of vegetation decreased drastically.

Insect herbivores were not considered in the calculations, but studies of herbivory by insects on Scots pine estimated it to be 0.7% of the total needle biomass and 2.5% of the total needle production in one year /Larsson and Tenow 1980/. Root consumption by phytophagous nematodes was estimated to 0.3% of the annual production of fine roots /Magnusson and Sohlenius 1980/. Herbivory by insects during outbreaks may, however, amount to a major portion (up to 50%) of NPP /Schowalter et al. 1986/. If the figures for Scots pine are representative for the landscape as a whole they indicate that this consumption would be of similar size as for the vertebrate herbivores.

8.5.3 Human consumption

The potential flux of carbon to humans from products derived from vegetation was of the same order as herbivore consumption when the catchment area contained agriculture land. The potential human consumption of meat and milk was one order of magnitude lower than the consumption of plants and was similarly dependent on the catchment's potential to sustain cattle. The highest fluxes of carbon to humans are found within catchments that both cultivate crops and have enough arable land to sustain cattle. These calculations are based on the assumption that livestock only eat fodder grown within the catchment, thereby maximizing the potential exposure to accumulated bioavailable radionuclides within a catchment. If the land was used to produce maximum yield, i.e. by growing barley on all arable land, this would increase the flux of carbon from vegetation to humans by 30%, but would on the other hand eliminate the lower carbon flux from cattle to humans. The flux of carbon from hunting is low in comparison with the two other fluxes. These figures suggest that the largest potential fluxes of radionuclides via food intake to humans are found within catchments having agricultural activities and that arable land is the single most important vegetation type for potential exposure of cattle and humans to radionuclides. The absolute figures can be used to calculate human exposure, depending on population size and habits with regard to use of locally produced food and import and export of food.

The three case studies of human production of food (crops, meat and milk) showed that current production is far from potential production with regard to organic matter. In Forsmark, food production based on regional statistics was only 0.8% of the potential maximum production, assuming crop production on all agricultural land. The corresponding figure for Laxemar-Simpevarp was 15%, suggesting a higher utilization of potential resources in that area.

The potential berry and fungi yield in Forsmark is higher than the actual food production from hunting, crops or cattle. This is not the case in Laxemar-Simpevarp, where both milk and crop production are higher. However, the high berry and fungi yield is the potential yield that is available for picking, and the actual utilization of berries in Sweden has been estimated to be close to 5–7% of the yield /Kardell and Carlsson 1982/.

8.5.4 Confidence and uncertainties

There is great spatial variation within a regional area as an effect of different abiotic and biotic conditions and of disturbances, such as logging and thinning in forestry management or agriculture. In this section, results have been presented in order to describe the present-day situation with regard to vegetation types, their spatial distribution, the food web and the human land use. Furthermore, two contrasting potential cases of human use of the landscape were presented.

In a previous modelling approach for the Laxemar-Simpevarp area /Löfgren et al. 2006/ using both field-derived data and literature to describe the vegetation and soil pools and fluxes, the NPP range between the different catchments was between 432 and 709 gC m^{-2} y^{-1} (including EM mycelia production). The corresponding figures using the LPJ-GUESS-modelled carbon balances resulted in the range 425 to 534 gC m^{-2} y^{-1} (no EM mycelia production). EM mycelia contributed less than 80 gC m^{-2} y^{-1} per catchment, suggesting that this estimate was lower and had less variation in space than the previous estimate. The approach presented here is built on vegetation data generated by a model driven by site-specific climate parameters, where the different vegetation types have been modelled during a specific time period to approximate an appropriate age of the different vegetation types describing the vegetation at the site (see Section 7.2.2). Using a specific year to describe current conditions (in 2005) reduces the variation in climate-driven fluxes in comparison with an approach based on data from estimates describing different years (and consequently different solar radiation inputs, soil temperatures etc.). Moreover, the modelled fluxes are mechanistically correlated, whereas they were not directly related to each other in the previous model version for Laxemar-Simpevarp (apart from being representative for a certain vegetation type). However, it is important to note that the results in the previous version are plausible, whereas the results presented here are considered to be more representative in a short-term (10-year) perspective. These short-term predictions may be compared with the long-term (100-year) modelling in Chapter 7, predicting long-term assimilation and accumulation in ecosystems at both sites.

The use of three different scenarios to describe human use of the landscape is one way of describing the potential variation in these properties. It is land use that is the major factor determining the potential harvest rather than a comparatively small variation in the production of different crops or in the production estimates for different animals. The potential agricultural land in a catchment would therefore set the upper limit to the potential food production in an area. The potential for locally produced food is nearly 120 and 7 times higher, respectively (Forsmark and Laxemar-Simpevarp) compared with current production in the regions.

9 Distribution of elements among ecosystem compartments and mass balances

9.1 Introduction

A large number of radionuclides are of interest when considering a potential release from a deep repository into the biosphere. In most cases it is not possible to study the actual long-lived radionuclides themselves, so the distribution patterns of naturally occurring radionuclides or their stable isotopes have been used to study the long-term behaviour of the radionuclides that may originate from nuclear waste e.g. /Vera Tome et al. 2003, Chen et al. 2005/. Moreover, by describing the distribution of elements in general, and estimating the large inputs and outputs in the ecosystem, it is possible to infer and contrast different patterns caused by elements with different properties. Such an exercise also describes the range in behaviour of different elements, which could be indicative of the uncertainties involved in predicting the behaviour of elements in ecosystems. The biogeochemical cycling and storage of elements in an ecosystem is dependent on a large number of variables, such as climate, geological heterogeneity, flux of water and vegetation e.g. /Likens and Borman 1995/. Moreover, the interactions between elements and non-living and living compartments in an ecosystem are important in defining and regulating their flux and storage in an ecosystem e.g. /Chapin et al. 2002/.

This chapter describes how mass balance calculations of phosphorus and three naturally occurring radionuclides/stable isotopes were used to describe input and outputs, and to estimate accumulation within catchment areas. Furthermore, the distribution of over 60 different elements among ecosystem compartments was determined within the previously described 11 terrestrial catchments in Forsmark and 14 catchments in Simpevarp. Carbon, which has been described in Chapter 8, represents organic material and is equivalent to energy transfer within the food webs. Phosphorus is a macronutrient and can be regarded as an potential analogue to highly bioavailable radionuclides, and thorium, uranium and iodine are naturally occurring radioactive elements with radioisotopes (^{232}Th, ^{229}Th, ^{234}U, ^{238}U and ^{129}I) that have been suggested as being of importance in case of a release from a deep-sited high-level radionuclide repository. Uranium and thorium have no known biological role, whereas iodine appears to be a trace element essential to biota. These two naturally occurring radionuclides and iodine were chosen to cover a broad span with regard to radionuclide behaviour in the soil, since they have different soil solid/liquid partition coefficients (Kd), ^{232}Th and ^{229}Th (3,200–89,000 $l \cdot kg^{-1}$, /Thibault et al. 1990/), ^{234}U and ^{238}U (15–1,600 $l \cdot kg^{-1}$, /Thibault et al. 1990/) and ^{129}I (8–80 $l \cdot kg^{-1}$, /Sheppard et al. 2006/). A low Kd means a higher solubility in the soil water and therefore potentially more mobility and bioavailability.

A large data set is presented in this chapter for the purpose of supporting further calculations and discussions in the safety analysis for the two sites. Many of the data are therefore only presented in tables and are not further discussed in this chapter.

9.2 Methods

9.2.1 Conceptual model

Mass balance models describing the inputs and outputs of a large number of elements at the catchment scale were constructed in accordance with the conceptual illustration in Figure 9-1. The estimated input was atmospheric deposition, and the output was horizontal transport by water. The element content was estimated for four pools within each catchment. The consumer pool consists of carnivores, insectivores and herbivores, whereas the producer pool consists of all the vegetation above- and below-ground. The soil was divided into a litter/ humus pool and a mineral soil pool, based on differences in organic carbon content and adsorption properties. In the case of phosphorus, which is a well-described element, certain internal fluxes, such as weathering and vegetation demand, were also included to further elaborate the resulting mass balances.

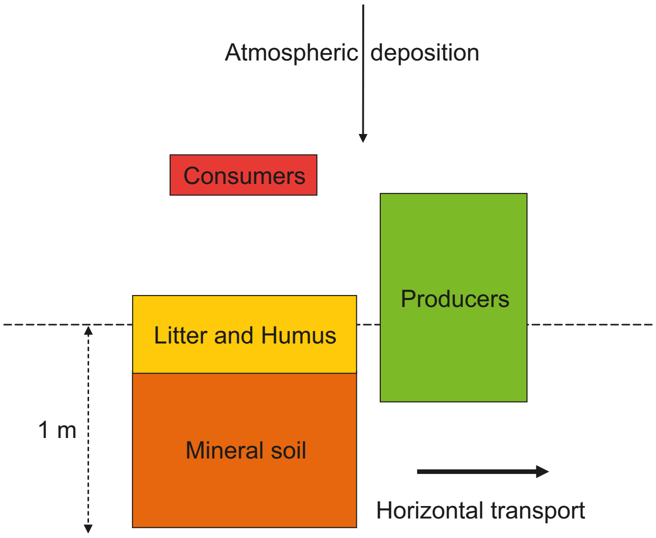


Figure 9-1. *The pools and fluxes that were used to describe the distribution of the four elements Th, U, I and P in terrestrial catchments.*

9.2.2 Estimation of element content

Elements can be distinguished according to physical and chemical characters into metalloids, metals, non-metals, lanthanides and actinides. The 62 elements considered in this chapter are the metals: Ag, Al, Ba, Be, Ca, Cd, Cs, Co, Cr, Cu, Fe, Ga, Hf, Hg, K, Li, Mg, Mn, Mo, Na, Nb, Ni, Pb, Rb, Sc, Sn, Sr, Ta, Ti, Tl, V, W, Y, Zn, Zr; non-metals: Br, C, Cl, I, N, P, S, Metalloids: As, B, Sb, Si; Lanthanides: Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Tm, Yb; and actinides Th, U. The chemical sampling of the different ecosystems and the fauna is described for Forsmark in /Hannu and Karlsson 2006/ and for Simpevarp in /Engdahl et al. 2006/.

Ten of the elements analyzed in soil samples were reported as their oxides (Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, MnO, Na_2O, P_2O_5, SiO_2, TiO_2). These values were converted to the concentration of each element using molar masses.

Some of the measurement results were below the detection limit, and these were replaced with a value equal to half the detection limit. For some of the elements, a large portion of the measurements were below the detection limit for consumers, and for the following elements these constituted a majority of the measurements: Ag, As, Be, Ga, Li, Ni, Pb, Sb, Th, Tl, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, V, W, I. Half the detection limit was nonetheless used for these values.

The carbon content in different compartments was modelled with LPJ-GUESS (Chapter 7) and estimated from site-specific measurements (wetlands) for a number of vegetation types covering the landscape. The carbon content of different compartments was added together in accordance with the pools in Figure 10-1. The element content of the pools in Figure 10-1 was estimated using the ratio between the element and carbon concentrations from the chemical characterization of a number of localities representing different vegetation types (Tables 9-1 and 9-2). This ratio was then multiplied by the carbon content of each compartment to give the element content of each compartment. The catchment areas are in the range of 0.07 to 2.08 km^2 and are further described in Figures 8-2 and 8-3, and Tables 8-1 and 8-2.

Vegetation and soil

In total, six different ecosystems were used to describe the catchments at each site with regard to differences in the ratio between each element and carbon. These descriptions of ratios were from a number of localities sampled at each site (Tables 9-1 and 9-2). The description of carbon pools presented in Chapter 8 used 15 different ecosystems to characterize the spatial differences with regard to carbon pools. Of these, the carbon pools for 12 ecosystems were modelled using the dynamic model LPJ-GUESS (see Chapter 7), whereas the carbon pools for the three wetland types were estimated using field-estimated site data (see Chapter 8).

These 15 ecosystems were grouped according to similarities in tree species or history, e.g. clear-cut and forest, into the five different ecosystems that were used to characterize the spatial differences with regard to elements other than carbon (Tables 9-3 and 9-4). The carbon content of each compartment according to Figure 9-1 was summed across the different ecosystems (Tables 9-3 and 9-4) and then multiplied by the vegetation-type-specific ratio between the element and carbon.

Data describing phosphorus concentrations in the wood for the Laxemar-Simpevarp localities were all 5 to 15 times higher than the Forsmark value (48 to 53 mg P g^{-1} dw) and was regarded to be a non-representative sample. See also discussion under 9.3.1 concerning other elements with high concentrations in the wood sample. These values were replaced with a value from a locality in the southern Sweden (Skogaby) from a young Norway spruce forest that was somewhat more than twice as high the Forsmark value (120 mg P g^{-1} dw) /Scarascia-Mugnozza et al. 2000/. The detection limit for iodine was three times higher for the wood samples from Laxemar-Simpevarp, and the decision to use half the detection limit for the concentration, when a sample was below the detection limit, therefore caused a non-existing pattern. It was therefore assumed that the iodine content of the wood was within a similar range at the two sites and the same value was used at both when it was below the detection limit (half the detection limit was taken to be 0.05 mg g^{-1} dw at both sites).

Table 9-1. Vegetation types and origin of element concentration data that were used to characterise these vegetation types in Forsmark. Most of the data were from Forsmark, but some came from Laxemar-Simpevarp. Most localities in column two were only sampled once for each pool. The SKB ID code is given in parentheses.

Vegetation type	Origin of chemistry data
Deciduous / Mixed forest	Mixed Norway spruce forest (AFM001068, Forsmark).
Coniferous forest	Norway spruce forest (AFM001247, Forsmark)
Forested wetland	Alder-Norway spruce, Alder wetland, and Norway spruce on partially drained peatland (AFM001076 Forsmark; ASM001434, ASM001440 Simpevarp).
Wetland	Alder wetland (field and bottom layer, and fine roots, AFM001076, Forsmark), mire (peat, Rönningerna, PFM006024, Forsmark)
Open wetland to lake	Reed belt (Frisksjön, ASM000110, ASM000111, ASM000112, Simpevarp) and humus (reed peat, PFM006024, Forsmark).
Agricultural land / Pasture	Mixed Norway spruce forest (soil, field layer, AFM001068, Forsmark)

Table 9-2. Vegetation types and origin of element concentration data that were used to characterise these vegetation types in Laxemar-Simpevarp. Most of the data were from Laxemar-Simpevarp, but some came from Forsmark. Most localities in column two were only sampled once for each pool. The SKB ID code is given in parentheses.

Vegetation type	Origin of chemistry data
Deciduous / Mixed forest	Oak forest (ASM001426, Simpevarp).
Coniferous forest	Norway spruce forest (ASM001440, Simpevarp).
Forested wetland	Alder-Norway spruce, Alder wetland, and Norway spruce on partially drained peatland (AFM001076 Forsmark; ASM001434, ASM001440 Simpevarp).
Wetland	Norway spruce on partially drained peatland (field and bottom layer, and roots) (ASM001440, Simpevarp, 1), peat (Klarebäcksmossen, PSM006562, Simpevarp).
Open wetland to lake	Reed belt (Frisksjön, ASM000110, ASM000111, ASM000112, Simpevarp) and humus (reed peat, PFM006024, Forsmark).
Agricultural land / Pasture	Oak forest (ASM001426, Simpevarp).

Table 9-3. Subset of vegetation types that were chemically characterized in the left column and vegetation types that were included in these in the right column for Forsmark.

Vegetation type	Carbon-modelled vegetation types (in accordance with the vegetation map categories)
Deciduous/Mixed forest	Old deciduous-dominated forestMixed forest (conifers/deciduous)
Coniferous forest	Young Scots pine Old Scots pine forest, mesic-wet types Dry Scots pine forest on acid rocks Old Norway spruce forest, mesic-wet types Old clear-cut, birch thicket Young Norway spruce Clear-cut
Forested wetland	Forested wetland, conifer-dominated Forested wetland, deciduous-dominated
Wetland	Open wetland
Open wetland to lake	Open wetland to lake
Agricultural land/Pasture	Arable land Pasture

Table 9-4. Subset of vegetation types that were chemically characterized in the left column and vegetation types that were included in these in the right column for Laxemar-Simpevarp.

Vegetation type	Carbon-modelled vegetation types (in accordance with the vegetation map categories)
Deciduous / Mixed forest	Oak-dominated deciduous forest Mixed forest (conifers/deciduous)
Coniferous forest	Young spruce-dominated forest, mesic-wet types Old spruce-dominated forest, mesic-wet types Young pine-dominated forest, mesic-wet types Old pine-dominated forest, mesic-wet types Dry pine forest on acid rocks New clear-cut 1999–2006 Old clear-cut, birch thicket
Forested wetland	Forested wetland, pine-dominated Forested wetland, birch-dominated
Wetland	Open wetland
Open wetland to lake	Open wetland to lake
Agricultural land / Pasture	Arable land Pasture

Consumers

The chemical characterization of the consumers was put together according to the three functional groups Herbivore I, Herbivore II and Carnivores at both sites. Herbivore I represented rodents and birds with a high rate of metabolism compared with the larger species included in Herbivore II (Table 9-5).

9.2.3 Input and output of elements to ecosystems

The input of elements in this area is from atmospheric deposition, whereas the output is horizontal transport by water into streams, lakes and the sea. No attempt has been made to describe weathering except for the phosphorus mass balance.

The elemental transport in surface water was estimated from concomitant measurements of concentrations and discharge in streams of Forsmark /Tröjbom et al. 2007, Appendix F/ and Laxemar-Simpevarp /Tröjbom et al. 2008, Appendix C/.

Table 9-5. Consumers are divided into three functional groups for which the element content is estimated from a subset of sampled representatives (column two). For example, elemental analysis of Fox represents the functional group carnivores.

Site	Functional group	Species/group	Sample size
Forsmark	Carnivores	Fox	1
	Herbivore I	Moose	7
	Herbivore II	Rodents*	8
Laxemar-Simpevarp	Carnivores	Fox	3
	Herbivore I	Moose	3
		Roe deer	3
	Herbivore II	Rodents*	9

*Estimates for rodents covered several species and a number of aggregated samples /Hannu and Karlsson 2006, Engdahl et al. 2006/.

Table 9-6. Subset of functional consumer groups that were chemically characterized in left column and different taxa included in these in right column for both sites.

Functional group	Species/group included
Carnivore	Fox, birds, insectivores (birds, amphibians, reptiles)
Herbivore I	Moose, roe deer, hares, wild boar, livestock
Herbivore II	Rodents, birds

Atmospheric deposition

The sources for estimating atmospheric deposition are presented in Table 9-8 (additional elements in Appendix 6). The deposition was multiplied by the precipitation for phosphorus and iodine, where the deposition was estimated as wet deposition in precipitation. For uranium and thorium, data from southern Sweden were used, where the total atmospheric load was estimated in beech forest for the winter period /Tyler and Olsson 2006/. They suggested further that this load was greater during the winter period than during the summer period. Consequently, the winter deposition (in Tables 9-7 and 9-8) was multiplied by 1.5 to approximate the total atmospheric deposition. This might entail an underestimate, but the dry deposition is higher in forests and the forests represented only 61% and 74% of the land area in the modelled catchments of Forsmark and Laxemar-Simpevarp, respectively.

Table 9-7. Values of atmospheric deposition (dry deposition and/or precipitation) used in mass balance models of Forsmark lakes. Data from 1) /Tröjbom and Söderbäck 2006a/, 2) /Tyler and Olsson 2006/.

Element	Precipitation (mm year^{-1})	Deposition (g m^{-2} year^{-1})	Reference	Comment
P	559	0.012	1	In precipitation as a mean from two stations (PFM002457 and PFM002564).
U	559	0.000003	2	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden.
Th	559	0.000005	2	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden.
I	559	0.00028	1	In precipitation based on two measurements at the site that were both below the detection limit of 1µg/l. Half the detection limit was assumed as the deposition value, which was in the lower range of the iodine deposition interval reported by /Sheppard et al. 2002/.

Table 9-8. Values of atmospheric deposition (dry deposition and/or precipitation) used in mass balance models of Frisksjön in Laxemar-Simpevarp. Data from 1) /Knape 2001/, 2)/Tyler and Olsson 2006/, 3) /Tröjbom and Söderbäck 2006b/.

Element	Precipitation (mm year^{-1})	Deposition (g m^{-2} year^{-1})	Reference	Comment
P	600	0.027	1	Data from Äspö, Laxemar-Simpevarp
U	600	0.000003	2	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden
Th	600	0.000005	2	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden
I	600	0.0003	3	In precipitation based on two measurements in Forsmark that both were below the detection limit of 1µg/l. Half the detection limit was assumed as the deposition value, which was in the lower range of the interval reported by /Sheppard et al. 2002/. Corrected for precipitation amount in Laxemar-Simpevarp

Horizontal transport with water

The transport of elements in surface water has been estimated from concomitant measurements of concentrations and discharge in streams in Forsmark and Laxemar-Simpevarp /Tröjbom et al. 2007, Appendix F, Tröjbom et al. 2008, Appendix C/. Such data were available for a number of elements (e.g. phosphorus). For the other elements, correlations between the concentrations of the more and less abundant elements were used /Tröjbom et al. 2007, Tröjbom et al. 2008/.

Weathering of phosphorus

Weathering of phosphorus was calculated for both sites. /Olsson and Melkerud 1989/ studied chemical and mineralogical changes during the genesis of a Podsol in southern Sweden. They determined the average rate of weathering for phosphorus since the last deglaciation (material < 2 mm) to be 0.009 gm^{-2}y^{-1}. This rate may have changed over time due to e.g. climatic variations and different vegetation. /Ulén and Snäll 1998/ compared the weathering rates in a forest catchment with the rates from an arable field (grain sizes < 2 mm). The rate of base cation weathering was estimated to be 10 times higher in the arable soil compared with the forest area. Soils used as arable land are generally more fine-grained than forest soils. Fine-grained material is more easily affected by weathering and the high weathering rates in the area used as arable fields can therefore be explained by a higher content of fine material in that area. Accordingly, all vegetation types with more coarse-grained soil types were assigned the average weathering value from above, whereas the more fine-grained soil types – such as mixed conifer/deciduous forest, deciduous forest, pastures and arable land – were the assigned the higher rate. Both sites are young and the expected weathering rate is expected to be somewhat higher than the long-term mean /Hedenström and Sohlenius 2008, Sohlenius and Hedenström 2008/, but this was not accounted for in the calculations.

9.3 Results and discussion

9.3.1 Distribution of elements among pools for all catchments

In general, most elements have their main distribution in the soil compartments except for chlorine, where nearly 75–80% of the total terrestrial chlorine pool is found in the vegetation. The non-metals are all found to a large extent in the producers, where the halogens are highly reactive and water-soluble. Moreover, N, P, S and Cl are all essential nutrients for plants. This also explains why many other elements occur in the producer pool, where B, Ca, Cu, K, Mg, Mn, Mo, Ni, Zn and I are regarded as micronutrients. Perhaps more interesting is the fact that Sb, Be, Cd, Hg, Rb, Sr, Tl and Br occurred to a certain extent in the plants. Sb is usually regarded as having a relative high mobility in the environment due to its occurrence in water, in association with carbon and bound to iron hydroxides /Greger 2004/. As a soluble salt, Be is easily taken up by plants and seems to follow the same route as Mg and Ca. Cd, a toxic heavy metal, and Hg are both readily absorbed by plant roots, and it was also here the highest concentrations were found. Interestingly, similar high concentrations were found for Hg in the bottom layer, suggesting that atmospheric deposition is an important flux for Hg.

Rb follows the uptake route of K, and the distribution factor Rb/K is close to one, even though there is a slight discrimination factor against Rb compared with K. Sr is often associated with Ca and the root uptake is related to mass-flow and exchange diffusion. Sr is mainly accumulated in the roots. Br has a strong correlation with organic carbon and is able to substitute for Cl in plants. Tl has chemical behaviour that is analogous to K /Greger 2004/.

A number of elements are to a greater extent represented in the pool of producers in Laxemar-Simpevarp, such as B, Ag, Ba, Ca, Co, Cs, K, Mg, Mn, Pb, Sr, Zn, Br and P. Of these, at least B, Ca, Co, K, Mg, Mn, Zn and P are regarded as essential elements for the plants and Cs, Sr and Br are closely associated with the transport pathways of some nutrients. A closer examination of the data reveals that the concentrations of these elements in the wood sample representing conifer forests were between 3 to 10 times higher than those found in Forsmark. This might suggest that the samples have a large content of phloem tissue and are therefore not representative for describing the biomass of sapwood/heartwood (see also under "Vegetation and soil" above).

The lanthanides differ somewhat in their distribution between the sites. In Laxemar-Simpevarp they are represented to a greater extent in the producers relative to the other compartments than in Forsmark. This is explained by a higher concentration of the elements in bryophytes and in the fine roots (between 2 to 10 times higher) than in the conifer forest samples. This is not reflected to same extent in the humus layer. In any case, this pattern suggests that atmospheric deposition may be higher in the forests of Simpevarp-Laxemar than in Forsmark for this group of elements.

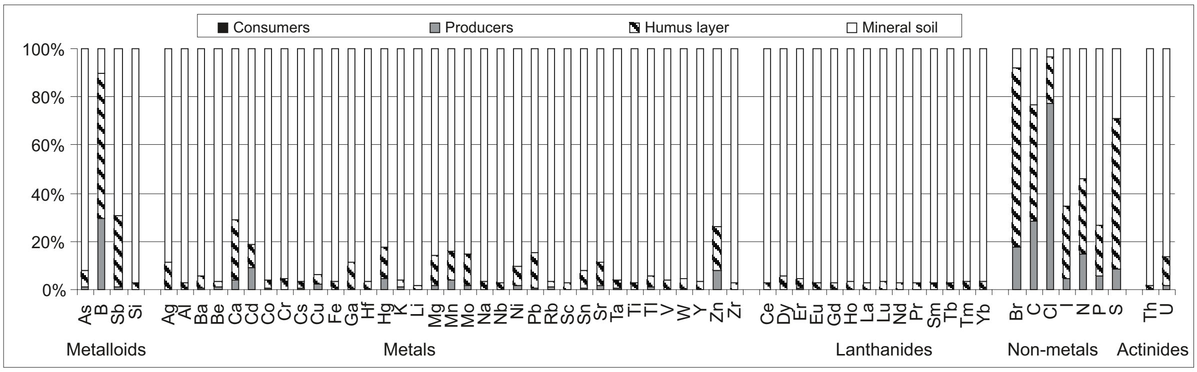


***Figure 9-2.** Distribution of 62 elements among the four pools mineral soil, humus layer, producers and consumers. Each pool is the sum of all the 11 catchments studied in Forsmark.*

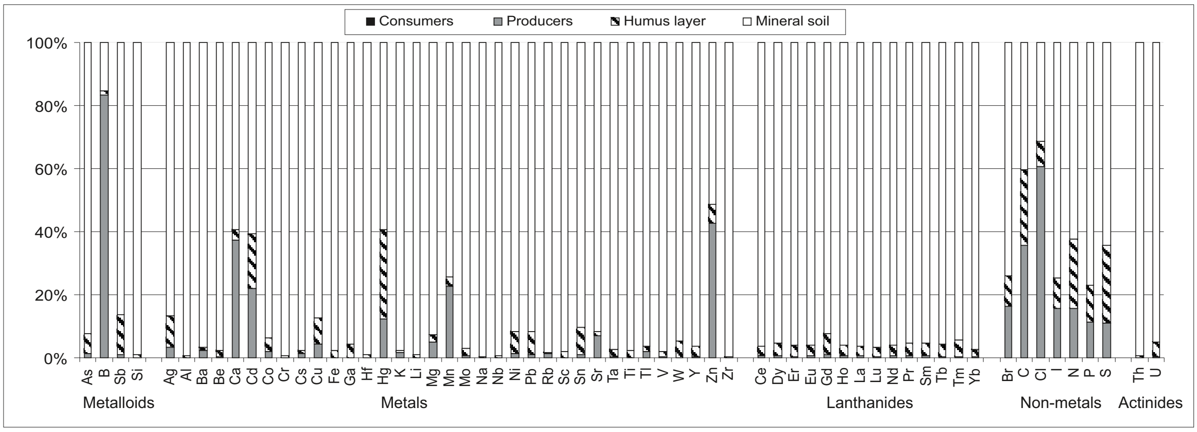


***Figure 9-3.** Distribution of 62 elements among the four pools mineral soil, humus layer, producers and consumers. Each pool is the sum of all the 14 catchments studied in Laxemar-Simpevarp.*

9.3.2 Concentrations of P, Th, U and I among pools within ecosystems

A detailed description of the underlying element concentrations is presented in Figure 9-4 for those elements that were analyzed by the mass balance approach.

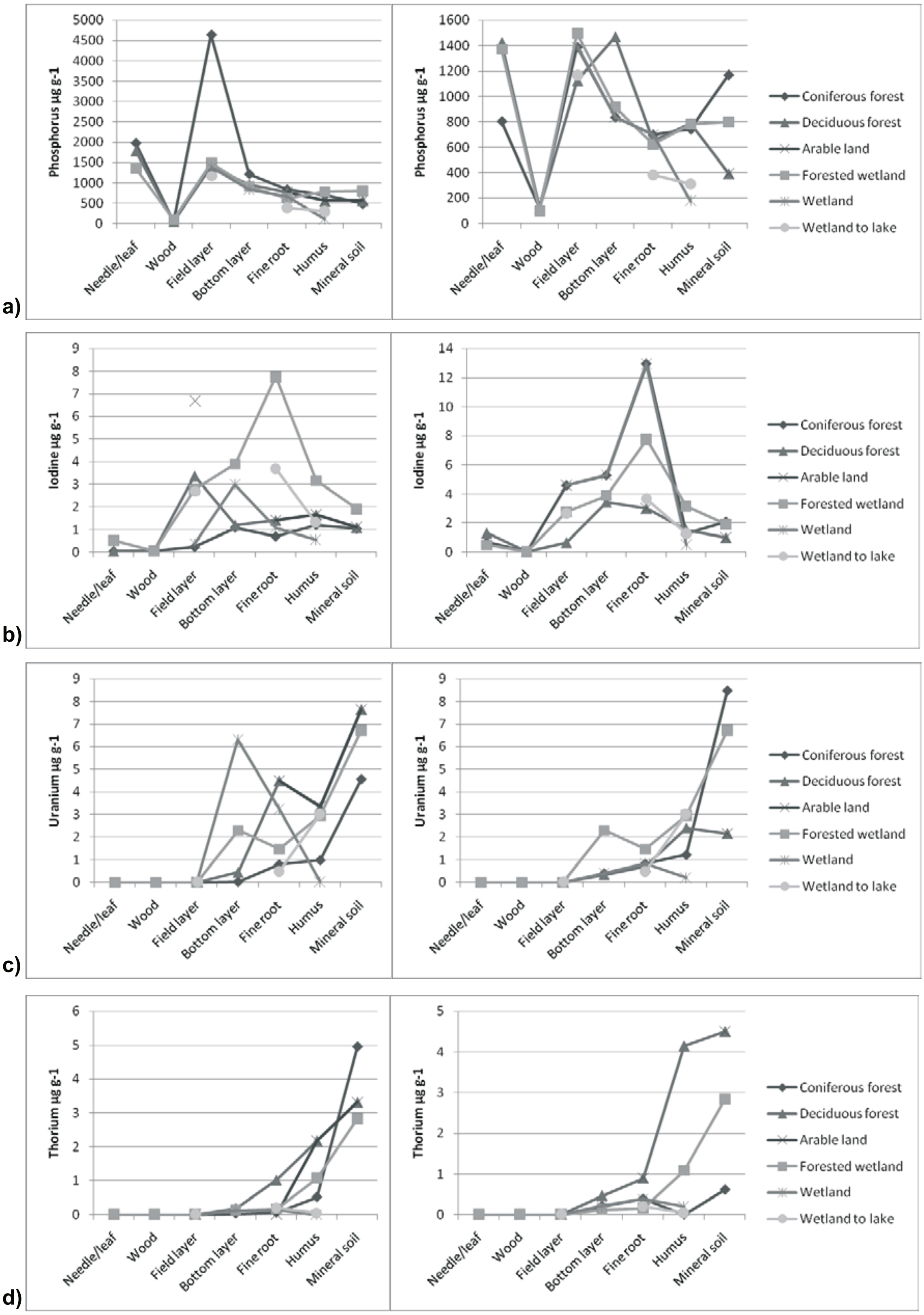


Figure 9-4. The element concentrations for a) phosphorus, b) iodine, c) uranium and d) thorium that were used to describe the pools in six different ecosystems in Forsmark (left) and Laxemar-Simpevarp (right).

9.3.3 Mass balances of P, Th, U and I among catchments

Mass balances for phosphorus, iodine, thorium and uranium for both sites are presented in Table 10-9. More detailed descriptions covering the different catchment areas are presented in Tables 10-10 to 10-17. The calculations suggest a net accumulation of phosphorus within both sites, where most of the atmospheric deposition is accumulated. Export per unit area was less in Forsmark than in Laxemar-Simpevarp: 1.7 mg P m^{-2} y^{-1} and 8.8 mg P m^{-2} y^{-}, respectively. Since NPP is of a similar magnitude for both sites (see Chapter 8), this indicates that the Forsmark soil retains more of the phosphorus and/or that the Laxemar-Simpevarp soil has a higher loss of phosphorus. In fact, the Forsmark soil is rich in calcium carbonate, which precipitates phosphorus to a greater extent, and arable land is more abundant in the Laxemar-Simpevarp catchments (8.5%) than in the Forsmark catchment (0.1%). The largest pool was found in the mineral soil, but a large part of this pool is inaccessible to the biota. Generally, between 20% and 30% of the phosphorus in the soil is available to plants, where the lower figure represents soils with higher pH (> 6.5), which is more applicable to the Forsmark conditions /Chapin et al. 2002/. There is a difference between the sites with regard to the relative phosphorus content of the vegetation and humus pools.

By using the information from the ecosystem model describing carbon pools and fluxes at the regional level for the same area, it is estimated that approximately 310 kg P y^{-1} was used for NPP by the vegetation in Forsmark. It was assumed that phosphorus was required in a proportion corresponding to its concentration in wood and that approximately 31% of the phosphorus was recycled within the vegetation /Finér 1989/. Moreover, by adding accumulation in wetlands, where /Sternbeck et al. 2006/ estimated the long term accumulation of phosphorus in one wetland to be 0.02 g P m^{-2} y^{-1} in Laxemar-Simpevarp, which would suggest that further 25 kg would be accumulated in wetlands (all wetlands included). This would entail that approximately 335 kg P could be accumulated in the area compared with the 83 kg P in Table 10-7. Accumulation is undoubtedly overestimated in the wetlands because many of the wetlands close to the coast in the Forsmark regional area are not yet accumulating peat to any great extent. Another source of phosphorus is weathering, which would make an additional 118 kg available, suggesting a source of 134 kg P so far unaccounted for. Furthermore, atmospheric deposition only included wet deposition, which suggests that the input of phosphorus could be somewhat higher.

A similar calculation for the Laxemar-Simpevarp area suggested that the wetlands accumulated approximately 3 kg P y^{-1} and the NPP used 1,550 kg P y^{-1}. The higher demand is explained by the higher concentration of phosphorus in the wood, see also under "Vegetation and soil". The net accumulation in the mass balance (Table 10-7) and weathering (457 kg P y^{-1}) amounted to 717 kg P, leaving a source of 836 kg P unaccounted for. The unaccounted-for source isdecomposition of litter, where phosphorus is released.

Iodine shows a somewhat similar pattern to phosphorus with regard to both the distribution between pools and differences between sites. Only a small fraction of the iodine in the soil is available, and liming is known to further reduce this availability /Fuge and Johnson 1986/. This indicates that the higher relative phosphorus content of the humus layer in Forsmark does not necessarily reflect a greater availability to plants. It is often suggested that the iodine in plants largely originates from the atmosphere /Greger 2004/. The higher relative content (and concentrations) of iodine in the producer pool compared to the soil could be attributable to the more than 10 times higher concentration of iodine in the tree roots of the conifer forest (most abundant vegetation type). The 2 to 5 times higher concentration in the bryophytes of the Laxemar-Simpevarp locality compared to Forsmark also indicates the potential origin of the iodine. Bryophytes obtain all of their element content from the atmosphere, which suggests that part of the difference in iodine content between the sites is due to higher iodine contents on the plant surface in Laxemar-Simpevarp rather than actual accumulation within the plants. Both sites seem to export more iodine than the input as atmospheric deposition. However, relative to the total area there is a larger export in Laxemar-Simpevarp (twice the area of Forsmark) than in Forsmark, and adding the potentially higher atmospheric deposition in Laxemar-Simpevarp suggests that retention of iodine in the catchments at Forsmark is greater than in the catchments at Laxemar-Simpevarp.

Uranium and thorium show a different pattern with low concentrations (Figure 9-2) and content within the biotic pools and the majority of the soil pools (Figure 9-3). There is a difference in the patterns of how uranium is distributed between the pools and how it is exported between the sites.

The higher uranium content in the humus layer in Forsmark originates from its somewhat higher concentration in several of the ecosystems, such as in peat on wetlands close to lakes. This is a much more abundant vegetation type in Forsmark than in Laxemar-Simpevarp. Similarly, the higher relative uranium content in biomass originates from high concentrations in the bryophytes on wetlands. Uranium is more mobile than thorium with regard to export at both sites. A net export of uranium and thorium most certainly originates from weathering of soil minerals, for which no estimates are available. The higher export of uranium in Forsmark compared with Laxemar-Simpevarp and the opposite pattern for thorium is more difficult to explain, although thorium seems to be retained in the soils of Forsmark, where the input is higher than the export.

9.3.4 Confidence and uncertainties

The pools have been estimated from a fairly small number of element estimates representing six ecosystems. This means that one or a few misleading samples would have a great impact on the final result. During the analysis, some estimates were partly replaced with more accurate data, i.e. wood phosphorus content. In the end a fairly consistent pattern was found when comparing the sites. Differences in patterns could also partly be explained based on the characteristics of the specific sites.

Two fluxes are estimated here: atmospheric deposition and export in streams. Few data describing deposition are available from the sites or even from other studies, whereas export has been estimated from site measurements over two years and one year for Forsmark and Laxemar-Simpevarp respectively. Little is known about atmospheric deposition of uranium and thorium in general, and for iodine no estimates have been found representing Swedish conditions. However, in the majority of the cases illustrated here, export is much greater than deposition. Nevertheless, the export calculations represent a mean for only two years in Forsmark or one year in Laxemar-Simpevarp, which suggests that the potential short-term variation is not fully covered in the calculations.

9.3.5 Conclusions

The element distribution among the four compartments mineral soil, humus layer, producers and consumers showed consistent patterns between the sites. Most of the elements found in a higher content in the vegetation were nutrients. The nutrients are found both in the group of the non-metals and in the group of metals. Many of the other elements found within the vegetation have analogous behaviour to nutrients and are therefore found accordingly. Other elements seem to be restricted to the fine roots, such as U, Cd and Hg. Generally, small amounts were found in the consumer pool and many elements were found to be below the detection limit.

The mass balances of four elements illustrated some different behavioural patterns, where the water-soluble micronutrient iodine was to a large extent incorporated into the vegetation and also transported further downstream into the lakes. The distribution of the macronutrient phosphorus was similar, but only a small quantity was transported from the terrestrial areas. The mass balance suggested a large retention of phosphorus at the catchment level, where a large part is retained in the vegetation. Thorium and uranium had their largest pools in the mineral soil and to a lesser extent in the humus layer. They showed a less mobile pattern with small amounts found in the vegetation or transported downstream. However, uranium was the element that had the highest export in relation to input of atmospheric deposition, suggesting a high weathering rate compared with thorium. Generally, it would be expected that weathering on these fairly young soils would be somewhat higher than the average for Sweden.

All of the elements are exported to a greater extent in the Laxemar-Simpevarp area than in the Forsmark area, except for uranium. Both phosphorus and iodine are known to precipitate in reactions with $CaCO_3$-rich soils /Greger 2004/, and agricultural land is more abundant in Laxemar-Simpevarp, which may explain a part of the higher retention of phosphorus in Forsmark in comparison with Laxemar-Simpevarp. The different patterns found for uranium and thorium are, however, difficult to explain.

Table 9-9. Mass balance calculations of the total content of phosphorus, iodine, uranium and thorium in all the catchments that were investigated in Forsmark (Fm) and Laxemar-Simpevarp (Sm). The second part of the table shows the relative contribution of each pool to the total content and the relative contribution of output and accumulation in relation to the input. A negative sign in the last column suggests that the area has a net export of the element.

Element	Site	Pools (g)				Input (g y^{-1})	Output/Acc. (g y^{-1})	
		Consumers	Producers	Humus/litter	Mineral soil	Deposition	Export	Acc.
P	Fm	17,278	16,199,498	58,034,611	201,473,169	96,735	13,660	83,075
	Sm	168,755	88,612,921	91,702,297	555,548,470	386,017	126,447	259,570
Iodine	Fm	0.3	24,499	166,155	355,546	2,224	9,066	–6,842
	Sm	1.6	292,062	175,907	1,253,654	4,290	35,100	–30,810
Uranium	Fm	0	34,835	247,417	1,789,283	24	3,705	–3,681
	Sm	0	16,815	169,984	3,308,707	43	2,062	–2,019
Thorium2)	Fm	0	1,535	30,101	1,855,522	60	25	35
	Sm	0	9,176	24,959	5,684,018	107	424	–317
P	Fm	0.01	6	21	73	100	14	86
	Sm	0.02	12	12	75	100	33	67
Iodine	Fm	0	4	30	65	100	408	–308
	Sm	0	17	10	73	100	818	–718
Uranium	Fm	0	2	12	86	100	15,522	–15,422
	Sm	0	0.5	5	95	100	4,807	–4,707
Thorium	Fm	0	0.1	2	98	100	42	58
	Sm	0	0.2	0.4	99	100	395	–295

Table 9-10. Mass balance calculations of the total content of phosphorus in all the catchments that were investigated in Forsmark. Accumulation is calculated as the difference between input weathering and deposition) and export. The percentage "Output/Acc." on last row is calculated as part of the total input.

Catchment	Pools (g)				Input (g y^{-1})		Output/Acc. (g y^{-1})	
	Consumers	Producers	Humus/litter	Mineral soil	Weathering	Deposition	Export	Acc.
Bolundsfjärden	4,094	3,048,425	14,683,296	43,343,172	24,697	22,339	2,694	44,341
Eckarfjärden	4,458	6,123,181	12,033,810	61,195,567	40,051	25,261	3,049	62,264
Fräkengropen	306	268,007	1,106,084	3,519,464	2,263	1,665	162	3,765
Gällsboträsk	4,504	2,989,802	15,089,104	52,498,115	24,657	25,937	4,632	45,963
Graven	851	753,170	3,291,708	7,727,861	4,127	4,602	647	8,082
Kungsträsket	279	179,217	727,915	3,110,021	1,280	1,482	142	2,620
Lake 2:2	162	107,160	716,590	1,582,454	598	808	52	1,354
N. bassängen	724	816,543	2,744,343	8,331,968	7,393	3,850	399	10,844
Puttan	495	629,681	2,491,571	4,441,701	3,604	2,658	418	5,845
Stocksjön	457	368,999	1,747,630	4,986,360	3,175	2,487	315	5,347
Varmbörs-fjärden	947	915,314	3,402,561	10,736,484	5,689	5,646	1,151	10,184
Sum	17,278	16,199,498	58,034,611	201,473,169	117,535	96,735	13,660	200,610
%	0	6	21	73	55	45	6	94

Table 9-11. Mass balance calculations of the total content of phosphorus in all the catchments that were investigated in Laxemar-Simpevarp. Accumulation is calculated as the difference between input (weathering and deposition) and export. The percentage "Output/Acc." on last row is calculated as part of the total input.

Catchment	Pools				Input (g y^{-1})		Output/Acc. (g y^{-1})	
	Consumers	Producers	Humus/litter	Mineral soil	Weathering	Deposition	Export	Acc.
6_1	30,293	9,072,772	12,758,018	88,046,349	63,69	54,090	25,500	92,280
7_1	373	832,181	1,610,613	3,043,646	3,453	5,758	1,500	7,711
7_2	14,062	8,125,218	12,393,782	49,642,545	42,181	47,010	17,200	71,990
8_1	1,527	1,946,773	3,910,114	25,133,637	6,849	13,366	3,500	16,714
9_1	28,092	9,483,544	11,037,537	86,352,805	64,300	49,821	22,500	91,620
9_2	9,721	3,011,120	5,000,736	27,963,108	21,333	20,717	10,700	31,351
9_3	3,848	881,769	1,358,557	10,375,251	7,144	5,992	3,400	9,736
10_1	43,398	25,665,358	23,380,930	165,017,662	135,960	92,892	3,547	225,305
10_2	6,033	2,084,623	2,912,332	18,654,268	14,271	12,423	5,700	20,994
10_3	3,048	1,815,658	2,447,959	11,352,913	9,470	8,623	3,400	14,694
10_4	16,093	8,144,861	3,852,983	19,988,669	38,830	27,031	14,000	51,860
10_5	2,021	4,807,965	2,658,149	7,928,323	7,543	7,835	2,600	12,778
10_6	6,495	9,615,955	4,103,090	25,687,406	27,055	24,018	7,800	43,273
10_7	3,751	3,125,125	4,277,497	16,361,888	14,877	16,442	5,100	26,219
Sum	168,755	88,612,921	91,702,297	555,548,470	456,957	386,017	126,447	716,526
%	0	12	12	75	54	46	15	85

Table 9-12. Mass balance calculations of the total content of iodine in all the catchments that were investigated in Forsmark. Accumulation is calculated as the difference between input and export. The percentage "Output/Acc." on last row is calculated as part of the total input.

Catchment	Pools				Input (g y^{-1})	Output/Acc. (g y^{-1})	
	Consumers	Producers	Humus/litter	Mineral soil	Deposition	Export	Acc.
Bolundsfjärden	0	3,239	44,676	26,680	514	2,223	–1,710
Eckarfjärden	0	13,893	29,674	126,147	581	2,023	–1,442
Fräkengropen	0	301	3,393	7,287	38	165	–126
Gällsboträsk	0	2,924	40,485	110,276	596	2,364	–1,768
Graven	0	935	10,663	16,255	106	531	–425
Kungsträsket	0	132	1,636	6,551	34	117	–83
Lake 2:2	0	88	1,585	3,348	19	57	–38
N. bassängen	0	839	9,495	16,965	88	429	–340
Puttan	0	696	9,031	9,145	61	309	–248
Stocksjön	0	457	5,484	10,343	57	260	–203
Varmbörsfjärden	0	996	10,033	22,549	130	588	–458
Sum	0	24,499	166,155	355,546	2,224	9,066	–6,842
%	0	4	30	65	100	408	–308

Table 9-13. Mass balance calculations of the total content of iodine in all the catchments that were investigated in Laxemar-Simpevarp. Accumulation is calculated as the difference between input and export. The percentage “Output/Acc.” on last row is calculated as part of the total input.

Catchment	Pools				Input (g y^{-1})	Output/Acc. (g y^{-1})	
	Consumers	Producers	Humus/litter	Mineral soil	Deposition	Export	Acc.
6_1	0	13,538	22,845	198,348	601	4,919	–4,318
7_1	0	1,717	2,839	6,160	64	523	–459
7_2	0	12,910	23,019	109,167	522	4,537	–4,014
8_1	0	3,794	6,875	46,098	149	1,225	–1,077
9_1	0	12,725	19,440	195,363	554	4,530	–3,976
9_2	0	5,046	8,788	62,320	230	1,883	–1,653
9_3	0	1,489	2,388	23,446	67	545	–479
10_1	0	26,837	50,940	374,165	1,032	8,222	–7,190
10_2	0	3,018	5,128	41,870	138	1,129	–991
10_3	0	2,349	4,307	25,223	96	783	–687
10_4	0	50,797	8,318	59,148	300	2,457	–2,157
10_5	0	67,278	5,558	17,646	87	712	–625
10_6	0	86,014	7,937	58,942	267	2,185	–1,918
10_7	0	4,551	7,525	35,759	183	1,495	–1,313
Sum	2	292,062	175,907	1,253,654	4,289	35,146	–30,856
%	0	17	10	73	100	819	–719

Table 9-14. Mass balance calculations of the total content of uranium in all the catchments that were investigated in Forsmark. Accumulation is calculated as the difference between input and export. The percentage “Output/Acc.” on last row is calculated as part of the total input.

Catchment	Pools				Input (g y^{-1})	Output/Acc. (g y^{-1})	
	Consumers	Producers	Humus/litter	Mineral soil	Deposition	Export	Acc.
Bolundsfjärden	0	1,167	68,963	109,395	6	856	–850
Eckarfjärden	0	27,773	40,245	672,153	6	977	–971
Fräkengropen	0	213	5,469	37,983	0	64	–63
Gällsboträsk	0	1,622	62,829	534,894	6	1,012	–1,006
Graven	0	1,182	13,709	78,448	1	180	–178
Kungsträsket	0	59	2,134	31,241	0	59	–59
Lake 2:2	0	19	2,211	15,598	0	59	–59
N. bassängen	0	898	14,290	96,588	1	31	–30
Puttan	0	518	16,511	49,011	1	148	–147
Stocksjön	0	249	9,676	53,432	1	99	–98
Varmbörsfjärden	0	1,134	11,380	110,540	1	220	–218
Sum	0	34,835	247,417	1,789,283	24	3,705	–3,681
%	0	1.7	12	86	100	15,522	–15,422

Table 9-15. Mass balance calculations of the total content of uranium in all the catchments that were investigated in Laxemar-Simpevarp. Accumulation is calculated as the difference between input and export. The percentage "Output/Acc." on last row is calculated as part of the total input.

Catchment	Pools				Input (g y^{-1})	Output/Acc. (g y^{-1})	
	Consumers	Producers	Humus/litter	Mineral soil	Deposition	Export	Acc.
6_1	0	689	21,768	523,101	6	289	–283
7_1	0	85	2,675	20,237	1	31	–30
7_2	0	654	22,112	303,185	5	250	–245
8_1	0	193	6,463	181,876	1	72	–70
9_1	0	620	18,584	510,472	6	266	–261
9_2	0	257	8,324	168,220	2	111	–109
9_3	0	76	2,265	61,416	1	32	–31
10_1	0	1,141	50,249	972,919	10	495	–485
10_2	0	147	4,876	111,305	1	66	–65
10_3	0	109	4,101	68,539	1	46	–45
10_4	0	3,091	8,248	89,762	3	144	–141
10_5	0	4,220	5,397	47,769	1	42	–41
10_6	0	5,312	7,760	149,292	3	128	–126
10_7	0	221	7,161	100,613	2	88	–86
Sum	0	16,815	169,984	3,308,707	43	2,062	–2,019
%	0	0.5	5	95	100	4,807	–4,707

Table 9-16. Mass balance calculations of the total content of thorium for all the catchments that were investigated in Forsmark. Accumulation is calculated as the difference between input and export. The percentage "Output/Acc." on last row is calculated as part of the total input.

Catchment	Pools				Input (g y^{-1})	Output/Acc. (g y^{-1})	
	Consumers	Producers	Humus/litter	Mineral soil	Deposition	Export	Acc.
Bolundsfjärden	0	236	7,130	404,660	14	6	8
Eckarfjärden	0	691	7,709	537,609	16	6	10
Fräkengropen	0	27	511	31,665	1	0	1
Gällsboträsk	0	229	8,049	506,978	16	7	9
Graven	0	80	1,301	74,880	3	1	1
Kungsträsket	0	11	452	30,557	1	0	1
Lake 2:2	0	6	442	15,878	0	0	0
N. bassängen	0	75	1,208	67,278	2	1	1
Puttan	0	53	788	38,771	2	1	1
Stocksjön	0	38	763	45,287	2	1	1
Varmbörsfjärden	0	89	1,749	101,958	3	2	2
Sum	0	1,535	30,101	1,855,522	60	25	35
%	0	0.1	1.6	98	100	42	58

Table 9-17. Mass balance calculations of the total content of thorium in all the catchments that were investigated in Laxemar-Simpevarp. Accumulation is calculated as the difference between input and export. The percentage "Output/Acc." on last row is calculated as part of the total input.

Catchment	Pools				Input (g y^{-1})	Output/Acc. (g y^{-1})	
	Consumers	Producers	Humus/ litter	Mineral soil	Deposition	Export	Acc.
6_1	0	496	1,605	946,570	15	59	–44
7_1	0	50	118	18,230	2	5	–4
7_2	0	439	2,093	478,208	13	52	–39
8_1	0	124	155	51,239	4	14	–10
9_1	0	463	1,514	945,627	14	55	–41
9_2	0	171	365	286,593	6	32	–27
9_3	0	53	113	113,059	2	9	–7
10_1	0	946	13,082	1,824,408	26	93	–67
10_2	0	105	324	197,345	3	0	3
10_3	0	80	273	114,727	2	11	–8
10_4	0	1,540	2,302	175,739	8	39	–31
10_5	0	1,994	1,015	80,763	2	8	–6
10_6	0	2,564	1,542	298,506	7	29	–22
10_7	0	152	458	153,006	5	19	–15
Sum	0	9,176	24,959	5,684,018	107	424	–317
%	0	0.2	0.4	99	100	395	–295

10 Postglacial terrestrial development and vegetation change

The long-term ecosystem development in the inshore land and sea areas of Fennoscandia is driven mainly by two factors: climate change and shoreline displacement. A third factor affecting ecosystems is human land use, which has become more and more important over time as the human population has increased and the appropriation of resources has increased exponentially.

The climate changed repeatedly during the Quaternary period, thereby changing the conditions for biota that to a high degree define the ecosystems. Such climatic changes have directly changed the conditions for ecosystem formation, e.g. mire and bog complexes, and have caused north- and south-ward migration of species and ecological communities. Changes of species distributions have the potential to affect entire ecosystems, e.g. the emergence or disappearance of species that may have a key function in the ecosystem, such as the megaherbivores that are thought to have kept the forests fairly open, or a predator that may directly alter the food web and thereby the whole ecosystem. In this perspective, human land use is also an important component that has in many ways shaped the landscape of today.

The second important factor, shoreline displacement, has strongly affected both Forsmark and Laxemar-Simpevarp since the last deglaciation and is still causing a relatively predictable change in the abiotic environment, e.g. in water and nutrient availability. It is therefore appropriate to describe the origin and succession of some major ecosystem types in relation to shoreline displacement. The sections below both have a general perspective on the long-term change of climate, soil, fauna, ecosystem and human land use in Fennoscandia, and the regional perspectives of changes at Forsmark and Laxemar-Simpevarp.

10.1 Postglacial development of vegetation

The vegetation development in southern Sweden following the last deglaciation was primarily determined by climatic changes and the formation of new land areas, but human activities have also influenced large-scale vegetation development, especially during the last few millennia. Shortly after the retreat of the ice sheet, which started in southernmost Sweden in c 15,000 BC, the landscape was free of vegetation and can be characterized as a polar desert. Relatively soon, the ice-free areas were colonized, first by lichens and mosses, then by tolerant grasses and herbs. Pollen investigations from southern Sweden have shown that a sparse birch (*Betula* sp) forest covered the landscape soon after the deglaciation (e.g. /Björck 1999/).

During the period called the Younger Dryas (c 11,000–9500 BC) there was a decrease in temperature and the climate became arctic. Large areas of the deglaciated parts of Sweden were affected by permafrost, and much of the previously established flora and fauna disappeared. Only the most tolerant species remained and herb tundra developed. At the beginning of the Holocene c 9500 BC, the temperature increased again and southern Sweden was covered by forests, first dominated by birch and later by Scots pine (*Pinus sylvestris*) and hazel (*Corylus avellana*).

Northern Sweden was deglaciated during the early part of Holocene when the climate was relatively warm. These areas were therefore covered with forest, mainly consisting of birch and Scots pine, shortly after deglaciation. There was a cooling of the early Holocene climate during the so-called Preboreal oscillation, which was a 150 year long cooling period /Björck et al. 1996/. During the mid-Holocene, between 7,000 and 5,000 years ago, the summer temperature in southern Sweden was approximately 2°C warmer than at present. Forests with lime (*Tilia cordata*), oak (*Quercus robur*) and elm (*Ulmus glabra*) covered large parts of southern Sweden. These trees then had a much more northerly distribution than at the present day. However, cold events occurred also during the warm mid-Holocene. Results from Greenland ice cores presented by /Alley et al. 1997/ show that a cold event, half the amplitude of the Younger Dryas, occurred around 6200 BC. In a study of the Holocene climate of northern Sweden, /Karlén et al. 1995/ recognized more than ten small oscillations between a relatively warm and cold climate. The summer temperature during the warm periods was generally 1ºC warmer than at present, and during the cold periods it was 1 ºC colder than at present.

After the warm mid-Holocene, the temperature decreased and the forests have subsequently become more dominated by coniferous trees. Norway spruce (*Picea abies*) spread from northernmost Sweden southward during the Holocene. This species has not yet spread naturally to parts of Skåne and the Swedish west coast (e.g. /Lindbladh 2004/). /Davis et al. 2003/ reconstructed the Holocene climate in Europe from pollen data. They concluded that the warmer climate during the mid-Holocene was restricted to north-western Europe, whereas the climate further south was similar to or colder than that of today. The ecological history of Sweden during the last 15,000 years has been reviewed by e.g. /Berglund et al. 1996a/. In Figure 10-1, tree pollen diagrams from three Swedish regions show the vegetation succession from the last deglaciation to the present.

During the past few thousand years, the composition of the vegetation has changed not only due to climatic changes and the formation of new land areas, but also due to human activities. In southern Sweden, the introduction of agriculture and the subsequent opening of the landscape started c 5,000 years ago. It is often assumed that Sweden was more or less covered by forest before the introduction of agriculture. However, /Vera 2000/ suggested that grazing animals kept the European landscape relatively open. Some of the grazing animals that were common in the early Holocene have decreased or disappeared completely. /Lindbladh et al. 2003/ have suggested that fires also kept some forest types more open before humans started to have an impact on the forests in northern Europe.

10.1.1 The Forsmark area

When the latest deglaciation in Forsmark took place in approximately 8800 BC, the closest shore was situated c 100 km to the west of Forsmark. At that time, the Forsmark area was situated c 150 m below the surface of the Yoldia Sea /Söderbäck 2008/. Since the major part of the Forsmark regional model area was covered by water until c 500 BC, the post-glacial development of the area is determined mainly by the development of the Baltic basin and by shoreline displacement.

At around 500 BC, a few scattered islands situated in the western part of the regional model area were the first land areas to emerge from the brackish water of the Bothnian Sea. The surface of these first islands was covered by sandy till and exposed bedrock, i.e. similar to the present situation on the islands outside Forsmark area. Palaeo-ecological studies from the Florarna mire complex, situated c 30 km west of the regional model area indicate a local humid and cold climate at approximately this time /Ingmar 1963/.

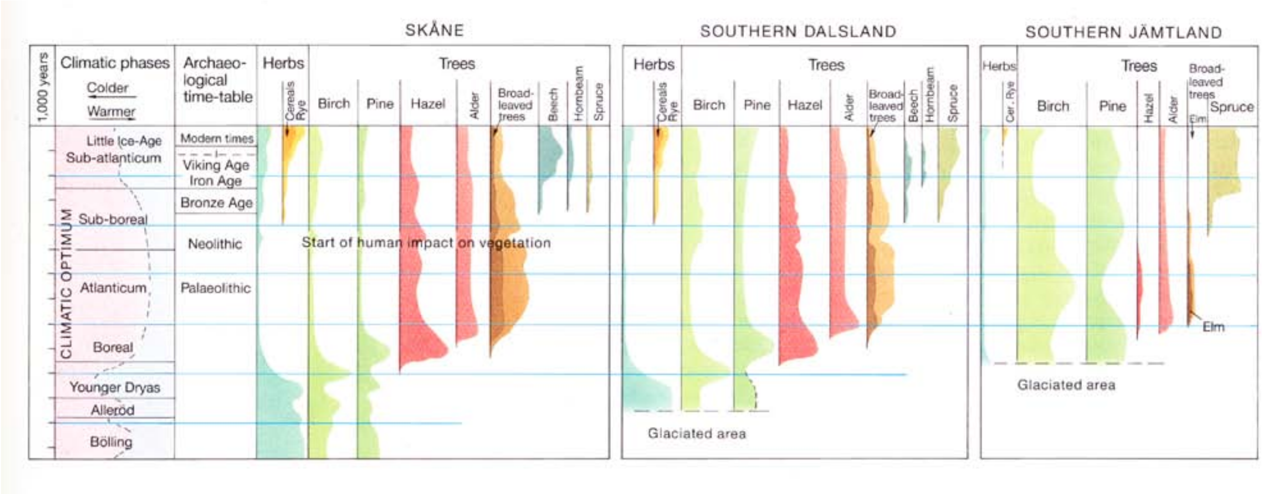


Figure 10-1. Pollen diagram showing how the composition of vegetation has changed from the last deglaciation to the present. The diagrams were made after analyses of sediment cores from Skåne, Dalsland, and Jämtland. The past summer temperature was somewhat higher than the present, something which is reflected by higher frequencies of pollen from broad-leafed trees (c 5,000–8,000 years ago). In southern Sweden agriculture was introduced in c 3000 BC, which is shown as an increase in the frequency of pollen from herbs (from /Fredén 2002/).

At 0 BC, the Bothnian Sea still covered most of the Forsmark area, whereas the islands in the western part of the regional model area had expanded in size. Land areas currently covered with peat had emerged, and at that time these newly isolated basins were small and shallow freshwater lakes/ponds, similar to the near-shore lakes that can be found in the area today. The apparent isolation of Lake Bruksdammen in the western part of the area around 0 BC is an artefact caused by the use of today's lake thresholds when constructing the map; the lake was probably created by man in the 17th century by damming the Forsmarksån river /Brunberg and Blomqvist 1998/.

At 1000 AD, the mainland had expanded further in the south-western part of the area. The isolation process of the Lake Eckarfjärden basin was initiated, but the bay still had an open connection with the Baltic in the northern part (cf./ Hedenström and Risberg 2003/). The area west of Lake Eckarfjärden presently occupied by the Stenrösmossen mire had emerged, and a short lake phase was succeeded by infilling of reed (cf. /Fredriksson 2004/). The Börstilåsen esker and the most elevated areas at Storskäret (Figure 10-2) constituted some small islands in the east, exposed to waves and erosion.

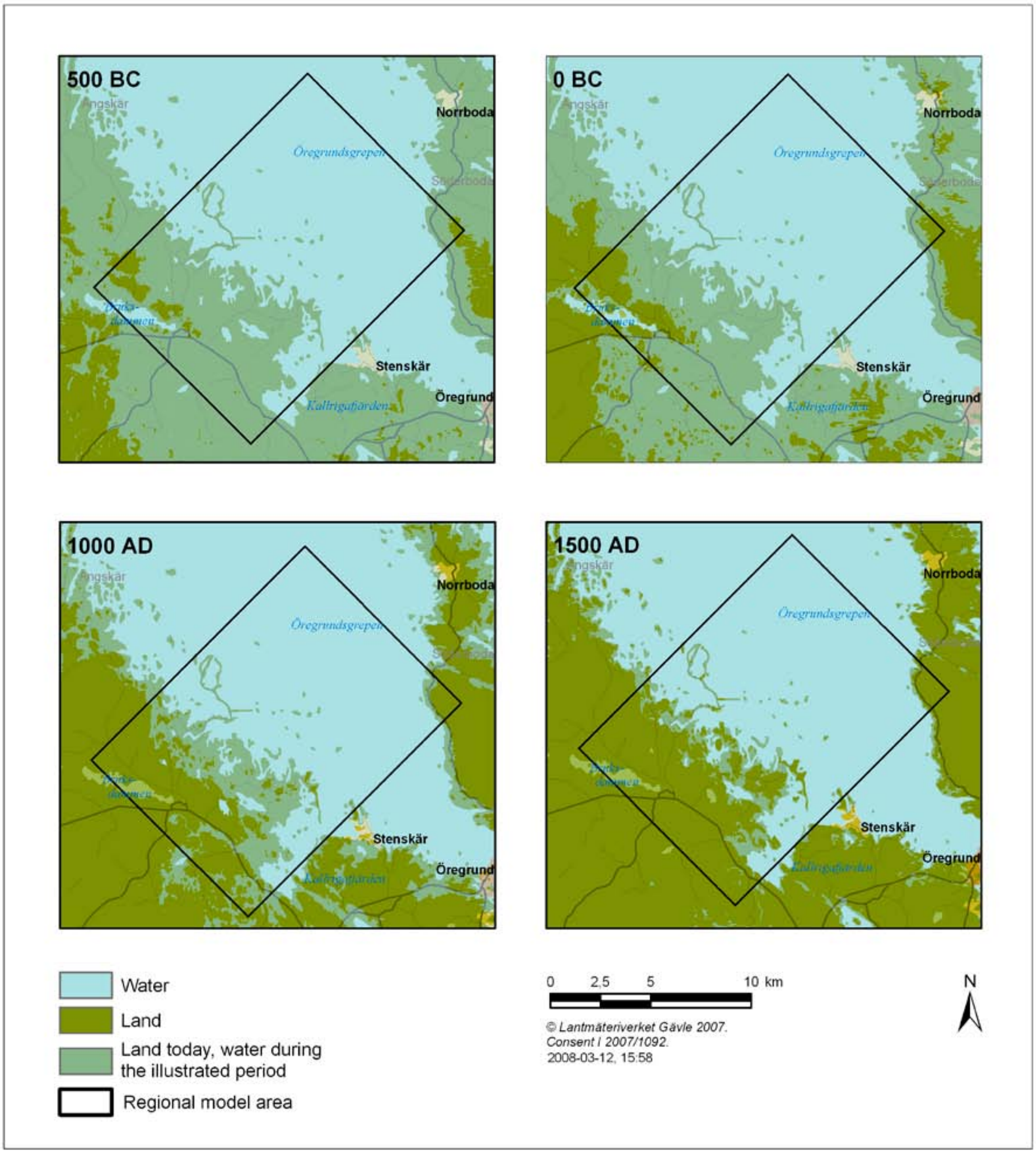


Figure 10-2. *The distribution of land and sea in the Forsmark area at 500 BC, 0 BC, 1000 AD and 1500 AD. From /Söderbäck 2008/.*

At 1500 AD, a considerable part of the regional model area had emerged from the Baltic and several freshwater lakes were isolated, e.g. Lake Eckarfjärden and Gällsboträsket. A shallow strait connected the bays that today are Lake Bolundsfjärden and Lake Fiskarfjärden. The northern part of this archipelago was heavily exposed to wave action, whereas the southern part was relatively protected. The area covered by clayey till at Storskäret formed a large island, partly protected from wave exposure by the Börstilåsen esker. A hundred years later, the strait between Bolundsfjärden and Fiskarfjärden had been cut off, and there were two bays with different conditions. At around 1650 AD, the major part of the area was situated above sea level.

The post-glacial development of ecosystems in the Forsmark area has principally been determined by the climate, the development of the Baltic basin and shoreline displacement, as described above and in Chapter 4. The first terrestrial ecosystems appeared around 500 BC, and the succession of both terrestrial and aquatic ecosystems has, in all essentials, followed the general patterns outlined above.

The vegetation development

In order to describe the Holocene vegetation history of the area during a longer timespan, the area for collecting data must be expanded to include more elevated regions such as the western part of the county of Uppland. /Karlsson 2007/ has recently compiled published investigations on pollen analyses from Uppland, together with results from stratigraphical investigations performed in connection with archaeological investigations for the construction of 90 km of new highway (E4) in northern Uppland. The following description is based mainly on the associated compilation of 12 pollen diagrams /Karlsson 2007/, and focuses on the vegetation history of Uppland during the Stone Age (c 5500–2300 BC). A palaeo-ecological description of South-Central Sweden /Berglund et al. 1996a/ is also used for the regional description.

In western Uppland, the first areas to emerge were mainly covered by till, bare bedrock and eskers. In all pollen diagrams, Scots pine and birch are the dominant trees when the sites were located in the outer archipelago, whereas a mixed deciduous forest containing e.g. oak, aspen (*Populus tremula*) and lime spread at sites located in the inner archipelago. Along the shores and in bays, alder (*Alnus*) and willow (*Salix*) were common, while in sheltered positions on fine-grained Quaternary deposits a temperate and nutrient-demanding tree flora consisting of elm and hazel was widespread.

Flat rocks and crevices close to the shore probably hosted a light-demanding flora such as common juniper (*Juniperus communis*), heather (*Calluna vulgaris*) and sheep sorrel (*Rumex acetosella*). A pioneer shrub found from the Mesolithic and onwards is sea-buckthorn (*Hippophaë rhamnoides*), which is one of the typical shrubs along the Forsmark coast today. Sea-buckthorn is very sensitive to competition from other plants and needs to colonize unweathered minerogenic deposits. These conditions are only found where new, unweathered and uncolonized land areas emerge, i.e. where the rate of vertical shore displacement is faster than approximately 5 mm/year.

As the land areas grew and the islands became part of the mainland, the number of pollen taxa found in the sediments increased, reflecting that a more diverse flora was developing at the sites. An event that is often identified in pollen diagrams from north-western Europe is the decline of elm pollen at c 3000 BC, known as the elm decline /Huntley and Birks 1983/. A number of causes have been suggested for the elm decline: climatic changes, elm disease, human activity or a combination of these. The elm decline can be traced in more than 50% of the pollen diagrams from Uppland and is dated to c 2500 BC /Karlsson 2007/.

Only few investigations are available to provide information on the local vegetation history. At the Hållnäs peninsula, c 35 km north of the Forsmark regional model area, biostratigraphical investigations were performed in connection with archaeological investigations /Ranheden 1989/. These investigations indicate traces of forest clearing from c 600–700 AD. Extensive land use and settlements from the Viking age and medieval period were identified in the fossil record, indicating that humans have been occupying the archipelago as new land has emerged from the Baltic.

A pollen investigation of sediment collected in the Kallrigafjärden has been performed /Bergkvist et al. 2003/. The sampling site was located close to the outlet of the Olandsån River, which means that the pollen record in the sediments will give a regional vegetation history. Norway spruce is present in the bottom layer of the sediment, indicating that the whole sediment sequence was deposited after the immigration of Norway spruce at c 0 AD/BC /Berglund et al. 1996/. Heather and sea-buckthorn pollen reflect the vegetation at the shores. High values of lime pollen may indicate that this species was important for fodder production and was therefore favoured by humans /Bergkvist et al. 2003/. Other traces of humans are corn (*Hordeum* sp) from far down in the sediment, indicating cultivation within the area. There are no radiocarbon dates for the analyzed sediments from Kallrigafjärden, so no absolute ages are known.

Weathering and leaching of carbonates will occur under all carbonate-rich vegetation types /Ingmar and Moreborg 1976/, leading to a gradual change to a flora adapted to environments with a lower pH. Accordingly, there will be a zone of vegetation favoured by high pH along the coast, and this zone will continuously move as new land areas emerge from the sea

10.1.2 The Laxemar-Simpevarp area

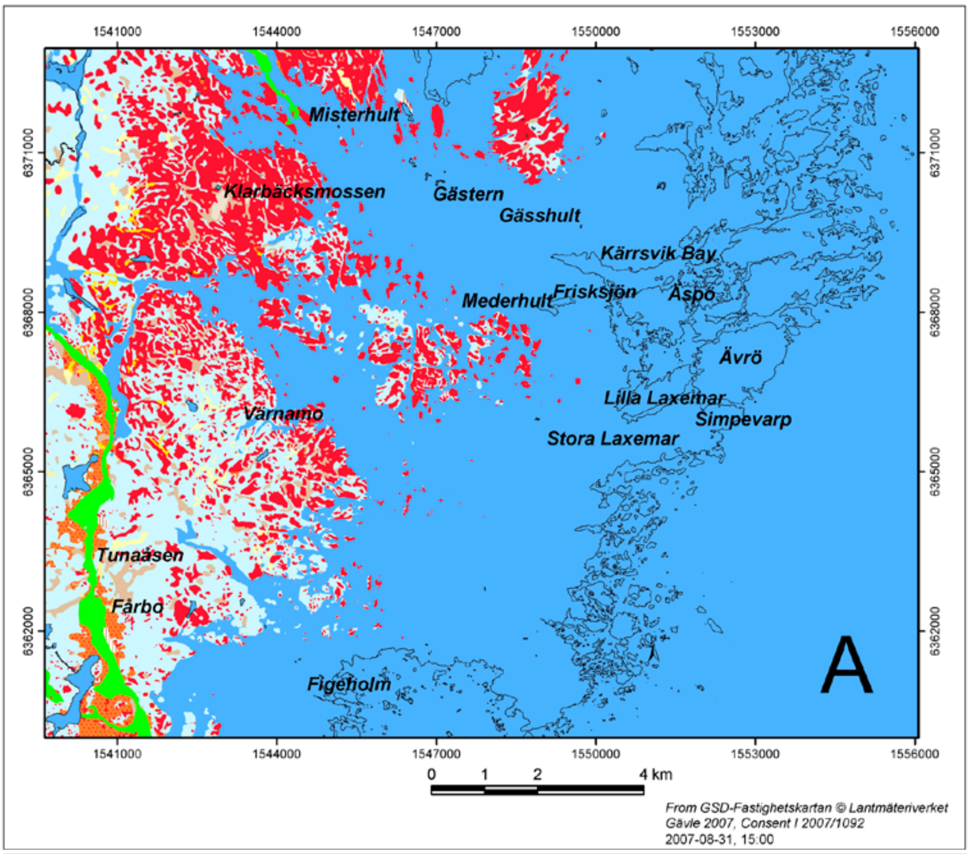
The last deglaciation in the Laxemar-Simpevarp area took place c 14,000 years ago, and the highest shoreline in the region is located c 100 m above the present sea level. Thus, the whole Laxemar-Simpevarp area is situated below the highest shoreline, since the highest point in the area is situated c 50 m above the present sea level. The sea level dropped fast during the end of the Baltic Ice Lake stage, from c 66 metres above present sea level (metres above sea level) around 10,000 BC to less than 20 metres above sea level just over 1,000 years later. Accordingly, the first islands in the area emerged from the sea around 9400 BC.

The Yoldia Sea stage (9500–8800 BC) was characterized by regressive shoreline displacement, whereas the onset of the Ancylus Lake stage around 8700 BC was characterized by a transgression with total amplitude of c 11 m. Figure 10-3 shows the former shoreline in the Laxemar-Simpevarp area at three different occasions during the Holocene. At around 8000 BC, i.e. in the middle of the lacustrine Ancylus Lake stage, the shoreline was situated just above 20 metres above sea level, which means that the western part of the Laxemar-Simpevarp regional model area was free of water. Between 8000 BC and 5000 BC, i.e. the first part of the Littorina Sea stage, shoreline displacement was mostly regressive, although there are indications of several minor transgressions during that period. At 5000 BC, when the shoreline was situated c 15 metres above present sea level, the central parts of the regional model area were free of water, but the fissure valleys still constituted long and narrow coastal bays which intersected the area. At 2000 BC, most of today’s terrestrial areas had emerged from the sea and the coastal bays decreased considerably in size. Since 0 BC, the sea level has dropped c 3 m, but this has resulted in only minor changes in the distribution of land and sea in the regional model area. The present areas covered with gyttja clay coincide with areas which were once sheltered bays. The areas that today are used as arable land were during the Littorina Sea long and narrow bays (Figure 10-3).

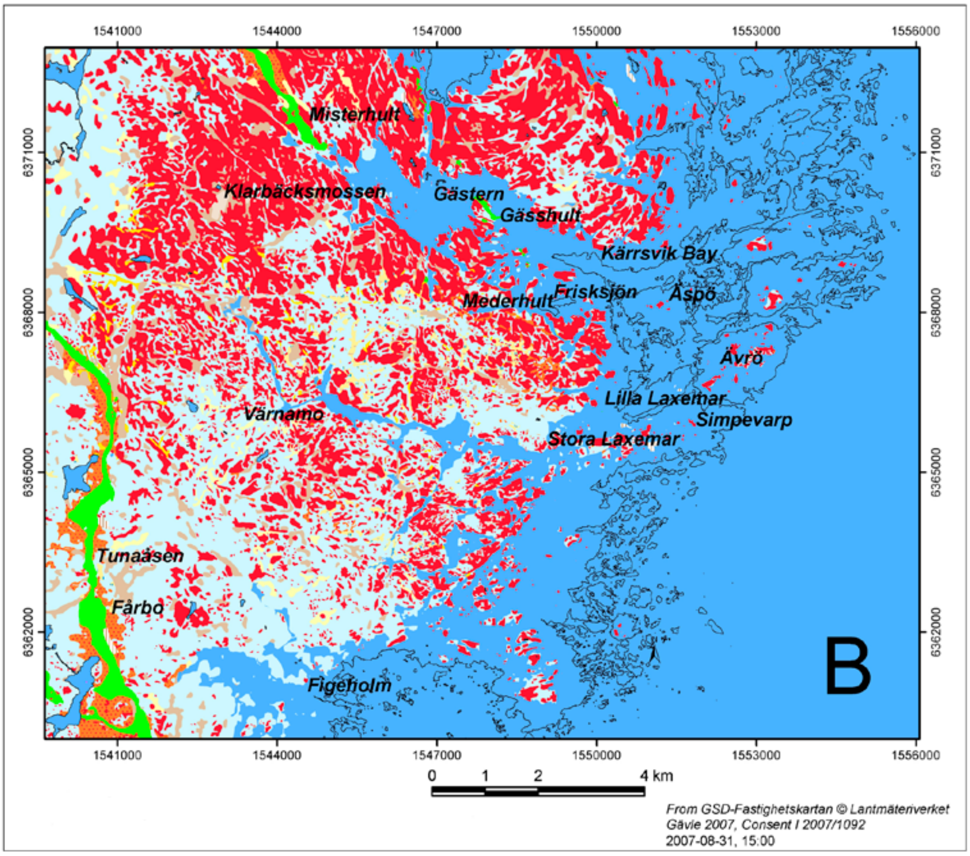
Similarly to the Forsmark area, the postglacial development of ecosystems in the Laxemar-Simpevarp area is principally determined by the climate, the development of the Baltic basin and the shoreline displacement, as described above and in Chapter 4. The first terrestrial ecosystems appeared around 9000 BC, and the succession of both the terrestrial and aquatic ecosystems has in all essentials followed the general patterns outlined above. Site-specific information that can be added to the general successional trajectories includes regional vegetation history, the local and regional lake ontogeny and the development of areas used as arable land.

The vegetation development

Stratigraphical investigations of pollen from Blekinge show the succession of terrestrial plants in south-eastern Sweden from the latest deglaciation to the present /Berglund 1966/. Shortly after the Laxemar-Simpevarp area was deglaciated in c 12,000 BC, it was characterized by tundra vegetation dominated by herbs and bushes and a low coverage of trees. During the following Alleröd chronozone, a sparse birch and Scots pine forest dominated the vegetation. In southern Sweden, the following cold Younger Dryas chronozone was characterized by tundra vegetation, which is reflected in a high proportion of wormwood (*Artemisia*) pollen. In stratigraphical studies in the Laxemar-Simpevarp area, /Lagerbäck et al. 2004/ found evidence of tundra conditions during the Younger Dryas.

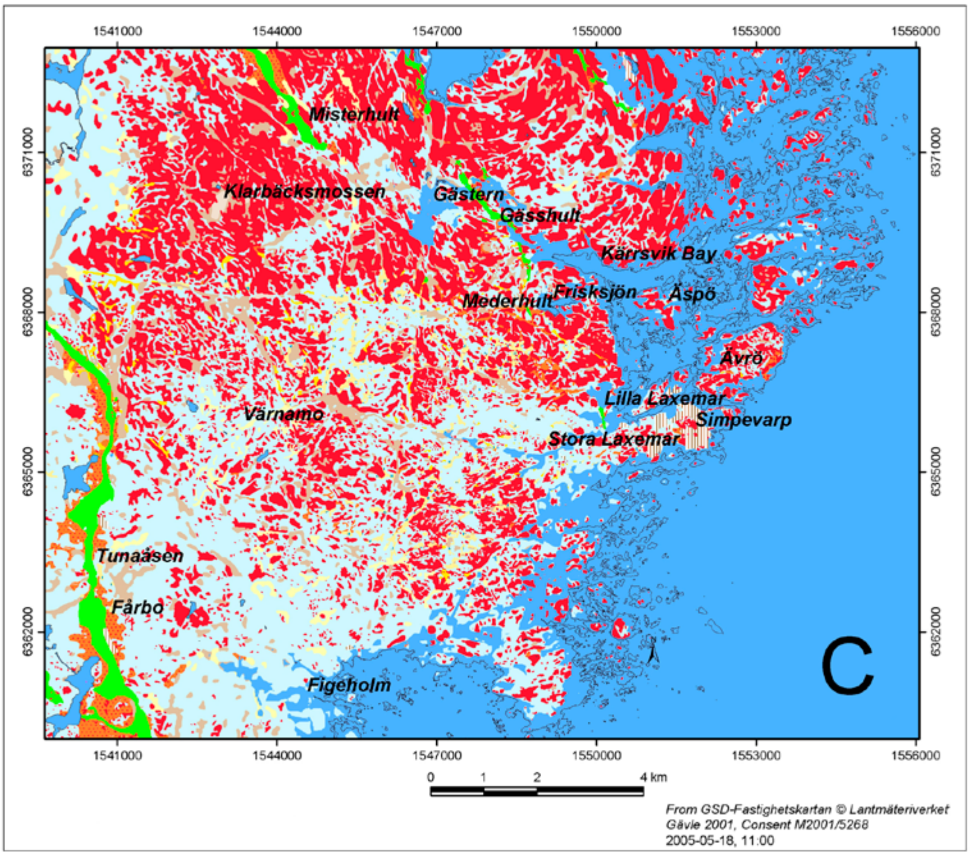


From GSD-Fastighetskartan © Lantmäteriverket
Gävle 2007, Consent I 2007/1092
2007-08-31, 15:00



From GSD-Fastighetskartan © Lantmäteriverket
Gävle 2007, Consent I 2007/1092
2007-08-31, 15:00

Figure 10-3. *Distribution of land and sea in the Laxemar-Simpevarp area at four different times during the Holocene, A) 7800 and 8650 BC (one before and one after the Ancylus transgression), B) 3900 BC, C) 1100 BC. The sea level was 19 (A), 12 (B) and 5 (C) meters higher than at present at the three times shown on the maps. Red color is rock outcrop, light blue is till and yellow colour is glacial clay and gyttja clay (see also legend in Figure 3-5). From /Söderbäck 2008/.*



From GSD-Fastighetskartan © Lantmäteriverket
Gävle 2001, Consent M2001/5268
2005-05-18, 11:00

Figure 10-3. *Continued.*

At the beginning of the Holocene, c 9500 years BC, the temperature increased and south-eastern Sweden was first covered by forests dominated by birch and later by forests dominated by Scots pine and hazel. During the period 7000–4000 BC, forests consisting of lime, oak and elm covered south-eastern Sweden (e.g. /Berglund 1966, Küttel 1985/). The spread and establishment of beech (*Fagus sylvatica*) and Norway spruce in southern Sweden has been investigated in several studies /Björkman 1996, Bradshaw and Lindbladh 2005/. Norway spruce spread from the north and reached the Laxemar-Simpevarp area less than 1,000 years ago /Lindbladh 2004/. It is possible that domestic animals were involved in the spread of spruce, since grazing animals avoid spruce /Björkman 1996/. Beech has spread over southern Sweden during the last 4,000 years. The species was common in eastern Småland two thousand years ago, but has since disappeared from that area /Bradshaw and Lindbladh 2005/. The decline of beech was probably caused by human activities.

A pollen investigation covering the last c 1,500 years has been carried out on sediments from two lakes situated 20 and 25 kilometres west of Fårbo /Aronsson and Persson, unpublished data/. The results show an increase of *Juniperus* (juniper) and *Cerealea* (corn) c 1,200 years ago, which indicates that areas used as arable land and for pasture increased during that time.

10.2 Postglacial development of soil, organic carbon and nitrogen pools

When new land is exposed, plant colonization takes place and organic matter is added to the soil through litter fall. The accumulation of soil organic matter depends on the litter input and the decomposition of soil organic matter. Over time these two processes come into a state of equilibrium where decomposition balances litter input, and as a consequence the organic carbon stock in the soil fluctuates around a constant value. The time required for this equilibrium to establish itself varies, but may be up to 10,000 years /Birkeland et al. 1999/. For Scandinavian forest soils this time has been reported to be approximately 2,000 years /Liski et al. 1998/. However, disturbances such as forest fires or other catastrophic events as well as forest management may temporarily upset this equilibrium. The size of the carbon and nitrogen stocks depends on environmental conditions such as climate, soil moisture and soil fertility. These factors may influence litter input and the decomposition rate to different degrees. On moist sites the decomposition rate is inhibited, whereas forest growth and litter fall may be high, which may result in a higher accumulation rate. The distribution of the accumulated organic matter in the soil profile depends on the soil type that is developed. For example, Podzol soil types have large amounts of organic matter concentrated in the organic horizon, whereas in Cambisol types the organic matter is distributed more evenly in the upper soil profile due to bioturbation. This means that if the aim is to investigate variation in carbon stock, the soil type must be considered.

Reference field data from the National Forest Soil Inventory (NFSI) from the period 1993–2002 were used to describe the development of carbon and nitrogen stocks in forest soil during the postglacial period and to estimate the time required for the stocks to reach a steady state. A total of 4,697 sites in the NFSI (Figure 10-4) were sampled in the mineral soil, and the soil carbon and nitrogen stocks were estimated to a depth of 50 cm in the mineral soil for these sites. From these data, a subset of sites on Podzol type soils (Iron Podzol, Humic Podzol and transitional forms between Podzol and Cambisol) which represents the dominant forest soil types was used in the analyses.

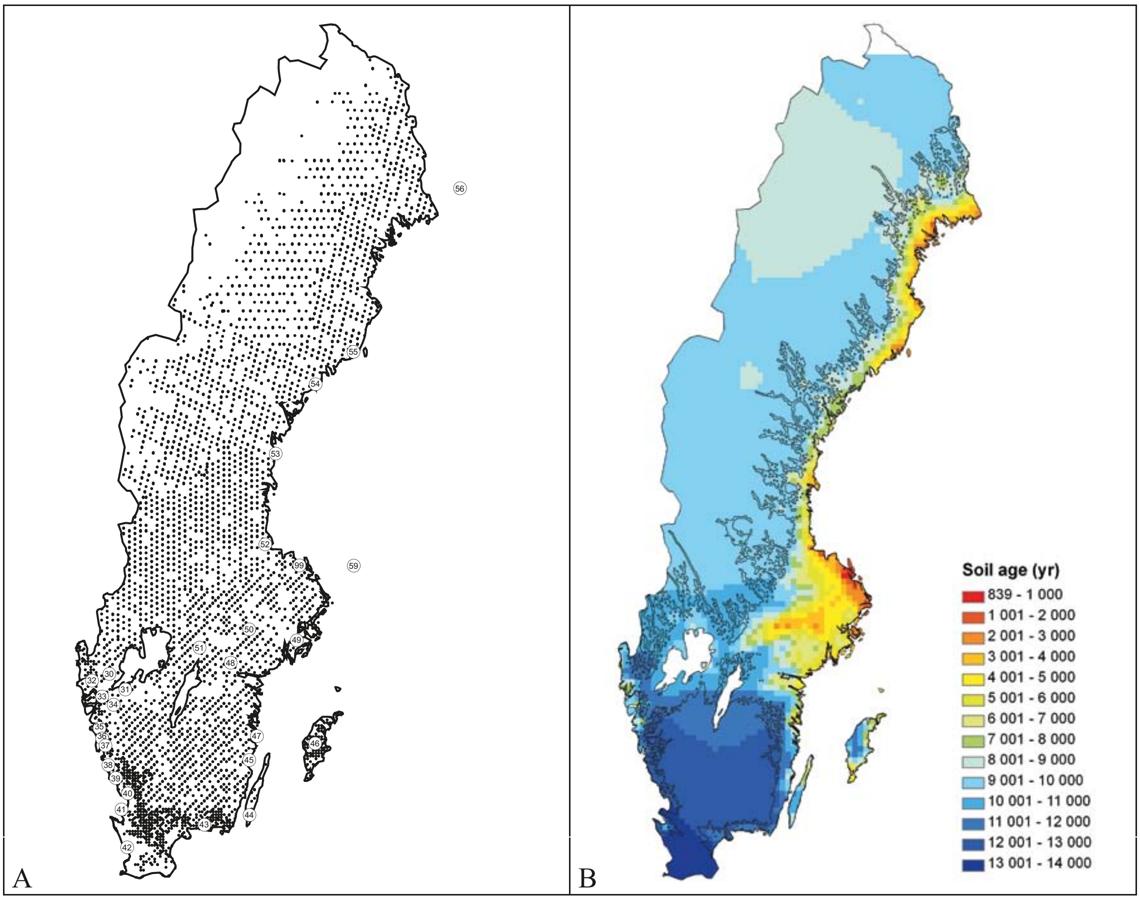


Figure 10-4. *A) Plots in National Forest Soil Inventory, where soil carbon stock has been estimated to a depth of 65 cm (4,697 plots) and 28 sites with shoreline displacement functions /Påsse 1997/. B) Soil age distribution in Sweden and the highest shoreline.*

Soil samples were taken from the forest floor and from up to three layers in the mineral soil: the top of the B horizon, 45–55 cm from the top of the organic layer (B–C horizon) and 55–65 cm from the top of the mineral soil (C horizon). The soil carbon stock for each sampled soil layer was calculated using the following function:

$$C_{pool} = \sum_{\text{i=soil layer}} (C_{conc}/100) \times BD \times DEPTH_i \times \left(1 - C_{stone}/100\right)$$

where C_{pool} is the carbon pool (kg m^{-2}), C_{conc} is the carbon concentration (%), BD is the bulk density (kg m^{-3}), DEPTH is the layer depth (m), and C_{stone} is the stone content (%). For nitrogen stocks, nitrogen replaced carbon concentrations in the function. The bulk density was determined from functions by /Nilsson and Lundin 2006/. The stone content was estimated from inventory data by the so-called Viro's rod penetration method /Viro 1952/. To estimate the total stock, the stock for the layers between the sampled soil layers was estimated by interpolation, and finally the stocks for all layers down to 50 cm were added together.

The soil age was determined based on shoreline displacement functions developed by /Påsse 1997/, which were determined for 28 sites in Sweden. These functions give the elevation of the sea as a function of age before present (before 1950). For each site in the NFSI, the function associated with the most closely located site in /Påsse 1997/ was applied. The elevation for each site in the NFSI was taken from the Swedish digital terrain model (Lantmäteriverket GSD) and this elevation was inserted into the shoreline displacement functions. The equation was solved using the SAS statistical software SAS 9.1 (SAS Institute Inc.) to get the age since the site was exposed. The soil age for areas above the highest shoreline was assumed to be the age since ice withdrawal, as given by the National Atlas of Sweden /Fredén 2002/. The analyses were limited to sites with a maximum age of 10,000 years, since it was the dynamics in the first millennia that was of the greatest interest.

The number of NFSI sites in the youngest age classes was very small, which can be seen in the frequency distribution of the age classes (Figure 10-5). The young areas were mainly found along the coast of Uppland, around Lake Mälaren and in the northernmost part of the Swedish coastline ((Figure 10-4B). The oldest soils were found in the southern part of Sweden, where the retreat of the ice cover was earliest and where the land was never submerged beneath the sea. The relationships between the carbon stocks in the soil and the age of the soil were weak, due to the great variability (Figure 10-6). Variability was even greater for the nitrogen stocks (Figure 10-7). However, the

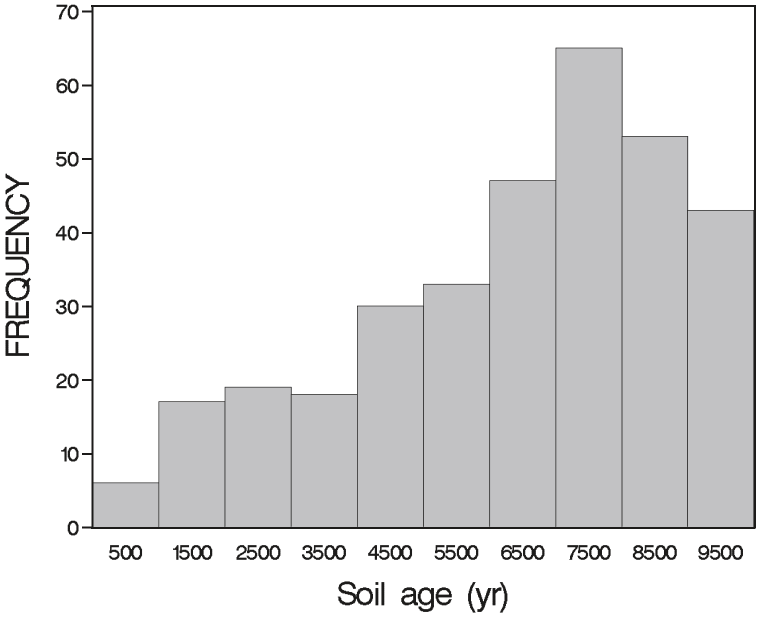


Figure 10-5. *Frequency distribution of soil age for plots in the National Forest Soil Inventory located on till parent material. Only plots below the highest shoreline are included.*

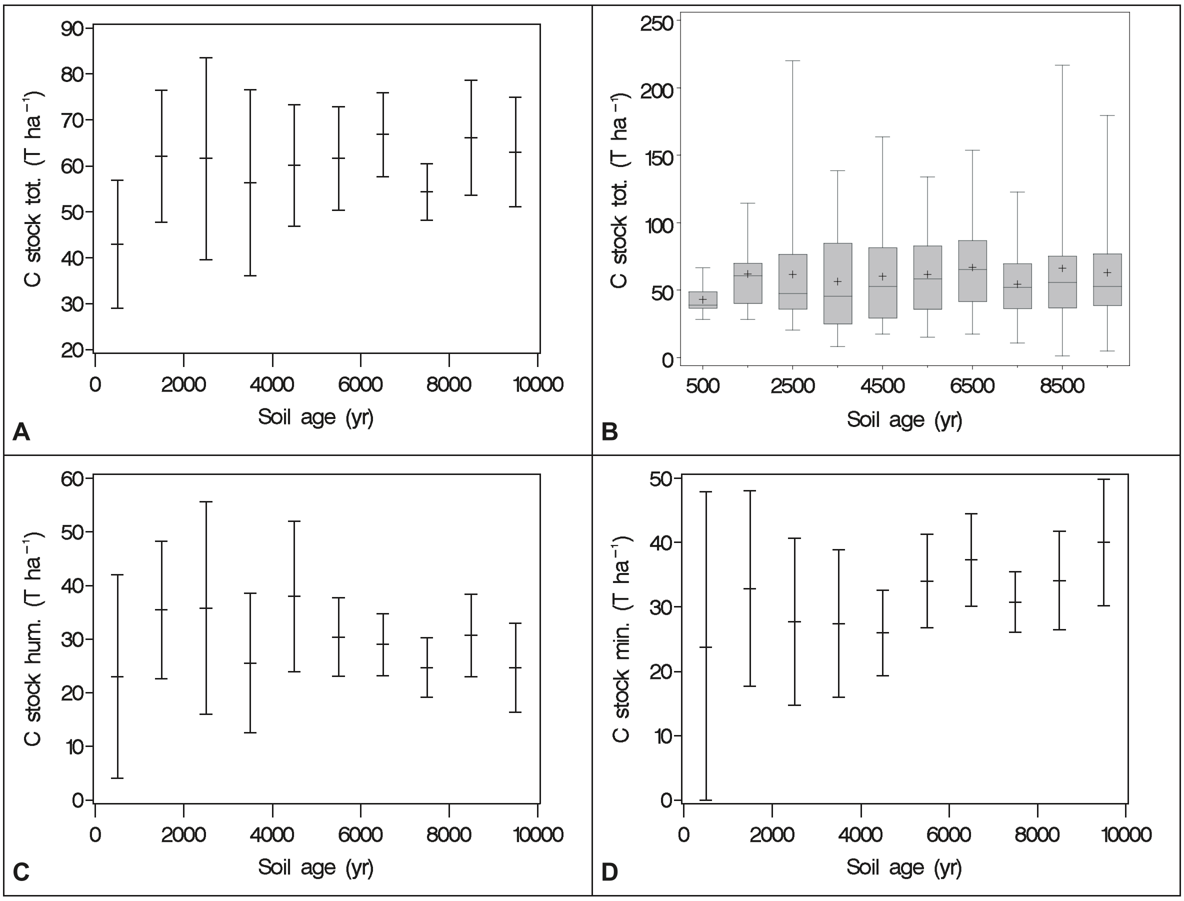


Figure 10-6. *Soil carbon stock in Podzols versus soil age, where figure (A), (C) and (D) shows mean and 95% confidence intervals. In (B) the line in the boxes represents the median, the box the upper and lower quartiles, the addition sign is the mean and the lines shows the minimum and maximum. (A) and (B) represent the total stock, (C) the stock in the humus layer and (D) the stock in the mineral soil to a depth of 50 cm.*

results indicated an increase in total carbon stock for Podzol soils during the first c 2,500 years, after which it remained stable. For carbon, there was greater variation in mineral soil than in the humus layer (Figure 10-6 (C and D)). For the humus layer (Figure 10-6 (C)) there was an increase in stocks during the first c 2,500 years, whereas for the mineral soil there was too much scatter for any pattern to be seen. The NFSI plots within each of the age classes were rather evenly distributed geographically, and the results were not associated with any climate gradient. For Histosol soils, data were scarce for the youngest age classes, but the carbon and nitrogen stocks on these young sites were quite large. This might be due to the gradual formation of peat soils as sea bays are transformed into lakes and become filled with vegetation such as Sphagnum mosses. At the time when the site rises above sea level, a large amount of organic matter might already have formed.

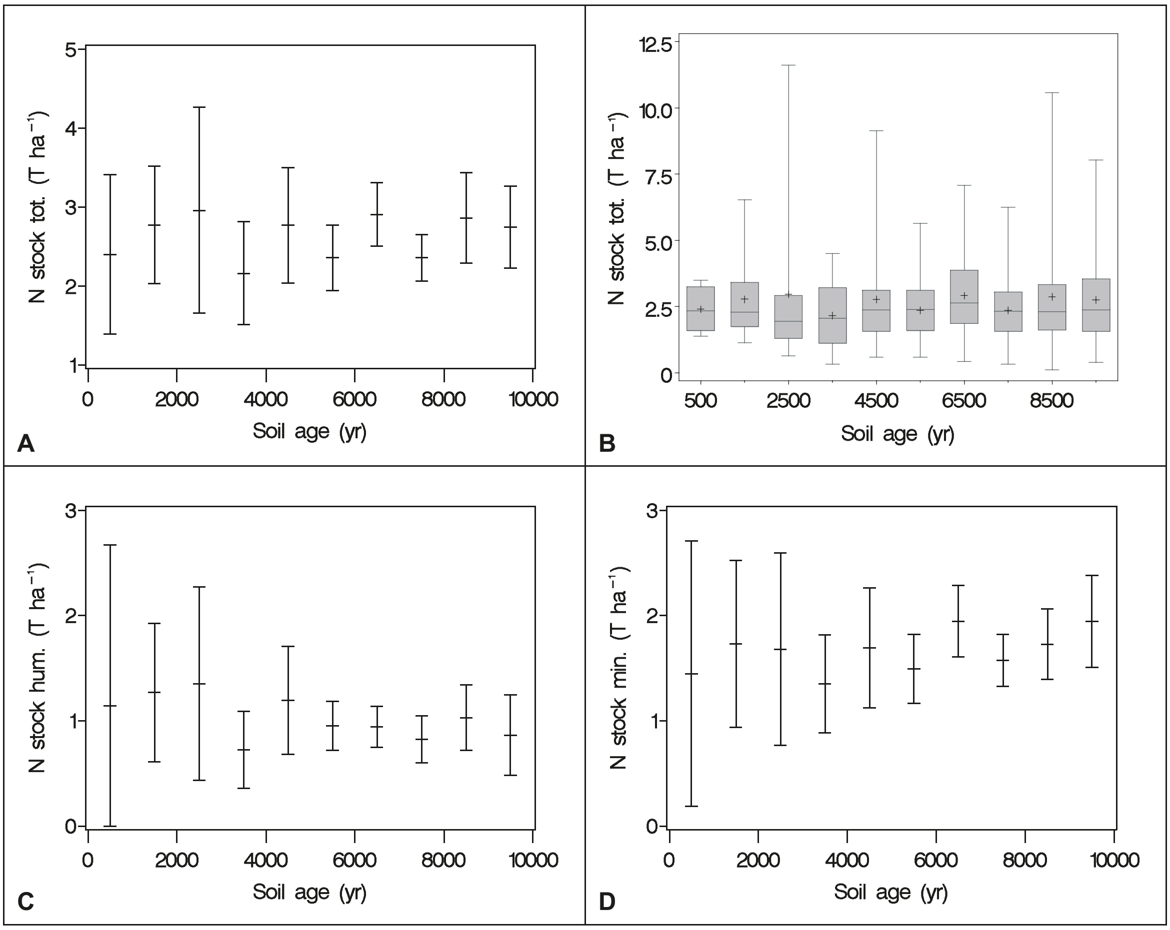


Figure 10-7. *Soil nitrogen stock in Podzols versus soil age including, where figure (A), (C) and (D) shows mean and 95% confidence intervals. In (B) the line in the boxes represents the median, the box the upper and lower quartiles, the addition sign is the mean and the lines shows the minimum and maximum. (A) and (B) represent the total stock, (C) the stock in the humus layer and (D) the stock in the mineral soil to a depth of 50 cm.*

The relationships between concentrations of carbon and nitrogen in the sampled mineral soil horizons and soil age are presented in Figure 10-8 and Figure 10-9. For the concentrations in the B horizon, the results were similar to the total stocks, although an increase in carbon and nitrogen concentrations at older ages could be seen as well. In the B–C horizon the relationship with age was similar, although variability was greater. This might have been caused by a larger heterogeneity in B–C data, since these samples may consist of material from different horizons. For the C horizon there was an increase in carbon and nitrogen concentrations until an age of c 6,000 years, although there were some extreme values for ages of 1,500 and 5,500 years. This may indicate a slower dynamic between input to this layer and decomposition of organic matter for the deeper horizons, and a longer period before an equilibrium is reached. The quality of the organic matter decreases with depth, and it is therefore decomposed at a slower rate /Bosatta and Ågren 1996/.

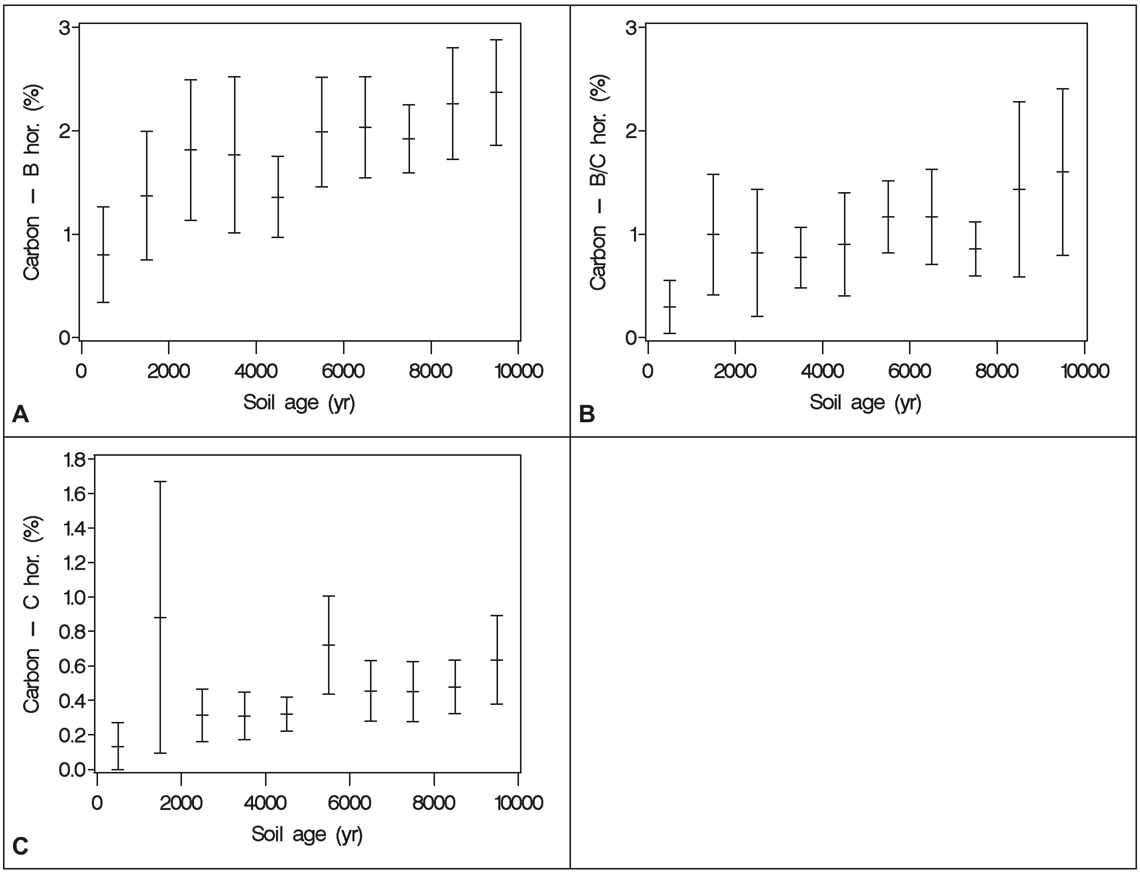


***Figure 10-8.** Mean soil carbon concentration in Podzols versus soil age including 95% confidence intervals. (A) represents the B horizon, (B) the B–C horizon, and (C) the C horizon.*

The results in this study indicate that the total carbon and nitrogen stocks in Podzol soils reach equilibrium after approximately 2,500 years. In deeper soil layers the carbon concentration seems to increase for c 6,000 years and then level off. The concentrations of carbon and nitrogen produced a somewhat different pattern compared to the stocks with a tendency for increasing concentrations over time. The results are uncertain though, because of the large variability in the data.

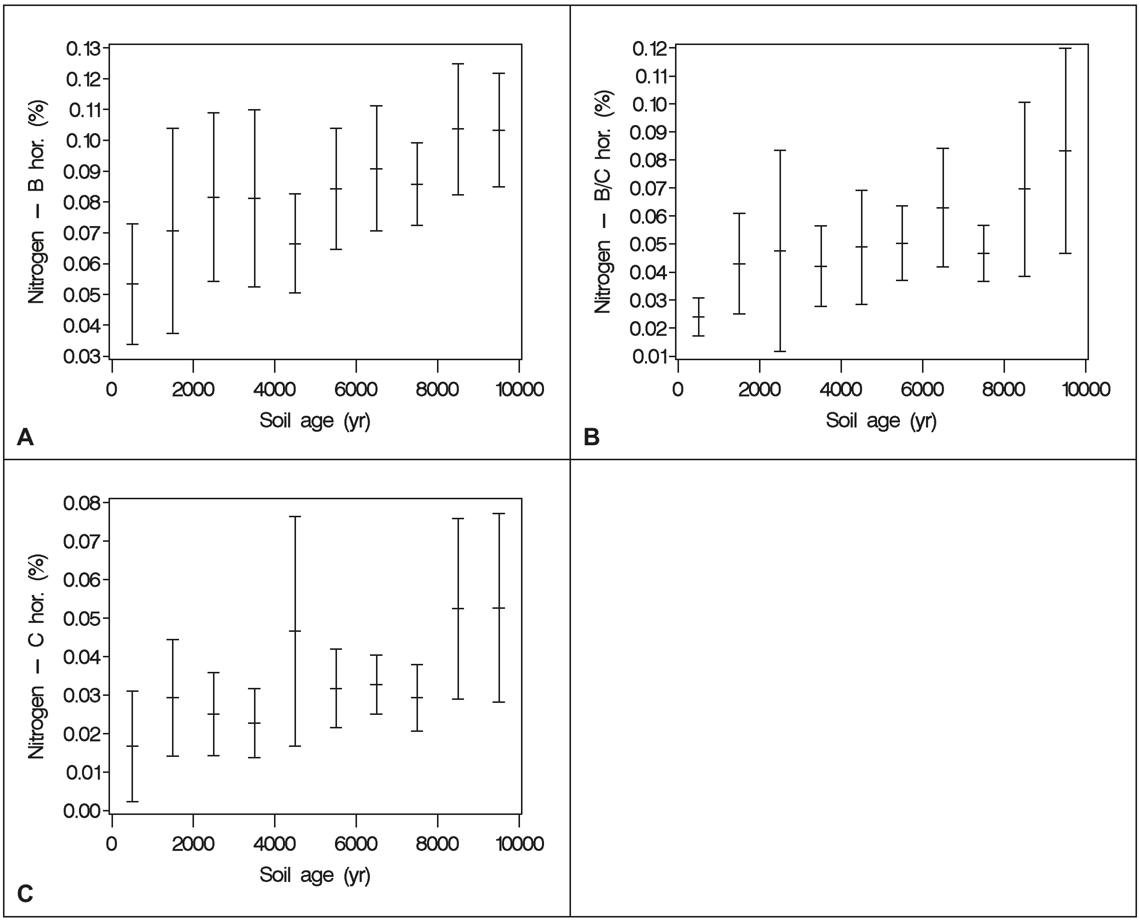


Figure 10-9. *Mean soil nitrogen concentration in Podzols versus soil age including 95% confidence intervals. (A) represents the B horizon, (B) the B/C horizon, and (C) the C horizon.*

10.3 Postglacial changes in faunal composition

The climate variations have also affected the faunal composition. There are several early findings of mammal species such as reindeer and mammoth, which lived in southern Sweden shortly after the deglaciation. In the cold but nutrient-rich sea along the Scandinavian west coast, the mammal fauna was characterised by arctic species, e.g. polar bear and a variety of seal and whale species. During the shift to warmer climate at the beginning of Holocene the early mammal species disappeared, and the open landscape in the southern parts of Sweden was dominated by large grazers, e.g. bison, wild horse and aurochs. Certain animal species which today occur further south lived in southern Sweden during the warmest phase of the Holocene (e.g. pond turtle, *Emys orbicularis*). Most of the current mammal fauna was established in southern Sweden during the early Holocene. Some of the early established species, such as aurochs and bison, are now extinct in Sweden, however /Berglund et al. 1996b/.

10.4 Ecosystems, succession and human land use

Succession is a directional change of ecosystem structure and functioning, which may occur over time scales from decades to millennia. Succession may be a result of new land emerging (primary succession) or of disturbance such as after a clear-cut (secondary succession). The vegetation development and the species community through time are constrained by the availability of dispersal propagules and local abiotic conditions (i.e./ Rydin and Borgegård 1991, Löfgren and Jerling 2002/). In the investigated coastal areas, the overall regressive shoreline displacement transforms the near-shore sea bottom to new terrestrial areas or to freshwater lakes. The subsequent development of these terrestrial areas and lakes may follow different trajectories depending on factors such as fetch during the marine shore stage, slope and surrounding topography. A schematic illustration of some of the main trajectories is shown in Figure 10-10, where the sea bottom is the starting point and the end point is an inland bog or a forest locality.

The starting conditions for ecosystem succession from the original sea bottom in a coastal area are strongly dependent on the topographical conditions. Deep bottoms accumulate sediments (accumulation bottoms) at a higher rate than shallow bottoms (transport bottoms). During regressive shoreline displacement, a sea bay may become isolated from the sea at an early stage and, thereafter, gradually turn into a lake as the water becomes fresh, or it may remain a bay until it is uplifted by shoreline displacement and becomes a wetland or a forest. The Baltic Sea shore can be divided into four main shore types: rocky shores, shores with more or less wave-washed till, sandy shores and shores with fine sediments. Wave-exposed shores will be subject to a relocation of earlier allocated sediments and these shores will emerge as wave-washed till. The grain size of the remaining sediments will therefore be a function of the fetch or wave exposure at the specific shore /Sohlenius and Hedenström 2008/.

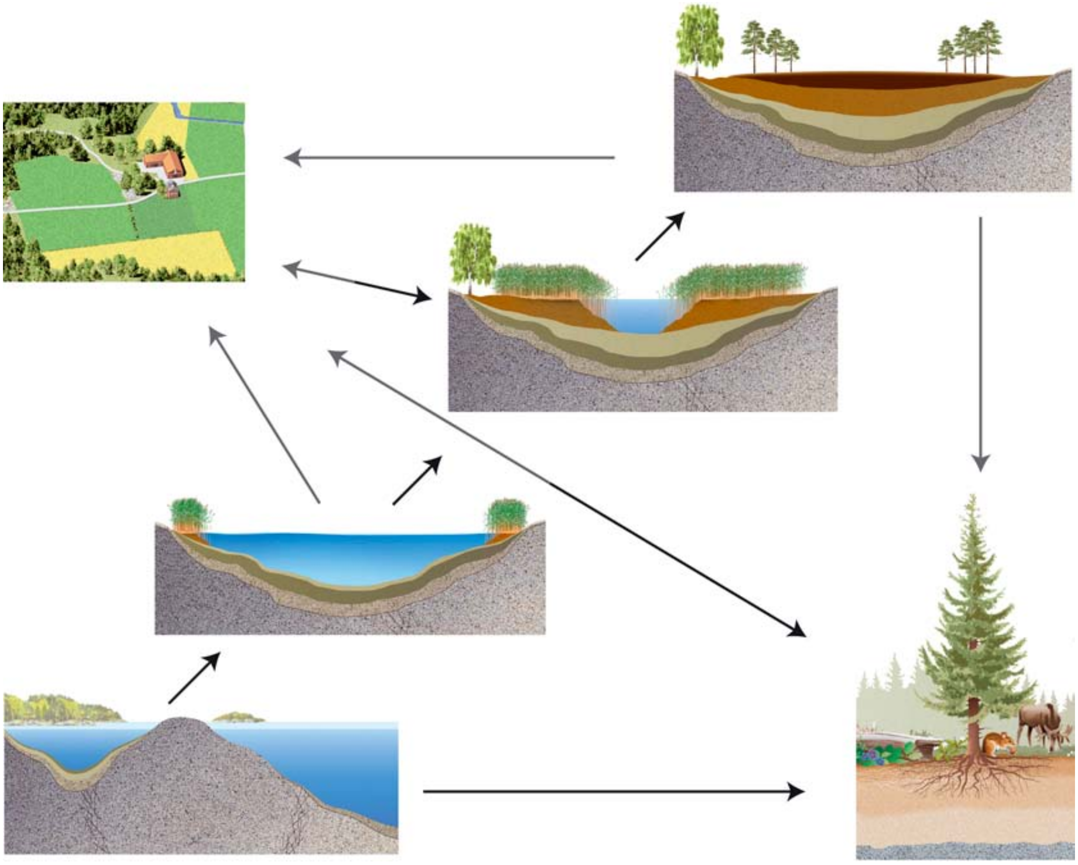


__Figure 10-10.__ A schematic illustration of the major ecosystems that may be found at certain points during a temporal sequence, where the original sea bottom slowly becomes land due to shoreline displacement. Black arrows indicate natural succession, while grey arrows indicate human-induced changes to provide new agricultural land or improved forestry. Agricultural land may be abandoned and will then develop into forest or, if the hydrological conditions are suitable, into a fen. A forest may be "slashed and burned" and the resultant material used as agriculture land. From /Söderbäck 2008/.

In coastal basins that will later develop into lakes, there is a threshold in the mouth of the basin towards the open sea. This threshold allows settling fine material to accumulate in the deeper parts of the basin. Provided that the water depth is less than 2–3 m, different macrophyte species (e.g. *Chara* sp.) colonize the illuminated sediments. Along the shores, *Phragmites* and other aquatic vascular plants colonize the system, and a wind-sheltered littoral zone is developed. In both of these habitats, colonization by plants reduces the water currents, resulting in increased sedimentation and accelerated terrestrialization of the bay. When the threshold is lifted above the sea level, inflow of fresh surface water and groundwater slowly changes the system from a brackish to a freshwater stage. The long-term fate of all lakes is inevitable infilling and transformation to a wetland, the final result depending on local hydrological and climatic conditions.

Almost all vegetation types in southern Sweden have been strongly influenced by human activities in the past as well as the present. This influence has varied over time depending on the size of human population. Some vegetation types, such as agricultural land, are man-made, whereas other types are kept at a successional stage otherwise found during a restricted period following shoreline displacement, e.g. a meadow. The following sections describe the formation and development of three major vegetation types: wetlands, agricultural land and forests. Each vegetation type description is followed by a description of historical land use in general and more specifically for both sites.

10.4.1 Wetlands

Wetland succession has been debated in the scientific literature /Mitsch and Gosselink 2000/. Wetlands are often described as ecotones, that is, transitional spatial gradients between adjacent aquatic and terrestrial environments. Thus, wetlands can be considered transitional in both space and time. As ecotones, wetlands usually interact strongly with varying external forces from both ends of the ecotone. These forces may drive a wetland towards its terrestrial neighbour if, for example, water levels drop or toward its aquatic neighbour if water levels rise. Alternatively, plant production of organic matter may raise the level of the wetland, resulting in a drier environment favouring other kinds of species. Fluctuating hydrologic conditions are the major factor controlling the vegetation pattern /Niering 1989/.

Coastal areas in Sweden are exposed to post-glacial shoreline regression to such an extent that it isolates sea bays, giving rise to new lakes. At a later stage, a shallow lake gradually fills up as organic material decomposes and accumulates. This, together with land uplift, may transform the lake into a mire (see earlier chapter, Figure 10-11). The most common succession for a shallow

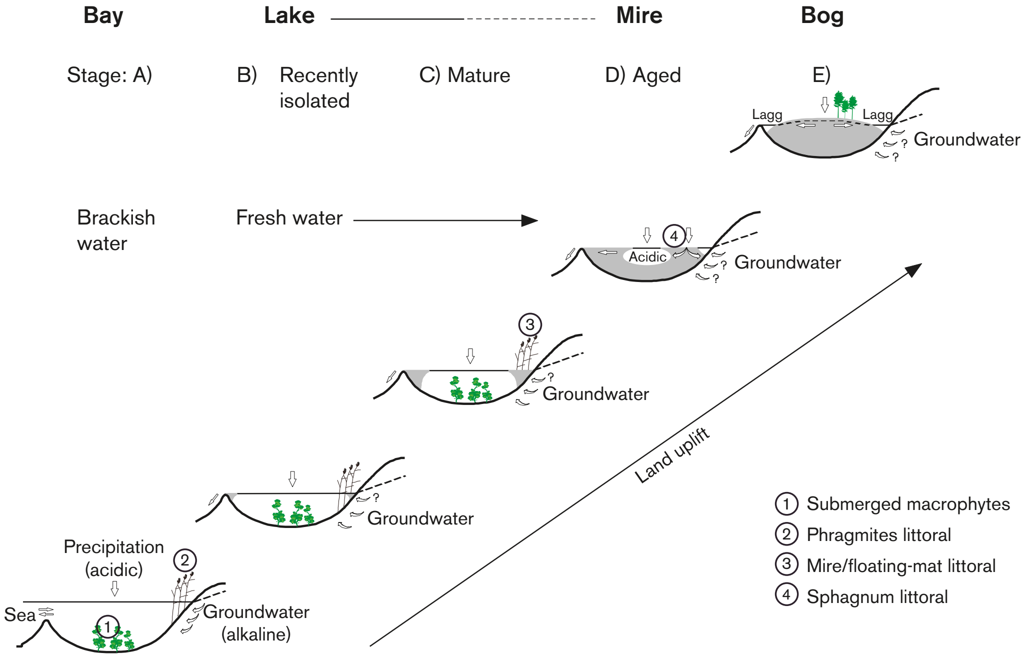


***Figure 10-11.** Schematic description of the ontogeny of a closed-off bay of the sea to a mire. The figures represent different important components of the ecosystem. Modified from /Brunberg and Blomqvist 2000/.*

lake is that it becomes a reed marsh, a fen, possibly with a stage of swamp, and eventually a bog (Figure 10-12), which is the most common endpoint /Walker 1970/. In anoxic sediment, peat starts to accumulate. As the land rises, the fen becomes more and more elevated and at some stage it starts to leach out nutrients /Jonsell and Jonsell 1995/. The fen nutrient content decreases, promoting *Sphagnum* mosses which can create large carpets of peat that retain water. Finally, the fen turns into a bog as nutrient levels and pH decrease in the wetland.

There are three principal ways for a mire to be developed /Kellner 2003/:

1. Primary mire formation. This is when the fresh soil surface is directly occupied by mire vegetation after emergence from water or ice. Primary peat production will occur at the sites that are wet during sufficiently long parts of the growing season to promote mire vegetation. At the same time as the peat grows (in height), it will most likely also expand laterally, either by lake filling (terrestrialization) or by paludification, see below. This type of mire formation is common along the coast of Uppland and in northern Sweden.
2. Terrestrialization. This constitutes a hydroseral succession from an open water basin into a mire /von Post and Granlund 1926, Korhola and Tolonen 1996/. Two formation pathways are described by /Mitsch and Gosselink 2000/: the first is terrestrialization by infilling in a lake basin, or quaking peatland succession, where mosses together with floating or half rooted vegetation cover produce a peat mass that gradually develops from the edges towards the middle of the lake. The peat growth from the borders facilitates a colonization of first shrubs and then trees, forming rings towards the centre. After some peat growth it becomes thick enough to isolate the surface from groundwater influence. Some parts then become more nutrient-poor and finally turn into a raised bog. The other process described by /Mitsch and Gosselink 2000/ is detritus sedimentation on the lake bottom, whereby enough material is built up for marsh vegetation to grow, which continues the build-up of peat, permitting a transition into a fen and later a bog.
3. Paludification. This is the conversion of a mineral soil ecosystem into a mire ecosystem. The terrestrial ecosystems are overgrown by mire-forming vegetation. This process can be brought about by climate changes, geomorphological changes, beaver ponds, forest logging, but more often by a natural advancement of peatlands. The low permeability of adjacent peat layers contributes to a rise of the groundwater table, supporting the lateral expansion of mire vegetation. Paludification is considered to be the predominant cause of mire formation in the wetter parts of Sweden /Rydin et al. 1999/.

All three types of processes are likely to have occurred or to be occurring in the Forsmark and Laxemar-Simpevarp areas, but peatland infilling in lakes (terrestrialization) /von Post and Granlund 1926/ is probably the most common type of peatland development in the areas around the investigated sites. The richer types of mires will undergo natural long-term acidification while turning into a more bog-like mire. It seems that the end result of mire development, in the boreonemoral

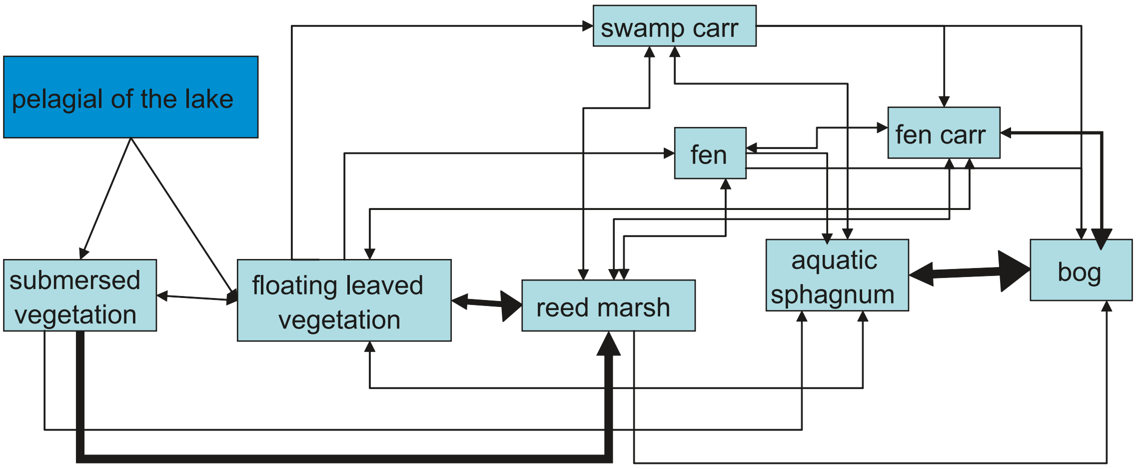


***Figure 10-12.** Wetland succession pathways from lake, through marsh and fen, to bog. Bold lines and arrows show the most common pathways. After /Walker 1970/.*

and southern boreal areas of Sweden is the bog /Rydin et al. 1999/. The bog can, however, have Scots pines if the peat can support their weight and some studies (e.g. /Gunnarsson et al. 2002 and references therein/) indicate that Scots pine have become established and increasingly common on bogs in recent years.

Land use

Historically, wetland areas were often seen as unfit for use as agricultural or forestry land because of their high water content. They also bred mosquitoes and diseases and were therefore referred to as "festering swamps", "mosquito hells", and "water sick areas". Nevertheless, mires were frequently used for haymaking, and rich fens were more important than poor fens in this respect. Haymaking slows down or stops the succession of a rich fen, resulting in poorer fen-like stages due to the inhibition of peat formation /Elveland 1978/. In Sweden, from the end of the 19th century until the middle of the 20th century, wetlands were not considered a good choice for agriculture. Little was then known of the fact that drainage led to large quantities of accumulated matter that resulted in lowering of the water table, causing a switch from anaerobic conditions to aerobic conditions and initiating decomposition and erosion of peat-dominated soil. Subsequently, great efforts were made to dry out wetlands by draining, digging ditches and lowering lake levels in order to use the land for agriculture and forest industry and to feed the growing population. Such activities peaked in the 1930s /Eliasson 1992/. As much as 90% of the wetlands have been drained in some areas in southern Sweden /Svanberg and Vilborg 2001/.

In Finland, a cultivation method for peatlands was created that consisted of several steps /Myllys 1996/. First the mire was drained, and then the dry mire surface area was burned. Manure and sometimes mineral soil was mixed with the ash layer, resulting in higher crop yields. After some years the area was burned again to restore its fertility. This method of burning destroyed the peat and valuable nutrients were actually lost, especially from nitrogen-rich fens. The quality of the peat used for agriculture varied depending on what sort of peat it was. Moderately decomposed Carex peat was classified as the best peat soil, while undecomposed *Sphagnum* peat soils were considered the worst. However, with new technical methods, liming practices and fertilizers, these old classifications became less important.

Peat cutting has a long tradition in Sweden. Peat was often used as soil improvement material, as bedding in animal barns, and during difficult times for heating /Svanberg and Vilborg 2001/. Peat cutting for energy production in Sweden ended in the 1960s, but was started again in the 1980s.

The Forsmark area

Land suitable for cultivation is situated in the low-lying parts of the terrain and often occurs in small irregular pockets in the surrounding boulder-rich terrain. This meant that the arable fields were, in many cases, small with irregular geometric forms. It is only in the area around the central part of Valö and in the area in the immediate proximity of the Forsmark ironworks that we find larger open areas dominated by arable land (map Appendix I). To increase the amount of fodder, small farms and individual families carried out haymaking with the reeds and grasses on wetland areas. These areas were often distant and hard to reach and were mainly used by poor families that needed to feed their animals. Until the middle of the 19th century there were large wetland areas in the woodlands. These areas were subsequently drained and then cultivated as arable land. Some of these areas are still cultivated whereas others are now deserted and, in some cases, have become woodlands.

As an example of drainage of wetlands to gain agricultural land, Table 10-1 shows a decrease in wetland areas in Valö in the Forsmark area and an increase in arable land and meadows between the years 1709 and 1829 /Berg et al. 2006/.

The Laxemar-Simpevarp area

The agrarian revolution and the changes that took place during the 19th century also affected the farms and people in the Laxemar-Simpevarp area. New roads were built and new ownership structures became apparent in the landscape. New stone walls were built in straight lines and divided the landscape into separate domains. The meadows were to some degree abandoned and wetlands were reclaimed as arable land in many areas of the region. Landscape change was dramatic during the period encompassed in the study by /Berg et al. 2006/, i.e. between 1940 and 1980. About 74 million square metres of arable land were abandoned between 1940 and 1980. According to the calculations, only 3.8 million new square metres were ploughed in 1980. Of the original 114 million square metres of arable land in 1940, only 41 million were still in production in 1980.

The areal extent of arable land, and even more so of meadows, increased throughout the 18th and 19th centuries. The wetlands in the wooded areas were then also being used as meadows. At the same time, the old meadows located near human settlements were transformed into arable land. The increase in population and the increasing number of farms during the period may partly explain this situation. Another possible explanation is that fishing and fishing-related incomes declined in relation to other incomes and that agriculture increased in importance as a source of income at the same time.

One of the obvious changes that can be observed on maps spanning the period from 1689 to 1872 (e.g./ Söderbäck 2008/) is an increase in meadows located in the central part of the village. In the 17th century, meadows were concentrated in the eastern part, close to the settlement. Most of the meadows were in the same fenced-in area as the arable land. The picture has changed dramatically one hundred years later, and many of the former wetlands and peatlands were now being used as meadows. This can be interpreted as a result of the increase in population and hence a greater pressure on the landscape, but also probably a change in production with larger livestock requiring winter fodder /Berg et al. 2006/.

10.4.2 Agricultural land

The distribution of agricultural land in Sweden today is largely associated with postglacial deposits /Angelstam 1992, Sporrong et al. 1995/. The agricultural land in Laxemar-Simpevarp today is characterized by having clay-silt as the dominant QD in the surface layer, closely followed by clayey gyttja (and gyttja clay). However, the clay-silt category includes both clay gyttja and gyttja clay as well as clay because of differences in classification for parts of the area.

The largest arable land unit in the Forsmark area is found on clayey till. Gyttja as the dominant soil on agriculture land is scarce in this area, which suggests that present-day agricultural areas are seldom preceded by an extended lake phase with organic sediment deposition. A part of the agriculture land has a dominant peat layer, which is built up during the phase as a wetland. Due to different mapping techniques, the peat classification into different types has not been uniform on all the sites. In areas where detailed mapping has been performed, more nutrient-rich fen and nutrient-poor bog peat were distinguished /Rudmark et al. 2005/. In these areas, all agricultural areas were located on fen peat. In the western area, peat was mapped as unclassified peat. However, fen peat is probably dominant in this area as well. One category having clay gyttja (and gyttja clay) with a thin layer of peat suggests a somewhat faster succession where the wetland stage was rather short or that the peat has oxidized during a long period of cultivation. Another category of agriculture land with regard to QD is characterized by more coarse grained non-organic materials that were deposited during the sea phase, such as wave-washed sand, gravel and till.

Table 10-1. The areal extent of arable land and other land-use types in the mapped areas in Valö in square metres. Observe that the total areas differ somewhat over time. The older map from 1709 covers a larger area. It is clear, however, that the extent of arable land and meadows has increased and the wetland area has decreased.

	1709	1829
Arable land	890,597 (2.15%)	1,400,276 (4.75%)
Meadow	5,919,645 (14.30%)	8,031,235 (27.23%)
Wetlands	5,232,176 (12.64%)	990,382 (3.36%)
Water	1,651,885 (3.99%)	51,335 (0.17%)
Total	41,387,890 (100.00%)	29,489,330 (100.00%)

Land use

Before the modernisation of agriculture, only fairly dry soils could be cultivated. Heavy clays and wetlands were used for mowing, and stone-ridden tills and bedrock were grazed. In Nynäs in Södermanland, it was found that thin soils on bedrock were used for cultivation close to the villages in the 17th and 18th centuries /Cousins 2001/. As management intensity and population increased, more of the medium-fertile soils were used for agriculture, whereas the poorest soils were set aside for grazing /Rosén and Borgegård 1999/. However, this trend came to an end as management was rationalized by the use of fertilisers and better equipment in the early 20th century. This development of farming and the development of forest tools and machinery altered the land use and its association with different soils. Sweden has experienced a nationwide regression in agricultural activities, and if former farmland areas are left unattended, they will eventually become forests that in most cases will be dominated by Norway spruce. During the late 1900s, farmers have been encouraged to plant coniferous trees on arable land, thereby accelerating the succession into forest.

The Forsmark area

In the early 18th century, there were a large number of crofters in the forest situated to the north of the Forsmark ironworks. A map from 1734 shows that there were 19 crofters spread throughout this area. The crofters had small areas of arable land and meadows were situated close to their houses. These crofts were probably established during the 17th century as a consequence of the labour demand from the ironworks. The crofts were located in the woodlands, often in small valleys with fertile soil. By the beginning of 20th century, the number of crofters had increased to 120. The crofts represent a new wave of colonization in the area, which took place from the 17th century onwards. The crofts also represent the physical manifestation of the labour requirements of the Forsmark ironworks. At the beginning of the 20th century, the area was quite densely settled (Figure 10-13). Many of these crofters' places are still used today, but not for agriculture. Instead, they are used as summer houses or as permanent residences.

In the Forsmark region, most of the arable land remained unchanged between the early 1900s and the 1950s. The land use in the Forsmark region in the late 19th century can be seen in the detailed map of hundreds (*Sw. häradskartan*). From these maps it is possible to discern arable land, meadows, settlements and other information (Figure 10-13) /Berg et al. 2006/. Some of the arable land, comprising about 26 million square metres (equivalent to c 18% of the total amount of arable land), was abandoned during the period. However, during the same period almost 65 million new square metres of arable land was created in other places in the region. The total amount of arable land in the Forsmark region in 1950 was 148 million square metres /Berg et al. 2006/.

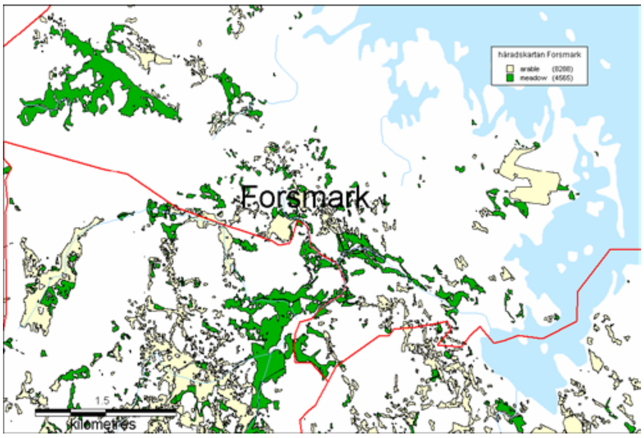


Figure 10-13. *Extent of arable land and meadows from the map of hundreds (Sw. häradskartan), 1905. In the Forsmark area, large areas of meadow covered the lower elevated parts of the landscape. From /Berg et al. 2006/.*

Many of the large estates abandoned agriculture during the 20th century and the land was leased out. The decrease in the number of farms has also brought many changes to the region. Many of the farms belonging both to the old nobility and to the freeholders were converted to dwelling houses of different types. The large areas of forest that were needed for the production of charcoal were in many cases purchased by large timber companies. The surviving farms often bought arable lands in order to merge into larger holdings. Another possibility was to lease land from the land owners not involved in farming. To some extent, this arable land was then used solely for the production of silage and fodder, and not as arable land.

Two elderly farmers in the area were interviewed, and they pointed out many small fields on the map that were harvested in the old days but are today overgrown with shrubs and trees. It can be concluded that there have also been local transitions where many smaller fields (which the elderly farmers remember as having been cultivated in the past) have been abandoned, become overgrown and closed /Berg et al. 2006/.

The Laxemar-Simpevarp area

Detailed historical maps of the investigated region indicate that most farms were in fact small, and that the arable fields principally consisted of patches of land, which were often filled with clearance cairns. In the early maps from the 17th and 18th centuries, many meadows can be observed. The meadows were often located next to the cultivated fields. Small wooded areas or single trees could grow in the meadow without preventing the production of winter fodder. The leaves and twigs from the trees were used as fodder for smaller animals such as goats or sheep /Berg et al. 2006/. Before the 17th century, large parts of the region were owned by the crown, but during the 19th century this changed. When the nobles took over, several industrial investments were made. The nobles brought new inventions to the region during the 19th and 20th centuries. Bogs and wet-meadows became arable land through ditching, and stone fences were built to protect the forest from the livestock /Lundqvist 2006/. Landscape transformation in the Laxemar-Simpevarp region was dramatic in the middle of the 20th century. Of the 114 million square metres of arable land in 1940, only 41 million were still in production in 1980, i.e. approximately 36% of the former arable land. Only 3.8 million square metres of new arable land were ploughed in 1980. The forms of the arable fields can also be analyzed in relation to the changes. It is common that field configurations have become simplified over time, i.e. that the irregular shapes and forms have been changed into simple rectangular forms /Berg et al. 2006/ to make cultivation more efficient.

Another important characteristic of the region is the location of farms on the coast or in the archipelago. These farms, such as the ones on Ävrö, show that arable production was not always the most important form of livelihood for the farm economy. The location of such settlements, sometime relatively far away from arable land, was closely connected to the importance of fishing /Berg et al. 2006/. The households in the archipelago had strong traditions and a high degree of self-sufficiency, where fishing and livestock-raising constituted the main occupations. The many islands in the region provided excellent pastures for the livestock. Cultivated products such as cereal were exchanged with farmers from the mainland. During the 18th and 19th centuries, the number of households increased dramatically in the region and the reclamation of land was intense /Lundqvist 2006/. People practised livestock-raising, which was so intense that many areas in the archipelago were overgrazed. There was no agriculture worth mentioning in the archipelago before the middle of the 18th century, when it became more frequent. Agriculture was always limited, though, due to the lack of suitable land /Lundqvist 2006/.

The extent of arable and especially meadow land increased during the 18th and the 19th centuries. During the early phase, most of the intensively used lands were located close to settlements, but this subsequently changed and many parts of the landscape were brought into agricultural production. Crofts also emerged in most hamlets, but they were not particularly numerous. At the time of the land reforms in the 19th century, some farms were moved from their original locations and relocated to the areas with “new” arable lands. This often affected the crofts, which sometimes had to be moved even further away from the old hamlets to agriculturally less advantageous locations. During the 20th century, the extent of arable land began to decrease. The changes were most pronounced in the latter half of the century. This coincides with the introduction of tractors, modern machinery and the adjustment in the size of a viable farm. Following the Second World War, the number of farms decreased, and in many small hamlets in the region there was only one or no active farm left. To some extent this has lead to the merging of farms, but the general trend is that most old farms remain as property even though farming is no longer carried out by the present owners. This has led to a complex system of leaseholds, where one farm can lease many farms or parts of former farms – a system still in use today. The need for large areas of arable land and the small sizes of the farms also increases the number of leaseholds needed for a farm to survive. The specialization of agriculture has also made it more efficient. Some farmers have focused on milk production while others focus on meat, cereal production, etc. This has had the effect that many arable fields are nowadays only used for fodder or for silage production. Before this change, fodder production was incorporated into a system of rotation between crops and fodder. Several lakes were also lowered during the early to mid 20th century, e.g. the former Lake Gästern. Certain of the areas used as arable land have consequently been drained quite recently /Sohlenius and Hedenström 2008/.

Concluding comments

The main differences in land use history between the sites were summarized by /Berg et al. 2006/ as follows: Firstly, a difference in traditional land use can be recognized between the sites. It seems that there has been more diverse land use in the Laxemar-Simpevarp area, focusing more on fishing, hunting and berry-picking. In the Forsmark area, however, land use has been more focused on the traditional practice of growing crops. Secondly, the reorganization of farms has been carried one step further towards obtaining farms of sufficient size in the Forsmark area than in the Laxemar-Simpevarp area. In the Laxemar-Simpevarp area, most farms are still intact from the time of the land reforms, and the current land users are instead leasing many tracts of land from other farms, with up to 25 leases in some cases. In the Forsmark area, large forest companies bought whole farms in the post-war period and sold off the arable land to family farmers. In the Laxemar-Simpevarp area, most farms are still owned by the same families as in the early twenties. Thirdly, the spatial dimensions are different in terms of field size and distribution. Today it is necessary to have somewhere in the region of 50 to 60 cows to have a solid economic base for milk production. In the Laxemar-Simpevarp area, however, there is not enough grassland close to the hamlets and not enough fodder-producing areas in the proximity of farms to make it economically sustainable. According to those who were interviewed, this makes the establishment of a dairy farm in the region increasingly difficult. In the Forsmark area, however, it is still possible to keep that number of cows, which has resulted in modernization and investments in milking machines and new stables.

/Berg et al. 2006/ summarized the two case studies as follows: it can be said that land use in both areas regarded on a large scale is agriculturally marginal. In both areas, land use is to some extent dependant on subsidies. On the other hand, in the Laxemar-Simpevarp area many landowners do not see much of a future for farming, whereas in the Forsmark area the idea of farming as a source of revenue and a livelihood is still alive. This is an example of a subtle psychological factor that will probably have effects on how land will be used in the future /Berg et al. 2006/.

10.4.3 Forest

Land uplift continuously creates new terrestrial areas. The most important abiotic conditions affecting the vegetation community on the sea shore are soil type, degree of exposure and salinity /Jerling 1999/. Soil type is strongly related to the degree of exposure, where more wave-exposed areas contain larger stone fractions than areas with low exposure. Studies of the vegetation on the Baltic Sea shores show that emerging areas are rapidly colonized by vegetation /Ericson and Wallentinus 1979/. Due to the flooding frequency and salt spray intensity, vegetation composition does not change independently of the land uplift rate until many years after the emergence of sites from the sea /Cramer 1986/. The Baltic Sea shore can be divided into four different types: rocky shores, shores with wave-washed till, sandy shores and shores with fine sediments. In the Laxemar-Simpevarp area, rocky shores are the most common, followed by shores with wave-washed till; shores with fine sediments also occur. The emerging rocky and till shores have a sea shore vegetation zonation that is defined by their tolerance to water inundation and salt sprays /Jerling 1999, Jerling et al. 2001/. The first pioneer woody species are blackthorn (*Prunus spinosa*) and alder. Both these species have a litter that is rich in nitrogen, and this facilitates the establishment of many species. Bushes and trees create a varied light environment and new habitats. In this way, the flora and vegetation change steadily but with a relatively high degree of determinism e.g. /Svensson and Jeglum 2000/. In most areas with a thicker soil layer, Norway spruce forest has to be regarded as the climax vegetation type. Scots pine would probably be more restricted to areas with a shallower, more nutrient poor soil layer if forestry management were to decrease and fire were once again to become a natural disturbance in the landscape /Sjörs 1967, Engelmark and Hytteborn 1999/.

The most important structuring factor in the northern boreal forests has been the occurrence of different fire intervals. The fire interval is shorter in areas with shallower soil, and more fire-tolerant pine therefore dominates less productive soil and the forests. More productive and mesic sites are characterized by longer fire intervals and dominated by spruce. Other important disturbances may be insect outbreaks, windstorms and clear-cuts. The spatial scale of these disturbances determines whether they may promote recruitment of new even-aged cohorts or multi-aged stand structures. On less fire-prone soils, a more small-scale gap dynamic, due to the falling of a single or several trees, is important for regeneration. Fire has also been an important factor in the south of Sweden, as forests were often used for shifting agriculture, were areas were logged, burnt and then used for sowing crops. These small fields were then abandoned due to a steady decrease in productivity. Later on there was a general trend until the early 20th century that farmland expanded into forested areas. However, as in other developed countries, former agriculture land is often brought back to forest as agriculture production becomes more efficient /Angelstam 1992/. Today, fire has lost its importance in many regions due to efficient fire suppression.

Land use

During the first phase of the Younger Stone Age, the dense forests were cleared, often by the use of fire, and the open areas created were first cultivated for some years and then used as grazing land. When the available soil nutrients were depleted, the area was abandoned and became overgrown. After 30–40 years it was possible to clear and use the area again. The extensive farming, in combination with a growing population, means that large areas were utilized. Within c 1,000 years, human land use had brought about large changes of the landscape in southern Sweden /Söderbäck 2008/.

Tar and lumber also became commercially important. It is difficult to evaluate the relative importance of natural factors affecting the conifer forests. However, the lack of management is important for the species richness in the boreal forests /Esseen et al. 1992/. In the past there were no sharp borders between forest and agricultural land, as forest were grazed and areas were mowed or cultivated in non-permanent fields. Extensive grazing of livestock in the forests is believed to have been an important factor affecting the plant communities around villages in the more densely populated parts of Sweden. Effects of forest grazing may still be a factor in plant community change in forests today, although this has so far not been well documented.

The Forsmark area

Mining iron has had an important role in the region since the Iron Age /Mattson and Stridberg 1980/. As the iron industry became more organized in the 16th century, forests were cut down to feed furnaces and mines with wood and charcoal. The region around the Lake Mälaren was almost depleted of trees at the end of this period /Welinder et al. 1998/. The settlement situation in the Forsmark area in the early-modern period was heavily dependent on the establishment of the *Forsmarks bruk* ironworks. In the 17th century, a large number of ironworks were established around Dannemora. Most of these are known as *Vallonbruk* due to the fact that people from southern and south-eastern Belgium, i.e. Walloons, established them or ran them during the 17th and 18th centuries. A prerequisite for iron production was a large and reliable supply of charcoal (Figure 10-14). The forest was therefore the single most important resource in the Forsmark region due to charcoal production, but the wood was also needed for building material and for fuel. *Lövsta* ironworks was permitted annually to forge c 1,105 tonnes of bar iron that required c 20,000 m^3 of charcoal. Producing this amount of charcoal required an estimated 30,000 days of work /Renting 1996/. Most of the charcoal had to be produced close to the production site /Karlsson 1990/. These figures indicate that the supply of charcoal was as crucial as the ore for production to be able to function on a regular basis. To ensure preservation of the forests and maintain production, forestry in the modern sense was introduced relatively early in these areas. Since iron was an important product for the country, the crown tried to restrict the use of the forests by spatially separating the mines, the blast furnaces and the forges from one another, i.e. certain areas were dedicated solely to one of these activities /Kardell 2003/.

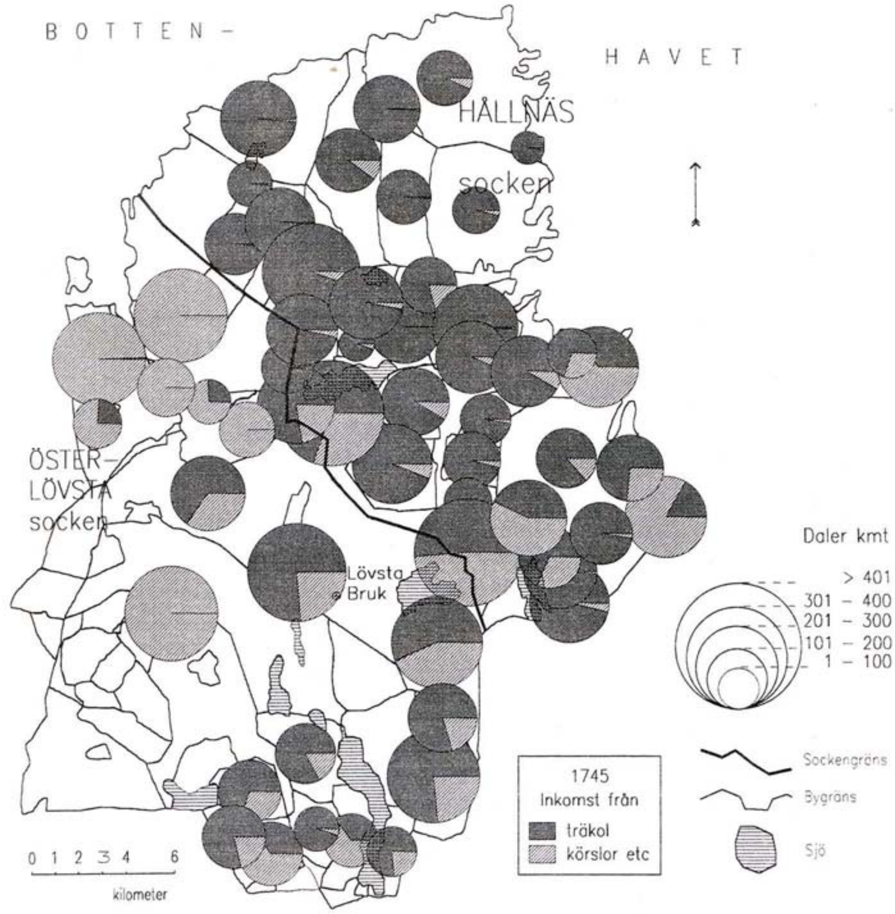


Figure 10-14. *One of the important sources of income for farmers was charcoal, but transportation of ore and finished products was also important for the local economy. This map shows the relative importance of the two types of income in the region around Lövsta bruk in 1745 /Renting 1996, p 131/. In the circles dark grey represents income from charcoal and light grey represents income from transportation. From /Berg et al. 2006/.*

In the 1950s and 1960s, a number of large estates abandoned farming and focused on forestry instead. This transition can be attributed to the large increases in the costs of employing people to cultivate and run large farms /Flygare and Isacson 2003/. These large estates were converted to or sold out to large forest companies, who retained the forests but often sold off the arable land to smaller family farmers. All present-day farms in the area are former family farms /Berg et al. 2006/.

The current landscape cannot be fully understood without understanding the effects of the iron industry and the landowners. The landscape in the archipelago and the surrounding areas should also be viewed in the context of the fact that the mines, the blast furnaces, and the forges were central places of employment in the region /Berg et al. 2006/.

The Laxemar-Simpevarp area

The forests in the Laxemar-Simpevarp area were used for many different purposes, such as pastures, firewood, fencing material, subsistence needs, slash-and-burn (Sw. *svedjebruk*), as well as production of charcoal, tar and potash. In addition to sawmill activities, production of charcoal, tar and potash was in many cases an important part of the household economy. Trading with timber was advantageous since the timber was easily transported in the coastal areas. In the Laxemar-Simpevarp region, there was also a boat-building tradition that grew into a minor shipbuilding industry during the 19th century /Lundqvist 2006/.

From the early-modern period onwards, the large forested areas, which were jointly owned by many farms and small hamlets, were divided between the different land-owners. This is an important change in the management of forests. The creation of different holdings with clear boundaries created the type of forestry that we are used to seeing today, a forest with often similar vegetational characteristics within rectangular demarcated areas (Figure 10-15). We can observe a partitioning of the farms from the 17th century onwards. This further changed the land ownership structure in that land holdings became smaller.

Concluding comments

Current land use in the Forsmark and Laxemar-Simpevarp areas is in some respects typical of forested rural areas in Sweden: small-scale family farming based on grazing animals dominates in both areas. However, there are some subtle but important differences. First, a difference in traditional land use can be recognized between the sites. It seems that there has been more diverse land use in the Laxemar-Simpevarp area, focusing more on fishing, hunting and berry-picking. In the Forsmark area, however, land use has been more focused on the traditional practice of growing crops. Secondly, the reorganization of farms has been carried one step further towards obtaining farms of sufficient size in the Forsmark area than in Laxemar-Simpevarp area. In the Laxemar-Simpevarp area most farms are still intact from the time of the land reforms, and the current land users are instead leasing many tracts of land from other farms, with up to 25 leases in some cases. In the Forsmark area, large forest companies bought whole farms in the post-war period and sold off the arable land to family farmers. In the Laxemar-Simpevarp area, most farms are still owned by the same families as in the early twenties.

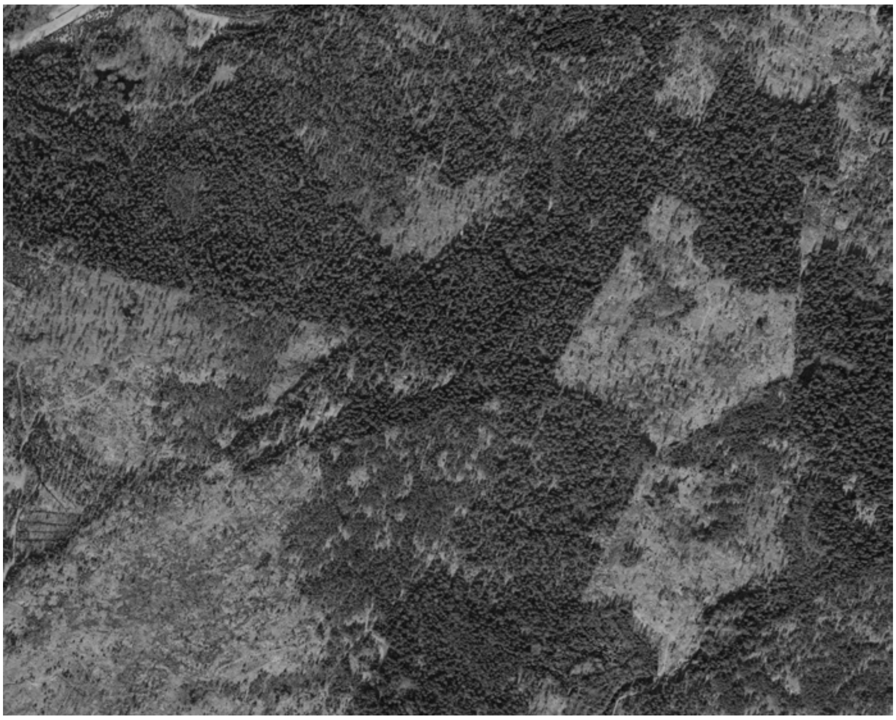


Figure 10-15. *The rectangular pattern in the forests can be observed in many parts of the investigated area. This pattern is often attributed to the new division of the forests that took place as a result of the land reforms during the 17th and 18th centuries. This aerial photograph from 2001 of the forests between Finnshult and Fallegärde, north-west of Oskarshamn, exemplifies this well. From /Berg et al. 2006/.*

11 Future development – some implications for terrestrial ecosystem properties

11.1 Introduction

The long-term development of the terrestrial landscape in Forsmark and Laxemar-Simpevarp is driven mainly by two factors: shoreline displacement and climate change. Since the last deglaciation, shoreline displacement has more or less continuously exposed land to successional processes, where a time transgressive landscape development can be found from the shoreline to further inland. Long-term processes such as soil formation leave patterns on gradients describing thousands of years of change (see Section 10.2), whereas colonization and extinction processes leave patterns within the vegetation community on outwashed till on gradients describing hundreds of years. The landscape of both Forsmark and Laxemar-Simpevarp must be considered young, especially as regards the successional development of a number of ecosystems such as wetlands and lakes. Along with shoreline displacement, the climate also has profound effects on successional processes. For example, the water balance affects both weathering processes in the soil and the succession of wetlands into different bog types /Rydin et al. 1999/. Climate will also determine the available species pool during the early succession as well as in later vegetation stages. A third more short-term factor is human land use, which to a large extent is determined by cultural and socioeconomic factors.

This chapter discusses how these three factors may affect ecosystem properties and functions, and the magnitude of such effects. Generally, predictions of future development are associated with more uncertainties than the historical description presented in Chapter 10. The development of the area may be different from that expected solely based on history, due to e.g. climate change caused by increased greenhouse gas-induced warming. Such changes are expected to influence important characteristics of the biosphere, such as the ability to grow different crops, the hydrological cycle, sea-level changes, and the salinity of the Baltic Sea.

The descriptions of the future development in the following text are based on existing knowledge of past, known processes, such as shoreline displacement, and knowledge of the current situation, such as existing ecosystems, climate, and geometry. All these descriptions have their uncertainties. The descriptions presented here are, therefore, potential future cases, but the temporal and spatial scope of various climatic conditions is uncertain due to limitations in underlying data and conceptual models e.g. /Kjellström et al. 2009/. The following discussions concerning ecosystem properties mainly concern processes that may be important for the distribution of radionuclides and should be regarded as a background for the parameterization of the dose modelling that is described in Chapter 13.

11.2 Successional change and ecosystem properties

The ecosystem in focus for the radionuclide modelling is the wetland that may develop as soon as the land emerges from the sea and prevail during an entire interglacial. If the wetland is preceded by a lake and/or sea bay stage, the peat is deposited on top of already accumulated sediment (cf. primary mire formation Chapter 10). Generally, shoreline displacement will determine the existence and characteristics of a transition from the marine stage into the lake stage. Continuous sedimentation resulting in infilling and reed expansion will transform the lake into a wetland and change the hydrological conditions. Today, reed is the major initial contributor to lake infilling in the region, but reed peat is also commonly found in the older part of peat stratigraphies in the region e.g. /Bergström 2001, Fredriksson 2004/. The different successional stages of the wetland will differ in important properties such as vegetation, net primary production (NPP) and peat accumulation. The reed expansion is generally followed by stages characterized by Bryales peat, *Carex* peat, fen wood peat and *Sphagnum* peat /Bergstöm 2001, Fredriksson 2004/. NPP will probably be highest in the shore meadow and in the phase where a lake is turned into a wetland by an expanding reed belt (see Tables 4-5 and 4-6). The peat layer generally thickens with time, with thin layers in wetlands close to the coast and thicker layers further inland /Hedenström and Sohlenius 2008/. Most wetlands are discharge areas; furthermore, the raised bog, with rain-fed production on the bog plane and its restricted or non-existent connection to the groundwater table, is of less interest to a safety assessment where the radionuclides enter the ecosystem from below. Wetlands have the potential of being used for agricultural purposes throughout their development. Haymaking may occur throughout the succession, whereas cultivation of crops requires draining of the wetland. Generally, the potential yield after drainage will decrease drastically if *Sphagnum* peat dominates the surface layers (i.e. a bog) and other wetlands would be preferred for agricultural purposes.

11.3 The radionuclide modelling approach

The radionuclide model is described in detail in /Andersson 2010/, but the general modelling approach is to model fluxes of radionuclides in so called biosphere objects that are defined as discharge areas for radionuclides entering from deep groundwater discharge. The biosphere object may be in three different ecosystem states: sea, lake or forested wetland, which is also the successional trajectory over time. A number of criteria are used to define the transition between the ecosystems, see /Lindborg 2010/. The ecosystem inherits the radionuclide inventory from the preceding ecosystem, and the model parameterization changes depending on the ecosystem. The temporal development of the successional trajectory and the resulting parameterization of biosphere objects are primarily dependent on shoreline displacement, which is briefly described below.

11.3.1 Shoreline displacement

A major crustal phenomenon that has affected and continues to affect northern Europe following the melting of the latest continental ice sheet is the interplay between isostatic recovery on the one hand and eustatic sea level variations on the other. Isostatic recovery is a continuous process, which is an effect of the unloading of the Earth's crust by the retreat of the Weichselian ice sheet (the last glacial period in northern Europe, occurring approximately 115,000–10,000 years before present (BP)). The rate of isostatic recovery has decreased significantly since the deglaciation (i.e. over about the last 10,000 ears) and has during the last 100 years been about 6 mm per year in Forsmark and 1 mm per year in Simpevarp /Ekman 1996/. Land uplift and resulting shoreline displacement have strongly influenced biosphere conditions in the past and will do so in the future as well, for example by successional changes on newly exposed land and by sediment redistribution (erosion, resuspension and sedimentation). The estimated rate of historical and future shoreline displacement is shown in Figure 11-1 and is further discussed in /Lindborg 2010/. In future ecosystems, it is assumed that today's early successional stages of vegetation and associated fauna will gradually migrate in the landscape, following shoreline displacement. Figure 11-2 shows an example of the distribution of different vegetation types and potential land use at different time pionts in the future. Shoreline displacement will mainly affect the ecosystem types by determining when biosphere objects enter the different successional stages sea – lake – terrestrial wetland with the passage of time. Sea level will also affect the potential for draining and cultivating wetlands by defining the base level for surface run-off.

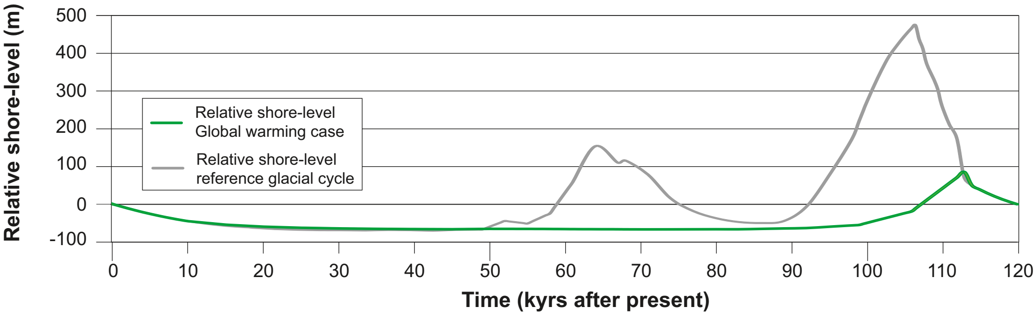


Figure 11-1. *Shore-level evolution at Forsmark for the reference glacial cycle (black) and the global warming climate case (grey). Negative numbers indicate that the area is situated above the contemporary sea-level. The curve was constructed with results from observations of present-day uplift rates /Påsse 2001/. There are significant uncertainties in the future shore-level development, which, in contrast to what is shown in the figure, may result in a sea transgression at Forsmark during the first thousands of years of the evolution. From /SKB 2010b/.*

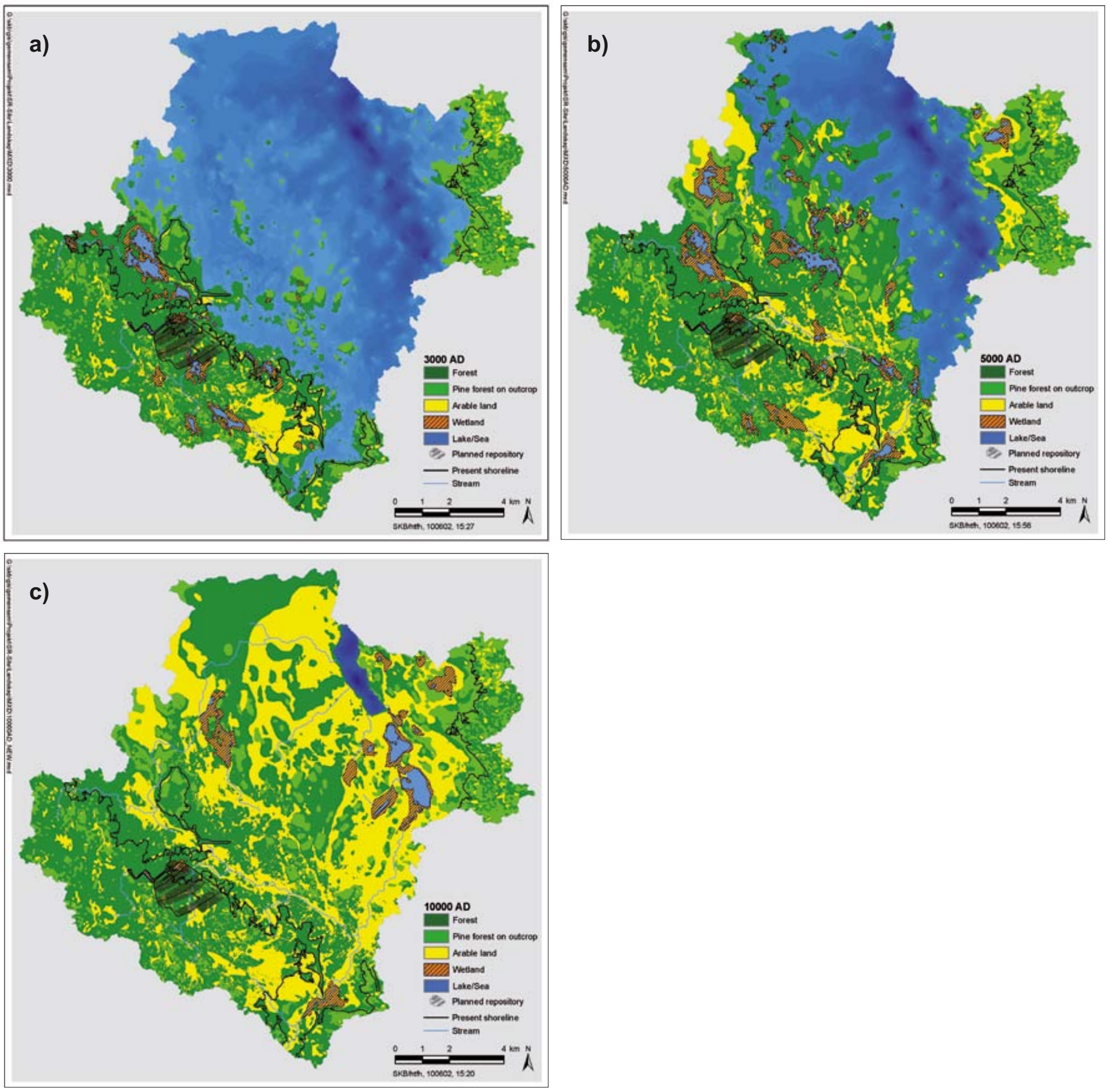


Figure 11-2. *Modelled distribution of different vegetation types and of arable land in Forsmark at a) 3000 AD, b) 5000 AD and c) 10,000 AD. All areas that potentially can be cultivated are represented on the map as arable land /Chapter 4 in Lindborg 2010/. The present shoreline is marked as a black line and darker shades of blue represent deeper sea. Figure from /Lindborg 2010/.*

11.3.2 Climate domains during the modelled time period

In SR-Site, six different climate cases are described for the future evolution of Forsmark /SKB 2010b/. Two of these are will be discussed below: the reference evolution and a global warming case, which together cover the full range of potential effects associated with surface ecosystems. In both cases the site is subjected to a number of different climate conditions, or climate domains: it may be covered by an ice sheet, be submerged, or have permafrost or temperate climate conditions (as today), see Figure 11-3. These domains are defined by how different surface processes are affected by the climate conditions. In the reference evolution case, the succession of climate domains follows a reconstruction of environmental conditions of the last glacial cycle /SKB 2010b/. The deglaciation is followed by a period where the area is submerged by water (neither of these events is seen in Figure 11-3). After that, temperate climate conditions prevail for about 8,000 years. Climate conditions within the temperate climate domain may be colder, warmer, wetter or drier than today's climate. After the initial temperate period, the first short period of permafrost conditions ensues. Subsequently, the periods with temperate climate conditions are replaced by progressively longer periods of permafrost conditions, before the first phase of ice sheet coverage, at around 60,000 years into the reference evolution. The glacial conditions are replaced by submerged conditions, followed by a period dominated by permafrost conditions.

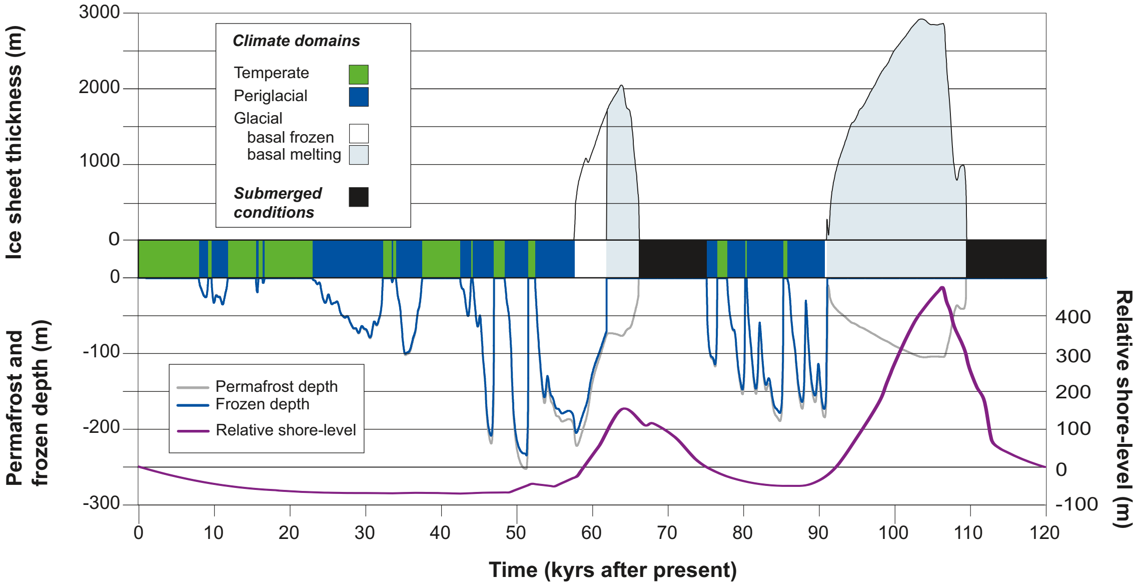


Figure 11-3. *Evolution of important climate-related variables at Forsmark for the coming 120 kyrs in the SR-Site reference glacial cyclc /SKB 2010b/.*

After that, the main phase of ice sheet coverage ensues, starting about 90,000 years into the evolution. At the end of this glacial cycle, the site is again deglaciated, around 120,000 AD /SKB 2010b/.

In addition to the reference evolution, a global warming case has been constructed, starting with a prolonged initial temperate period that prevails for about 60,000 years before the first period with permafrost conditions. After that the same sequence of events occurs as in the reference evolution /SKB 2010b/.

11.4 Climate domains and ecosystem properties

By taking the succession of ecosystems into account as the shoreline regression proceeds, it would also be possible to cover a large part of the potential variation in ecosystem properties within a prevailing climate domain at the site. However, a changing climate adds further variation to the existing span in providing estimates of ecosystem properties representing the different successional stages at the site.

A large number of studies have been devoted to the description of how different terrestrial ecosystem properties in northern Europe may change as a direct effect of global warming, e.g. /Morales et al. 2007, Ministry of Environment 2007, BACC 2008/. However, for radionuclide modelling over a time period of 100,000 years a broader approach has to be taken to cover the full extent of expected climate conditions. /Kjellström et al. 2009/ conducted steady state numerical modelling of a number of climate cases and presented some of the potential variables as temperature, precipitation and runoff for each of these cases. Vegetation development was modelled separately and then fed back in a second run of the climate model. Relevant results from /Kjellström et al. 2009/ are presented briefly below, followed by a discussion of the implications for some ecosystem properties related to the dose modelling.

11.4.1 Climate domains and vegetation composition in a 100,000 year perspective

/Kjellström et al. 2009/ selected appropriate time periods from the last glacial-interglacial cycle, including periods with extreme climate conditions to quantify extreme temperatures, precipitation and evaporation, including their annual variation. This was done with climate models, where the setup of forcing conditions for the model simulations was based on selected periods during the

Weichselian, the Holocene (i.e. the present interglacial starting about 10,000 yrs BP) and a future hypothetical case with warmer climate than today. Steady-state simulations of equilibrium climates for the different periods were then compared to the pre-industrial climate and the "recent past" climate representing the years 1961–2000. Examples from three climate domains where studied:

1. A warm period a few thousand years into the future with increased greenhouse gas concentrations.
2. A glacial period during the Last Glacial Maximum (LGM), 21,000 years BP.
3. A periglacial period during Greenland Stadial (GS) 12 during Marine Isotope Stage (MIS) 3, at 44,000 years BP.

A warm period (1) (Global warming)

The estimated seasonal mean temperature was up to 5°C warmer in summer and up to 7.5°C warmer in winter over Scandinavia in the warm case as compared with the simulation of the recent past. Seasonal mean summer temperatures in Sweden vary from 12 to 18°C, whereas winter temperatures vary from 0 to 6°C. The annual mean temperatures for Forsmark and Laxemar-Simpevarp in a potential warm case are presented in Table 11-1 /Kjellström et al. 2009/. The simulated climate of the warm case clearly resembles many of the scenarios for the 21st century from the climate model intercomparison project (CMIP3) as presented by the Intergovernmental Panel on Climate Change /Meehl et al. 2007/. The uncertainties related to the future forcing in the warm case are great, and the possibility of either lower or higher greenhouse gas concentrations than the ones used cannot be ruled out. Differences between the modelled mean annual temperature and precipitation and the recent past are presented in Table 11-2 for Forsmark and Laxemar-Simpevarp.

Table 11-1. 50-year averages of annual mean temperature (T) and precipitation (PR) and runoff (R) for Forsmark and Oskarshamn in the regional climate model simulations /Kjellström et al. 2009/. Runoff is not given for the glacial period. The standard deviation from nine grid boxes closest to the location is shown in parentheses.

Simulation	T (°C)	PR (mm/year)	R (mm/year)
Forsmark			
Warm	8.0 (0.3)	852 (66)	249 (102)
Recent past	4.7 (0.6)	666 (93)	175 (113)
Periglacial	–7.8 (0.9)	438 (53)	170 (40)
Last glacial maximum	–20.3 (1.0)	564 (161)	–
Oskarshamn			
Warm	9.2 (0.5)	929 (196)	283 (168)
Recent past	6.2 (0.3)	806 (192)	242 (158)
Periglacial	–3.2 (0.5)	582 (117)	218 (80)
Last glacial maximum	–13.2 (1.0)	581 (71)	–

Table 11-2. Summary of results as the difference between recent past (1961–2000) and modelled annual mean temperature (∆T) and precipitation (∆PR) for different climate periods at Forsmark and Laxemar-Simpevarp in Sweden. The change in global annual mean temperature (∆T) is taken from a global climate model. From /Kjellström et al. 2009/.

Simulation	Change in global annual mean	Change in annual means Forsmark	 Oskarshamn
	∆T (°C)	∆T / ∆PR (°C / %)	∆T / ∆PR (°C / %)
Warm	+2.1	+3.6 / +21	+3.2 / +12
Recent past	0	0	0
Periglacial	–5.6	–12.5 / –34	–9.4 / –29
Last glacial maximum	–6.9	–25.0 / –15	–19.3 / –33

Modelling of the vegetation with the dynamic vegetation model LPJ-GUESS e.g. /Sitch et al. 2003/ generated data to describe the vegetation under the modelled global warming climate conditions /Kjellström et al. 2009/. Boreal coniferous forests shifted northward relative to their present-day distribution due to warm winters that prevent regeneration in southern parts of their current range /Sykes and Prentice 1995/, whereas dry summers with enhanced evapotranspiration relative to recent past conditions limit tree growth in Mediterranean areas. The modelling result suggests that both Forsmark and Laxemar-Simpevarp are dominated by broadleaved trees in these conditions. Simulated vegetation biomass, leaf area index and net primary production are shown in Figure 11-4.

A periglacial period (2)

In the periglacial period, Forsmark and Laxemar-Simpevarp are in distal position to the ice-sheet margin (Forsmark about 100 km, Laxemar-Simpevarp > 200km). A mean annual ground temperature between –5 and –2°C is defined as the boundary for discontinuous permafrost (50–90% of landscape covered by permafrost) and –5°C and colder as the boundary for continuous permafrost (90–100%) /Heginbottom et al. 1995/. For the modelled periglacial period in Forsmark and Laxemar-Simpevarp, the annual mean temperature is about –9°C and –5°C, respectively. According to /Heginbottom et al. 1995/, these low temperatures indicate that climate conditions are favourable for continuous permafrost (covering more than 90% of the landscape). Precipitation is low at both sites compared with the glacial climate (Table 11-2). The cold and dry climate with partially snow-free conditions is favourable for development of permafrost at both sites.

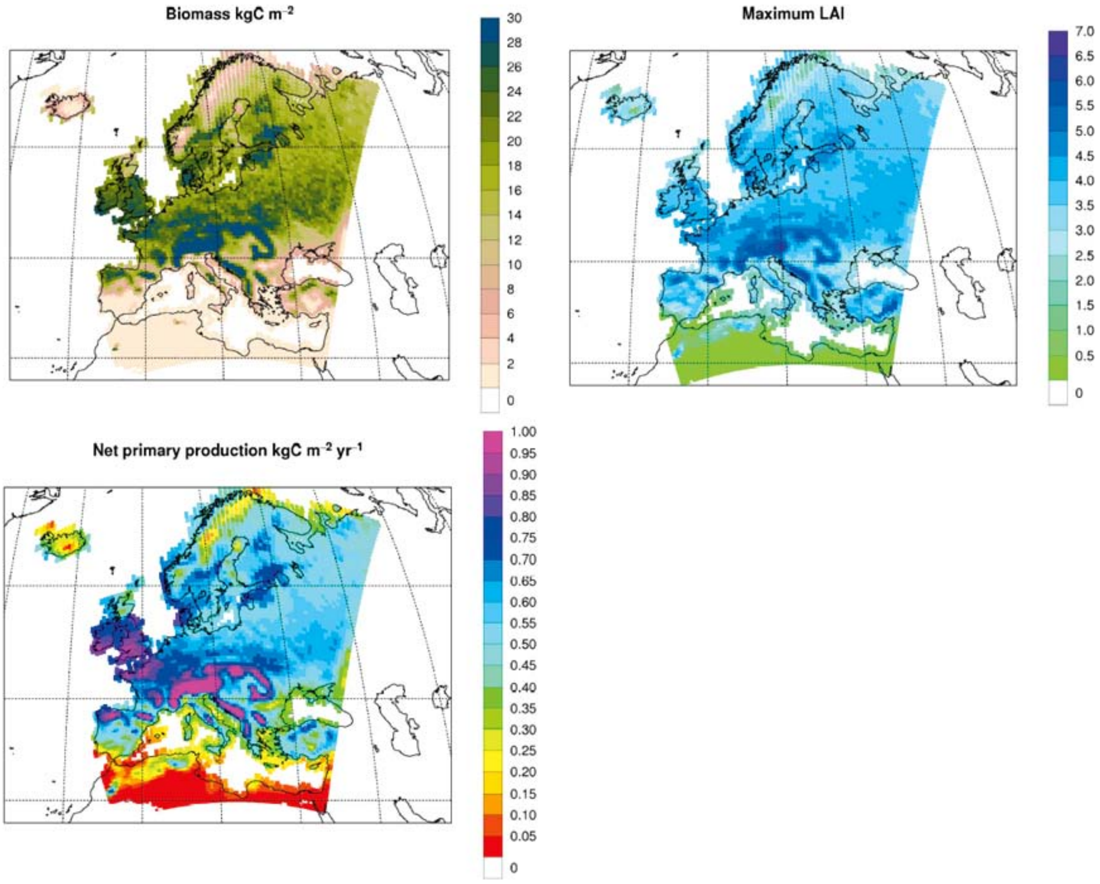


***Figure 11-4.** Vegetation biomass (kgC m^{-2}), maximum growing season leaf area index (LAI; projected foliar area/ground area) and net primary production (NPP, kgC m^{-2} yr^{-1}) as simulated by LPJ-GUESS forced by the initial RCA3 climate for the warm case (WARM-r). From /Kjellström et al. 2009/.*

In the simulated vegetation distribution of the periglacial period, herbaceous vegetation is found in southern Sweden (Forsmark and Laxemar-Simpevarp) and in central Finland, followed by mountain birch-type woodland further south. Broadleaved trees and boreal conifers co-dominate the forest in central Europe, while 'Mediterranean' type evergreen vegetation is restricted to southernmost coastal Europe and northern Africa. Tree cover is mainly restricted to continental Europe and the Mediterranean coast, with treeless tundra (represented in LPJ-GUESS by the herbaceous plant functional type) extending further north into Fennoscandia. Broadleaved birch may extend further northward beyond the boreal conifer forest (pine) limit around central Germany.

A glacial period (3) (Last glacial maximum)

Forsmark and Laxemar-Simpevarp had been in a subglacial position for several thousands of years at the time of the last glacial maximum (Table 13-2). Essentially, this means that terrestrial surface processes are ineffective, and therefore irrelevant to transport and accumulation of radionuclides.

11.4.2 Climate domains and crop production

Crop production exists under most of the prevailing climate conditions found today, although there are some conditions that must be fulfilled. Availability of water, sunlight and nutrients are the basic factors that sustain plant growth.

A warm period

A comparison between the present-day barley yield in southernmost Sweden (Skåne) and the Stockholm region (Mälardalen) gives a difference of 16% (approximate temperature difference of 1.5˚C) /Eckersten et al. 2007/. A similar comparison between the south (Skåne) and the north (Västerbotten) shows a difference in yield of 122% (an approximate temperature difference of 5˚C) /Eckersten et al. 2007/. These figures do not take into account differences such as soil properties. This difference is, however, not reflecting the actual difference of the total yield between the areas today (irrespective of crop), due to differences in land use. For example becomes hay more common in the north and hay has a higher yield. The change in climate will consequently change conditions for the cultivation of different crops, and results from /Eckersten et al. 2007/ suggest that this factor is important to the total yield of the region. Hence the change in regional yield will not necessarily be as dramatic as suggested by comparing the yield of a specific crop, due to changes in the land use.

A periglacial period

A lower mean annual temperature will reduce the yield of cereal production (see above), and the specific conditions found in a permafrost landscape will dramatically change the potential for cultivation. There are examples of agricultural production in tundra areas where the vegetation period is about 24 days (> +5˚C), with a mean annual temperature of around –5.9˚C /Khudyakov et al. 1999/. In this area a mixture of the perennial grasses *Poa pratensis* and *Alopecurus pratensis* was sown in artificial meadows where the permafrost table was found at a depth of 1.5 m below the ground surface. These meadows have been managed for more than 35 years and large quantities of fertilizers have been used to sustain growth (105 kg $ha^{-1}year^{-1}$) /Archegova 2007/. No data describing the yield for this or similar sites has been found. The soil was classified as surface-gley plowed tundra soil.

11.4.3 Climate domains and wetland properties

Very few data are available on the natural changes in peatland vegetation as a result of different climate conditions /Limpens et al. 2008/. The species composition of temperate and boreal ombrotrophic peatlands (bogs) appears to be very stable over shorter time periods /Limpens et al. 2008 and references therein/. Investigations of peat humification patterns over 10,000 years from bogs in central Sweden suggest periodic climate shifts between wetter and drier conditions e.g. /Borgmark and Wastegård 2008, Borgmark 2005b/. Drier or warmer conditions correspond to more humified peat, whereas colder or wetter correspond to less humified peat. It is more uncertain how these patterns may be transferred to peat accumulation under more fen-like conditions. Generally, higher content of sedges in fen-like wetlands results in a peat with a higher degree of humification (a lower accumulation rate of organic material) than peat developed under more bog-like conditions dominated by Sphagnum species /Mäkilä and Gozlar 2008/. Some understanding of how wetland properties may change over long periods of time may be obtained from comparisons of wetland properties over present-day climate gradients i.e. a "substituting time for space"-approach, but also from paleoecological reconstructions of peatlands. Figure 11-5 shows the span of biomasses and NPPs for the modelled cases described above and field estimates from Forsmark and Laxemar-Simpevarp, as well as from other biomes such as tundra and tundra wetland.

A warm period

A warmer climate usually means potentially more biomass and NPP, as well as reduced carbon storage in the short term depending on the magnitude of the climate change /Chapin et al. 2002, BACC 2008/. /Craft et al. 2008/ showed that C sequestration was negatively correlated to the mean annual air temperature for temperate freshwater peatlands in the USA. A similar pattern has also been described from the former Soviet Union, where a lower accumulation of peat was found under more nemoral conditions compared to boreal conditions /Gorham 1991/. Peat production in peatlands is also a function of precipitation, and warmer conditions combined with more precipitation may result in periods of unchanged peat accumulation.

A periglacial period

A decreasing temperature will eventually change a nemoral or boreal environment to a more tundra-like environment. This will lead to lower biomasses and NPPs in both forested taiga and tundra peatlands /Gower et al. 2001, Wielgolaski et al. 1981/. Such a change might also increase relative carbon storage in relation to NPP, whereas the actual amount that is stored, e.g. as peat, will be lower than under present conditions. Peat accumulation rates show characteristic patterns during the ontogeny of the bog, where the different successional stages are characterised by different dominating vegetation. The earlier fen stage often have a lower peat accumulation rate i.e. /Jauhiainen et al. 2004/ and increases during the earlier bog stages, but decreases later /Clymo 1984/. The carbon accumulation

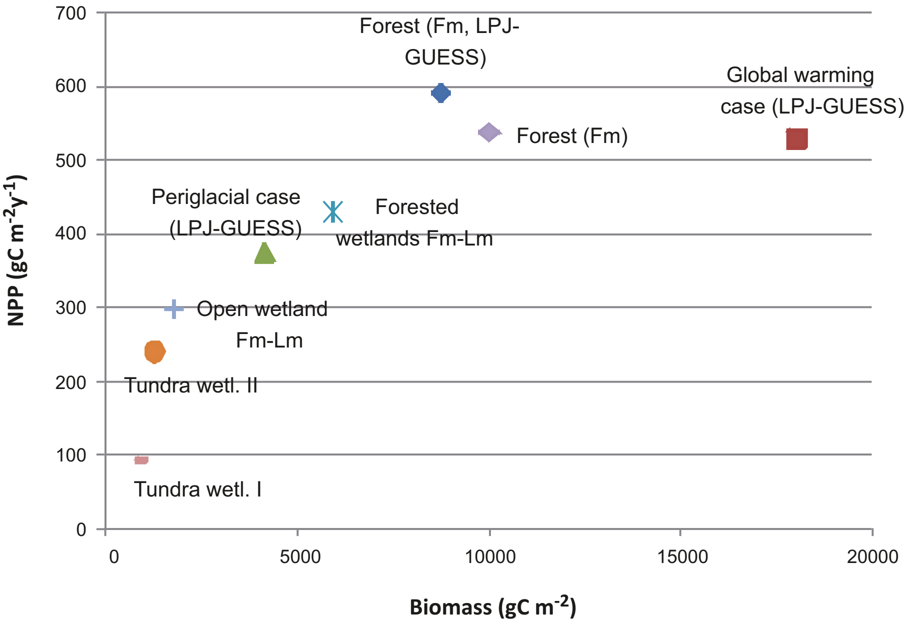


Figure 11-5. *Relationship between NPP and biomass for different vegetation types in different climates. Tundra wetland I is a median of nine tundra wetlands /Wielgolaski et al. 1981/. Tundra wetland II is from Kangerlussuaq, Greenland /Clarhäll 2011/. Wetland data from Forsmark and Laxemar-Simpevarp are presented in Section 4.1 and Chapter 6. The LPJ-GUESS estimates describe terrestrial areas in Forsmark (Forest, see Chapter 7, whereas the periglacial and the global warming estimates are a mean of the seven grid boxes closest to Forsmark from the LPJ-GUESS modelling based on data presented in /Kjellström et al. 2009/).*

or the peat increment is dependent on both the successional stage (autogenic processes) and on the climate (allogenic processes). A moister climate generally increases the peat increment, as the water table increases. Peat deposits in boreal regions tend to be deeper than those in the subarctic region, and boreal regions have higher long-term net accumulation rates /Bridgham et al. 2001 and references therein/. /Vardy et al. 2000/ compared long-term apparent rates of carbon accumulation for boreal and arctic mires and these data suggested that mires having permafrost had at least no more than half the carbon accumulation rate as those in the boreal region. Carbon accumulation rates of 1.4 gC $m^{-2}y^{-1}$ have been reported from arctic Alaska /Vardy et al. 2000 and references therein/. However, the variation in results may also reflect other properties and e.g. the different results by /Tolonen and Turunen 1996/ and /Turunen et al. 2002/ (26 gC $m^{-2}y^{-1}$ compared to 18.5 gC $m^{-2}y^{-1}$ in Table 11-3) was suggested to partly be a result of an overrepresentation of terrestrialized mires whereas paludifed, shallow mires were underrepresented in the earlier study /Turunen et al. 2002/. Table 11-3 compares some figures of long-term apparent rates of carbon accumulation for boreal and arctic mires.

11.4.4 Transitions between different climate domains

Transitions between different ecosystems due to a changing climate may lead to other responses that are difficult to predict. The recent debate concerning effects of global warming has generated literature describing mostly short-term responses to temperature increases spanning over a few degrees. Reviews, e.g. for temperate and boreal forests /Hyvönen et al. 2007/ and peatlands /Limpens et al. 2008/, have shown that single-factor responses can be misleading due to the large number of interactions between different factors and feedbacks. From the perspective of a safety assessment, the most critical scenario is if large reservoirs e.g. of organic matter/biomass, were suddenly released during a short time span as a consequence of a transition between two climate domains. This release could then again be accumulated and reach even higher concentrations compared to the original position. If no secondary accumulation occurs or is less than the initial accumulation, the release would eventually only lead to dispersal and dilution of the radionuclides. Transitions between climate domains (as defined above) is generally a slow process spanning thousands of years, but there may be cases where sudden changes could occur as a response to long-term changes reaching a threshold. However, the extent and magnitude of such potential sudden changes as an effect of climate change must still be regarded as poorly known From the perspective of dose calculations extending over the lifetimes of different taxa, it may therefore be relevant to refer to literature from which it may be possible to infer ecological consequences from minor temperature changes, e.g. global warming or present-day temperature gradients.

Transition from a colder to a warmer climate domain

Generally, it has been suggested that an increased temperature has a negative effect on the water table and a positive effect on decomposition and causes a general decline in carbon sequestration in wetlands in the long term e.g. /Limpens et al. 2008/. This is probably true for a positive temperature change in the case of temperate and boreal peatlands (the case of Forsmark today). The effects of such a change for frozen peatlands, causing the permafrost to thaw, will, however, be more uncertain /Limpens et al. 2008/. On the one hand, the water released by the melting of the ice may increase

Table 11-3. Estimated average long-term apparent rates of carbon accumulation (LARCA) for boreal and arctic mires.

	Average long-term apparent rates of carbon accumulation (gC $m^{-2}y^{-1}$)	Reference
Low arctic/High subarctic Canada	14.2	(N=4) /Vardy et al. 2000/
Subarctic Canada	9	/Tarnocai 1988/
High arctic (Baffin Island)	0.4–2.4	/Schlesinger 1990/
Finland	18.5	/Turunen et al. 2002/
Boreal and subarctic Canada	29	(N=138) /Gorham 1991/
Former Sovjet Union	30	/Botch et al. 1995/
Forsmark (Rönningarna)	38	(N=1) /Sternbeck et al. 2006/

the water residence time, promoting peat formation and thus local carbon accumulation but increasing CH_4 emission. The C sequestration rate of collapse scars in thawing peatlands may be high ($172 \pm 154\ gCm^{-2}\ y^{-1}$) /Myers-Smith et al. 2008/ and a future climate warming could lead to increased collapse and thereby peat expansion and greater carbon storage /Camill and Clark 1998, Robinson and Moore 2000/. On the other hand, if the permafrost layer is continuous the thawing could lead to drainage, stimulating decomposition processes /Hilbert et al. 2000/. In peatlands with discontinuous permafrost, severe fire events may contribute to permafrost thawing, leading to more permanent vegetation changes and potentially increasing carbon accumulation in the long term /Kuhry 1994, Schuur et al. 2008/.

Transition from a warmer to a colder climate domain

A transition from the climate prevailing today to a colder climate has been investigated and discussed to a lesser extent. Generally, the opposite trend as suggested from patterns across different climates would be found (see Section 11.4.4). More temperate fens/peatlands would be able to accumulate more peat, whereas northern peatlands would have a slower accumulation rate, but preserve the peat accumulated previously.

11.5 Land use

Different regions in the world reflect different trends of land use change. While in most developing countries the main and currently growing trend is conversion of natural habitats into agricultural land /Linkie et al. 2004, Sala et al. 2005/, in many Western nations the main land use trends are expansion of urban and forest areas and abandonment of marginal agricultural land /MacDonald et al. 2000, Cramer et al. 2008, Vellend et al. 2007/. Abandonment of agricultural land is driven by a combination of factors, ranging from the physical constraints of the landscape to economic and social drivers /Strijker 2005, Koulouri and Giourga 2007/. Migration to urban areas (leading to a diminishing and aging rural population), highly competitive global markets and limitations on mechanization in areas with physical restrictions such as steep slopes or stony ground, are some of the most common causes of abandonment /Firmino 1999, Flinn et al. 2005, Petanidou et al. 2008/. A combination of these drivers is generally more pronounced in remote and isolated regions, such as mountain zones or marginalized areas where productivity is low, e.g. areas with salty soils, poorly drained areas and farmland edges /Foster 1992, MacDonald et al. 2000, Cramer et al. 2008, Gellrich et al. 2007/.

The potential extension of future land use in a region can be predicted based on historical information on the maximum past extent and its distribution among soil types. These historical aspects are elaborated on in Chapter 10 and in /Söderbäck 2008/. Some aspects, such as agricultural development and crop production, are even more difficult to foresee. /Eckersten et al. 2007/ concluded that the effects of climate change on productivity in Europe as a whole may be small compared with the effects of improved technology. In one estimated case, climate change up to 2,050 improved the yield for the whole of Europe by 5 to 10%, whereas technical development improved the average per-hectare yield by 85 to 160%. Generally, the trend of highly increasing yields in Europe has reduced the need for land to grow crops on. Such a trend will probably lead to a situation where the high-yield growing areas of today will be more intensively used, whereas more peripheral agricultural areas, such as those found in the Forsmark and Laxemar-Simpevarp investigation areas, will be abandoned or used for other purposes. However, a future emphasis on locally produced agricultural products grown under more environmental sustainable conditions may lead to an opposite trend.

12 Important processes for transport and accumulation of radionuclides – a comparison with the radionuclide model

12.1 Introduction

This section provides an extensive description of processes influencing transport and accumulation of radionuclide in ecosystems considered in the safety assessment in SR-Site biosphere. It is essential that processes of importance for the transport and accumulation of radionuclides in the ecosystems are described in the construction of the radionuclide model for the biosphere. The aims of this chapter are the following:

1. Identify interactions between different components in the ecosystem that are important for the transport and accumulation of radionuclides.
2. Identify the processes behind the interactions.
3. Demonstrate that interactions of significance for the transport and accumulation of radionuclides are included in the radionuclide modelling. Interactions are considered to be included in the radionuclide modelling if they are represented in the radionuclide model or in the parameterisation of the model. Processes may be included in parameterisation either directly or indirectly if parameter values are based on *in situ* measurements where the effects of the process are included.

Ecosystems are extremely complex and contain a large number of processes and the aim of this chapter has not been to specify all the separate processes. The focus has rather been to identify interactions between different components in the ecosystems important for accumulation and transport of radionuclides and to characterise these interactions in terms processes. Full definitions of all processes discussed here can be found in /SKB 2010e/.

The estimated degree of importance of a process interaction is evaluated solely in terms of its potential effect on doses to humans and the environment from radionuclides released from a deep repository. Hence, process interactions of great importance from an ecological point of view may not necessarily be rated as important for the radionuclide modelling. In the radionuclide model, the worst case scenario is always considered and therefore, process interactions induced by humans are not included if they lead to lower doses. One example is aquaculture for fish that severely alters the natural ecosystem but that from a radiological impact point of view it is uninteresting since radiation exposure would be decreased due to consumption of uncontaminated food pellets by the fish.

Although only process interactions important for radionuclide transport are considered a large number of processes and complex interactions are still incorporated. When developing conceptual and mathematical models to illustrate transport in an ecosystem there is a risk that important components and interactions are omitted or underestimated due to the complexity of the ecosystem. The risk can be reduced if a systematic approach to characterisation is used, e.g. through the application of interaction matrixes /Avila and Moberg 1999/. Therefore, to ensure that all relevant and important processes for the transport and/or accumulation of radionuclides are identified and considered in the radionuclide model, an interaction matrix is used both for analysis and presentation.

All major processes in the ecosystems are listed in the interaction matrix. The period considered in the assessment is around 100,000 years representing a glacial cycle. It is assumed that human behaviour during that period is similar to human behaviour today. The interaction matrices for the biosphere are valid for the entire glacial cycle, i.e. including temperate, periglacial and glacial conditions, although the primary focus is on a temperate climate. This is justified by the fact that the highest exposure are expected in temperate conditions since production will decrease at colder climate and agricultural use of land will not be possible at perioglacial and gliacial conditions. Only climate conditions that may occur in Sweden are included, which means that processes applicable only to other climate regions such as rainforests or deserts are not considered in this report. When terrestrial ecosystems are referred to in the remainder of this chapter, wetland ecosystems and agricultural land on such drained wetlands are implied. Wetlands have been identified as potential discharge areas for deep groundwater in the SR-Site safety assessment and are the natural end stage of the succession from aquatic to terrestrial ecosystems /Lindborg 2010/. Wetlands have also a long history of being used as agricultural land after drainage. However, for farmland water fluxes from geosphere and deeper regolith layers to the upper regolith layers are not considered since these fluxes are small or insignificant when the wetlands are drained

12.2 Concept of the interaction matrix

The general principles of an interaction matrix (IM) are illustrated in Figure 12-1. The ecosystem of interest is divided into various components that are listed along the lead diagonal of the matrix. These components, are in the following context, referred to as diagonal elements. These diagonal elements can be spatially or conceptually distinct. Thus, for example, two elements might be water in regolith and surface water (physically distinct) or herbivores and carnivores (conceptually distinct). An element may also be a property such as temperature. It is worth noting that different types of biota are distinguished by ecosystem function. Thus, omnivores do not appear in the interaction matrix because functionally they are a mix of herbivores and carnivores. The number of diagonal elements is a compromise between the need to keep the matrix to a manageable size and the requirement to be as specific as possible in defining the processes relating the various diagonal elements.

Processes that relate the diagonal elements (i.e. interactions) are entered into the off-diagonal elements, as shown in Figure 12-1. Note that the matrix is read in a clockwise sense, so that processes by which Component A affect Component C are found in the top right element, whereas processes by which Component C affect Component A are found in the bottom left element. It is important to ensure that the effects of processes are direct and are not mediated by interactions via a third element listed on the lead diagonal.

To specify all processes in an ecosystem model is not doable and from the perspective of radionuclide transport also unnecessary. Instead, processes similar to each other and/or with a similar mechanism or result have been grouped into larger comprehensive processes in the biosphere interaction matrix. As an example, the process ‘reaction’ includes chemical reactions in water and within biota (metabolic reactions) and thereby this particular process includes hundreds (or even thousands) of possible sub-processes if all separate reactions were treated individually.

The concept of interaction matrixes and methodology for determining diagonal elements and group processes are further described in /SKB 2010e/.

12.3 The limnic/marine/terrestrial interaction matrices

An aquatic IM for the limnic and marine ecosystems is presented in Figure 12-2, and an terrestrial IM for the terrestrial ecosystems is presented in Figure 12-3. The IMs are based on the general biosphere IM presented in /SKB 2010e/ and processes common to all three ecosystems are described together in Section 12.5. When the relevance of a process for a specific ecosystem differs, this is noted in the description in Section 12.5.

The aquatic and terrestial IMs includes 15 diagonal elements and 51 processes. The colour coding used in Figures 12-2 and 12-3 displays the priorities in the IMs, process interactions significant for transport and accumulation of radionuclides are coloured dark yellow, whereas insignificant process interactions are light yellow, and irrelevant process interactions are coloured white. The importance of process interactions in this IM is based on temperate conditions, i.e. process interactions are valid also for other climate domains during an interglacial but may be more or less important. Diagonal elements, processes and interactions are further described in the following sections.

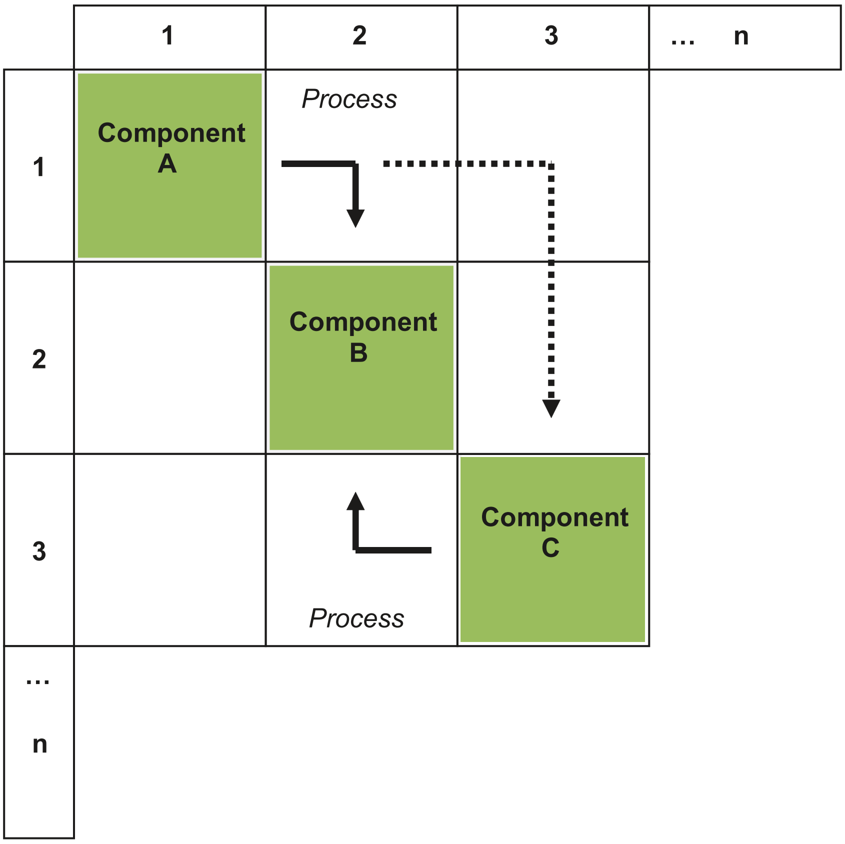


Figure 12-1. *Conceptual illustration of an interaction matrix (IM). The diagonal elements A, B and C are key components of the ecosystem and are placed on the diagonal. The off-diagonal elements (white boxes) represent processes. The arrows illustrate e.g. how Component A (1:1) affects Component B (2:2) through a process (1:2). The matrix is always read clockwise, e.g. processes by which component A affect component C are found in the top right element, whereas processes by which component C affect component A are found in the bottom left element. Coordinates are read (row: column).*

Necessary for dose assessment	Not necessary for dose assessment	No interaction

	1	2	3	4	5	6	7
1	**GEOSPHERE (B.C.)**	a) Change in rock surface location b) Weathering	a) Habitat supply	a) Habitat supply	a) Habitat supply		
2	a) Consolidation b) Loading	**Regolith**	a) Element supply b) Habitat supply c) Light related processes d) Relocation	a) Element supply b) Food supply c) Habitat supply	a) Food supply b) Habitat supply	a) Habitat supply	a) Habitat supply
3	a) Intrusion	a) Bioturbation b) Death	**Primary producers**	a) Habitat supply b) Stimulation/inhibition	a) Food supply b) Habitat supply c) Stimulation/inhibition	a) Food supply b) Habitat supply c) Stimulation/inhibition	a) Habitat supply b) Stimulation/inhibition
4	a) Intrusion	a) Bioturbation b) Consumption c) Death d) Decomposition	a) Stimulation/inhibition	**Decomposers**	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition
5	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Habitat supply c) Stimulation/inhibition	a) Consumption b) Habitat supply c) Stimulation/inhibition	**Filter feeders**	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition
6	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Stimulation/inhibition	a) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	**Herbivores**	a) Food supply b) Stimulation/inhibition
7	a) Intrusion	a) Bioturbation b) Death	a) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	**Carnivores**
8	a) Intrusion b) Material use	a) Death b) Material use c) Relocation	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination e) Stimulation/inhibition
9	a) Change of pressure b) Convection c) Weathering	a) Relocation b) Saturation	a) Habitat supply b) Water supply	a) Habitat supply b) Water supply	a) Water supply	a) Water supply	a) Water supply
10	a) Change of pressure b) Convection c) Loading d) Weathering	a) Relocation b) Resuspension	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Water supply
11	a) Convection b) Weathering	a) Deposition b) Phase transition c) Weathering	a) Element supply b) Food supply c) Light-related processes d) Stimulation/inhibition	a) Element supply b) Food supply c) Habitat supply d) Stimulation/inhibition	a) Element supply b) Food supply c) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition
12	a) Convection	a) Reactions	a) Element supply b) Stimulation/inhibition	a) Element supply	a) Element supply	a) Element supply	a) Element supply
13	a) Convection b) Weathering	a) Physical properties change b) Weathering	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition
14	a) Radionuclide release	a) Deposition b) Irradiation	a) Exposure	a) Exposure	a) Exposure	a) Exposure	a) Exposure
15	a) Change in rock surface location	a) Change in rock surface location b) Import c) Saturation d) Terrestrialisation	a) Import b) Light-related processes	a) Import	a) Import	a) Import	a) Import

Figure 12-2. *The aquatic interaction matrix (IM) used for limnic and marine ecosystems in SR-Site. The colour coding display the priorities in the IM, process interactions significant for transport and accumulation of radionuclides are coloured dark yellow, whereas insignificant process interactions are light yellow, and irrelevant processes interactions are coloured white. In cases where an interaction box contains more than one interaction, the interaction with the highest priority determines the colour of the interaction box.*

8	9	10	11	12	13	14	15
a) Material supply	a) Convection	a) Convection	a) Convection	a) Convection	a) Convection	a) Radionuclide release	
a) Food Supply b) Habitat supply c) Material supply	a) Convection b) Thresholding	a) Acceleration b) Convection b) Thresholding	a) Phase transition b) Reactions c) Resuspension d) Sorption/desorption	a) Reactions	a) Convection b) Heat storage c) Light-related processes d) Pressure change	a) Phase transition b) Sorption/desorption	a) Export b) Thresholding
a) Food supply b) Material supply c) Stimulation/inhibition	a) Excretion b) Uptake	a) Acceleration b) Covering c) Excretion d) Interception e) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Acceleration b) Excretion c) Particle releas/trapping d) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition	a) Decomposition b) Excretion c)Uptake	a) Acceleration b) Decomposition c) Excretion d) Movement e) Uptake	a) Consumption b) Death c) Decomposition d) Excretion e) Particle release/trapping f) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition		a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition		a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-relaetd processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Consumption b) Food supply c) Material supply d) Stimulation/inhibition		a) Excretion b) Movement c) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
Humans	a) Uptake c) Water use	a) Acceleration b) Antropogenic release c) Covering d) Excretion e) Movement f) Uptake g) Water use	a) Anthropogenic release b) Death c) Excretion d) Uptake e) Water use	a) Acceleration b) Anthropogenic release c) Excretion d) Uptake	a) Anthropogenic release b) Convection c) Light-related processes d) Reactions	a) Anthropogenic release b) Excretion c) Growth d) Sorption/desorption e) Uptake	a) Export
a) Water supply	**Water in regolith**	a) Convection	a) Convection b) Physical properties change c) Relocation	a) Phase transition	a) Convection b) Heat storage	a) Convection	a) Export
a) Habitat supply b) Water supply	a) Convection	**Surface water**	a) Convection b) Physical properties change	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Convection c) Heat storage d) Light related processes	a) Convection	a) Export b) Import
a) Stimulation/inhibition	a) Convection	a) Convection	**Water composition**	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Light-related processes c) Reactions	a) Phase transition b) Sorption/desorption	a) Export
a) Deposition b) Element supply c) Stimulation/inhibition	a) Convection b) Phase transition	a) Convection b) Deposition c) Phase transition d) Wind stress	a) Deposition b) Phase transition c) Wind stress	**Local atmosphere**	a) Change of pressure b) Convection c) Heat storage d) Phase transition e) Light-related processes f) Reactions	a) Convection b) Sorption/desorption	a) Export
a) Stimulation/inhibition	a) Phase transition	a) Convection b) Phase transition	a) Convection b) Physical properties change c) Reactions	a) Change of pressure b) Convection c) Phase transition	**Temperature**	a) Reactions b) Phase transition	a) Export
a) Exposure			a) Decay b) Radiolysis c) Reactions	a) Phase transition	a) Decay	**Radionuclides (*)**	a) Export
a) Import	a) Import	a) Convections b) Import c) Sea level change d) Terrestrialisation	a) Import	a) Import b) Reactions	a) Import b) Light-related processes	a) Import	**External conditions**

	1	2	3	4	5	6	7
1	**GEOSPHERE (B.C.)**	a) Change in rock surface location b) Weathering					
2	a) Consolidation b) Loading	**Regolith**	a) Element supply b) Habitat supply c) Light related processes d) Relocation	a) Element supply b) Food supply c) Habitat supply	a) Food supply b) Habitat supply	a) Habitat supply	a) Habitat supply
3	a) Intrusion	a) Bioturbation b) Death	**Primary producers**	a) Habitat supply b) Stimulation/inhibition	a) Food supply b) Habitat supply c) Stimulation/inhibition	a) Food supply b) Habitat supply c) Stimulation/inhibition	a) Habitat supply b) Stimulation/inhibition
4	a) Intrusion	a) Bioturbation b) Consumption c) Death d) Decomposition	a) Stimulation/inhibition	**Decomposers**	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition
5	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Habitat supply c) Stimulation/inhibition	a) Consumption b) Habitat supply c) Stimulation/inhibition	**Filter feeders**	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition
6	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Stimulation/inhibition	a) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	**Herbivores**	a) Food supply b) Stimulation/inhibition
7	a) Intrusion	a) Bioturbation b) Death	a) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	**Carnivores**
8	a) Intrusion b) Material use	a) Death b) Material use c) Relocation	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination d) Stimulation/inhibition	a) Consumption b) Material use c) Species introduction/ extermination e) Stimulation/inhibition
9	a) Change of pressure b) Convection c) Weathering	a) Relocation b) Saturation	a) Habitat supply b) Water supply	a) Habitat supply b) Water supply	a) Water supply	a) Water supply	a) Water supply
10	a) Change of pressure b) Convection c) Loading d) Weathering	a) Relocation b) Resuspension	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Water supply
11	a) Convection b) Weathering	a) Deposition b) Phase transition c) Weathering	a) Element supply b) Food supply c) Light-related processes d) Stimulation/inhibition	a) Element supply b) Food supply c) Habitat supply d) Stimulation/inhibition	a) Element supply b) Food supply c) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition
12	a) Convection	a) Reactions	a) Element supply b) Stimulation/inhibition	a) Element supply	a) Element supply	a) Element supply	a) Element supply
13	a) Convection b) Weathering	a) Physical properties change b) Weathering	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition
14	a) Radionuclide release	a) Deposition b) Irradiation	a) Exposure	a) Exposure	a) Exposure	a) Exposure	a) Exposure
15	a) Change in rock surface location	a) Change in rock surface location b) Import c) Saturation d) Terrestrialisation	a) Import b) Light-related processes	a) Import	a) Import	a) Import	a) Import

Figure 12-3. *The terrestrial interaction matrix (IM) used for terrestrial ecosystems in SR-Site. The colour coding display the priorities in the IM, process interactions significant for transport and accumulation of radionuclides are coloured dark yellow, whereas insignificant process interactions are light yellow, and irrelevant processes interactions are coloured white. In cases where an interaction box contains more than one interaction, the interaction with the highest priority determines the colour of the interaction box.*

8	9	10	11	12	13	14	15
a) Material supply	a) Convection	a) Convection	a) Convection	a) Convection	a) Convection	a) Radionuclide release	
a) Food Supply b) Habitat supply c) Material supply	a) Convection b) Thresholding	a) Acceleration b) Convection b) Thresholding	a) Phase transition b) Reactions c) Resuspension d) Sorption/desorption	a) Reactions	a) Convection b) Heat storage c) Light-related processes d) Pressure change	a) Phase transition b) Sorption/desorption	a) Export b) Thresholding
a) Food supply b) Material supply c) Stimulation/inhibition	a) Excretion b) Uptake	a) Acceleration b) Covering c) Excretion d) Interception e) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Acceleration b) Excretion c) Particle releas/trapping d) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition	a) Decomposition b) Excretion c)Uptake	a) Acceleration b) Decomposition c) Excretion d) Movement e) Uptake	a) Consumption b) Death c) Decomposition d) Excretion e) Particle release/trapping f) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition		a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Food supply b) Material supply c) Stimulation/inhibition		a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-relaetd processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Consumption b) Food supply c) Material supply d) Stimulation/inhibition		a) Excretion b) Movement c) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
Humans	a) Uptake c) Water use	a) Acceleration b) Antropogenic release c) Covering d) Excretion e) Movement f) Uptake g) Water use	a) Anthropogenic release b) Death c) Excretion d) Uptake e) Water use	a) Acceleration b) Anthropogenic release c) Excretion d) Uptake	a) Anthropogenic release b) Convection c) Light-related processes d) Reactions	a) Anthropogenic release b) Excretion c) Growth d) Sorption/desorption e) Uptake	a) Export
a) Water supply	**Water in regolith**	a) Convection	a) Convection b) Physical properties change c) Relocation	a) Phase transition	a) Convection b) Heat storage	a) Convection	a) Export
a) Habitat supply b) Water supply	a) Convection	**Surface water**	a) Convection b) Physical properties change	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Convection c) Heat storage d) Light related processes	a) Convection	a) Export b) Import
a) Stimulation/inhibition	a) Convection	a) Convection	**Water composition**	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Light-related processes c) Reactions	a) Phase transition b) Sorption/desorption	a) Export
a) Deposition b) Element supply c) Stimulation/inhibition	a) Convection b) Phase transition	a) Convection b) Deposition c) Phase transition d) Wind stress	a) Deposition b) Phase transition c) Wind stress	**Local atmosphere**	a) Change of pressure b) Convection c) Heat storage d) Phase transition e) Light-related processes f) Reactions	a) Convection b) Sorption/desorption	a) Export
a) Stimulation/inhibition	a) Phase transition	a) Convection b) Phase transition	a) Convection b) Physical properties change c) Reactions	a) Change of pressure b) Convection c) Phase transition	**Temperature**	a) Reactions b) Phase transition	a) Export
a) Exposure			a) Decay b) Radiolysis c) Reactions	a) Phase transition	a) Decay	**Radionuclides (*)**	a) Export
a) Import	a) Import	a) Convections b) Import c) Sea level change d) Terrestrialisation	a) Import	a) Import b) Reactions	a) Import b) Light-related processes	a) Import	**External conditions**

12.4 Diagonal elements in the interaction matrix

In the biosphere IM, 15 diagonal elements are identified (Figure 12-2 and 12-3). The diagonal elements with ecosystem-specific examples are described in Table 12-1. Note that the definitions of these diagonal elements are often more wide-reaching than inferred by their short names and a more comprehensive description of the diagonal elements is given in /SKB 2010e/.

Table 12-1. Elements (diagonal elements) of the limnic, marine and terrestrial ecosystems interaction matrix (IM). Placement is the numbering of boxes in the matrix according to row:column (see Figure 12-2 and 12-3).

Placement	Element	Definition
1:1	Geosphere	Geosphere is the rock surrounding the repository. It also includes deep groundwater and gases present in the saturated zone in the bedrock. In the ecosystems IM the geosphere corresponds to the solid rock below the sediments (aquatic ecosystems) and soils (terrestrial ecosystems).
2:2	Regolith	Regolith is the unconsolidated material that covers almost the Earth's entire surface and is composed of weathered rock debris covering the rock beneath it, as well as glacial and postglacial deposits, newly formed soils and sediments including dead organic material /Jones et al. 1992/. In the ecosystems (limnic, marine and terrestrial) IM the regolith corresponds to the sediment and soils including dead organic matter. It also includes rock outcrops.
3:3	Primary producers	Primary producers are autotrophic organisms able to use sunlight or the oxidation of inorganic compounds as an energy source to synthesise organic compounds from inorganic carbon sources. The organic compounds are used as fuel for cellular respiration and growth. Primary producers include green plants, algae and autotrophic bacteria (e.g. /Campbell 1993/). In the IM, primary producers include, phytoplankton, microphytobenthos, emergent and submerged macrophytes and macroalgae (aquatic), as well as grasses, herbs, bushes and trees (terrestrial).
4:4	Decomposers	Decomposers are organisms (bacteria, fungi or animals) that feed on dead plant and animal matter and break down complex organic compounds into carbon dioxide, water and inorganic compounds (e.g. /Begon et al. 1996, Porteous 2000/). In a sense, most carnivores live on dead material as they most often kill their prey, and plant matter is dead before its digestion in herbivores begins. However, decomposers do not actively affect the rate at which their food resource becomes available, but are instead dependent on other factors such as senescence, illness, fighting or shredding of leaves, whereas herbivores, filter feeders and carnivores directly affect the rate at which their resources become available /Begon et al. 1996/. In the IM decomposers include bacteria, some species of benthic fauna (aquatic) as well as bacteria, soilfauna and earthworms (terrestrial). Benthic and soil fauna may be omnivores, thus a mix of decomposers, herbivores and carnivores.
5:5	Filter feeders	Filter feeders are aquatic organisms that feed on particulate organic matter and small organisms (phytoplankton and zooplankton) filtered out by circulating the water through the animal's system. Filter feeders include a wide range of animals such as bivalves (e.g. mussels), sponges, crustaceans (e.g. shrimps) and even whales. Filter feeders are an important group of organisms in aquatic ecosystems as they can greatly affect the amount of particulate matter and nutrients in the water, and transport particulate matter from the water column into biota (e.g. /Holland 1993, Soto and Mena 1999, Wilkinson et al. 2008/). Hence they are treated as a separate diagonal element although they conceptually are a mix of decomposers, herbivores, and carnivores.
6:6	Herbivores	Herbivores are animals that feed on primary producers, i.e. plants, algae and autotrophic bacteria. Omnivores are functionally a mix of herbivores and carnivores and are included both here and in carnivores (see below). In the IM herbivores include zooplankton, benthic fauna and some fish species (aquatic) as well as insects, rodents and larger mammals (terrestrial).

7:7	Carnivores	Carnivores are animals that feed on other animals. Omnivores are functionally a mix of herbivores and carnivores and are included both here and in herbivores (see below). In the IM carnivores may include some species of zooplankton, benthic fauna, fish (aquatic), as well as, insects, mammals and birds (terrestrial).
8:8	Humans	Humans are defined as all human beings living in the affected area. This diagonal element includes the number of persons but also their activities in the modelled area. In the IM, activities such as fishing, water pumping and anthropogenic releases are included (aquatic) as well as agriculture, irrigation and construction (terrestrial).
9:9	Water in Regolith	Water in regolith is the water in the saturated zone of the regolith and the pore water in the unsaturated zone. All physical states of water are considered, i.e. this diagonal element includes also frost and ice. This diagonal element includes the quantity of water in regolith, whereas the chemical composition of the water is treated under water composition (see below). Water in regolith does not include the water in the bedrock as this is handled in the geosphere matrix.
10:10	Surface Waters	Surface water is defined here as water on the Earth's surface, collecting on the ground or in streams, rivers, lakes, open water wetlands or oceans, as opposed to water in rock, regolith or atmosphere /Heath 1987/. Atmospheric water is addressed under gas and local atmosphere in the matrix, in contrast to the classification made by some other authors, e.g. /Watson and Burnett 1993/ who include rain, fog and snow in surface water. Rainwater on rock surfaces, snow and ice on land and on water, as well as droplets on e.g. vegetation are included in surface water. This diagonal element includes the quantity of surface water, whereas the chemical composition of the water is addressed under water composition (see below).
11:11	Water Composition	Here, water composition comprises dissolved elements and compounds, colloids and suspended particles (including dead organic matter) in surface water and water in regolith. The content of ions and elements determines e.g. pH-values, salinity, and nutrient concentrations. Thus, water composition is important to the presence and viability of biotic components in aquatic ecosystems. Various transport, chemical and biological processes affect water composition (e.g. /Stumm 2004/).
12:12	Gas and local Atmosphere	Gas and local atmosphere includes the local atmosphere and gas in regolith and in water in regolith as well as gas bubbles in surface water. Gas flow and gas composition are included in this element which, therefore, includes wind and the content of particulates in the local atmosphere, i.e. water droplets, pollen, etc. The local atmosphere is defined as the layer of the atmosphere above the studied area that participates in gas exchange with the studied area. It is surrounded by the atmosphere, which is a boundary to the biosphere system. Gas bubbles in water are included in this diagonal element, whereas dissolved gases are treated in water composition.
13:13	Temperature	Temperature is the unique physical property that determines the direction of heat flow between two objects placed in thermal contact /Pitt 1986/. Here, temperature is restricted to the temperature in the physical component of the system of interest (i.e. all physical diagonal elements such as geosphere, regolith, biota, and water). Temperature is dependent on climate, and local effects on climate belong to this diagonal element, whereas large-scale climate systems belong to external factors.
14:14	Radionuclides	Radionuclides include radionuclides in all physical and biological components of the biosphere system in question (i.e. in all physical diagonal elements such as geosphere, regolith, biota, and water).
15:15	External Conditions	External conditions are all external factors that affect the local conditions considered within the biosphere matrix or are affected by the biosphere identified in the matrix. External conditions include surrounding ecosystems and the atmosphere above and beyond the lateral boundaries of the local atmosphere. They also include global conditions such as global climate and solar insolation.

12.5 Processes in the interaction matrix

In total, 51 processes were identified in the biosphere IM. Biosphere processes are listed in Table 12-2 together with a short definition whereas a comprehensive description of the processes is given in /SKB 2010e/. In Table 12-2, a reference is also given to where in the IM the processes occur. Figure 12-4 is a conceptual representation of the Radionuclide model in which the incorporation of important processes is shown.

The International Atomic Energy Agency (IAEA) has produced a database of features, events and processes (FEPs) used for safety assessments of repositories for radioactive waste by several countries. All IAEA FEPs related to the biosphere are included in the processes here (unless irrelevant for Swedish conditions). Definitions of IAEA FEPs and how these correlate to the processes used by SKB can be found in SKB's FEP database, see further the /SKB 2010f/.The numbering in the FEP database is presented in the right column in Table 12-2 and is also used in Figure 12-4.

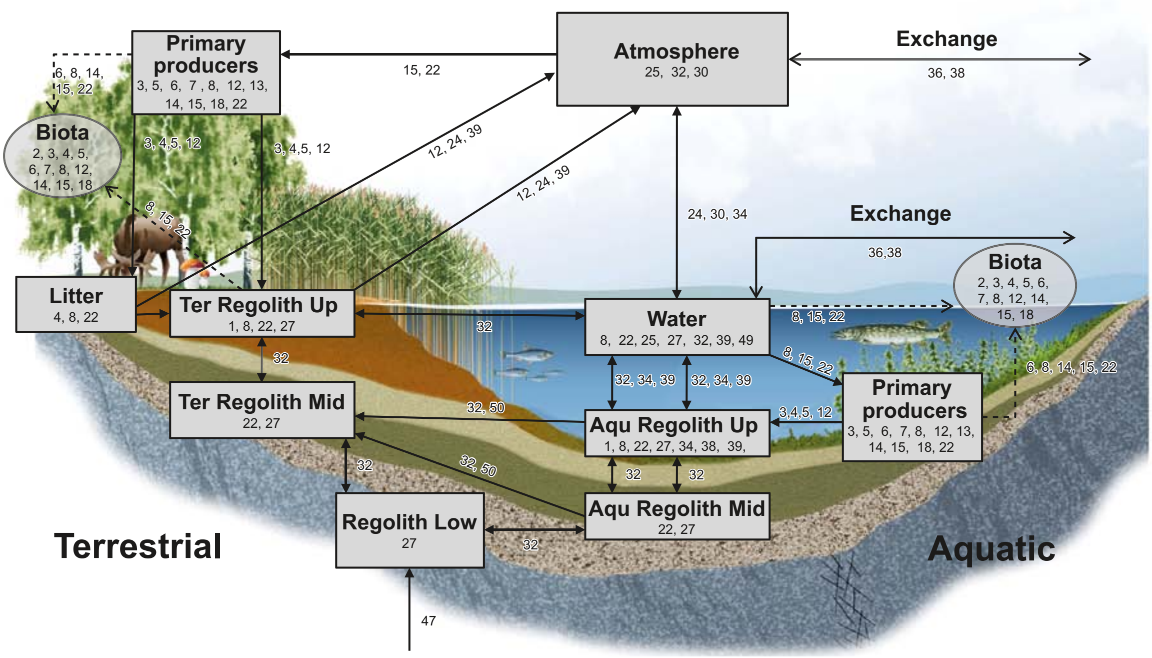


Figure 12-4. Conceptual illustration of the Radionuclide model for the biosphere and the location of processes identified as important (represented by numbers according to Table 12-2). Processes may occur in more locations than pointed out in the figure, because only the major occurrence is shown in the figure in order to improve readability. Boxes represent compartments, arrows represent fluxes, and dotted arrows represent concentration computations for biota (these are not included in the mass balance). The model represents one object which contains an aquatic (right) and a terrestrial part (left) with a common lower regolith and atmosphere. A detailed explanation of the Radionuclide model can be found in Chapter 10. Some of the processes identified as important to consider, e.g. decay, thresholding, external and internal exposure are not included in the illustration since they are hard to illustrate (but they are considered in the model).

Table 12-2. Processes in the interaction matrix (IM) for the limnic, marine and terrestrial ecosystems. In the third column, the specific coordinates for the interactions between elements are presented. The coordinates refer to the location in the IM (Figure 12-2 and 12-3) where the boxes are numbered according to row: column. In the fourth column, the location in the radionuclide model is listed. Processes marked with * denote that the processes are caused, or associated with, both human and non-human biota.

Process	**Definition**	**Interactions in the matrix** **(read row:column)**	**Necessary to consider in the radionuclide modelling (dark yellow box in IM (Figure 12-2 and/or 12-3)**	**Numbering according to number in SKBs FEP data base, see /SKB 2010f/.**
Biolgical processes				
Bioturbation	The mixing of elements and particles in both aquatic and terrestrial regolith by organisms.	3:2, 4:2, 5:2, 6:2, 7:2	yes	1
Consumption*	When organisms feed on solid material and/or on other organisms.	4:2, 4:11, 5:3, 5:4, 5:5, 5:6, 5:7, 6:3, 7:4, 7:5, 7:6, 7:7, 7:8, 8:3, 8:4, 8:5, 8:6, 8:7	yes	2
Death*	The generation of dead organic matter by organisms.	3:2, 3:11, 4:2, 4:11, 5:2, 5:11, 6:2, 6:11, 7:2, 7:11, 8:2, 8:11	yes	3
Decomposition	The breakdown of organic matter by organisms.	4:2, 4:9, 4:10, 4:11	yes	4
Excretion*	The excretion of water or elements to the surrounding media by humans and other organisms.	3:9, 3:10, 3:11, 3:12, 3:14, 4:9, 4:10, 4:11, 4:12, 4:14, 5:10, 5:11, 5:12, 5:14, 6:10, 6:11, 6:12, 6:14, 7:10, 7:11, 7:12, 7:14, 8:10, 8:11, 8:12, 8:14	yes	5
Food supply	The fraction of produced biomass and particulate matter that can be used as a food source for humans and other organisms.	2:4, 2:8, 3:5, 3:6, 3:8, 4:5, 4:7, 4:8, 5:5, 5:7, 5:8, 6:5, 6:7, 6:8, 7:5, 7:7, 7:8, 8:7, 11:3, 11:4, 11:5	yes	6
Growth*	The generation of biomass by organisms.	3:14, 4:14, 5:14, 6:14, 7:14, 8:14	yes	7
Habitat supply	The providing of habitat for organisms by abiotic elements or other organisms.	1:3, 1:4, 1:5, 1:6, 2:3, 2:4, 2:5, 2:6, 2:7, 2:8, 3:3, 3:4, 3:5, 3:6, 5:3, 5:4, 9:3, 9:4, 10:3, 10:4, 10:5, 10:6, 10:7, 10:8, 11:4	yes	8
Intrusion	Non-human organisms or humans enter the repository, for example by locomotion, drilling or growth.	3:1, 4:1, 5:1, 6:1, 7:1, 8:1	no	9
Material supply	The amount of material that is available for human utilisation for purposes other than feeding.	1:8, 2:8, 3:8, 4:8, 5:8, 6:8, 7:8	no	10
Movement*	Animal locomotion in surface water.	4:10, 5:10, 6:10, 7:10, 8:10	no	11
Particle release/trapping*	Organisms release particles (for example by fragmentation, spawning and pollen release) or trap particles (for example with gills, feathers and slime).	3:11, 3:12, 4:11, 5:11 6:11, 6:12, 7:11, 7:12	yes	12

Primary production	The fixation of carbon by primary producers in photosynthesis.	3:3	yes	13
Stimulation/inhibition*	When one diagonal element positively or negatively influences another diagonal element. The extreme of inhibition prevents settlement and leads to exclusion from the model areas.	3:3, 3:4, 3:5, 3:6, 3:7, 3:8, 4:3, 4:4, 4:5, 4:6, 4:7, 4:8, 5:3, 5:4, 5:5, 5:6, 5:7, 5:8, 6:3, 6:4, 6:5, 6.6, 6:7, 6:8, 7:3, 7:4, 7:5, 7:6, 7:7, 7:8, 8:3, 8:4, 8:5, 8:6, 8:7, 8:8, 11:3, 11:4, 11:5, 11:6, 11:7, 11:8, 12:3, 12:8, 13:3, 13:4, 13.5, 13.6, 13:7, 13:8	yes	14
Uptake*	The incorporation of water or elements from the surrounding media into humans and other organisms.	3:9, 3:10, 3:11, 3:12, 3:14, 4:9, 4:10, 4:11, 4:12, 4:14, 5:10, 5:11, 5:12, 5:14, 6:10, 6:11, 6:12, 6:14, 7:10, 7:11, 7:12, 7:14, 8:10, 8:11, 8:12, 8:14	yes	15
Processes related to human behaviour				
Anthropogenic release	Release caused by humans of substances, water or energy into the local biosphere.	8:10, 8:11, 8:12, 8:13, 8:14	yes	16
Material use	Human utilisation of the environment for purposes other than feeding.	8:1, 8:2, 8:3, 8:4, 8:5, 8:6, 8:7	no	17
Species introduction/extermination	Introduction or extermination of species from the model area by human activities. (e.g. introduction of crayfish in lakes).	8:3, 8:4, 8:5, 8:6, 8:7	yes	18
Water use	Water use by humans for other purposes than drinking, e.g. washing, irrigation and energy production. May affect the water table.	8:9, 8:10, 8:11	yes	19
Chemical, mechanical and physical processes				
Change of pressure	Pressure change in air or water above a surface.	9:1, 10:1, 10:13, 11:13, 12:13, 13.12	no	20
Consolidation	Any process whereby loosely aggregated, soft, or liquid earth materials become firm and coherent rock.	2:1, 2:2	no	21
Element supply	The availability of elements and substances for use by organisms.	2:3, 2:4, 11:3, 11:4, 11:5, 11:6, 11:7, 12:3, 12:4, 12:5, 12:6, 12:7, 12:8	yes	22
Loading	Force caused by the weight of material that affects the underlying rock.	2:1, 10:1	no	23
Phase transitions	Changes between different states of matter: solid, liquid and gas.	2:11, 2:14, 9:12, 10:12, 11:2, 11:12, 11:14, 12:9, 12:10, 12:11, 12:13, 13:9. 13:10, 13:12, 13:14, 14:12	yes	24
Physical properties change	Changes in volume, density and/or viscosity.	9:11, 10:11, 13:2, 13:11	yes	25

Reactions	Chemical reactions excluding weathering, decomposition and photosynthesis.	2:11,2:12, 3:13, 4:13, 5:13, 6:13, 7:13, 8:13, 11:13, 12:2, 12:13, 13:11, 13:14, 14:11, 15:12	no	26
Sorption/desorption	Dissolved substances adhere to surfaces or are released from surfaces.	2:11, 2:14, 3:14, 4.14, 5.14, 6.14, 7:14, 8:14, 11:14, 12:14	yes	27
Water supply	The amount of water available for drinking and other uses by humans and other organisms.	9:3, 9:4, 9:5, 9:6, 9:7, 9:8, 10:3, 10:4, 10:5, 10:6, 10:7, 10:8	no	28
Weathering	Disintegration of solid matter into smaller pieces.	1:2, 9:1, 10:1, 11:1, 11:2, 13:1, 13:2	no	29
Wind stress	A mechanical force generated by wind affecting the biosphere.	12:10, 12:11	yes	30
Transport processes				
Acceleration	The change in velocity of a fluid or body over time and/or the rate and direction of velocity change. May be either positive or negative (retardation).	2:10, 3:10, 3.12, 4.10, 5.10, 6:10, 8.10, 8:12	no	31
Convection	The transport of a substance or a conserved property with a fluid or gas.	1:9, 1:10, 1:11, 1.12, 1:13, 2:9, 2:10, 2:13, 3:13, 4.13, 5:13, 6.13, 7.13, 8:13, 9:1, 9:10, 9:11, 9:13, 9:14, 10:1, 10:9, 10:11, 10:13, 10:14, 11:1, 11:9, 11:10, 12:1, 12:9, 12:10, 12:13, 12:14, 13:1, 13:10, 13:11, 13:12, 15.10	yes	32
Covering	The covering of surface water by e.g. vegetation or ice that reduces light and prevents the exchange of gases and particles between the water and the atmosphere.	3:10, 8:10	no	33
Deposition	Vertical transfer of a material or element to a surface of any kind due to gravitation, e.g. sedimentation, rainfall, and snowfall.	11:2, 12:8, 12:10, 12:11, 14:2	yes	34
Export	Transport out of the model area.	2:15, 3:15, 4:15, 5:15, 6:15, 7:15, 8:15, 9:15, 10:15, 11:15, 12:15, 13:15 14:15	no	35
Import	Transport into the model area.	10:15, 15:2, 15:3, 15:4, 15:5, 15:6, 15:7, 15:8, 15:9, 15:10, 15:11, 15:12, 15:13, 15:14	yes	36
Interception	The amount of precipitation that does not reach the ground but is retained on vegetation.	3:10	no	37
Relocation	The horizontal transport of solid matter and sessile organisms from one point to another.	2:3, 8:2, 9:2, 9:11, 10:2, 10:3, 10:4, 10:5, 10:6, 10:12, 11:12	yes	38
Resuspension	The stirring up of previously settled particles in water or air.	2:11, 10:2, 10:12, 11:12	yes	39

Saturation	Water content that affects physical and chemical properties of the regolith	9:2, 15:9	no	40
Radiological and thermal processes				
Decay	The physical transformation of radionuclides to other radionuclides or stable elements.	14:11, 14:13	yes	41
Exposure	The act or condition of being subject to irradiation. Exposure can either be external exposure from sources outside the body or internal exposure from sources inside the body.	14:3, 14:4, 14:5, 14:6, 14:7, 14:8	yes	42
Heat storage	The storage of heat in solids and water.	2:13, 9:13, 10:13, 12:13	yes	43
Irradiation	The process whereby an object is exposed to ionising radiation and absorbs energy.	14:2	no	44
Light related processes	Processes related to the light entering the biosphere (insolation), e.g. absorption, attenuation, reflection and scattering.	2:3, 2:13, 3:13, 4:13, 5:13, 6:13, 7:13, 8:13, 10:13, 10:13, 11:3, 11:13, 12:13, 15:3, 15:13	yes	45
Radiolysis	The disintegration of molecules caused by radionuclide decay.	14:11	no	46
Radionuclide release	Release of radionuclides from the repository for spent nuclear fuel.	1:14, 14:1	yes	47
Landscape development processes				
Change in rock surface location	Changes in the location of the rock surface due to isostatic rebound or repository-induced changes.	1:2, 15:1, 15:2	yes	48
Sea level change	Alteration in the level of the sea relative to the land.	15:10	yes	49
Terrestrialisation	Infilling of a lake or shallow sea basin with mire vegetation.	15:2, 15:10	yes	50
Thresholding	The occurrence and location of thresholds delimits water bodies like lakes and sea basins.	2:9, 2.10, 2.15	yes	51

12.6 Interactions in the ecosystems

Diagonal elements may interact with each other by one or more processes. Some processes occur in many places in the IM. Although a process may be important for dose assessment in the interaction between two diagonal elements, it may be insignificant for the dose assessment in the interaction between two other diagonal elements. The significance for the radionuclide modelling, i.e. determining dose to man, is considered for each interaction at which a process is identified as mediating that interaction. In Figures 12-2 and 12-3, the significant process interactions are coloured dark yellow, whereas insignificant process interactions are coloured light yellow, and irrelevant processes interactions are coloured white. Thus, dark yellow process interactions have to be consider in the radionuclide modelling whereas light yellow process interactions do not have to be considered.

There are a large number of interactions among diagonal elements of the IM that are included in the radionuclide model even though they do not strictly need to be considered. This is because the radionuclide model is based on site-specific data and thereby implicitly includes many of the processes in the matrix, e.g. primary production is measured *in situ* and hence all processes affecting this parameter during present conditions (also those that are believed to have a small effect) are thereby included indirectly.

Below, each box in the IM is described separately to fully illustrate by which processes each diagonal component interacts with the other diagonal elements. Processes whereby diagonal components interact are presented in alphabetical order, i.e. they are not listed by importance in the radionuclide modelling. However, for each interaction, the processes are listed that need to be considered in the radionuclide modelling for each ecosystem (limnic, marine and terrestrial) and how the processes have been included in the radionuclide model or parameterisation of the model. The boxes in the interaction matrix are numbered according to row: column (see Figure 12-2 and 12-3).

1:1 Geosphere is a diagonal element (further described in Section 12.3). The geosphere is situated at the boundary of the biosphere matrix and processes by which the geosphere affects the geosphere are not described in this report. The reader is referred to /SKB 2001, SKB 2006d, SKB 2010f/ for more information on this topic.

1:2 Geosphere affects **regolith** by the processes a) Change in rock surface location and b) Weathering.

a) Change in rock surface location – Change in rock surface location may be caused by e.g. collapse of caverns resulting in cave-in of the surrounding rock. Other examples could be neotectonic movements /Lagerbäck et al. 2005/. This affects the stress conditions in the surrounding rock and may affect the height of the regolith. However, cavern collapse would be greatly attenuated at the surface, and fault throws of more than ~0.1 m are highly unlikely for deep repositories /SKB 2001/. Therefore other processes affecting regolith are more important for the topography and this interaction need not to be considered in the radionuclide modelling.

b) Weathering – Weathering of a solid rock (geosphere) may form regolith. However, weathering of the solid rock has a minor influence on the formation of regolith compared with other regolith formation processes (e.g. peat formation and sedimentation) and, therefore, it does not need to be considered this interaction in the radionuclide modelling.

1:3 There are no processes by which the **Geosphere** affects **primary producers** that are relevant to include in the radionuclide modelling.

1:4 There are no processes whereby the **Geosphere** affects **decomposers** that are relevant to include in the radionuclide modelling.

1:5 There are no processes by which the **Geosphere** affects **filter feeders** that are relevant to include in the radionuclide modelling.

1:6 There are no processes whereby the **Geosphere** affects **herbivores** that are relevant to include in the radionuclide modelling.

1:7 There are no processes by which the **Geosphere** affects **carnivores** that are relevant to include in the radionuclide modelling.

1:8 Geosphere affects **humans** by the process a) Material supply.

a) Material supply – Mineral resources can be used as material by humans and may influence the location of human settlements. However, the modelled area in Forsmark is underlain by granitic rocks and can be described as sterile from an ore viewpoint /Lindroos et al. 2004/. There are no deposits of industrial minerals or commercial stone in the area. An area south of the regional model area has a small ore potential for iron, however the type of ore is of no mining interest and compared with central parts of Bergslagen, the Forsmark area's ore potential is insignificant. Water from the geosphere may influence humans, but this interaction is via water in regolith. Therefore human utilisation of the geosphere is assumed to be small and this interaction does not need to be considered in the radionuclide modelling.

1:9 Geosphere affects **water in regolith** by the process a) Convection.

a) Convection – The hydrology in the geosphere influences the discharge and recharges of groundwater (i.e. convection) and thereby the hydrology in the regolith. Hydrological modelling /Bosson et al. 2010/ suggests that this influence is small and mainly is found along the shoreline or the mire surrounding the lake. Effects of water discharge from the geosphere to the regolith (discussed in Section 3.3.3 of this report and Section 4.3.7 in /Aquilonius 2010/ is acknowledged in the transport calculations in the radionuclide modelling (see interaction 1:14).

1:10 Geosphere affects **surface water** by the process a) Convection.

a) Convection – The hydrology in the geosphere influences the discharge and recharge of groundwater (convection) and thereby the surface water hydrology. However, precipitation and hydrology in the regolith are of more importance for convection of surface water and this interaction does not need to be considered in the radionuclide modelling. Discharge from the geosphere is included in the safety assessment in the transport calculations in the radionuclide modelling (see interaction 1:14).

1:11 Geosphere affects **water composition** by the process a) Convection.

a) Convection – Transport of elements in groundwater may affect the water chemistry in regolith and could be of importance for elements that only occur in the rock and the repository. Surface water chemistry on the other hand, is assumed to be more influenced by other factors. Nevertheless, the effect on water composition from this interaction both in regolith and surface waters is indirectly included in the radionuclide model as water composition measured *in situ* are used in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

1:12 Geosphere affects **gas and local atmosphere** by the process a) Convection.

a) Convection – The transport and release of gas from the geosphere may influence the amount and composition of gas in the biosphere. The transport of gas from the geosphere is normally of little significance in comparison to gas content in e.g. regolith (i.e. elements in gas form entering the gas phase of the regolith would be very diluted in the regolith gas phase). However, gas transports of e.g. H_2, CO_2, CH_4, Rn and SO_2 from a repository may be important and this interaction needs to be considered in the radionuclide modelling. The transport of C-14 is the largest radioactive gas flux within the biosphere and is covered in the interaction 1:14 and included in the radionuclide modelling (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

1:13 Geosphere affects **temperature** by the process a) Convection.

a) Convection – The heat exchange between geosphere and biosphere will affect the temperature in the biosphere. However, the temperature in surface waters and light related processes mainly determine the temperature in the regolith and surface waters. Therefore, the effect of the Geosphere on temperature does not need to be considered in the radionuclide modelling. The exception is during permafrost conditions when this interaction may be of importance (permafrost is considered in supporting calculations in the radionuclide modelling), see the **Biosphere synthesis report**. Although this interaction does not need to be considered in temperate conditions in radionuclide modelling, the effect of the interaction is indirectly included in temperature-dependent parameters, since parameter values are based on site data obtained under prevailing conditions (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

1:14 Geosphere affects **radionuclides** by the process a) Radionuclide release.

a) Radionuclide release – The release of radionuclides in water and gas phases from the geosphere affects the transport of radionuclides in aqueous and gaseous form in the biosphere. This is a significant interaction in the radionuclide modelling and it is included in the radionuclide model (see Chapter 10). (This process is called 'Contaminant transport' in the Geosphere interaction matrix /SKB 2006d/.

1:15 There are no processes by which **geosphere** affects **external conditions** that are relevant to include in the radionuclide modelling.

2:1 Regolith affects **the geosphere** by the processes a) Consolidation, and b) Loading.

a) Consolidation – The transformation of regolith to solid rock is a slow process that implies a gradual reduction in volume and increase in density in response to increased load or compressive stress. This process is affected by the weight of regolith (thickness and density). For the transport of radionuclides in the radionuclide model, the thickness and the density of the regolith is included. However, the likely degree of consolidation would be very limited under present-day conditions and thus this interaction does not need to be considered in the radionuclide modelling.

b) Loading –The thickness of the regolith affects the stress on the geosphere. The depth of regolith is relatively small in the regional model area /Hedenström and Sohlenius 2008/ and should have a minor impact on the mechanical stress on the geosphere and, therefore, this interaction does not need to be consider in the radionuclide modelling.

2:2 Regolith is a diagonal element that is further described in Section 12.3. The regolith affects the regolith by the processes a) Consolidation, and b) Relocation.

a) Consolidation – The transformation of regolith to solid rock is a slow process that implies a gradual reduction in volume and increase in density in response to increased load or compressive stress. This process is affected by the weight of regolith (thickness and density). For the transport of radionuclides in the radionuclide model, the thickness and density of regolith is included. However, the likely degree of consolidation would be very limited under present-day conditions and would have little impact on the amount and characteristics of regolith and thus this interaction does not need to be considered in the radionuclide modelling.

b) Relocation – The inclination and the topography of the land influence the possibility for and the extent of relocation of materials e.g. via resuspension and landslides. However, the low relief in the area suggests that this would be a rare phenomenon and that it does not need to be considered in the radionuclide modelling. However, due to shore-line displacement, the regolith is affected and the topography changes over time. The digital elevation model (DEM) adopted describes changes in topography over time in the regional model area and thus this interaction is considered in the radionuclide modelling (/Brydsten and Strömgren 2010/ and Chapter 10 in /Andersson 2010).

2:3 Regolith affects **primary producers** by the processes a) Element supply, b) Habitat supply, c) Light related processes, and d) Relocation.

a) Element supply – Micro-algae living in the sediments and rooted aquatic vegetation acquire some of their nutrient supply from the regolith. This is also true for terrestrial primary producers. Accordingly, this interaction might constitute a route of transport of radionuclides from regolith to biota and the interaction need to be considered in the radionuclide modelling. Hence, this interaction is included in the radionuclide model through the use of bioconcentration factors (BCF), which describe the relation between elements in the regolith and primary producers (described in /Nordén et al. 2010/).

b) Habitat supply – The regolith is one of several important factors for the settlement of primary producers, as primary producers are often dependent on the substrate (e.g. in aquatic ecosystems hard vs. soft bottoms, in terrestrial ecosystems coarse vs. fine-grained regolith). Habitat distribution differentiating between regolith conditions in aquatic ecosystems is described in Chapter 3 in this report, Chapter 4 in /Aquilonius 2010/ and in Chapter 3 in this report. This interaction needs to be included in the radionuclide modelling, since the occurrence of biota is important for transfer and accumulation of radionuclides. Accordingly, it is included in the radionuclide model as biomass of various organism types (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Light related processes – the topography of the sediments may shade primary producers and thereby influence primary production. This interaction is assumed to be less important than effects of e.g. water depth, transparency, and element supply. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, it is indirectly included in the radionuclide model as the biomass of biota is based on site-specific measurements in which the effect of regolith is included (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

d) Relocation – Relocated regolith may deposit on primary producers and this might affect their production and biomass. Sedimentation is important for the transfer of radionuclides between water and sediment, but the effect of regolith on primary producers is not considered sufficiently important to include in the radionuclide modelling. Nevertheless, the net effect on biomass and primary production is included in the radionuclide modelling as the parameters biomass and net productivity are based on measurements *in situ* under prevailing depositional conditions (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

2:4 Regolith affects **decomposers by** the processes a) Element supply, b) Food supply, and c) Habitat supply.

a) Element supply – Bacteria present within the sediment take up elements directly from the sediment and thereby the regolith supplies elements to decomposers. This may be an important pathway for radionuclide transport from sediments into biota and thus this interaction needs to be considered in the radionuclide modelling. The amount of regolith is specified but not all elements may be available to decomposers. However, this interaction is included in the radionuclide model through the parameter net productivity where decomposers are assumed to utilize elements from, among other sources, the regolith (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Food supply – Regolith can be used as a food source by decomposers. This may be an important pathway for radionuclide transport from sediments into biota and thus this interaction needs to be considered in the radionuclide modelling. Although the amount of available food is not specified (amount of regolith is specified but some regolith may be unavailable for decomposers), this interaction is included in the radionuclide modelling through the parameter net productivity where decomposers are assumed to feed on, among other sources, regolith (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Habitat supply – Regolith is important for the settlement of decomposers as they are often dependent on a certain kind of substrate (hard vs. soft bottoms). Habitat distribution differentiates, in aquatic ecosystems, between hard bottoms and soft bottoms, and in terrestrial ecosystems between coarse and fine-grained regolith. Habitat distributions differentiating between regolith conditions in aquatic and terrestrial ecosystems are described in Chapter 3 in this report, in Chapter 4 in /Aquilonius 2010/ and in Chapter 3 in /Löfgren 2011/. This interaction needs to be included in the radionuclide modelling since occurrence of biota is important for transfer and accumulation of radionuclides and, accordingly, it is included as biomass of biota (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

2:5 Regolith affects **filter feeders** by the process a) Habitat supply.

a) Habitat supply –Filter feeders occur only in aquatic ecosystems. Regolith is important for the settlement of filter feeders as they are often dependent on the substrate. Thus, some species (e.g. in limnic ecosystems *Dreissena polymorpha* and in marine ecosystems *Mytilus edulis*) thrive on hard bottoms (i.e. geosphere) and others (e.g. in limnic ecosystems *Anodonta anatine* and in marine *Macoma baltica*) thrive on soft bottoms (i.e. regolith). The habitat distribution differs between hard bottoms and soft bottoms in aquatic ecosystems, and is, for marine ecosystems described in Section 4 in /Aquilonius 2010/, and for limnic ecosystems in Section 3.7.4 in this report. Hence, for aquatic ecosystems this interaction needs to be included in the radionuclide modelling, since the occurrence of biota is important for transfer and accumulation of radionuclides. Accordingly, this interaction is included as biomass of biota in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

2:6 Regolith affects **herbivores** by the process a) Habitat supply.

a) Habitat supply – The settlement of herbivores is mainly determined by the availability of primary producers and, therefore, the effect of regolith on the settlement of herbivores does not need to be considered in the radionuclide modelling. Nevertheless, it is indirectly included in the radionuclide model as biomass of biota based on site-specific measurements, in which the effect of regolith is included (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

2:7 Regolith affects **carnivores** by the process a) Habitat supply.

a) Habitat supply – Regolith is not directly important for carnivores, as they are not as dependent on substrate as on the availability of food. Nevertheless, it is indirectly included in the radionuclide model as biomass of biota based on site-specific measurements, in which the effect of regolith is included (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

2:8 Regolith affects **humans** by the processes a) Food supply, b) Habitat supply, and c) Material supply.

a) Food supply – Regolith may be consumed accidentally with food or on purpose, e.g. by children. The accidental incorporation needs to be considered in the radionuclide modelling and, accordingly, the amount accidentally incorporated together with food is included in the radionuclide model /Nordén et al. 2010/. The intake on purpose does not need to be considered in the radionuclide modelling as LDF calculations are based on grown up individuals and these do not eat regolith.

b) Habitat supply – Human settlement is mainly determined by the area, soil type, and the type of ecosystem. The last determines the amount of available food and this interaction needs to be considered in the radionuclide modelling. Accordingly, the area of biosphere objects with which groups of humans are associated, is included in the radionuclide model (see /Brydsten and Strömgren 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Material supply – Humans may use regolith as material supply e.g. sand in concrete for buildings or peat used for generating heat. However, the terrestrial ecosystem considered in the radionuclide modelling is a mire or a drained mire (see this report and Chapter 10 in /Andersson 2010) and peat and/or regolith from aquatic ecosystems is not usually used as material supply for buildings. Moreover, postglacial sand and other types of building material would be taken from other less contaminated areas than from peat covered low-laying areas that are in need of drainage before further utilisation. In earlier safety assessments the contribution to dose from the use of peat as fuel does not alter the resulting doses in radionuclide model /Avila et al. 2010/. Therefore, this interaction does not need to be considered in the radionuclide modelling.

2:9 Regolith affects **water in regolith** by the processes a) Convection, and b) Thresholding.

a) Convection – The magnitude and distribution of the water flow in the regolith is influenced by the hydraulic conductivity and storage capacity (porosity) of the regolith. This is an important process to consider in the radionuclide modelling. Accordingly, the depth and properties (Kd, density, porosity) of regolith (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report, Chapter 11 in this report, and /Nordén et al. 2010/) together with water transport in the regolith /Bosson et al. 2010/ are included in the radionuclide modelling.

b) Thresholding – The regolith determines the location of thresholds and thereby influences the water in regolith. Thresholds are important for the development of the landscape and this interaction needs to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model through the succession from sea to lake to land in the Digital Elevation Model (DEM) together with sedimentation models /Brydsten and Strömgren 2010/.

2:10 Regolith affects **surface water** by the processes a) Acceleration, b) Convection, and c) Thresholding.

a) Acceleration – In aquatic ecosystems the bottom topography determines the water depth and influences thereby the height of the waves. In addition, the fetch (the distance over which the blowing wind is not disturbed) influences wave formation e.g. sheltered areas occuring behind islands. Water depth is important for transport and accumulation of radionuclides and thus it needs to be considered in the radionuclide modelling. Therefore this interaction is considered in the radionuclide model where water depth is included in the calculation of parameter values (Chapter 10 in /Aquilonius 2010/, Chapters 10 and 11 in /Andersson 2010/, and /Brydsten and Strömgren 2010/).

b) Convection – Regolith affects surface water by upward transport of water and by influencing wave formation. Water transport is important for transport of radionuclides and wave formation is important for the advective flow and residence time of sea water. Thus, this interaction needs to be considered in the radionuclide modelling. Water transport from the regolith to surface water is included in the hydrological models /Bosson et al. 2010/ that are used to derive input parameter values for the radionuclide model (Chapter 10). Wave formation is considered by using the Digital Elevation Model (DEM), which supplies all the geometric measures (the bottom topography) and the models for sedimentation /Brydsten and Strömgren 2010/.

c) Thresholding – Thresholding includes all processes that affect the occurrence and location of thresholds that delimit water bodies in height. Thresholds are important for the development of the landscape and this interaction needs to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model through the succession from sea to lake to land in the Digital Elevation Model (DEM) together with sedimentation models (see /Brydsten and Strömgren 2010/ and Chapter 10 in /Andersson 2010/).

2:11 Regolith affects **water composition** by the processes a) Phase transitions, b) Reactions c) Resuspension, and d) Sorption/desorption.

a) Phase transitions – Regolith may affect water composition by leaching (in which minerals attached to solids are solubilised from the regolith and released to the water). The location of and chemical composition of the regolith and the mineralogy of rock surfaces thereby influence the chemical composition of the water. The rate of leaching of non-radioactive elements is not important for the radionuclide modelling but the net result, i.e. concentrations of elements in the water, may be of importance. However, other factors are assumed to be of greater importance for water chemistry and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of the interaction is indirectly included since water chemistry measured *in situ* is used in the calculations of parameters in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Reactions – Elements in the regolith may be altered due to chemical reactions such as redox changes (oxidation) and elements may thereby be released to the water and influence the water composition. Other factors are assumed to have greater influence on the water chemistry and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of this interaction is indirectly included since water chemistry measured *in situ* is used in the calculations of parameters in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Resuspension – The size distribution of the particles in the regolith influences the amount of material resuspended in the water and thereby the content of particulate matter in the water (further described in Sections 3.6 and 3.9 for limnic ecosystems and in Chapter 3 in /Aquilonius 2010/ for marine ecosystems. Resuspension is an important route of transfer from sediments to water and needs to be considered in the radionuclide modelling. Accordingly, it is included as a parameter in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

d) Sorption/desorption – The composition and grain size (available surfaces for sorption) of the regolith will affect the extent of sorption of dissolved elements and particulates and thus the composition of the water in the regolith. The rate of sorption of non-radioactive elements is not important for the transport and accumulation of radionuclides but the net result, i.e. concentrations of elements in the water, may be of importance. However, sorption and desorption is assumed to be in equilibrium and reflected in present water chemistry. Nevertheless, the effect of this interaction is included in the radionuclide modelling by the use of water chemistry data measured *in situ* when calculating parameters in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

2:12 Regolith affects **gas and local atmosphere** by the process a) Reactions.

Reactions – Elements in the regolith may react with elements in the gas phase in the regolith. The amounts of gases in regolith in aquatic and terrestrial systems are most often small and are not considered to be severely affected by elements in the regolith, and therefore the transport and accumulation of radionuclides are not significantly influenced. This interaction therefore does not need to considered in the radionuclide modelling.

2:13 Regolith affects **temperature** by the processes a) Convection, b) Heat storage c) Light related processes and d) Pressure change.

a) Convection – The composition and the grain size of regolith affects the heat transport (conduction) in the regolith and thereby influences the temperature in the different parts of the biosphere system. Other factors (e.g. heat storage of surface water) are assumed to have a greater influence on temperature and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of this interaction is indirectly included since temperature statistics measured *in situ* are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Heat storage – The density and thermal properties of the regolith determine the amount of heat that can be stored in a given volume of regolith per unit of temperature change. The heat storage of water is of greater importance for the temperature in aquatic ecosystems and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of this interaction is indirectly included since temperature statistics measured *in situ* are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Light related processes – The reflection properties of the regolith influence the amount of sunlight absorbed and thereby the temperature in the regolith in terrestrial areas. In aquatic ecosystems, regolith is always covered with water and the major part of the adsorption take place in the water column and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of this interaction is indirectly included both in terrestrial and aquatic ecosystems since temperature statistics measured *in situ* are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

d) Pressure change – in terrestrial ecosystems the topography of the regolith affects the pressure which may lead to heating or cooling, so called adiabatic temperature changes. However, the model area that is affected by a release of radionuclides will always be a coastal site and will not be associated with any large changes in topography (as would be the case in e.g. mountain areas) and therefore this interaction does not need to be included in the radionuclide modelling of any ecosystem.

2:14 Regolith affects **radionuclides** by the processes a) Phase transitions and b) Sorption/desorption.

a) Phase transitions – The regolith may affect the concentration of dissolved radionuclides by dissolution to the gas phase of natural radionuclides included in minerals in the regolith. In comparison with sorption and desorption this process involves very small amounts of radionuclides, and the main focus of the safety assessment is the repository induced radionuclides and this interaction does not need to be considered in the radionuclide modelling.

b) Sorption/desorption – The composition and grain size (available surfaces for sorption) of the regolith will affect the extent of sorption of radionuclides and thereby the distribution of radionuclides between regolith and water. The degree of sorption of radioactive elements is important for transport and accumulation of radionuclides and thus needs to be considered in the radionuclide modelling. Accordingly, it is included as radionuclide specific Kd values used in the radionuclide model (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

2:15 Regolith affects **external conditions** by the processes a) Export, and b) Thresholding.

a) Export – The main exports of material from the aquatic systems are export of water and particles, whereas export of regolith is minor. Thus, the effect on the receiving ecosystem (i.e. external conditions) should, in contrast, in most cases be small and this interaction does not need to be considered in the radionuclide modelling.

b) Thresholding – Regolith determines the location of thresholds and thresholds influence the external conditions as they determine the functioning of the landscapes (lakes, land, and wetlands). Thresholds are important for the development of the landscape and this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model through the succession from sea to lake to land in the Digital Elevation Model (DEM) together with sedimentation models (/Brydsten and Strömgren 2010/ and Chapter 10 in /Andersson 2010/).

3:1 Primary producers affect **geosphere** by the process a) Intrusion.

a) Intrusion – Hypothetically roots may penetrate into fractures in the solid rock and into the plugged and backfilled access tunnels. This could in turn affect rock structures, hydraulic conductivity, potential for erosion, physical and mechanical properties of the tunnels, and amounts of biological material. In the aquatic systems in Forsmark there are few rooted species, but chemotropic primary producers may be present in backfills and boreholes. However, these are assumed to only be present within the geosphere and do not need to be considered in the radionuclide modelling. The root penetration depth of the terrestrial vegetation will generally be restricted to the upper 0.5 m, where the majority of roots are found. Deeper roots may be found, mainly in dry habitats such as pine forests on bedrock, but will not penetrate deep enough to affect the backfilled access tunnels. Therefore this interaction does not need to be considered in the radionuclide modelling.

3:2 Primary producers affect **regolith** by the processes a) Bioturbation, and b) Death.

a) Bioturbation – Micro-primary producers are present within the regolith and may influence the composition of the regolith, e.g. by influencing oxygen concentrations. Bioturbation by root production in aquatic ecosystems is of minor importance since there are few rooted species in aquatic ecosystems in Forsmark. However, in the terrestrial ecosystems this interaction may be important. The composition of regolith is important for transport and accumulation of radionuclides and this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is considered since composition of the regolith and depth of the oxygenated layer measured *in situ* are used in the parameterisation of the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Death – Primary producers affect the amount of dead organic matter in the regolith of the ecosystems when dying and by litter fall. This flux of organic matter may be important for the redistribution of radionuclides in ecosystems and needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production for the aquatic ecosystems in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

3:3 Primary producers is a diagonal element further described in Section 12.3. Primary producers affect other primary producers by the processes a) Primary production, b) Habitat supply, and c) Stimulation/inhibition.

a) Primary production – Primary production is the fixation of carbon by primary producers mediated by photosynthesis. This is an important process that generates biomass which is fundamental for the existence of the diagonal element primary producers. Primary production is important for the incorporation of radionuclides (especially C-14) into biota and this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as net primary production of biota (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Habitat supply – In aquatic ecosystems macrophytes are often colonised by epiphytic algae. The biomass of epiphytic flora on terrestrial vegetation is small in relation to biomass of the non-epiphytic vegetation. This interaction does not directly influence the transport of radionuclides in ecosystems and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production are included in the parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Stimulation/inhibition – Primary producers may stimulate each other e.g. by sexual reproduction or inhibit each other by e.g. resource competition. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

3:4 Primary producers affect **decomposers** by the processes a) Habitat supply, and b) Stimulation/inhibition.

a) Habitat supply – Macrophytes are often colonised by epiphytic bacteria. Primary producers may affect the decomposers by the quality of the litter. These interactions are considered to be of relatively low importance to the transport of radionuclides in the ecosystems and therefore do not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance, production and decomposition, are included in the parameter calculations for the radionuclide model (Chapter 9 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Stimulation/inhibition – Primary producers may stimulate decomposers by e.g. providing a substrate for epiphytic bacteria or they may inhibit decomposers by competition for resources e.g. phytoplankton and bacterioplankton competing for dissolved nitrogen and phosphorus.

This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in the parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

3:5 Primary producers affect **filter feeders** in aquatic ecosystems by the processes a) Food supply, b) Habitat supply, and c) Stimulation/inhibition. This interaction is not applicable in terrestrial ecosystems since filter feeders are lacking there.

a) Food supply – Primary producers function as food for filter feeders (e.g. the consumption of phytoplankton). This may be an important transfer pathway for radionuclides and the interaction need to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic communities (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Habitat supply – Macrophytes can be colonised by filtering species of hydrozoans or small mussels. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Stimulation/inhibition – Primary producers may inhibit filter feeders by e.g. space competition or toxin production. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

3:6 Primary producers affect **herbivores** by the processes a) Food supply, b) Habitat supply, and c) Stimulation/inhibition.

a) Food supply – Primary producers function as food for herbivores. This may be an important transfer pathway for radionuclides and the interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic communities (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Habitat supply – Primary producers may be colonised by e.g. herbivorous snails. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Stimulation/inhibition – Primary producers may stimulate herbivores by e.g. providing substrate and a food source of specifix quality and palatability. Primary producers may inhibit herbivores by e.g. toxin production. This interaction does not influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

3:7 Primary producers affect **carnivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Primary producers may stimulate carnivores by e.g. providing sheltered areas for reproduction. Primary producers may inhibit carnivores by e.g. toxin production. This interaction does not influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the safety radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

3:8 Primary producers affect **humans** by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply – Humans may consume primary producers as a food source and therefore the primary production that may be used as food by humans needs to be considered in the radionuclide modelling. However, in Sweden today, very few (if any) limnic primary producers are used as food and the food supply is set to zero for aquatic ecosystems in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Material supply – There are no primary producers in the aquatic ecosystems in Forsmark today that it is realistic to consider as being utilised as a material supply and therefore this interaction does not need to be considered in the radionuclide modelling. In the terrestrial ecosystem, reed belts in wetlands surrounding lakes may be used in thatching. However, even if thatching occurs, the effect on exposure to humans will be small and this interaction does not need to be considered in the radionuclide modelling for any ecosystem.

c) Stimulation/inhibition – Primary producers may affect humans e.g. toxic algal blooms in aquatic ecosystems. However, inhibition of humans would lead to less utilisation of the ecosystem and thereby less risk of exposure to potential radionuclides. In contrast, stimulation would lead to increasing utilisation by humans. However, as a cautious assumption, maximum utilisation of the ecosystem is assumed in the safety assessment and hence this interaction does not need to be considered in the radionuclide modelling.

3:9 Primary producers affect **water in regolith** by the processes a) Excretion, and b) Uptake.

a) Excretion – Microphytobenthos in aquatic ecosystems and rooted plants living in the regolith in ecosystems may excrete water into the regolith. However, the effect of the excretion of water by primary producers on the amount of water in regolith in the ecosystems is minimal, since the excretion of water is very small compared to the water volume in the regolith. Thus, this interaction does not need to be considered in the radionuclide modelling.

b) Uptake – In aquatic ecosystems most primary producers take up water directly from surface water and the effect of the uptake of water by primary producers is minimal in comparison to the water volume in the regolith. Plant uptake of water can significantly affect water in regolith in terrestrial ecosystems in general and the effect is considered in hydrological modelling. In the other terrestrial ecosystem modelled in the radionuclide model (i.e. agricultural land) irrigation takes place, so also there, regolith are assumed to be unaffected by plant uptake. Hence, this interaction does not need to be considered in the radionuclide modelling.

3:10 Primary producers affect **surface waters** by the processes a) Acceleration, b) Covering, c) Excretion, d) Interception, and e) Uptake.

a) Acceleration – The type and amount of primary producers influence the movement of water, e.g. by overgrowing of a narrow sound or algae in surface water. Other factors influencing water movements are probably more important than the reduction of velocities due to primary producers and this interaction does not need to be considered in the radionuclide modelling.

b) Covering – The covering by biota in aquatic ecosystems is small since most primary producers are submerged and this interaction therefore does not need to be considered in the radionuclide modelling. Also in terrestrial ecosystems this interactions is assumed to be of minor importance.

c) Excretion – The effect of excretion by primary producers on surface waters in aquatic ecosystems is minimal, since the excretion of water is very small compared to the water volume of the aquatic system. Thus, this interaction does not need to be considered in the radionuclide modelling. Also in terrestrial ecosystems this interactions is assumed to be of minor importance.

d) Interception – Interception is the amount of precipitation that does not reach the ground but is retained on vegetation. In the aquatic ecosystems in the regional model area, most biota is submerged and therefore interception does not need to be consider in the radionuclide modelling. In terrestrial ecosystems interception may affect the runoff and this is considered in hydrological models.

e) Uptake –The effect of uptake by primary producers on surface waters in aquatic ecosystems is minimal, since the uptake of water is very small compared to the water volume of the aquatic system. Thus, this interaction does not need to be considered in the radionuclide modelling.

3:11 Primary producers affect **water composition** by the processes a) Death, b) Excretion, c) Particle release/trapping, and d) Uptake.

a) Death – Primary producers affect the amount of dead organic matter in surface water of ecosystems mainly due to death, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. This flux may be important for the redistribution of radionuclides in the ecosystem and needs to be considered in the radionuclide modelling. Death is included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Excretion – Excretion of elements by primary producers may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect if this interaction is included in the calculation of parameter values for the radionuclide model, by the use of *in situ* measured water composition (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces. Primary producers in terrestrial areas release large amounts of particles by pollen release, but this interaction goes via gas and local atmosphere (see below). In aquatic ecosystems, macrophytes may also release particles although most probably in smaller quantities. Particles may be attached to macrophytes in aquatic ecosystems however this is most likely of minor significance compared to particle trapping by e.g. filter feeders (5:5) and this interaction does not need to be consideredfor aquatic ecosystems in the radionuclide model. Nevertheless, the effect on water composition of particle release and trapping by primary producers is included in the radionuclide model as concentrations of particles that are measured *in situ* (thereby including the effect of this interaction (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

d) Uptake – Uptake by primary producers may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is included by the use of *in situ* measured water composition in the calculation of parameter values for the radionuclide model, (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

3:12 Primary producers affect **gas and local atmosphere** by the processes a) Acceleration, b) Excretion, c) Particle release/trapping, and d) Uptake.

a) Acceleration – The type, amount and location of primary producers determine the degree of sheltering and influence thereby wind directions and velocities. However, the turbulence and changing wind direction are more variable than the physical obstruction by vegetation, especially in aquatic systems with few emergent species. Therefore, this interaction does not need to be considered in the radionuclide modelling.

b) Excretion – Primary producers affect the gas and local atmosphere by excreting oxygen during photosynthesis. Terrestrial primary producers have a direct impact on the gas content in the local atmosphere. In aquatic ecosystems the excretion of gas to the water volume may influence the amounts of gas in surface water and thereby transport of gases across the air-water interface. Accordingly, this interaction needs to be considered in the radionuclide modelling. Therefore, the excretion of gases by primary producers is included in the calculation of the parameters concerning gas uptake and release and primary production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Particle release/trapping – Particle release and trapping to and from the atmosphere is small from aquatic ecosystems. Emergent macrophytes can spread particles with wind but most macrophytes in the aquatic ecosystems at Forsmark are submerged. In terrestrial ecosystems this interaction may be frequent, although the importance for transfer and accumulation of radionuclides is considered as minor. Therefore this interaction does not need to be considered in the radionuclide modelling.

d) Uptake – Primary producers may take up carbon dioxide and other elements (e.g. iodine) and release oxygen in terrestrial and aquatic ecosystems. In aquatic ecosystems the uptake of gas from the water volume may influence the amounts of gas in surface water and thereby transport of gases across the air-water interface. Accordingly, this interaction needs to be considered in the radionuclide modelling. The uptake of gases by primary producers is included in the calculation of the parameters concerning gas uptake and release and primary production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

3:13 Primary producers affect **temperature** by the processes a) Convection, b) Light related processes, and c) Reactions.

a) Convection – Vegetation can act as an insulator between the atmosphere and underlying water or regolith and thereby affect the transport of heat in the biosphere. In the aquatic ecosystems at Forsmark, the abundance of emergent macrophytes is low, but in the terrestrial ecosystems the vegetation may have an insulating effect. Other factors (e.g. heat storage of surface water) are assumed to have a greater influence on temperature. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, it is indirectly included since temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Light related processes – The type, amount and location of primary producers determine the degree of adsorption and reflection of radiation and influence thereby the temperature in the biosphere. The radiation absorption by biota in aquatic ecosystems will be very small compared with the radiation absorption by the water body and this interaction does not need to be considered in the radionuclide modelling. Terrestrial vegetation does affect the temperature significantly and the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction), which are used for calculations of parameter values applied in the radionuclide model (Chapter 9 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of vegetation in aquatic ecosystems is limited compared with the heat absorption by the water body and therefore this interaction does not need to be considered in the radionuclide modelling. This effect is also assumed to be of insignificant importance in terrestrial ecosystems. Nevertheless it is indirectly included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (Chapter 9 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

3:14 Primary producers affect **radionuclides** by the processes a) Excretion, b) Growth, Sorption/desorption, and d) Uptake.

a) Excretion – The excretion of radionuclides by primary producers affects the concentration of radionuclides in primary producers as well as in other components of the biosphere and this interaction needs to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model as bio-concentration factors (BCF) (see /Nordén et al. 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Growth – Growth can potentially lower the concentration of radionuclides in primary producers due to dilution of radionuclides in biomass and need to be considered in the radionuclide modelling. This is included in the radionucide modelling by the use of empirically derived concentration ratios which takes into account the effect of growth at present condition (see /Nordén et al. 2010/ for descirpiton of CR).

c) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, sorption and desorption are included in the radionuclide model as bio-concentration factors (BCF) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

d) Uptake – The uptake of radionuclides by primary producers affects the concentration of radionuclides in primary producers as well as in other components of the biosphere and this interaction needs to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model as bio-concentration factors (BCF) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

3:15 Primary producers affect **external conditions** by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem the biota leave, since the exporting biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem (i.e. external conditions) should, in contrast, in most cases be smaller (due to dilution in downstream aquatic objects). Supporting calculations has been performed to confirm this for the Forsmark area and this interaction does not need to be further considered in the radionuclide modelling. However, since it is important for the exporting system, the export of primary producers is included in the export of particulate matter in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

4:1 Decomposers affect **geosphere** by the process a) Intrusion.

a) Intrusion – Macro-decomposers can only enter the repository in the geosphere if the passage is open to the repository (which is not assumed in the base case /SKB 2011/ and even then, it is unlikely that the macro-decomposers would thrive at a depth of 500 m. Micro-decomposers, on the other hand, are assumed to exist in the repository and are important to consider in the safety assessment for the geosphere. Accordingly, this interaction is treated as microbial interactions in the geosphere model, see /SKB 2010f/.

4:2 Decomposers affect **regolith by** the processes a) Bioturbation, b) Consumption, c) Death, and d) Decomposition.

a) Bioturbation – Decomposers affect the regolith in ecosystems by bioturbation (by e.g. worms). Bioturbation affects the physical properties and the chemical composition of the upper regolith which may be important for the transport of radionuclides and thus needs to be considered in the radionuclide modelling. Bioturbation is included in the radionuclide model as the depth of the upper oxygenated layer that has been investigated *in situ* (thereby including the effects of this interaction) (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Consumption – Decomposers may consume large quantities of organic compounds in the regolith and thereby affect the composition of the regolith. This interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Death – Decomposers affect the amount of dead organic matter in the regolith of ecosystems mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and this interaction needs to be considered in the radionuclide modelling. Accordingly, in ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

d) Decomposition – The type and efficiency of decomposers affects the content and quality of organic material in the regolith and this interaction needs to be considered in the radionuclide modelling. For the terrestrial ecosystem, decomposition in the mire is included in the radionuclide model as a parameter describing the long-term decomposition of organic material. In the aquatic ecosystems, decomposition is included in the radionuclide model through net productivity, i.e. the decomposition is subtracted from the gross production and only the net productivity of the system is used (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

4:3 Decomposers affect **primary producers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Decomposers may inhibit primary producers by e.g. resource competition whereas they stimulate primary producers mainly indirectly by influencing water composition and regolith characteristics in aquatic ecosystems. In terrestrial ecoststems effects from fungus biodiversity that increases mineralisation and presence of myccorrhizal species can both directly affect primary production. However, this interaction is less studied in wetlands.

This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

4:4 Decomposers affect **decomposers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Decomposers may stimulate each other by e.g. mating and they may inhibit each other by e.g. resource and space competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

4:5 Decomposers affect **filter feeders** in the aquatic ecosystems by the processes a) Food supply, and b) Stimulation/inhibition. This interaction is not applicable in terrestrial ecosystems since filter feeders are lacking there.

a) Food supply – Decomposers may function as a food source for filter feeders (e.g. filtering of pelagic bacteria). This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as net productivity of the biotic community (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Stimulation/inhibition – Decomposers may stimulate filter feeders by e.g. providing food of different quality. Decomposers may inhibit filter feeders by e.g. competition for substrate and resources. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

4:6 Decomposers affect **herbivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Decomposers may inhibit herbivores by e.g. substrate competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

4:7 Decomposers affect **carnivores** by the processes a) Food supply, and b) Stimulation/inhibition.

a) Food supply – Decomposers may function as a food source for carnivores (e.g. consumption of macro-decomposers, bacteria and fungi). This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Stimulation/inhibition – Decomposers may stimulate carnivores by e.g. providing food of different quality or they may inhibit carnivores by e.g. competition for space. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

4:8 Decomposers affect **humans** by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply – Decomposers, e.g. fungi and crayfish (that are omnivorous and thus a mix of decomposers, herbivores and carnivores), may function as a food source for humans and therefore this interaction needs to be considered in the radionuclide modelling. Accordingly consumption of crayfish is included in the radionuclide model (see Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Material supply – Material use of decomposers by humans is small and the supply of decomposers for human utilisation does not need to be considered in the radionuclide modelling.

c) Stimulation/inhibition – There are no decomposers that are likely to stimulate or inhibit human utilisation of the environment and therefore this interaction does not need to be considered in the radionuclide modelling.

4:9 Decomposers affect **water in regolith** by the processes a) Decomposition, b) Excretion and c) Uptake.

a) Decomposition – The type and efficiency of decomposers may influence the water content in the regolith as decomposers release water from pores and cells. The effect of decomposition on the amount of water in regolith in aquatic and mire ecosystems is minimal, since the release of water is very small compared to the water volume. Thus, this interaction does not need to be considered in the radionuclide modelling.

b) Excretion – Decomposers (e.g. bacteria) living in the regolith excrete water into the regolith. The effect of the excretion of water by decomposers on the amount of water in regolith in aquatic and mire ecosystems is minimal, since the excretion of water is very small compared to the water volume. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Uptake – Decomposers (e.g. bacteria) living in the regolith take up water from the regolith. The effect of the uptake of water by decomposers on the amount of water in regolith in aquatic and mire ecosystems is minimal, since the uptake of water is very small compared to the water volume. Thus, this interaction does not need to be considered in the radionuclide modelling.

4:10 Decomposers affect **surface water** by the processes a) Acceleration, b) Decomposition, c) Excretion, d) Movement, and e) Uptake.

a) Acceleration – The type and amount of decomposers attached to any surface may influence the properties of the surface and thereby water movement. Other forcing factors will have a much larger effect on surface water movement than decomposers and this interaction does not need to be considered in the radionuclide modelling.

b) Decomposition – Decomposers release water during decomposition, but the effect on surface waters is insignificant considering the large water volumes in aquatic ecosystems, and the effect of this interaction on temporarily occurring surface waters in terrestrial ecosystems is minimal for the same reason, therefore this interaction does not need to be considered in the radionuclide modelling.

c) Excretion – The excretion of water by decomposers is very small compared to the water volume of the aquatic system and to the water volume found below the surface of e.g. a mire, hence the effect on surface water is insignificant. Therefore, this interaction does not need to be considered in the radionuclide modelling.

d) Movement – The movement of organisms in surface waters may have an influence on the surface water movement. However, aquatic decomposers are relatively small and will most likely not affect a water body such as a sea/lake or a temporarily occurring surface water body during flooding or heavy rainfall. Moreover, the water is assumed to be homogenously mixed so this interaction does not need to be considered in the radionuclide modelling.

e) Uptake – The uptake of water by decomposers is very small compared to the water volume of the aquatic system and to temporarily occurring surface waters in terrestrial ecosystems. Hence, the effect on surface water due to uptake by decomposers is insignificant and does not need to be considered in the radionuclide modelling.

4:11 Decomposers affect **water composition** by the processes a) Consumption, b) Death, c) Decomposition, d) Excretion, f) Particle release/trapping, and g) Uptake.

a) Consumption – Decomposers may consume large quantities of organic compounds in water and thereby affect the water composition and also the transport and accumulation of radionuclides. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community where secondary production of decomposers is included. In addition, water composition, which is measured *in situ* (thereby including the effect of consumption), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Death – Decomposers affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Decomposition – Decomposers may influence the water composition by altering the structure of organic compounds. This may influence the transport and accumulation of radionuclides and this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model and thereby this interaction is indirectly included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

d) Excretion – Excretion by decomposers may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

e) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces and thus this interaction needs to be considered in the radionuclide modelling. The effect on water composition of particle release and trapping by decomposers is included in the radionuclide model as concentrations of particles that are measured *in situ* (thereby including the effect of this interaction) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

f) Uptake – Uptake by decomposers may be important for the transport and accumulation of radionuclides as it affects chemical parameters such as pH and concentration of oxygen. Therefor this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

4:12 Decomposers affect **gas and local atmosphere** by the processes a) Excretion, and b) Uptake.

a) Excretion – Decomposers excrete gases, mainly carbon dioxide and methane, and thereby influence the gas fraction in water and regolith. As an example, large amounts of methane gases have been found in sediments of lakes and shallow bays during site investigations in Forsmark /Borgiel 2004a/, and a large proportion of this gas is likely the result of decomposing organic regolith /Karlsson and Nilsson 2007/. Carbon dioxide is quantitatively the most important gas entering the atmosphere and this interaction is included in the calculation of transport and accumulation of C-14 in the radionuclide model (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Uptake – Elements present in gas bubbles in water may be taken up by decomposers, i.e. methanotrophs. However, the uptake from gas bubbles should be minor compared to uptake from water and this process does not need to be considered in the radionuclide modelling.

4:13 Decomposers affect **temperature** by the processes a) Convection, b) Light related processes, and c) Reactions.

a) Convection – Organisms can act as an insulator between atmosphere and underlying water and thereby affect the transport of heat in the biosphere. However, the density of decomposers is small and other factors (e.g. heat storage of surface water will have greater impact on temperature in the ecosystems. Thus this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Light related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will be very small compared to the radiation absorption by the other components, e.g. water bodies and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of decomposers is limited compared with the heat absorption by e.g. the water bodies and therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

4:14 Decomposers affect **radionuclides** by the processes a) Excretion, b) Growth, c) Sorption/desorption, and d) Uptake.

a) Excretion – The excretion of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, excretion is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

b) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in the radionuclide modelling. This is included in the radionucide modelling by the use of empirically derived concentration ratios which takes into account the effect of growth at present condition (see /Nordén et al. 2010/ for descirpiton of CR).

c) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore need to be considered in the radionuclide modelling. Accordingly, sorption and desorption are included in the radionuclide model by using element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

d) Uptake – The uptake of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, uptake is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

4:15 Decomposers affect **external conditions** by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem the biota leave since the exported biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream objects) and this interaction does not need to be considered in the radionuclide modelling. However, since important for the exporting system, the export of decomposers is included in the export of particulate matter (including both abiotic and biotic particles) in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

Since filter feeders only are present in aquatic ecosystems the following interactions, 5:1–5:15, is only valid for aquatic ecosystems and does not treat interactions in terrestrial ecosystems.

5:1 Filter feeders affect **geosphere** in aquatic ecosystems by the process a) Intrusion.

a) Intrusion – Filter feeders normally penetrate at most a few decimetres through a sediment surface and it is highly unlikely that they would intrude to repository depth of 500 metres even if the passage was open (which is not assumed in the base case). Therefore, this interaction does not need to be considered in the radionuclide modelling.

5:2 Filter feeders affect **regolith** in aquatic ecosystems by the processes a) Bioturbation, and b) Death.

a) Bioturbation – Filter feeders (e.g. bivalves) may affect the regolith by bioturbation which may alter the physical properties and chemical composition of the upper regolith. In the aquatic ecosystem at Forsmark, the filter feeders are scattered in space and their effect on the regolith is relatively small. Therefore, this interaction does not need to be considered in the radionuclide modelling. However, bioturbation by other organisms may be important and the depth of the upper oxygenated sediment layer is included as a parameter in the radionuclide model. Since the depth of the upper oxygenated layer has been investigated *in situ* (thereby including the effects of filter feeders) this interaction is indirectly included in the radionuclide model (Chapter 10 in /Aquilonius 2010/and Chapters 10 and 11 in /Andersson 2010/).

b) Death – Filter feeders affect the amount of dead organic matter in the regolith in aquatic ecosystems mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

5:3 Filter feeders affect **primary producers** in aquatic ecosystems by the processes
a) Consumption, b) Habitat supply, and c) Stimulation/inhibition.

a) Consumption – Filter feeders may consume large quantities of primary producers (e.g. bivalves filtering phytoplankton). This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

b) Habitat supply – Filter feeders may provide a substrate for epiphytic algae. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effect of the interaction, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

c) Stimulation/inhibition – Filter feeders may inhibit primary producers by e.g. competition for space. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effect of the interaction, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

5:4 Filter feeders affect **decomposers** in aquatic ecosystems by the processes a) Consumption, b) Habitat supply, and c) Stimulation/inhibition.

a) Consumption – Filter feeders may consume large quantities of decomposers (e.g. bivalves filtering pelagic bacteria). This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model through the representation of net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

b) Habitat supply – Filter feeders may provide a substrate for epiphytic bacteria. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effect of the interaction, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

c) Stimulation/inhibition – Filter feeders may inhibit decomposers by e.g. competition for resources and substrate. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effect of the interaction, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

5:5 Filter feeders affect **filter feeders** in aquatic ecosystems by the processes a) Consumption, b) Food supply, and c) Stimulation/inhibition.

a) Consumption – Larval filter feeders may be consumed by other filter feeders. However, the consumption of filter feeders is small compared to the consumption of other organisms and particles. Therefore this interaction does not need to be considereded in the radionuclide modelling. Nevertheless, the effect of this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

b) Food supply – Filter feeders are available as food source for other filter feeders as they may consume each other's larval stages. However, the consumption of filter feeders is small compared to the consumption of other organisms and particles. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect of this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

c) Stimulation/inhibition – Filter feeders may stimulate each other e.g. by mating. Filter feeders may inhibit each other by e.g. competition for resources. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on filter feeders, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

5:6 Filter feeders affect **herbivores** in aquatic ecosystems by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Most herbivores are too large to be consumed by filter feeders (with the exception of some zooplankton) and filter feeders consumption of herbivores is probably of minor importance for the transport of radionuclides. Thus, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

b) Stimulation/inhibition – Filter feeders may potentially stimulate herbivores by e.g. food selection of some species that stimulate other species. Filter feeders may inhibit herbivores, e.g. by competition for substrate. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of the interaction, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

5:7 Filter feeders affect **carnivores** in aquatic ecosystems by the processes a) Consumption, b) Food supply, and c) Stimulation/inhibition.

a) Consumption – Carnivores (except for some larvae) are most likely too large to be consumed by filter feeders and this interaction is probably of minor importance for radionuclide transport.

Thus, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

b) Food supply – Filter feeders may function as a food source for carnivores. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, in this report). and Chapters 10 and 11 in /Andersson 2010/).

c) Stimulation/inhibition – Filter feeders stimulate carnivores mainly indirectly by e.g. decreasing the amount of suspended particles in water, hence better visibility in the water column which in turn is beneficial for a hunting predator. Filter feeders may inhibit carnivores by e.g. competition for substrate. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on carnivores, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

5:8 Filter feeders affect **humans** in aquatic ecosystems by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply –Filter feeders may function as a food source for humans and this interaction needs to be considered in the radionuclide modelling. However, in the aquatic ecosystems in Forsmark there are few if any edible filter feeders present today and consumption of freshwater filter feeders has historically been low also globally /Parmalee and Klippel 1974/ and the consumption of filter feeders by humans is set to zero in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Material supply – Humans may use the shells from filter feeders in e.g. handicraft or as nutritional supplements in breeding of domestic birds. However, today no activities of this kind in Forsmark are known to the authors, and even if they were, it would most likely contribute only minor to dose since it has been shown that the major long-term risk from human exposure to radionuclides from a repository is from internal exposure /Avila and Bergström 2006/. Therefore this interaction does not need to be considered in the radionuclide modelling.

c) Stimulation/inhibition – Some species of filter feeders, e.g. *Dreissena polymorpha*, are known to cause problems for human utilisation of water resources by e.g. clogging of water filters /Griffiths et al. 1991/. However, the same species may improve water quality by grazing on toxic cyanobacteria and may be used as biofilters /Dionisio Pires et al. 2005/. There are no species present in the aquatic ecosystems in Forsmark today that inhibit human utilisation and therefore inclusion of this interaction does not need to be consider in the radionuclide modelling. This leads to a cautious assessment since inhibition of human utilisation of water resources would lead to a decrease in radiation dose.

5:9 There are no processes by which **filter feeders** affect **water in regolith** that are relevant to include in the radionuclide model.

5:10 Filter feeders affect **surface water** in aquatic ecosystems by the processes a) Acceleration, b) Excretion, c) Movement, and d) Uptake.

a) Acceleration – The type and amount of filter feeders attached to surfaces may hypothetically influence the properties of the surfaces and thereby water movement. In lakes and in sea, other forcing factors will have greater effects on the surface-water movement than filter feeders and this interaction does not need to be considered in the radionuclide modelling.

b) Excretion – is the excretion of water or elements to the surrounding media by humans and other organisms. The excretion of water by filter feeders is very small compared to the water volume of the aquatic system and this interaction therefore does not need to be considered in the radionuclide modelling.

c) Movement – Filter feeders influence the water flow by filtering water. However, compared to the turnover rates of water the effect of filter feeders is small at Forsmark since the abundance of filter feeders is relatively low. Moreover the water is assumed to be homogenously mixed and therefore this interaction does not need to be considered in the radionuclide modelling.

d) Uptake – is the incorporation of water or elements from the surrounding media by humans and other organisms. The uptake of water by filter feeders is very small compared to the water volume of the aquatic system and this interaction therefore does not need to be considered in the radionuclide modelling.

5:11 Filter feeders affect **water composition** in aquatic ecosystems by the processes a) Death, b) Excretion, c) Particle release/trapping, and d) Uptake.

a) Death – Filter feeders affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Excretion – Excretion by filter feeders may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces and thus this interaction needs to be considered in the radionuclide modelling. Filter feeders can trap large amounts of particles from the water by filtering thereby affecting water composition and attributes such as turbidity /Soto and Mena 1999, Wilkinson et al. 2008/. Filter feeders can release particles by e.g. releasing offspring. The particle release and trapping by filter feeders is included in the radionuclide model parameterisation as concentrations of particles that are measured *in situ* (thereby including the effect of this interaction) (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

d) Uptake – Uptake by filter feeders may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

5:12 Filter feeders affect **gas and local atmosphere** in aquatic ecosystems by the processes a) Excretion, and b) Uptake.

a) Excretion – Filter feeders may excrete gases and thereby influence the gas fraction in water and regolith. However, the gas excretion should be minor compared to e.g. that from decomposers (see 4:12) and this interaction should have only a minor effect on transport and accumulation of radionuclides and therefore does not need to be considered in the radionuclide modelling.

b) Uptake – Elements present in gas bubbles in water may be taken up by filter feeders. However, the uptake from gas bubbles should be minor compared to uptake from water and this process therefore does not need to be considered in the radionuclide modelling.

5:13 Filter feeders affect **temperature** in aquatic ecosystems by the processes a) Convection, b) Light related processes, and c) Reactions.

a) Convection – Organisms can act as an insulator between atmosphere and underlying water and thereby affect the transport of heat in the biosphere. However, the density of filter feeders is relatively small in Forsmark and other factors (e.g. heat storage of surface water) will have greater impact on temperature in the aquatic ecosystems. Thus this interaction does not need to be considered in the radionuclide model. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Light related processes – The colour and structure of biota can affect the absorption of radiation and thereby affect temperature. The radiation absorption by biota in aquatic ecosystems will be very small compared to the radiation absorption by the water body and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of filter feeders is limited compared with the heat absorption by the water body and therefore this interaction does not need to be considereded in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

5:14 Filter feeders affect **radionuclides** in aquatic ecosystems by the processes a) Excretion, b) Growth, c) Sorption/desorption, and d) Uptake.

a) Excretion – The excretion of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, excretion is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

b) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in the radionuclide modelling. This is included in the radionuclide modelling by the use of empirically derived concentration ratios which takes into account the effect of growth at present condition (see /Nordén et al. 2010/ for descirpiton of CR).

c) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, sorption and desorption are included in the radionuclide model by using element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

d) Uptake – The uptake of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, uptake is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

5:15 Filter feeders affect **external conditions** in aquatic ecosystems by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem since the exporting biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream aquatic objects) and this interaction does not need to be considered in the radionuclide modelling. However, since it is important for the exporting system, the export by filter feeders (e.g. offspring) is included in the export of particulate matter in the radionuclide model (includes both abiotic and biotic particles) in the (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

6:1 Herbivores affect **geosphere** by the process a) Intrusion.

a) Intrusion – Herbivores normally penetrate at most a few centimetres through a sediment surface and it is highly unlikely that they would intrude to repository depth of 500 metres even if the passage was open (which is not assumed in the base case). Therefore, this interaction does not need to be considered in the radionuclide modelling.

6:2 Herbivores affect **regolith** by the processes a) Bioturbation, and b) Death.

a) Bioturbation – Herbivores may affect the regolith by bioturbation which may alter the physical properties and chemical composition of the upper regolith. Herbivores do not penetrate the sediment to any large extent in aquatic ecosystems and their contribution to bioturbation should be small. Therefore, this interaction does not need to be considered in the radionuclide modelling.

However, bioturbation by other organisms may be important and the depth of the upper oxygenated sediment layer is included as a parameter in the radionuclide model. Since the depth of the upper oxygenated layer has been investigated *in situ* (thereby including the effects of herbivores) this interaction is indirectly included in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Death – Herbivores affect the amount of dead organic matter in the regolith mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and this interaction needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

6:3 Herbivores affect **primary producers** by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Consumption of primary producers is an important transfer of energy in the ecosystem and this interaction is important to consider in the radionuclide modelling. Accordingly, the consumption by herbivores is included in the radionuclide model as net productivity of the biotic community (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Stimulation/inhibition – Herbivores may inhibit some species of primary producers by e.g. substrate competition. Besides that, herbivores mainly indirectly stimulate primary producers by inhibiting other organisms, e.g. changed competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on primary producers, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

6:4 Herbivores affect **decomposers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Herbivores may stimulate decomposers by e.g. differences in the quality of food produced. Herbivores may inhibit decomposers by e.g. substrate competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on decomposers, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

6:5 Herbivores affect **filter feeders** in aquatic ecosystems by the processes a) Food supply, and b) Stimulation/inhibition.

a) Food supply – Herbivores may provide a food source for filter feeders (e.g. zooplankton and gametes). However, most herbivores are too large to be consumed by filter feeders and this interaction is probably of minor importance for the transport of radionuclides. Thus, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Stimulation/inhibition – Herbivores stimulate filter feeders by e.g. providing food of different quality. Herbivores may inhibit filter feeders by e.g. competition for substrate and resources. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on filter feeders, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

6:6 Herbivores affect **herbivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Herbivores may inhibit each other by e.g. competition for substrate and resources. Herbivores may stimulate each other by e.g. mating. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on herbivores, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

6:7 Herbivores affect **carnivores** by the processes a) Food supply, and b) Stimulation/inhibition.

a) Food supply – Herbivores may function as a food source for carnivores. This may be an important pathway for radionuclide transfer and needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Stimulation/inhibition – Herbivores may inhibit carnivores by e.g. substrate competition. Herbivores may stimulate carnivores by e.g. providing food of different quality. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on carnivores, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

6:8 Herbivores affect **humans** by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply – Herbivores may function as a food source for humans who may consume herbivorous fish or game. This interaction may be an important radionuclide transport route to humans and is important to include in the radionuclide modelling. Accordingly, the secondary production of herbivores and consumption by humans are included in the radionuclide model as consumption of fish and game (Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Material supply – For aquatic ecosystems, even if it does occur that shoes and various accessories are manufactured from for example from fish skin /Rahme and Hartman 2006/ and skin from mammals, it will be in insignificant amounts and it has not been reported from Forsmark. Hence, this process therefore does not need to be considered in the aquatic part of radionuclide modelling. For terrestrial ecosystems, it is more common that herbivores are utilised as material supply (e.g. skin). However, since the contribution to dose to humans from external sources are assumed to be small compared to the doses from inhalation and ingestion, this interaction does not need to be considered in the radionuclide modelling.

c) Stimulation/inhibition – There is no identified stimulation or inhibition by herbivores of human utilisation of the ecosystem at Forsmark except for fishing or hunting which is treated in food supply (see a, above). Therefore this interaction does not need to be considered in the radionuclide modelling.

6:9 There are no processes by which **herbivores** affect **water in the regolith** that are relevant to include in the radionuclide modelling.

6:10 Herbivores affect **surface water** by the processes a) Acceleration, b) Excretion, c) Movement, and d) Uptake.

a) Acceleration – The type and amount of herbivores attached to surfaces (e.g. snails) may hypothetically influence the properties of the surfaces and thereby water movement in aquatic ecosystems, although other forcing factors will have greater effect on surface water movement than herbivores. In terrestrial ecosystems no known interaction of this kind is identified and this interaction therefore does not need to be considered in the radionuclide modelling.

b) Excretion – The excretion of water by herbivores is very small compared to the water volume of the aquatic system and to surface waters in terrestrial ecosystems, and this interaction does not need to be considered in the radionuclide modelling.

c) Movement – The movement of animals in surface waters may have an influence on surface water movement. However, the animals will most probably not affect large water bodies such as lakes. Moreover the water is assumed to be homogenously mixed so this interaction does not need to be considered in the radionuclide modelling.

d) Uptake – The uptake of water by herbivores is very small compared to the water volume of the aquatic system and to surface waters in terrestrial ecosystems in Forsmark, and this interaction therefore does not need to be considered in the radionuclide modelling.

6:11 Herbivores affect **water composition** by the processes a) Death, b) Excretion, c) Particle release/trapping, and d) Uptake.

a) Death – Herbivores affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Excretion – Excretion by herbivores may be important for the transport and accumulation of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces. Particle release by herbivores may sometimes be intense (e.g. at spawning) but most often the contribution to particle release and trapping from herbivores is assumed to be small. In terrestrial ecocsytems the release and trapping of particles to/from surface water by herbivores is assumed to be insignificant. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless it is included in the radionuclide model parameterisation as concentrations of particles that are measured *in situ* (thereby including the effect herbivores) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

d) Uptake – Uptake by herbivores may be important for the transport and accumulation of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

6:12 Herbivores affect **gas and local atmosphere** by the processes a) Excretion, b) Particle release trapping, and b) Uptake.

a) Excretion – Herbivores (e.g. herbivorous zooplankton in aquatic ecosystems and grazing animals in terrestrial ecosystems) may excrete gases and thereby influence the gas fraction in water, regolith and local atmosphere. However, the gas excretion should be small from herbivores and have little effect on gas and local atmosphere. Therefore, this interaction does not need to be considered in the radionuclide modelling.

b) Particle release/trapping – Herbivorous birds may release or trap particles in the atmosphere. However, this interaction is assumed to be minimal in comparison to the particle release and trapping by e.g. primary producers and this interaction does not need to be considered in the radionuclide modelling.

c) Uptake – Elements present in gas bubbles in water may be taken up by herbivorous animals. In addition terrestrial birds and mammals take up elements directly from the atmosphere. However, the uptake from gas bubbles in water should be minor compared to uptake from water and in addition uptake from atmosphere should be minimal compared to the volume of the atmosphere. This process therefore does not need to be considered in the radionuclide modelling.

6:13 Herbivores affect **temperature** by the processes a) Convection, b) Light related processes, and c) Reactions.

a) Convection – Aquatic benthic herbivores can act as an insulator between the water and underlying regolith and may influence the temperature of the underlying regolith or rock. However, the density of herbivores is relatively small in Forsmark and other factors (e.g. heat storage of surface water) will have a greater impact on temperature in the aquatic ecosystems. Terrestrial herbivores represent a rather small part of the total biomass and the effect on the temperature will be insignificant. Thus this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 9 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Light related processes – The colour and structure of biota can affect the absorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will be very small compared to the radiation absorption by the water or regolith body and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of herbivores is limited compared with the heat absorption by the water and regolith body and therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

6:14 Herbivores affect **radionuclides** by the processes a) Excretion, b) Growth, c) Sorption/desorption, and d) Uptake.

a) Excretion – The excretion of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considereded in the radionuclide modelling. Accordingly, excretion is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

b) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in the radionuclide modelling. This is included in the radionucide modelling by the use of empirically derived concentration ratios which takes into account the effect of growth at present condition (see /Nordén et al. 2010/ for description of CR).

c) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, sorption and desorption are included in the radionuclide model by using element-specific BCF-values (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

d) Uptake – The uptake of radionuclides by biota is important for the transport and accumulation of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, uptake is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

6:15 Herbivores affect **external conditions** by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem radionuclide inventory if contaminated biota migrate since it could cause a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream aquatic objects) and does not need to be considered in the radionuclide modelling. Export of herbivores in aquatic ecosystems (e.g. zooplankton) is included in the export of particulate matter (includes both abiotic and biotic particles) in the radionuclide model (Chapter 9 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/). Generally, terrestrial herbivores or herbivorous fish leaving the ecosystems are not included in the radionuclide modelling which is a cautious approach, since export of herbivores containing radionuclides would reduce the amounts of radionuclides in the exporting system.

7:1 Carnivores affect **geosphere** by the process a) Intrusion.

a) Intrusion – Carnivores normally penetrate at most a half a metre through a regolith surface and it is highly unlikely that they would intrude to repository depth of 500 meters even if the passage was open (which is not assumed in the base case). Therefore, this interaction does not need to be considered in the radionuclide modelling.

7:2 Carnivores affect **regolith** by the process a) Bioturbation, and b) Death.

a) Bioturbation – Carnivores may affect the regolith by bioturbation which may alter physical properties and chemical composition of the upper regolith. However, carnivores most probably have a local and limited effect on the regolith and this interaction does not need to be considered in the radionuclide modelling. However, bioturbation by other organisms may be important and the depth of the upper oxygenated regolith layer is included as a parameter in the radionuclide model. Since depth of the upper oxygenated layer has been investigated *in situ* (thereby including the effects of carnivores) this interaction is indirectly included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Death – Carnivores affect the amount of dead organic matter in the regolith mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and this interaction needs to be considered in the radionuclide modelling. In ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

7:3 Carnivores affect **primary producers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Carnivores may stimulate or inhibit herbivores directly, but mainly they stimulate primary producers indirectly by reducing the amounts of herbivores. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on primary production, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

7:4 Carnivores affect **decomposers** by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Carnivores consume decomposers. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Stimulation/inhibition – Carnivores may stimulate decomposers by e.g. by providing food of different quality. Carnivores may inhibit decomposers by e.g. resource competition. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on decomposers, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

7:5 Carnivores affect **filter feeders** in the aquatic ecosystems by the processes a) Consumption, b) Food supply, and c) Stimulation/inhibition.

a) Consumption – Carnivores consume filter feeders. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Food supply – Carnivores may function as a food source for filter feeders. Carnivores (except for some larvae) are most likely too large to be consumed by filter feeders and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Stimulation/inhibition – Carnivores may inhibit filter feeders by e.g. resource competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on filter feeders, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

7:6 Carnivores affect **herbivores** by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Carnivores consume herbivores. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Stimulation/inhibition – Carnivores may stimulate or inhibit some species of herbivores by favouring certain species in their diet. This interaction does not influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on herbivores, such as species distribution, abundance and production are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

7:7 Carnivores affect **carnivores** by the processes a) Consumption, b) Food supply and c) Stimulation/inhibition.

a) Consumption – Carnivores consume carnivores. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Food supply – Carnivores may function as a food source for other carnivores. This may be important for transport and accumulation of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Stimulation/inhibition – Carnivores may stimulate each other by e.g. mating. Carnivores may inhibit each other by e.g. competition for space and resources. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on carnivores, such as species distribution, abundance and production, are included in parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

7:8 Carnivores affect **humans** by the processes a) Consumption, b) Food supply, c) Material supply, and d) Stimulation/inhibition.

a) Consumption – In ecosystems at Forsmark there are no carnivores that feed on humans at present. Even if carnivores that could kill and eat humans (e.g. bear) were to occupy Forsmark this would not lead to higher radionuclide doses for humans and therefore this interaction does not need to be considered in the radionuclide modelling.

b) Food supply – Carnivores, e.g. carnivorous fish and mammals, may function as a food source for humans. Primarily fish may be an important route of transport of radionuclides to humans and needs to be considered in the radionuclide modelling. Accordingly, the production of edible carnivorous fish is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Material supply – Even if it does occur that shoes and various accessories are manufactured from for example pike skin /Rahme and Hartman 2006/ and skin from mammals, it is in insignificant volumes and such production has not been reported from Forsmark. Hence, this process does not need to be considered in the radionuclide modelling.

d) Stimulation/inhibition – There is no identified stimulation or inhibition by carnivores of human utilisation of the ecosystems at Forsmark and this interaction does not need to be considered in the radionuclide modelling.

7:9 There are no processes by which **Carnivores** affect **water in regolith** that are relevant to include in the radionuclide modelling.

7:10 Carnivores affect **surface water** by the processes a) Excretion, b) Movement, and c) Uptake.

a) Excretion – The excretion of water by carnivores is very small compared to the water volume of the aquatic system and the surface water in terrestrial ecosystems, and this interaction does not need to be considered in the radionuclide modelling.

b) Movement – The movement of animals in surface waters may have an influence on surface-water movement. However, the aquatic animals are relatively small and the terrestrial animals will only occasionally be located in water bodies, and this will most probably not affect water bodies, so this interaction therefore does not need to be considered in the radionuclide modelling.

c) Uptake – The uptake of water by carnivores is very small compared to the water volume of the aquatic system and the terrestrial surface waters and this interaction therefore does not need to be considered in the radionuclide modelling.

7:11 Carnivores affect **water composition** by the processes a) Death, b) Excretion, c) Particle release/trapping, and d) Uptake.

a) Death – Carnivores affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in the radionuclide modelling. In aquatic ecosystem models used for background calculations for the radionuclide model, death is included as estimated excess of production, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. Death is also included in the calculations of net ecosystem production in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Excretion – Excretion by carnivores may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Particle release/trapping – The concentration of particles in water is important for the transport of radionuclides attached to particle surfaces. Particle release by carnivores may sometimes be intense (e.g. at spawning) but most often the contribution to particle release and trapping from carnivores is assumed to be small. In terrestrial ecocsytems the release and trapping of particles to/from surface water by carnivores is assumed to be insignificant. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, particle release/trapping is included in the radionuclide model parameterisation as concentrations of particles that are measured *in situ* (thereby including the effect carnivores) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in /Nordén et al. 2010/ and Chapters 10 and 11 in /Andersson 2010/).

d) Uptake – Uptake by carnivores may be important for the transport of radionuclides as it affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide. Therefore this interaction needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of uptake and excretion), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

7:12 Carnivores affect **gas and local atmosphere** by the processes a) Excretion, b) Particle release/trapping, and c) Uptake.

a) Excretion – Carnivores (e.g. carnivorous fishes, birds and mammals) may excrete gases and thereby influence the gas fraction in water and directly to the local atmosphere. However, the gas excretion should be small from carnivores and have little effect on gas and local atmosphere. Therefore, this interaction does not need to be considered in the radionuclide modelling.

b) Particle release/trapping – Carnivorous birds may release or trap particles to/from the atmosphere but this interaction is assumed to be minimal in comparison to particle release trapping by e.g. primary producers and this interaction therefore does not need to be considered in the radionuclide modelling.

c) Uptake – Elements present in gas bubbles in water may be taken up by carnivorous animals. In addition terrestrial carnivorous birds and mammals take up elements directly from the atmosphere. However, the uptake from gas bubbles in water should be minor compared to uptake from water and in addition uptake from atmosphere should be minimal compared to the volume of the atmosphere. This process therefore does not need to be considered in the radionuclide modelling.

7:13 Carnivores affect **temperature** by the processes a) Convection, b) Light related processes, and c) Reactions.

a) Convection – Carnivores can act as an insulator between the water and underlying regolith and may influence the temperature of the underlying regolith or rock. However, the density of carnivores is relatively small in Forsmark and other factors (e.g. heat storage of surface water) will have greater impact on temperature in the ecosystems. Thus this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Light related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will be very small compared to the radiation absorption by the water and regolith body and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of carnivores is limited compared with the heat absorption by the water body and therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

7:14 Carnivores affect **radionuclides** by the processes a) Excretion, b) Growth, c) Sorption/desorption, and d) Uptake.

a) Excretion – The excretion of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considereded in the radionuclide modelling. Accordingly, excretion is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

b) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in the radionuclide modelling. This is included in the radionucide modelling by the use of empirically derived concentration ratios which takes into account the effect of growth at present condition (see /Nordén et al. 2010/ for descirpiton of CR).

c) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in the radionuclide modelling. Accordingly, sorption and desorption are included in the radionuclide model by using element-specific BCF-values (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

d) Uptake – The uptake of radionuclides by biota is important for the transport and accumulation of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, uptake is included in the radionuclide model as element-specific bio-concentration factors (BCFs) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

7:15 Carnivores affect **external conditions** by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem the biota leave since the exporting biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream aquatic objects) and this interaction does not need to be considered in the radionuclide modelling. As it is important for the exporting system, the export by of carnivores (e.g. zooplankton) is included in the export of particulate matter (includes both abiotic and biotic particles) in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/). Carnivorous fish leaving the aquatic ecosystems are not included in the radionuclide model which is a cautious assumption, since export of fish containing radionuclides would reduce the amounts of radionuclides in the aquatic upstream ecosystem.

8:1 H**umans** affect **geospher**e by the processes a) Intrusion, and b) Material use.

a) Intrusion – Human intrusion may have a large impact on radionuclide transport and needs to be considered in the radionuclide modelling. However, human intrusion into the repository is unlikely due to the large depth of the repository and in the base case; humans are not assumed to enter the geosphere. All human activities that directly disturb the conditions in the geosphere (e.g. drilling) are treated as separate cases in the safety assessment, see /SKB 2011/.

b) Material use – Minerals and fossil fuels in the geosphere may be used by humans. Iron ores have been utilised in the Bergslagen region (Uppland), and are still utilised today in Dannemora (www.dannemoramineral.se). Compared with central parts of Bergslagen, the Forsmark area's ore potential is insignificant and the entire candidate area is free of ore potential /Lindroos et al. 2004/. Therefore this interaction does not need to be considered in the radionuclide modelling.

8:2 Humans affect **regolith** by the processes a) Death, b) Material use, and c) Relocation.

a) Death – Humans may affect the amount of dead organic matter in regolith by e.g. municipal release (aquatic ecosystems) and by agricultural measures like fertilizing (terrestrial ecosystems), which contains organic matter such as faeces. This flux should however be of minor importance for the transport and accumulation of radionuclides in the ecosystems and does not need to be considered in the radionuclide modelling.

b) Material use – Regolith may be utilised by humans, e.g. peat used as fuel. For terrestrial ecosystems this has been considered in a supporting calculation /Avila et al. 2010/. However, regolith below lakes/marine basins are unlikely to be used by humans and this interaction does not need to be considered in the radionuclide modelling of aquatic ecosystems.

c) Relocation – Humans may affect and relocate regolith by e.g. dredging, digging and filling. Humans may lower thresholds in lakes (thereby affecting the regolith) to gain farmland. The transformation to farmland and thresholds may be important for the transport and accumulation of radionuclide and this interaction needs to be considered in the radionuclide modelling. This interaction is already included in the base case where all lakes transform into farmland, so a threshold change only alters time of transformation. Thereby, the effect of humans on regolith is accounted for in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

8:3 Humans affect **primary producers** by the processes a) Consumption, b) Material use, c) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – Humans may potentially utilize primary producers as a food source. Although this may be important for humans (3:8) the effect on primary producers should be minor and does not need to be considered in the radionuclide modelling. Terrestrial primary producers used for food are considered not to be restricted by human consumption and are assumed to always be present when the ecosystem is present. Since consumption by humans is important for the dose assessment the consumption of primary producers is evaluated in the radionuclide model (Chapter 9 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson

2010/). However, in Sweden today, very few (if any) aquatic primary producers are consumed and the consumption by humans is set to zero in the aquatic part of the radionuclide model.

b) Material use – Humans may utilise primary producers as building material etc. From terrestrial ecosystems, wood may be used in construction and reed belts may be used as in thatching. There are no aquatic primary producers in the ecosystems in Forsmark today that are being utilized. Although it may occur in the future the effect on primary producers will most probably be small. In most cases the effect on primary producers are assumed to be small and exposure of humans are not assumed to be higher than if spending time in the natural ecosystem (i.e. highest external exposure is assumed to be given from ground cf. /Nordén et al. 2010/) and this interaction does not need to be considered.

c) Species introduction/extermination – Humans may affect the settlement of primary producers by active dispersal, introduction or extermination of species. Examples of introduction of species to Swedish lakes and streams are Canadian pondweed (*Elodea Canadensis*, Sw. vattenpest), western water weed (*Elodea nuttallii*, Sw. small vattenpest), and fringed water-lily (*Nymphoides peltata*, Sw. sjögull) /Olsson 2000b, Naturvårdsverket 2007/. There are also numerous examples from terrestrial ecosystems. However, although important from an ecological view point, introduction and extermination of species of primary producers are considered to be of minor importance for radionuclide transport and thus do not need to be considered in the radionuclide modelling.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit certain species of primary producers. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on primary production, such as species distribution, abundance and production are included in the radionuclide model (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

8:4 Humans affect **decomposers** by the processes a) Consumption, b) Material use, c) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – The feeding by humans on decomposers is assumed to have a negligible impact on decomposers in Forsmark today and does not need to be considered in the radionuclide modelling. However, since consumption by humans is important for the dose assessment the consumption of limnic decomposers (e.g. crayfish which are omnivorous) and terrestrial (fungi) is included in the radionuclide model even if this does not occur in Forsmark today. Hence, consumption of limnic crayfish does occur in other lakes in the region and as a cautious assumption in the radionuclide model this interaction is included (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Material use – In ecosystems, material use of decomposers by humans is considered an insignificant process and this interaction does not need to be considered in the radionuclide modelling.

c) Species introduction/extermination – Humans may introduce decomposers (e.g. crayfish that are omnivorous) to aquatic environments. For most species, introduction or extermination of species are important from an ecological view point whereas the effect on radionuclide transport is considered to be minor. However, when introducing species utilised for food by humans, introduction may have a large impact on the exposure to radionuclides by humans and thus this interaction needs to be considered in the radionuclide modelling. This is considered in the radionuclide model, where, as a cautious assumption crayfish are included as a food source even though they are not present in the lakes today (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/). Cultivation or extermination of other edible decomposers in aquatic ecosystems at Forsmark is considered unlikely and do not need to be considered in the radionuclide modelling.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit decomposers. The human interference with decomposers are assumed to be small and this interaction therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on decomposers, such as species distribution, abundance and production are included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

8:5 Humans affect **filter feeders** in aquatic ecosystems by the processes a) Consumption, b) Food supply, c) Material use, d) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – The potential consumption of filter feeders by humans is assumed to have a negligible impact on the filter feeder population and does not need to be considered in the radionuclide modelling. Since consumption by humans is important for the dose assessment, the consumption of filter feeders is evaluated in the radionuclide model. However, in Forsmark there are few if any edible filter feeders present today and consumption of freshwater filter feeders has historically been low also globally /Parmalee and Klippel 1974/ and the consumption of filter feeders by humans is set to zero in the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Material use – Humans may use the shells from filter feeders in e.g. handicraft or as nutritional supplements in breeding of domestic birds. However, today no activities of this kind in Forsmark are known to the authors, and this interaction therefore does not need to be considered in the radionuclide modelling.

c) Species introduction/extermination – Humans may introduce filter feeders by cultivation but it is unlikely that they will exterminate filter feeders. Introduction of filter feeders does not need to be considered in the radionuclide modelling. Although cultivation may greatly influence the aquatic ecosystem from an ecological viewpoint, from the exposure of radionuclides viewpoint, it will not affect the transfer and accumulation of radionuclides in negative way. Cultivation of biota would decrease concentrations of radionuclides in the ecosystem due to the requirements of food import for the cultivated animals (e.g. pellets) which will dilute the organic matter in the ecosystem. Therefore, as a cautious assumption, introduction of filter feeders is not included in the radionuclide model.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit filter feeders. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on filter feeders, such as species distribution, abundance and production are included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

8:6 Humans affect **herbivores** by the processes a) Consumption, b) Material use, c) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – Humans may feed on herbivores and this interaction needs to be considered in the radionuclide modelling. As consumption by humans is important for the dose assessment the potential production is estimated from herbivore populations that are exposed to fishing and hunting. The consumption of herbivores (i.e. some species of fish, crayfish and game) is included in the radionuclide model (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Material use – For aquatic ecosystems, even if it does occur that shoes and various accessories are manufactured from for example from fish skin /Rahme and Hartman 2006/ and skin from mammals, it will be in insignificant amounts and it has not been reported from Forsmark. Hence, this process therefore does not need to be considered in the aquatic part of radionuclide modelling. For terrestrial ecosystems, it is more common that herbivores are utilised as material supply (e.g. skin). However, since the contribution to dose to humans from external sources are assumed to be small compared to the doses from inhalation and ingestion, this interaction does not need to be considered in the radionuclide modelling.

c) Species introduction/extermination – Humans may introduce herbivores to terrestrial (game) and aquatic environments (e.g. crayfish that are omnivorous). For most species, introduction or extermination of species is important from an ecological view point whereas the effect on radionuclide transport is considered to be minor. Exceptions to this are if introduced species cause a cascade effect altering the entire food web (and thereby flux of radionuclides) as happened e.g. in Lake Victoria when Nile perch were introduced (e.g. /Goldschmidt et al. 1993/). The largest effect of an introduction for the exposure of humans is when the introduced species are utilised for food and this interaction needs to be considered in the radionuclide modelling. This is considered in the radionuclide model, where, as a cautious assumption crayfish are included as a food source in the lakes even though they are not present in the lakes today (see Chapter 9 in /Aquilonius 2010/ and Chapter 10 and 11 in /Andersson 2010/). Cultivation or extermination of other edible herbivores in aquatic ecosystems at Forsmark is considered unlikely and does not need to be considered in the radionuclide modelling. As a cautious assumption we have chosen to neglect the possibility of extermination of fish species (a reduced fish biomass most certainly leads to a reduced flux of radionuclides to humans). In addition, we have assumed no aquaculture, which is also a cautious assumption as aquaculture demands extra nutrition for the fish (i.e. pellets) which would dilute the amounts of radionuclides in the fish.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit herbivores. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on herbivores, such as species distribution, abundance and production are included in the radionuclide model (see Chapter 9 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

8:7 Humans affect **carnivores** by the processes a) Consumption, b) Food supply, c) Material use, d) Species introduction/extermination, and e) Stimulation/inhibition.

a) Consumption – The feeding by humans on carnivores is assumed to have a negligible impact on the carnivore populations and this interaction does not need to be considered in the radionuclide modelling. Since consumption by humans is important for the dose assessment the consumption of carnivores (i.e. some species of fish) is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Food supply – In ecosystems at Forsmark there are no carnivores that feed on humans at present. Even if carnivores that could kill and eat humans (e.g. bear) were to occupy Forsmark they are not likely to have humans as a primary food source and this process does not need to be considered in the radionuclide modelling.

c) Material use – For aquatic ecosystems, even if it does occur that shoes and various accessories are manufactured from for example from fish skin /Rahme and Hartman 2006/ and skin from mammals, it will be in insignificant amounts and it has not been reported from Forsmark. Hence, this process therefore does not need to be considered in the aquatic part of radionuclide modelling. For terrestrial ecosystems, it is more common that carnivores are utilised as material supply (e.g. skin). However, since the contribution to dose to humans from external sources are assumed to be small compared to the doses from inhalation and ingestion, this interaction does not need to be considered in the radionuclide modelling.

d) Species introduction/extermination – Humans may introduce carnivores (e.g. crayfish that are omnivorous) to aquatic environments. For most species, introduction or extermination of species are important from an ecological view point whereas the effect on radionuclide transport is considered to be minor. However, when introducing species utilised for food, introduction may have a large impact on the exposure to radionuclides by humans and thus this interaction needs to be considered in the radionuclide modelling. Accordingly, this is considered in the radionuclide model, where, as a cautious assumption crayfish are included as a food source even though they are not present in the lakes today(see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/). Cultivation or extermination of other edible carnivores in ecosystems at Forsmark is considered unlikely and this interaction does not need to be considered in the radionuclide modelling. As a cautious assumption we have chosen to neglect the possibility of extermination of fish or seal species (a reduced biomass most certainly lead to a reduced flux of radionuclides to humans). In addition, we have assumed no aquaculture, which is also a cautious assumption as aquaculture demands extra nutrition for the fish (i.e. pellets) which would dilute the amounts of radionuclides in the fish.

e) Stimulation/inhibition – The activities of humans may stimulate or inhibit carnivores. This interaction does not significantly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in the radionuclide modelling. Nevertheless, the effects of stimulation and inhibition on carnivores, such as species distribution, abundance and production are included in the parameter calculations for the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

8:8 Humans affect **humans** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Humans may interact in many ways. However, in the radionuclide modelling, maximum sustainable use of the ecosystem is assumed and no further considerations are needed.

8:9 Humans affect **water in regolith** by the processes a) Uptake, and b) Water use.

a) Uptake – Humans may affect water content and flow in the regolith by extraction from wells for drinking. Intensive utilization may empty wells in dry summer months. This may affect the number of people living in an area and thus the transport of radionuclides to humans. Therefore, this interaction needs to be considered in the radionuclide modelling. In the radionuclide model, as a cautious assumption, water in the regolith is not a limiting factor for how many humans may utilise the area and uptake is not assumed to influence the amount of water in the regolith. However, the water uptake by humans is included in the radionuclide model to assess dose to humans (see /Avila et al. 2010/ and Chapter 10 in /Andersson 2010/).

b) Water use – Humans may affect the water content and flow in the regolith by e.g. water extraction from wells or artificial infiltration of municipal water. Intensive utilization may empty wells in dry summer months. This may affect the number of people living in an area and thus the transport of radionuclides to humans. Therefore, this interaction needs to be considered in the radionuclide modelling. In the radionuclide model, as a cautious assumption, water in regolith is not a limiting factor for how many humans may utilise the area and water use is not assumed to influence the amount of water in the regolith. In the radionuclide model, water use by humans is included e.g. as irrigation /Avila et al. 2010/ and Chapter 10 in /Andersson 2010/.

8:10 Humans affect **surface water** by the processes a) Acceleration, b) Anthropogenic release, c) Covering, d) Excretion, e) Movement, f) Uptake, and g) Water use.

a) Acceleration – Humans may influence water movement by constructions, e.g. dams, large-scale export, piping, and wave generation. Dam may have effect on the retention time in aquatic systems. A large span of retention times for aquatic ecosystems is already included in the radionuclide by the use of different biosphere objects of different sizes and different location in the landscape. Moreover, generally humans are considered to have a small impact on water movement compared to natural forces and this interaction does not need to be considered in the radionuclide modelling.

b) Anthropogenic release – Humans may influence the amount of surface water by releasing water by e.g. pumping from one location to another or by industrial discharge. This may influence the water retention times that are important for radionuclide transport. Therefore this interaction needs to be considered in the radionuclide modelling. In the radionuclide model this interaction is included in the water exchange estimate by assuming today's condition, i.e. no large releases occur into lakes. However, in marine ecosystems, discharge of cooling water from the nuclear power plant for the present conditions is included in calculation of water retention time which is a parameter in the radionuclide model /Karlsson et al. 2010/.

c) Covering – Use of icebreakers by humans influences the amount of surfaces covered with ice and may thereby potentially influence surface water movement. The influence of icebreakers on surface water is considered insignificant and this interaction does not need to be considered in the radionuclide modelling.

d) Excretion – Excretion of water by humans (urine) will not affect the amount of surface water in ecosystems since the volume is much smaller than the volume of surface waters and this interaction therefore does not need to be considered in the radionuclide modelling.

e) Movement – Human activities e.g. large-scale export, piping, wave generation etc. may have an influence on amount and movement of surface waters. Flow of surface water may have an effect on radionuclide transport and needs to be considered in the radionuclide modelling. No large-scale activities affecting surface water movements occur in Forsmark lakes today and are considered unlikely also in the future. Thus this interaction is not included in the radionuclide modelling.

f) Uptake – This may be important for the distribution of radionuclides and the interaction therefore needs to be considered in the radionuclide modelling. In the radionuclide modelling, as a cautious assumption, surface water is not a limiting factor for how many humans may utilise the area and water use is not assumed to influence the amount of surface water. Nevertheless, the water uptake by humans is included in the radionuclide model to assess dose to humans (/Avila et al. 2010/ and Chapter 10 in /Andersson 2010/).

g) Water use –Humans utilising lakes as freshwater reservoir may influence the water levels. This may be important for the distribution of radionuclides and the interaction therefore needs to be considered in the radionuclide modelling. In the radionuclide model, as a cautious assumption, surface water is not a limiting factor for how many humans may utilise the area and water use is not assumed to influence the amount of surface water. Nevertheless, the water use by humans is included in the radionuclide modelling e.g. as irrigation in order to assess dose to humans (/Avila et al. 2010/ and Chapter 10 in /Andersson 2010/).

8:11 Humans affect **water composition** by the processes a) Anthropogenic release, b) Death, c) Excretion, d) Uptake, and e) Water use.

a) Anthropogenic release – Humans may influence the composition of water by releasing substances. Today, there is no large release by humans to the lakes and most likely anthropogenic releases will be small also in the future. If assuming prevailing conditions this interaction does not need to be considered in the radionuclide modelling. Possible causes for anthropogenic releases in future could be if aquaculture were set up where large amounts of nutrients are added as food for the fish/mussels. However, as stated in 8:5 8:6 and 8:7, aquacultures would lead to reduced radionuclide concentrations (due to dilution with uncontaminated material) so this scenario has not been included in the radionuclide model.

b) Death – Humans may affect the amount of dead organic matter in water by municipal release, which contains organic matter such as faeces. This flux should be minor compared to the dead organic matter produced by aquatic organisms and the effect on transport and accumulation of radionuclides should be insignificant. Therefore, this interaction does not need to be considered in the radionuclide modelling.

c) Excretion – Humans may influence the water composition by sewage which is known to increase e.g. nitrogen and phosphorus concentrations in water. Although the effect should be small for the entire aquatic area there may be local effects on the water chemistry by sewage. However, the water exchange is rather rapid in the future aquatic objects and therefore the excretion of humans is assumed to have a limited effect on the water composition and this interaction does not need to be considered in the radionuclide modelling.

d) Uptake – Humans may affect the water composition by filtering prior to using the water resource for drinking. Today, there is no large uptake by humans and most likely uptake will be small also in the future. If assuming prevailing conditions, this interaction does not need to be considered in the radionuclide modelling.

e) Water use – Humans may affect the water composition by filtering water for other purposes than drinking. Today, there is no large uptake by humans and most likely uptake will be small also in the future. If assuming prevailing conditions, this interaction does not need to be considered in the radionuclide modelling.

8:12 Humans affect **gas and local atmosphere** by the processes a) Acceleration, b) Anthropogenic release, c) Excretion, and d) Uptake.

a) Acceleration – Humans can potentially influence wind velocities and wind fields, by man-made structures such as buildings. This influence can be substantial in the immediate vicinity of those structures, whereas it is limited on a large scale. Therefore, the influence on mass transport is regarded as insignificant compared to natural causes for wind and this interaction does not need to be considered in the radionuclide modelling.

b) Anthropogenic release – Humans may influence the composition of the atmosphere by releasing substances. This is assumed to have minor influence on the dose to humans unless the release contains radionuclides, which is beyond the scope of this safety analysis. Therefore, this interaction does not need to be considered in the radionucide modelling.

c) Excretion – Humans can by respiration take up oxygen and release carbon dioxide. This is assumed to already be included in the composition of the atmosphere and this interaction does not need to be considered in the radionuclide modelling.

d) Uptake – Humans can by respiration take up oxygen and release carbon dioxide. This is assumed to already be included in the composition of the atmosphere and this interaction does not need to be considered in the radionuclide modelling.

8:13 Humans affect **temperature** by the processes a) Anthropogenic release, b) Convection, c) Light related processes, and d) Reactions.

a) Anthropogenic release – Human release may affect temperature, e.g. by increased temperature due to global warming or release heat from industries. Temperature changes leading to different climate conditions may have an effect on transport and accumulation of radionuclides and therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, this is considered in the safety assessment as a separate climate case (global warming case)

b) Convection – Humans may affect the flow of heat by constructing e.g. houses that in turn affect temperature by isolation. However, in comparison to other factors in the ecosystems, this is assumed to be insignificant and this interaction does not need to be considered in the radionuclide modelling.

c) Light related processes – Human constructions may affect the radiation balance. However, the effect of human constructions on temperature is assumed to be small and therefore this interaction does not need to be considered in the radionuclide modelling.

d) Reactions – The metabolic heat of humans has no effect on the temperature of aquatic ecosystems and therefore this interaction does not need to be considered in the radionuclide modelling.

8:14 Humans affect radionuclides by the processes a) Excretion b) Growth, c) Sorption/desorption, and d) Uptake.

a) Anthropogenic release – Human activities can affect the concentration of radionuclides in the biosphere system by e.g. the operation of nuclear facilities. The release of radionuclides due to such activities is beyond the scope of this safety analysis and this interaction does not need to be considered in the radionucide modelling.

b) Excretion – Humans may excrete radionuclides. This is important since it affects the exposure of humans and this interaction needs to be considered in radionuclide modelling. The excretion of radionuclides by humans is accounted for in dose coefficients (which include excretion) that are used in the radionuclide model. In the modelling, radionuclide concentrations in the biosphere are not affected by uptake, i.e. the radionuclides are assumed to be available for ongoing transport as well as human utilizion of the food source. Therefore the excreted radionuclides are not added to the biosphere compartments in the radionuclide model (because if included the amount of radionuclides could be higher than the initial concentration).

c) Growth – The growth and life span of humans affects the concentration of radionuclides in humans and this interaction needs to be considered in the radionuclide modelling. Accordingly this is considered in the radionuclide model as committed effective dose is calculated for an integrated time of 50 years /Nordén et al. 2010, Avila et al. 2010/.

d) Sorption/desorption – Sorption of radionuclides to humans either in terrestrial or aquatic ecosystems is not assumed to alter the radionuclide inventories in the ecosystem where they are sorbed. Thus, this interaction does not need to be considereded in the radionuclide modelling.

e) Uptake – The uptake of radionuclides by humans is important for the exposure of humans (further discussed interaction 14:8), but the effect on radionuclide concentrations in the environment due to uptake by humans is of minor importance and is as a cautious assumption not considered in the radionuclide modelling.

8:15 Humans affect **external conditions** by the process a) Export.

a) Export – The effect on external conditions by humans moving out of the model area is assumed to be small (i.e. the migration of people from Forsmark will be small compared to the human population outside Forsmark) and this interaction does not need to be considered in the radionuclide modelling. In addition, humans may harvest and thereby export matter (and energy) from an ecosystem. Also this process is considered to be of minor importance for the ecosystems and does not need to be considered in the radionuclide modelling.

9:1 Water in regolith affects **geosphere** by the processes a) Change of pressure, b) Convection, and c) Weathering.

a) Change of pressure – Change of pressure affect the pore water pressure in the rock. However, there should be minor changes in pressure over time and this interaction does not need to be considered in the radionuclide modelling.

b) Convection – The hydrology in the regolith influences the recharge and discharge of groundwater and thereby the hydrology in the geosphere and the composition of groundwater. This interaction may be important for the upward transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, discharge and recharge are included in the hydrological modelling that are used to calculate parameter values applied to the radionuclide model /Bosson et al. 2010/.

c) Weathering – The water flow in the regolith influences the weathering of rock. Weathering will not add radionuclides, unless the bedrock consists of radioactive minerals (which is not the case in Forsmark). Therefore, this interaction will have a minor effect on the transport and accumulation of radionuclides, and does not need to be considered in the radionuclide modelling.

9:2 Water in regolith affects **regolith** by the processes a) Relocation and b) Saturation.

a) Relocation – In ecosystems, the water in the regolith might affect the regolith by relocating it to another place, although other elements in the matrix (e.g. surface water) may affect the relocation of regolith to a larger degree. In the radionuclide model the upper regolith layer is treated as homogenously mixed and therefore it does not matter if regolith is relocated within an object, the prerequisites for accumulation of radionuclides will be identical. Therefore this interaction does not need to be considered in the radionuclide modelling.

b) Saturation – The magnitude and direction of the water flow influences the water content in the regolith. In the aquatic ecosystems and in the terrestrial mire ecosystem, the regolith is always saturated with water and this interaction does not need to be considered in the radionuclide modelling.

9:3 Water in regolith affects **primary producers** by the processes a) Habitat supply, and b) Water supply.

a) Habitat supply – Primary producers may live in the water in the regolith. However, in general they are more dependent on nutrient concentrations, light conditions and regolith characteristics (e.g. grain size, porosity) than on the amount of water in the egolith. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, biomass and production of microphytobenthos are included in the parameter calculations for the radionuclide model, since, these estimates are based on measurements *in situ*, the effect of water in regolith is included (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Water supply – The amount of water in the regolith can affect biota on land. In aquatic and terrestrial (mire) ecosystems the regolith is always saturated with water and therefore this interaction does not need to be considered in the radionuclide modelling. In other terrestrial ecosystems than mires, water in regolith may be more limiting to production but since irrigation takes place in the agricultural land in the radionuclide model this does not need to be further considered.

9:4 Water in regolith affects **decomposers** by the processes a) Habitat supply, and b) Water supply.

a) Habitat supply – Decomposers in the form of bacteria may live in the water in the regolith. However, bacteria are more dependent on nutrient concentrations and regolith characteristics (e.g. grain size, porosity) than on the amount of water in the regolith. Therefore this interaction does not need to be considered in the radionuclide modelling. Nevertheless, biomass and respiration of bacteria are included in the radionuclide model. Since these estimates are based on measurements *in situ*, the effect of water in the regolith is included (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Water supply – The amount of water in the regolith can affect biota on land. However, in aquatic ecosystems and in mires the regolith is always saturated with water and therefore this interaction does not need to be considered in the radionuclide modelling.

9:5 Water in regolith affects **filter feeders** in aquatic ecosystems by the process a) Water supply.

a) Water supply – The amount of water in the regolith can affect biota on land. However, in aquatic ecosystems the regolith is always saturated with water and therefore this interaction does not need to be considered in the radionuclide modelling.

9:6 Water in regolith affects **herbivores** by the process a) Water supply.

a) Water supply – The amount of water in the regolith can affect biota on land. However, in aquatic ecosystems and in mires the regolith is always saturated with water and therefore this interaction does not need to be considered in the radionuclide modelling.

9:7 Water in regolith affects **carnivores** by the process a) Water supply.

a) Water supply – The amount of water in the regolith can affect biota on land. However, in aquatic ecosystems and in mires the regolith is always saturated with water and therefore this interaction does not need to be considered in the aquatic part of the radionuclide modelling.

9:8 Water in regolith affects **humans** by the process a) Water supply.

a) Water supply – The amount of water in regolith affects the amount of water that can be extracted by humans. This may affect the location of wells and number of people living in an area and thus the transport of radionuclides to humans. Therefore, this interaction needs to be considered in the radionuclide modelling. In the radionuclide model, as a cautious assumption, water in regolith does not place a constraint on human activities. In the radionuclide model, the supply of water is used for uptake by drinking as well as water use in e.g. irrigation (see /Avila et al. 2010/ and Chapter 10 in /Andersson 2010/).

9:9 Water in regolith is a diagonal element defined as the water component in regolith. There are no processes by which water in regolith influences water in the regolith that are relevant to include in the radionuclide modelling.

9:10 Water in regolith affects **surface water** by the process a) Convection.

a) Convection – There is transport of water between the regolith and surface water. This interaction is of importance for the transport of radionuclides from the repository to the surface and needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as input from the hydrological model (see /Bosson et al. 2010/ and Chapter 13 in this report).

9:11 Water in regolith affects **water composition** by the processes a) Convection, b) Physical properties change, and c) Relocation.

a) Convection – Water in the regolith affects the water composition by mixing of deep and near-surface groundwater. This may be important for the transport of radionuclides and needs to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of convection between different layers), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/). In addition, convection between different regolith layers is modelled in the hydrological models that generate parameter values for the radionuclide model (see /Bosson et al. 2010/).

b) Physical properties change – Change in water pressure in the regolith induces density changes in the water in the regolith, in turn, affecting the water composition. This interaction is assumed to have a minor influence for the relatively thin deposits in the ecosystems at Forsmark. Therefore, this interaction does not need to be considered in the radionuclide modelling.

c) Relocation – The magnitude and direction of the water flow influences the extent of erosion (relocation) of the regolith and thereby the amount and type of particulates in the water. In comparison with other processes affecting the water composition this interaction is probably of minor significance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, water composition, which is measured *in situ* (thereby including the effect of this interaction), is included in the calculation of parameter values for the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

9:12 Water in regolith affects **gas and local atmosphere** by the process a) Phase transitions.

a) Phase transitions – Water in the regolith may become gaseous and thus a part of gas and local atmosphere. This interaction is a transport pathway for water but it is assumed that radionuclides are not directly connected to this pathway and this interaction does not need to be considered in the radionuclide modelling.

9:13 Water in regolith affects **temperature** by the processes a) Convection, and b) Heat storage.

a) Convection – The water content as well as the magnitude, direction and distribution of water flow in the regolith affect heat transport and thereby the temperature in the different parts of the biosphere system. Other factors (e.g. heat storage of surface water) are assumed to have a greater influence on temperature and this interaction does not need to be considered in the radionuclide modelling. Nevertheless it is indirectly included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Heat storage – The water content as well as the magnitude, direction and distribution of water flow in the regolith affect heat storage capacity and thus the temperature in the regolith. However, the temperature in ecosystems is mainly dependent on heat storage in surface waters and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, it is indirectly included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

9:14 Water in regolith affects **radionuclides** by the process a) Convection.

a) Convection – Water in regolith affects radionuclide concentrations by mixing and if different regolith layers are assumed to be homogenously mixed, advective fluxes between layers thereby give rise to transport of radionuclides. This interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in the radionuclide model as fluxes of radionuclides between different compartments of the biosphere system /Avila et al. 2010/.

9:15 Water in regolith affects **external conditions** by the process a) Export.

a) Export – Water in the regolith is exported to external water volumes. Since amounts of exported water will most probably be small compared to the volumetric flows in external objects (downstream lakes or marine basins), the effect on the receiving ecosystem should be small and this interaction does not need to be considered in the radionuclide modelling. Since losses by export may be important for the exporting ecosystem it is included in the radionuclide model by the use of values from the hydrological models (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

10:1 Surface water affects **geosphere** by the processes a) Change in pressure, b) Convection, c) Loading, and d) Weathering.

a) Change of pressure – The pressure of the water column may affect the pore water pressure in the rock. However, surface-water-level fluctuations are modest in Forsmark and there should be small changes in pressure over time due to surface water pressure. Therefore this interaction does not need to be considered in the radionuclide modelling.

b) Convection – The surface-water hydrology influences the recharge and discharge of groundwater and thereby the hydrology in the geosphere. This interaction may be important for the upward transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, discharge and recharge are included in the hydrological modelling that is used to calculate parameters values applied to the radionuclide model /Bosson et al. 2010/.

c) Loading – Changes in thickness of an ice sheet during periods of glaciation and deglaciation will affect the mechanical stress in the rock. It is dependent on gravitation, density and the height of the overlying matter. The effect on the geosphere is not a part of the biosphere modelling and thus does not need to be considered in the radionuclide modelling.

d) Weathering – Surface water flow influences the weathering of rock by e.g. ice scoring in near shore areas. Weathering will not add radionuclides, unless the bedrock consists of radioactive minerals (which is not the case in Forsmark). Therefore this interaction will have a minor effect on the transport and accumulation of radionuclides, and this interaction does not need to be considered in the radionuclide modelling.

10:2 Surface water affects **regolith** by the processes a) Relocation, and b) Resuspension.

a) Relocation – Surface water may affect the regolith by erosion i.e. relocating regolith from one point to another. This interaction is important for the distribution of radionuclides in the ecosystem and needs to be considered in the radionuclide modelling. Accordingly, this interaction is included in calculation of regolith depths and distribution in aquatic ecosystems /Brydsten and Strömgren 2010/ and as the various bottom substrates used in the calculation of parameter values applied to the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Resuspension – The magnitude and direction of water determines the amount of the regolith that takes part of resuspension. This interaction is important for the distribution of radionuclides in the ecosystem and needs to be considered in the radionuclide modelling. Accordingly, resuspension is included as a parameter in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

10:3 Surface water affects **primary producers** by the processes a) Habitat supply, b) Relocation, and c) Water supply.

a) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic biota. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model by parameters representing biomass, aquatic area, and mean depth (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Relocation – Relocation of organisms from one part of a aquatic basin to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Water supply – In aquatic ecosystems and in mires the organisms are, by definition, always surrounded by water, and therefore uptake of water is never limiting the uptake of radionuclides (which is calculated with BCF-factors). Organisms in other terrestrial ecosystems than mires may be limited by water supply but in the radionuclide modelling irrigation takes place and water is not assumed to limit production in these ecosystems either Therefore the water supply is not considered as an important interaction and does not need to be considered in the radionuclide modelling.

10:4 Surface water affects **decomposers** by the processes a) Habitat supply, b) Relocation, and c) Water supply.

a) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic biota. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model by parameters representing biomass, aquatic area, and mean depth (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Relocation – Relocation of organisms from one part of aquatic basins to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Water supply – In aquatic ecosystems and in mires the organisms are, by definition, always surrounded by water or dominated by periods with water, and therefore uptake of water never limits the uptake of radionuclides (which is calculated with BCF-factors). Organisms in other terrestrial ecosystems than mires may be limited by water supply but in the radionuclide modelling irrigation takes place and water is not assumed to limit production in these ecosystems either Therefore the water supply is not considered as an important interaction and does not need to be considered in the radionuclide modelling.

10:5 Surface water affects **filter feeders** in the aquatic ecosystems by the processes a) Habitat supply, b) Relocation, and c) Water supply.

a) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic biota. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model by parameters representing biomass, aquatic area, and mean depth (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Relocation – Relocation of organisms from one part of an object to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Water supply – In aquatic ecosystems the organisms are, by definition, always surrounded by water, and therefore uptake of water is never limiting the uptake of radionuclides (which is calculated with BCF-factors). Therefore the water supply is not considered as an important interaction for aquatic organisms and does not need to be considered in the radionuclide modelling.

10:6 Surface water affects **herbivores** by the by the processes a) Habitat supply, b) Relocation, and c) Water supply.

a) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of biota. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model by parameters representing biomass, aquatic area, and mean depth (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Relocation – Relocation of organisms from one part of a water body to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Water supply – In aquatic ecosystems and mires the organisms are, by definition, always surrounded by water, and therefore uptake of water is never limiting the uptake of radionuclides (which is calculated with BCF-factors). Organisms in other terrestrial ecosystems than mires may be limited by water supply but in the radionuclide modelling irrigation takes place and water is not assumed to limit production in these ecosystems either. Therefore the water supply is not considered as an important interaction and does not need to be considered in the radionuclide modelling.

10:7 Surface water affects **carnivores** by the by the processes a) Habitat supply, and b) Water supply.

a) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of biota. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model by parameters representing biomass, aquatic area, and mean depth (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Water supply – In aquatic ecosystems and mires the organisms are, by definition, always surrounded by water, and therefore uptake of water is never limiting the uptake of radionuclides (which is calculated with BCF-factors). Organisms in other terrestrial ecosystems than mires may be limited by water supply but in the radionuclide modelling irrigation takes place and water is not assumed to limit production in these ecosystems either Therefore the water supply is not considered as an important interaction and does not need to be considered in the radionuclide modelling.

10:8 Surface water affects **humans** by the by the processes a) Habitat supply, and b) Water supply.

a) Habitat supply – Human settlement is mainly determined by the area and type of the ecosystems, since this determines the amount of available food. The size and location of surface waters thereby affects the settlement of humans in the area and this interaction needs to be considered in the radionuclide modelling. The area of objects is included in the radionuclide model and thereby this interaction is considered /Lindborg 2010/.

b) Water supply – Water is extracted for drinking and other purposes by humans. Water supply may limit human utilisation of water bodies and this interaction needs to be considered in the radionuclide modelling. As a cautious assumption, surface water is assumed not to be a limiting factor for how many humans may utilise the area and water use is not assumed to influence the amount of surface water. The drinking of water and water use for e.g. irrigation is included in the radionuclide model to assess dose to humans (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

10:9 Surface water affects **water in regolith** by the process a) Convection.

a) Convection – There is a transport of water between surface water and regolith. In lake ecosystems, this interaction might be of importance for transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model by input from the hydrological model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

10:10 Surface water is a diagonal element defined as water collecting on the ground or in streams, rivers, lakes wetlands, or oceans, as opposed to groundwater or atmospheric water. There are no processes by which surface water directly affects surface water that are relevant to include in the radionuclide modelling.

10:11 Surface water affects **water composition** by the processes a) Convection, and b) Physical properties change.

a) Convection – The magnitude, direction and distribution of surface water flow affect the mixing of the water (or the opposite, stratification) and thereby also affect the water composition. This may be important for the distribution of radionuclides and thus needs to be considered in the radionuclide modelling. Water composition measured *in situ* at the surface and bottom of the water column indicates that in Forsmark the water column may be treated as a homogenously mixed water body, both in limnic and marine ecosystems. Stratification occurs during winter and/or summer but over a time period of a year it is assumed that the effects of stratification are reversed and that homogenous mixing is a good approximation of the long-term characteristics. In addition, the water chemistry used in calculations of parameter values applied to the radionuclide model is sampled from the whole water column, thereby taking into account any differences in water chemistry due to stratification (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Physical properties change – At very large depths generally only occurring in the sea, water is compressed and this may cause density effects. During an interglacial the aquatic ecosystems in Forsmark will as a maximum reach relatively shallow depths (<200 m), hence, this interaction will have insignificant effects and does not need to be considered in the radionuclide modelling.

10:12 Surface water affects **gas and local atmosphere** by the processes a) Phase transitions, and b) Relocation.

a) Phase transitions – Surface water may affect the atmosphere by transformation of water in surface waters to the gas phase by evaporation and sublimation. Evaporation is an important process for water balance, but the effects on local atmosphere are assumed to be negligible compared with air exchange between the local and global atmosphere. Hence, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, since evaporation is important for the water balance it is included in the radionuclide model parameterisation in the calculation of runoff /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/.

b) Relocation – The release of water droplets as sea spray or snow from snowdrifts influences the composition of gas. Both small and large particles may be released and thus, both relocation and resuspension occur (see below). In lakes, this interaction is assumed to have minor effect on the atmosphere. In seas, sea spray may influence the atmosphere. However, as radionuclides are heavily diluted in the seas, sea spray will contain very small amounts of radionuclides and this interaction is not considered important for transport of radionuclides. Consequently, this interaction does not need to be considered in the radionuclide modelling.

c) Resuspension – The release of water droplets as sea spray or snow from snowdrifts influences the composition of gas. Both small and large particles may be released and thus, both resuspension and relocation occur (see above). In lakes, this interaction is assumed to have minor effect on the atmosphere. In seas, sea spray may influence the atmosphere. However, as radionuclides are heavily diluted in the seas, sea spray will contain very small amounts of radionuclides and this interaction is not considered important for transport of radionuclides. Consequently, this interaction does not need to be considered in the radionuclide modelling.

10:13 Surface water affects **temperature** by the processes a) Change of pressure, b) Convection, c) Heat storage, and d) Light related processes.

a) Change of pressure – At large depths normally only occurring in the sea, adiabatic temperature increase may occur. Water with high density sink by gravitational forces and water becomes compressed when pressure increases. The compression leads to release of heat and thus a temperature increase, so called adiabatic temperature increase. However, very large water depths are needed to significantly increase the temperature, and the adiabatic temperature increase in sea water varies between 0.02 and 0.2°C per 1,000 m. Thus, this interaction does not need to be considered in the radionuclide modelling, since depths in aquatic ecosystems in Forsmark during an interglacial do not exceed 200 m. Nevertheless, since temperature statistics used for calculating parameter values in the radionuclide model are based on *in situ* measurements at prevailing conditions, any effect of adiabatic compression is indirectly included (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Convection – Surface water affects the temperature by heat transport in the water. However, this interaction is small compared to other factors influencing the temperature (e.g. heat storage of surface water) and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, it is indirectly included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Heat storage – The amount and thermal properties of surface waters affect the heat storage capacity and thus the temperature in the surface waters. The heat storage in surface water is important for the circulation of water and heat storage influences the formation of taliks during permafrost conditions. Thus this interaction needs to be considered in the radionuclide modelling. Heat storage is considered in the radionuclide model since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/). Moreover, the occurrences of taliks are included in a separate climate case (periglacial climate).

d) Light related processes – Wave-formation on the surface waters, and surface water area together with its volume and depth affect light reflection and the amount of radiation that is adsorbed and thereby the temperature in the surface waters. This is an important interaction which needs to be considered in the radionuclide modelling. The interaction is considered to be indirectly included in the radionuclide model since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculations of parameter values applied in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

10:14 Surface water affects **radionuclides** by the process a) Convection.

a) Convection – Distribution, magnitude and direction of surface water flow affect the concentration of radionuclides in aquatic ecosystems. Thus, this interaction needs to be considered in the radionuclide modelling. Water flow and retention time is included in the hydrological parameter values applied in the radionuclide model (see /Bosson 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/). Stratification, i.e. the opposite of mixing may lead to an uneven distribution of radionuclides in the water column. However, during one year it is assumed that the effects of stratification are reversed and that homogenous mixing is a good approximation of the long-term distribution in the water column.

10:15 Surface water affects **external conditions** by the processes a) Export, and b) Import.

a) Export – Export of surface water includes the water flow from an upstream to a downstream water body and water flooding from streams and lakes into terrestrial areas during periods with heavy water flows. Although, from an ecological viewpoint, flooding may have large effect, the effect of transported radionuclides from an upstream to downstream object should be minor due to dilution in the receiving object. Thus, this interaction does not need to be considered in the radionuclide modelling. However, since important for the exporting ecosystem, the export is included as export of matter in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Import – The effect on the area outside the model area should be minor due to the much larger volume of external basins compared with the model area in marine areas. In the limnic and terrestrial systems the import is even smaller as the only import occurs from occasional salt water intrusion from marine basins inside the model area, i.e. the effect on the external basin by this import to the model area should be insignificant (on a landscape level this is not external conditions, but on an object level it is). Therefore, this interaction does not need to be considered in the radionuclide modelling.

11:1 Water composition affects **the geosphere** by the processes a) Convection, and b) Weathering.

a) Convection – The composition of water in the regolith and surface waters infiltrating the geosphere may influence the composition of the groundwater. The water composition infiltrating the rock affects the composition in the rock. This is the reason why the salinity changes in the rock. This is important for the transport of radionuclides in the geosphere and is treated in geosphere modelling, see /SKB 2010f/.

b) Weathering – The water composition in the regolith influences the weathering of rock. The weathering of the rock is assumed to be low for the rock type in Forsmark. Thus, this interaction will have a minor effect on the transport and accumulation of radionuclides and does not need to be considered in the radionuclide modelling.

11:2 Water composition affects **the regolith** by the processes a) Deposition, b) Phase transitions, and c) Weathering.

a) Deposition – Sedimentation of particles and elements affect the composition of the regolith and can be important for the transport of radionuclides. Thus, this interaction needs to be considered in the radionuclide modelling. The concentration of particles in the water affects the sedimentation rate, i.e. the deposition. This is included in the radionuclide model as parameter values for particle concentration and sedimentation rate (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Phase transitions – The composition of the water in the regolith will affect chemical precipitation and dissolution reactions (and thereby phase transitions). This will influence the material composition, geometry and porosity of the regolith. The physical structure of the regolith is assumed to be a result of this interaction. Since the structure of the regolith is important for the transport and accumulation of radionuclides this interaction needs to be considered in the radionuclide modelling. This is indirectly included in the radionuclide model as parameter values representing regolith and chemical composition of water are based on *in situ* measurements, thereby including the effects of this interaction (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Weathering – The composition of water in the regolith and surface water influences the weathering of the regolith. For example the particle content in the water affects the amount of weathering. However, other factors are assumed to have larger effect on the regolith and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, this interaction is indirectly included in the radionuclide model as parameter values representing regolith and chemical composition of water are based on *in situ* measurements, thereby including the effects of this interaction (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

11:3 Water composition affects **primary producers** by the processes a) Element supply, b) Food supply, c) Light related processes, and d) Stimulation/inhibition.

a) Element supply – Primary producers use carbon dioxide in surface water. The amounts of carbon dioxide in water is large and is assumed to never limit primary production and therefore this interaction does not need to be considereded in the radionuclide modelling.

b) Food supply – Primary producers in ecosystems take up nutrients in surface water. Nutrients may limit the production of primary producers and thus this interaction needs to be considered in the radionuclide modelling. This is considered in the radionuclide model by assuming present-day conditions regarding water composition and using biomass and production estimates from measurements *in situ* (thereby including the effect of this interaction) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Light related processes – Water composition influences the light attenuation which in turn influences primary production in ecosystems. This determines the distribution of primary producers and needs to be considered in the radionuclide modelling. Light attenuation is considered in the parameterisation of the radionuclide model in the calculations of net primary production and depth of the photic zone (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

d) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) in surface waters will affect the production of primary producers and thereby amount of primary producers. Biomass and production is important for accumulation and transport of radionuclides and this interaction needs to be considered in the radionuclide modelling. The effect of this interaction is included in the radionuclide model as biomass and net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

11:4 Water composition affects **decomposers** by the processes a) Element supply, b) Food supply, c) Habitat supply, and d) Stimulation/inhibition.

a) Element supply – Aquatic decomposers use oxygen in surface water. Oxygen concentrations may be low in winter in shallow lakes and thereby limit the occurrence of macro-decomposers. This may affect accumulation and transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, e.g. crayfish (that are omnivores and a mix of decomposers, herbivores and carnivores) are assumed to not be present in very shallow lakes in the radionuclide model. Bacteria may use elements other than oxygen for respiration (e.g. sulphur) during anoxic conditions and therefore bacteria may be present in all environments, oxic or anoxic and no limitation on distribution has been set for them in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Food supply – Some bacteria feed on particulate matter in water and dissolved organic carbon. Carbon may be limiting for the production of bacteria and thus this interaction needs to be considered in the radionuclide modelling. This is considered in the radionuclide model by assuming present-day conditions regarding water composition and using biomass and production estimates from measurements *in situ* (thereby including the effect of this interaction (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Habitat supply – Some bacteria live attached to particulate matter in water or regolith and some live freely in the water column and bacteria are not dependent on water composition as habitat. Instead the water composition is more important as a food source (see above). Therefore, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, biomasses of bacteria and concentrations of particulate matter are included in the radionuclide model as it is important for other transport routes of radionuclides (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

d) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) in surface waters will affect the biomass and production of decomposers. Biomass and production are important for accumulation and transport of radionuclides and this interaction needs to be considered in the radionuclide modelling. The effect of this interaction is included in the radionuclide model as biomass and net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

11:5 Water composition affects **filter feeders** in aquatic ecosystems by the processes a) Element supply, b) Food supply, and c) Stimulation/inhibition.

a) Element supply – Filter feeders use elements e.g. oxygen in surface water. Although oxygen concentrations can be low in winter especially in lakes, the supply is considered to be enough to support a permanent population of filter feeders and this interaction does not need to be considered in the radionuclide modelling.

b) Food supply – Filter feeders feed on among others, resuspended regolith and resuspended material from the catchments. This may be an important transport pathway for radionuclides and needs to be considered in the radionuclide modelling. Accordingly, the amount of resuspended material as well as net productivity of biota (including filter feeders) is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) in surface waters will affect the biomass and production of filter feeders. Biomass and production are important for accumulation and transport of radionuclides and this interaction needs to be considered in the radionuclide modelling. The effect of this interaction is included in the radionuclide model as biomass and net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

11:6 Water composition affects **herbivores** by the processes a) Element supply, and b) Stimulation/inhibition.

a) Element supply – Aquatic and terrestrial herbivores may use essential elements in surface water, e.g. aquatic herbivores utilise dissolved oxygen in the water. In shallow lakes oxygen concentrations may be low in winter and thereby limit the occurrence of some herbivores. This may affect accumulation and transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, e.g. crayfish (that are omnivores and a mix of decomposers, herbivores and carnivores) are assumed to not be present in very shallow lakes in the radionuclide model. Likewise, fish are not assumed to be present in lakes with shallower depths than 1 m (see Chapters 10 and 11). Other limnic herbivores are assumed to be in resting stages (some species of zooplankton) or being able to find patches with oxygen (fish). In the sea, limiting oxygen conditions for herbivores may occur during high nutritional load and thereby large consumption of oxygen during decomposition, although it is assumed that the herbivores will move to other marine areas, and hence it is not necessary to include them in the radionuclide modelling as it is for lakes. In terrestrial ecosystems the effects of element composition will be minor on the herbivores, assuming present conditions. However, the effect of the interaction is still included in the terrestrial part of the radionuclide model, by the use of *in situ* measurements of biomass (see Chapter 13 in this report).

b) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) in surface waters will affect the biomass and production of herbivores. Biomass and production are important for accumulation and transport of radionuclides and this interaction needs to be considered in the radionuclide modelling. The effect of this interaction is included in the radionuclide model as biomass and net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

11:7 Water composition affects **carnivores** by the by the processes a) Element supply, and b) Stimulation/inhibition.

a) Element supply – – Aquatic carnivores use oxygen and terrestrial carnivores may use essential elements in surface water. In shallow lakes oxygen concentrations may be low in winter and thereby limit the occurrence of some carnivores. This may affect accumulation and transport of radionuclides and needs to be considered in the radionuclide modelling. Accordingly, e.g. crayfish (that are omnivores and a mix of decomposers, herbivores and carnivores) are assumed to not be present in very shallow lakes in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/). Likewise, fish are not assumed to be present in lakes with shallower depths than 1 m. Other carnivores, such as species of zooplankton and benthic fauna are assumed to be in resting stages or being able to find patches with oxygen. In the sea, limiting oxygen conditions for carnivores may occur during high nutritional load and thereby large consumption of oxygen during decomposition, although it is assumed that the carnivores will move to other marine areas, and hence it is not necessary to include them in the radionuclide modelling as it is for lakes. In terrestrial ecosystems the effects of element composition will be minor on the carnivores, assuming present conditions.

b) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) in surface waters will affect the biomass and production of carnivores. Biomass and production are important for accumulation and transport of radionuclides and this interaction needs to be considered in the radionuclide modelling. The effect of this interaction is included in the radionuclide model as biomass and net productivity of the biotic community (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

11:8 Water composition affects **humans** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – The water composition (e.g. salinity and toxicants) may affect humans and toxic elements and salinity determines human utilisation of water resources. Thus this interaction needs to be considered in the radionuclide modelling. Today, the surface water in Forsmark does not contain toxins that reduce human utilisation of the water resources. By assuming present conditions, no limitation of water resources due to toxins is assumed also for future freshwater systems in the radionuclide model. The surface water of lakes is assumed to be utilised also in periods with salt water intrusions. This is most probably an overestimate but is a conservative estimate in radionuclogical impact perspective.

11:9 Water composition affects **water in regolith** by the process a) Convection.

a) Convection – The composition of the water in the regolith will affect the density and viscosity of the water which in turn will affect the magnitude, distribution and direction of water flow in the regolith. The flow of water is important for the transport of radionuclides and thus this interaction needs to be considered in the radionuclide modelling. Accordingly it is taken into account in the hydrological model from which parameter values are taken for the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

11:10 Water composition affects **surface water** by the process a) Convection.

a) Convection – Water composition affects viscosity and density which in turn affect the transport of water. Since water transport is important for the transport of radionuclides this interaction needs to be considered in the radionuclide modelling. In lakes the density differences are small and the water chemistry has little effect on water transport. Therefore, density has not been considered in lakes. In marine areas on the other hand, the density is important for water transport and is included in the oceanographic model as a forcing factor driving the water exchange /Karlsson et al. 2010/. For both lakes and marine areas, water transport is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/and Chapters 10 and 11 in /Andersson 2010/).

11:11Water composition is a diagonal element defined as chemical composition of water which depends on dissolved elements and compounds, colloids, and suspended particles. There are no processes by which water composition directly affects water composition that are relevant to include in the radionuclide modelling.

11:12 Water composition affects **gas and local atmosphere** by the processes a) Phase transitions, and b) Relocation.

a) Phase transitions – There is an outflow of elements to the atmosphere by degassing and an inflow due to dissolution. This may be an important outflux of the radionuclide C-14 from aquatic systems and this may be important for the exporting system. However, the effect on the atmosphere is probably low, due to the large volume of the atmosphere in comparison to the volume of lakes and this interaction does not need to be considered in the radionuclide modelling. As it is important for the exporting aquatic ecosystem, this interaction is included as gas uptake and gas release to/from the atmosphere (see also interaction 12:11, Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Relocation – There may be an outflow of elements to the atmosphere by spray and snowdrift. Both small and large particles may be released and both relocation and resuspension occur (see Resuspension below). The composition of water affects the composition of the sea spray and thus composition of the atmosphere. This does not affect the atmosphere to any significant degree due to the large volume of the atmosphere in comparison with the potential amounts of spray or snowdrift. Therefore this interaction does not need to be considered in the radionuclide modelling.

c) Resuspension – There may be an outflow of elements to the atmosphere by spray and snowdrift. Both small and large particles may be released and both relocation and resuspension occur (see Relocation above). The composition of water affects the composition of the sea spray and thus composition of the atmosphere. This does not affect the atmosphere to any significant degree due to the large volume of the atmosphere in comparison with the potential amounts of spray or snowdrift. Therefore this interaction does not need to be considered in the radionuclide modelling.

11:13 Water composition affects **temperature** by the processes a) Changes of pressure, b) Light related processes, and c) Reactions.

a) Change of pressure – Water with high density will by gravitational forces sink and the water will be compressed when the pressure increases. Changes in pressure may result in heating or cooling, so called adiabatic temperature changes. Adiabatic temperature changes vary with sea water composition between 0.02 and 0.2°C per 1,000 m. However, this interaction is not relevant in the relatively shallow systems of Forsmark (maximum 200 m in Forsmark marine basins during an interglacial) and the process is not included in the radionuclide modelling.

b) Light related processes – Water composition has a large effect on the absorption of light which in turn affects temperature. Temperature in surface water is important for stratification and water movement and thus this interaction needs to be considered in the radionuclide modelling. Light absorption is included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Reactions – Reactions between substances in water can require heat or release heat and may thereby affect the temperature although the effect will be very small in comparison with temperature change induced by solar energy and therefore this process does not need to be considered in radionuclide modelling. Nevertheless, the effect of reactions on temperature is included since temperature statistics measured in situ (thereby including the effect of this interaction) are used for calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

11:14 Water composition affects **radionuclides** by the processes a) Phase transitions, and b) Sorption/desorption.

a) Phase transitions – The water composition in the different parts of the biosphere affects the dissolution/precipitation of radionuclides and thus the concentration of radionuclides in the water and as solid phases in the different parts of the biosphere. This interaction therefore needs to be considered in the radionuclide modelling. Dissolution and precipitation is not explicitly treated in the radionuclide model but is assumed to be included in the estimates of partitioning coefficients (Kd) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

b) Sorption/desorption – The water composition and amount of particles in the water in the different parts of the biosphere system affect the sorption and desorption of radionuclides and thus the concentration of radionuclides in the water and on the solid phases in the different parts of the biosphere system. This interaction needs to be considered in the radionuclide modelling. Accordingly it iincluded in the radionuclide model as concentration of particulate matter and different estimates of partitioning coefficients (Kd) (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

11:15 Water composition affects **external conditions** by the process a) Export.

a) Export – Export of particulate and dissolved substances from one aquatic ecosystem to an aquatic object downstream most often have little effect on the downstream object due to dilution in that object. Therefore, this interaction does not need to be considered in the radionuclide modelling. However, the export may influence the exporting lake and therefore the export of particulate and dissolved matter is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

12:1 Gas and local atmosphere affect **geosphere** by the process a) Convection.

a) Convection – Air intrusion can take place via human activities and can also be a consequence of land-rise and climatic changes leading to unsaturated conditions. However, in aquatic systems and mires (were the regolith is saturated with water) air flow from the atmosphere reaching the repository (i.e. comparable to intrusion by organisms) is unlikely since the geosphere is always covered by regolith and/or surface water. Therefore this interaction does not need to be considered in the radionuclide modelling.

12:2 Gas and local atmosphere affect **the regolith** by the process a) Reactions.

a) Reactions – Elements in the gas phase in regolith may react with it. The amounts of gases in the regolith below aquatic ecosystems and mires (where the regolith is saturated with water) are most often small and other factors (e.g. elements dissolved in water) are assumed to have greater impacts on the regolith. Therefore, this interaction is of minor importance for transport and accumulation of radionuclides and does not need to be considered in the radionuclide modelling.

12:3 Gas and local atmosphere affect **primary producers** by the processes a) Element supply, and b) Stimulation/inhibition.

a) Element supply – In terrestrial ecosystems primary producers utilise carbon dioxide for photosynthesis and this uptake is depended on the estimated net primary production, which sets the limits for the potential uptake of e.g. C-14, which is important to consider in the radionuclide modelling. Accordingly, this is considered in the parameterisation of the radionuclide model, In aquatic ecosystems most primary producers do not directly take up elements from the atmosphere (with exception for some emergent macrophytes) but most primary producers take up elements dissolved in water. Elements present in gas bubbles in water may be utilised as a supply for primary producers. However, the element supply from gas bubbles should be minor compared to elements dissolved in water (i.e. water composition) and this interaction does not need to be considered in the radionuclide modelling of aquatic or terrestrial ecosystems.

b) Stimulation/inhibition – The atmosphere includes shading by clouds that may inhibit primary production. However, the atmospheric conditions (including clouds) are assumed to be reflected in present conditions and do not need to be considered in the radionuclide modelling. The effect of clouds is indirectly included in the radionuclide model in parameter values representing primary production that include insolation measured at the sites (i.e. taking clouds into account) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

12:4 Gas and local atmosphere affect **decomposers** by the process a) Element supply.

a) Element supply – Elements present in gas bubbles in water may be utilised as a supply for decomposers in aquatic ecosystems. However, the element supply from gas bubbles should be minor compared to elements dissolved in water (i.e. water composition) and this interaction does not need to be considered in the radionuclide modelling.

12:5 Gas and local atmosphere affect **filter feeders** in aquatic ecosystems by the process a) Element supply.

a) Element supply – Elements present in gas bubbles in water may be utilised as a supply for filter feeders. However, the element supply from gas bubbles should be minor compared to elements dissolved in water (i.e. water composition) and this interaction does not need to be considered in the radionuclide modelling.

12:6 Gas and local atmosphere affect **herbivores** by the process a) Element supply.

a) Element supply – Elements present in gas bubbles in water may be utilised as a supply for herbivores in aquatic ecosystems. However, the element supply from gas bubbles should be minor compared to elements dissolved in water (i.e. water composition). Also in terrestrial ecosystems, this effect is considered insignificant and this interaction does not need to be considered in the radionuclide modelling.

12:7 Gas and local atmosphere affect **carnivores** by the process a) Element supply.

a) Element supply – Elements present in gas bubbles in water may be utilised as a supply for carnivores in aquatic ecosystems. However, the element supply from gas bubbles should be minor compared to elements dissolved in water (i.e. water composition). Also in terrestrial ecosystems, this effect is considered insignificant and this interaction does not need to be considered in the radionuclide modelling.

12:8 Gas and local atmosphere affect **humans** by the processes a) Acceleration, b) Deposition c) Element supply, and d) Stimulation/inhibition.

a) Acceleration – The magnitude of the wind velocities and the distribution of the wind field affect humans. However, it is unlikely that human utilisation of the aquatic ecosystems in Forsmark will be influenced by wind and this interaction does not need to be considered in the radionuclide modelling.

b) Deposition – Amounts of precipitation (rain and snow) influence the behaviour of humans. However, it is unlikely that amounts of precipitation in Forsmark will affect utilisation of the ecosystems. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Element supply – Elements in the atmosphere are utilised by humans, e.g. oxygen for breathing. The amount of oxygen in the atmosphere is never limiting for human activities and thus this interaction does not need to be considered in the radionuclide modelling. Inhalation of radionuclides, on the other hand is an important interaction but this is treated in interaction 14:8 as exposure.

d) Stimulation/inhibition – The atmosphere may inhibit humans by toxins, smog, and humidity. Assuming prevailing conditions, the atmosphere will have only a limited effect on human utilisation of the ecosystem. Therefore, this interaction does not need to be considered in the radionuclide modelling.

12:9 Gas and local atmosphere affect **water in regolith** by the processes a) Convection, and b) Phase transitions.

a) Convection – The atmospheric pressure and the pressure of existing gas will affect the location of the groundwater table and thus also the water content and the water movement in the regolith. This interaction can lead to upward transport in the soil of e.g. radionuclide and needs to be considered in the radionuclide modelling. Accordingly, it is considered in the hydrological modelling that produces parameter values for the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Phase transitions – Water in the gas phase of the regolith may condense and become liquid thereby a part of water in regolith. This interaction is of minor importance compared to other processes affecting the amount of water in the regolith and does not need to be considered in the radionuclide modelling. Nevertheless it is indirectly included in the hydrological modelling that is used to calculate parameters applied to the radionuclide model since the hydrological model is based on measurements of groundwater table *in situ*, thereby including the effect of this interaction (see /Bosson et al. 2010/ and Chapter 10 in /Andersson 2010/).

12:10 Gas and local atmosphere affect **surface water** by the processes a) Convection, b) Deposition, c) Phase transitions, and d) Wind stress.

a) Convection – The atmospheric pressure will affect surface water levels and thus also the distribution of surface waters amounts and the water movement and water turnover. This is important for distribution and transport of radionuclides and thus need to be considered in the radionuclide modelling. Residence times and advective flows, sea level and lake levels are included in the modelling of succession from sea to lake to land in the Digital Elevation Model (DEM) and as water volumes applied to the radionuclide model (see /Brydsten and Strömgren 2010/ and Chapter 10 in /Andersson 2010/).

b) Deposition – Deposition includes sedimentation, rainfall, and snowfall. The magnitude of the precipitation will influence the amounts of surface waters and the amounts of ice/snow on surfaces. This is important for distribution and transport of radionuclides and thus need to be considered in the radionuclide modelling. Accordingly it is included in the radionuclide model by the use of annual averages of precipitation (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Phase transitions – The atmosphere may affect the surface water by the transformation of water in surface waters to the gas phase by evaporation and sublimation. Phase transitions are important for amounts of water, water movement and water turnover. This is important for distribution and transport of radionuclides and thus need to be considered in the radionuclide modelling. Accordingly, evaporation is included in the water balances in the hydrological calculations of runoff that are used for parameterisation of the radionuclide model (see /Bosson et al. 2010/ and Chapter 10 in /Andersson 2010/).

d) Wind stress – The strength and direction of the wind will affect the movement of surface waters, e.g. wave formation and mixing of the water column. This is important for the distribution and transport of radionuclides and needs to be considered in the radionuclide modelling. Stratification occurs during winter and/or summer but during a time period of a year it is assumed that the effects of stratification are reversed and that homogenous mixing is a good approximation of the long-term statistics. In addition, parameter values based on biota and chemistry from surface waters applied to the radionuclide model are sampled from the whole water column, thereby taking into account any differences in water chemistry or distribution of biota due to stratification (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

12:11 Gas and local atmosphere affect **water composition** by the processes a) Deposition, b) Phase transitions, and c) Wind stress.

a) Deposition – Precipitation will influence the water composition. However, even though precipitation may vary between years, the effect on water composition is assumed to be minor and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the amount of precipitation is included in the hydrological model and water composition, which is measured *in situ* (thereby including the effect of deposition), is included in the calculation of parameter values for the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Phase transitions – The atmosphere may affect the water composition by transformation of water in surface waters due to material transfers to and from the gas phase by dissolution, degassing, evaporation and sublimation. This interaction may be an important pathway for outflux of the radionuclide C-14 from eco systems and needs to be considered in the radionuclide modelling. Accordingly, this interaction is considered in the radionuclide model in parameters describing carbon outflux and carbon uptake from the atmosphere (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Wind stress – Minor amounts of surface water may be blown away (i.e. sea spray) by the wind and cause concentration differences in the water composition. The magnitude of this process is assumed to be very small and this interaction does not need to be considered in the radionuclide modelling. However, it is indirectly included in the radionuclide model by the use of *in situ* measurements of water composition (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

12:12 Gas and local atmosphere is a diagonal element defined as the layer of gases above the ecosystem that participates in gas exchange with the water. The gas composition and the gas flow are included in this element. This element also includes atmospheric flow and wind. There are no processes by which gas and local atmosphere directly influence gas and local atmosphere that are relevant to include in the radionuclide modelling.

12:13 Gas and local atmosphere affect **temperature** by the processes a) Change of pressure, b) Convection, c) Heat storage, d) Phase transitions, e) Light related processes, and f) Reactions.

a) Change of pressure – Changes in air pressure may result in heating or cooling, so called adiabatic temperature changes. This is assumed to have a minor effect on temperature in comparison with solar radiation and hence the process does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Convection – The heat transport within the atmosphere is rapid but in ecosystems the temperature changes are dampened due to the heat storage of water and regolith and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Heat storage – The heat storage in atmosphere is limited compared to the storage in soil and water and thus this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

d) Phase transitions – Phase transitions can be exo- or endothermic and thereby affect the temperature. Other factors (e.g. heat storage of surface water and regolith) will have greater impact on temperature in the ecosystems. Thus, this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

e) Light related processes – The composition of the atmosphere affects the absorption/scattering/reflection of radiation and thus the temperature. Even though there are minor changes in air composition over the year, this is not assumed to result in large changes in temperature and this interaction does not need to be considered in the radionuclide modelling. However, the release of greenhouse gases may over time result in warmer climate and this is accounted for in a separate climate case (global warming case) in the radionuclide modelling (further described in /SKB 2010a, b/.

f) Reactions – Reactions may be exo- and endothermic thereby affecting the temperature. Other factors (e.g. heat storage of surface water and solar insolation) will have greater impact on temperature. Thus this interaction does not need to be considered in the radionuclide modelling. Nevertheless, the effect on temperature is indirectly included as temperature statistics measured *in situ* (thereby including the effect of this interaction) are used for calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

12:14 Gas and local atmosphere affect **radionuclides** by the processes a) Convection, b) Sorption/desorption.

a) Convection – The distribution, magnitude and direction of gas (including air) flow in the different compartments of the biosphere affects the concentration of radionuclides in gas phase in the compartments. This may be important for certain radionuclides, e.g. I-129 and C-14 and for these this interaction needs to be considered in the radionuclide modelling. Accordingly, the transport of gaseous radionuclides is considered in the radionuclide model (e.g. the transport of C-14 between water and air atmosphere, see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Sorption/desorption – The atmosphere could potentially influence the distribution of radionuclides by sorption of radionuclides in the gas phase on particles, pollen and water drops in the atmosphere. Since the radionuclides enters the ecosystems from below in SR-Site, this interaction is considered of small importance for the distribution of radionuclides and does not need to be considered in the radionuclide modelling.

12:15 Gas and local atmosphere affect **external conditions** by the process a) Export.

a) Export – The export of gas may be important for the transport of radionuclides from a local ecosystem but is assumed to be of little importance for the external conditions due to dilution in a large volume of the external atmosphere. Thus this interaction does not need to be considered in the radionuclide modelling. However, due to the importance for local ecosystems (objects), this interaction is included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

13:1 Temperature affects **geosphere** by the processes a) Convection, and b) Weathering.

a) Convection – The heat transport from the biosphere to the geosphere will affect the temperature in the geosphere. The comparatively small area of the ecosystems in the model area will have an insignificant effect on the temperature in the geosphere compared to the effect of the external biosphere. Thus, this interaction does not need to be considered in the radionuclide modelling.

b) Weathering – Hypothetically temperature changes may influence the speed of weathering. At temperate conditions, temperature change is assumed to be of minor importance compared to other processes that influence the weathering. At periglacial and glacial conditions weathering may be altered but the other factors are more important in determining dose to humansand this interaction does not need to be considered in the radionuclide modelling.

13:2 Temperature affects **regolith** by the processes a) Physical properties change, and b) Weathering.

a) Physical properties change – The temperature can affect the volume of the components of the regolith by e.g. freezing. However, the temperature range in regolith in the aquatic systems is relatively narrow due to the isolating effect of the water body and freezing of regolith is not assumed to occur in an interglacial period. Under glacial conditions, regolith in a lake may freeze but at glacial conditions humans are only assumed to utilize marine ecosystems at glacial conditions and thus this interaction does not need to be considered in aquatic part of the radionuclide model. In terrestrial ecosystems, the effect may be larger which is further discussed in this report.

b) Weathering – Freezing of regolith may cause weathering of the regolith. However, the temperature range in regolith in the aquatic systems is relatively narrow due to the isolating effect of the water body and freezing of regolith is not assumed to occur in an interglacial period. Thus this interaction does not need to be considered in aquatic part of the radionuclide model. The long term weathering of regolith in terrestrial ecosystems is affected by a number of factors and the process as such has been addressed in the radionuclide modelling for Forsmark by including data from the site Laxemar-Simpevarp in the radionuclide model, that represents a stage where most of the calcite has been leached (Chapter 4).

13:3 Temperature affects **primary producers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature may influence the settlement of organisms as different species thrive at different temperatures. Although temperature affect the productivity of primary producers light is often considered more important in aquatic ecosystems and high productivity may occur at both high and low temperatures. Thus, this interaction does not need to be considered in the aquatic part of the radionuclide modelling. For terrestrial ecosystems, temperature has a larger impact on primary production and this is considered through evaluation of production in the terrestrial ecosystems under periglacial conditions in the radionuclide model (see Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

13:4 Temperature affects **decomposers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature may influence the settlement of organisms as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and secondary production of decomposers (e.g. bacteria and crayfish) that may be important for distribution of radionuclides in the biotic community and exposure to man (production of herbivores may be utilised as food, see interactions 6:8 and 8:6). Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is included in the radionuclide model, as the parameter net productivity of the aquatic ecosystems which is calculated based on, among other factors, temperature. Similarly, in the terrestrial part of the radionuclide model, this effect is included in the parameter estimate of decomposition in wetlands (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

13:5 Temperature affects **filter feeders** in aquatic ecosystems by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature may influence the settlement of organisms as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and secondary production of herbivores that may be important for distribution of radionuclides in the biotic community. Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is included in the radionuclide model, as the parameter net productivity of the ecosystems which is calculated based on, among other factors, temperature (see Chapter 10 in /Aquilonius 2010/, and Chapters 10 and 11 in /Andersson 2010/).

13:6 Temperature affects **herbivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature may influence the settlement of organisms as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and secondary production of herbivores that may be important for distribution of radionuclides in the biotic community and exposure of man (production of herbivores may be utilised as food, see interactions 6:8 and 8:6). Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is included in the radionuclide model, as the parameter net productivity of the ecosystems which is calculated based on, among other factors, temperature (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

13:7 Temperature affects **carnivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature may influence the settlement of organisms as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and secondary production of carnivores that may be important for distribution of radionuclides in the biotic community and exposure of man (production of carnivores may be utilised as food, see interactions 7:8 and 8:7). Therefore this interaction needs to be considered in the radionuclide modelling. Accordingly, the effect of this interaction is included in the radionuclide model, as the parameter net productivity of the ecosystems which is calculated based on, among other factors, temperature (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

13:8 Temperature affects **humans** by the processes a) Stimulation/inhibition.

a) Stimulation/inhibition – Temperature influences where humans settle. In the radionuclide modelling humans are always assumed to utilise the environment in such a way that they get the highest reasonable exposure. Therefore this interaction does not need to be considered in the radionuclide modelling, e.g. temperature effects will not prevent humans from utilizing all parts of the ecosystem.

13:9 Temperature affects **water in regolith** by the process a) Phase transitions.

a) Phase transitions – The temperature affects the state of the water in the regolith (frozen or liquid). In aquatic systems, freezing of regolith is not assumed to occur in an interglacial period due to the isolating effect of the water body (with exception to regolith in water beneath very shallow ponds). Therefore this interaction does not need to be considered in the radionuclide model for aquatic ecosystems. In terrestrial , ground frost is a common feature during the winter period and this interaction needs to be considered in the terrestrial part of the radionuclide model. Effects of ground frost are included in calculations of hydrological flows and biotic parameters applied to the radionuclide model (Chapter 13).

13:10 Temperature affects **surface waters** by the processes a) Convection, and b) Phase transitions.

a) Convection – Changes in surface water temperature influence water densities and thus surface water movements and water renewal times. Temperature variations are important for mixing of water columns and thus needs to be considered in the radionuclide modelling. Accordingly, the effect of temperature on surface water is considered by including site specific measurements of water transport, water renewal times and water temperature in calculations of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

b) Phase transitions – Temperature affects the state of water (solid, liquid or gaseous). Freezing and evaporation of surface waters as a result of changes in temperature will affect water movement and amounts of water and ice. Ice coverage is important for transport of radionuclides, e.g. it prevents transport of radionuclides between surface water and atmosphere. Thus, phase transitions needs to be considered in the radionuclide modelling. Accordingly, they are included in the radionuclide model in calculations of parameter values dependent on ice coverage, e.g. productivity, degassing and gas uptake (in which period with ice coverage is included in the calculations) (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

13:11 Temperature affects **water composition** by the processes a) Convection, b) Physical properties change, and c) Reactions.

a) Convection – The temperature influences diffusion. However, other factors affecting water chemistry (such as mixing and water turnover) are more important, and this interaction does not need to be considered in the radionuclide modelling. Nevertheless, water composition, which is measured *in situ* (thereby including the effect of this interaction), is included in the calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Physical properties change – Temperature affects density and viscosity, which in turn may affect the water composition and stratification. The stratification/mixing are important for the distribution of radionuclides in aquatic ecosystems and thus, this interaction needs to be considered in the radionuclide modelling. Water composition measured *in situ* at the surface and bottom of the water column indicates that in Forsmark the water column may be treated as a homogenously mixed water body. Stratification occurs during winter and/or summer but over a time period of a year it is assumed that the effects of stratification are reversed and that homogenous mixing is a good approximation of the long-term characteristics. In addition, the water chemistry used in calculations of parameter values applied to the radionuclide model, are sampled from the whole water column, thereby taking into account any differences in water chemistry due to stratification. This variation in water composition caused by temperature is taken into account in the annual averages of water compositions used in the radionuclide modelling (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

c) Reactions – Temperature may have large effects the kinetics (rate of reactions) and chemical equilibrium. However if assuming prevailing conditions, water composition can be assumed to be reflected in site data and this interaction does not need to be considered in the radionuclide modelling. Water composition, which is measured *in situ* (thereby including the effect of temperature variations over the year) are used in the calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/ and Chapters 10 and 11 in /Andersson 2010/).

13:12 Temperature affects **gas and local atmosphere** by the processes a) Change of pressure, b) Convection, and c) Phase transitions.

a) Change of pressure – Changes in temperature contributes to pressure changes that affect air movements. Temperature is an important mechanism influencing the turnover of the atmosphere. However, external influences are assumed to have a greater effect on temperature than local occurrences and therefore, this interaction does not need to be considered in the radionuclide modelling.

b) Convection – The temperature influences diffusion but also, more importantly the stratification of the atmosphere and thereby the composition of the atmosphere and fluxes of elements. However, external influences are assumed to be of greater importance than the local effect and therefore, this interaction does not need to be considered in the radionuclide modelling.

c) Phase transitions – Temperature effects on gas are an important driving mechanism for phase transitions in the atmosphere. However, external influences are assumed to be larger than the local effect and therefore, this interaction does not need to be considered in the radionuclide modelling.

13:13 Temperature is a diagonal element that is a unique physical property. Temperature determines the direction of heat flow between two objects placed in thermal contact. If no heat flow occurs, the two objects have the same temperature; otherwise heat flows from the hotter object to the colder object. There are no processes where temperature directly affects temperature that are relevant to include in the radionuclide modelling.

13:14 Temperature affects **radionuclides** by the processes a) Phase transitions, and b) Reactions.

a) Phase transitions – Temperature can affect the transitions between different states of radionuclides, e.g. for iodine. For most radionuclides this does not occur and this interaction does not need to be considered in the radionuclide modelling.

b) Reactions – Radionuclides may react with other elements and change states. The kinetics and chemical equilibria are influenced by temperature. The seasonal temperature variation encompasses the natural extremes for kinetics and chemical equilibria of radionuclides. Thus, it is assumed that the annual average includes this variation and this interaction does not need to be considered in the radionuclide modelling.

13:15 Temperature affects **external conditions** by the process a) Export.

a) Export – The export of heat is regarded as quantitatively unimportant for the external conditions (i.e. surrounding ecosystem and atmosphere) and therefore this interaction does not need to be considered in the radionuclide modelling.

14:1 Radionuclides affect **geosphere** by the process a) Radionuclide release.

a) Radionuclide release – Transport of radionuclides and toxicants in water and gas phase from the repository into the geosphere will affect the amount of these in the geosphere and this interaction needs to be considered in the radionuclide modelling. In the radionuclide model, the important flux is the upward, from geosphere to biosphere (interaction 1:14), whereas the flux of radionuclides to the geosphere is included as a source term.

14:2 Radionuclides affect **regolith** by the processes a) Deposition, and b) Irradiation.

a) Deposition – Deposition of radionuclides on the surfaces of regolith may change the physical and chemical properties (mineralogy) of the surfaces. The amounts of radionuclides considered in this safety assessment are too small to have any significant effect on the properties of the regolith and this interaction does not need to be considered in the radionuclide modelling. However, the deposition is important for the accumulation of radionuclides during the infilling of lakes that drives the transformation of lakes into arable land. Therefore deposition is an important element of landscape evolution and is included in the radionuclide model as sediment growth (see interaction 11:2, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in this /Andersson 2010/).

b) Irradiation – Irradiation of material in the regolith by radionuclides in the materials and in the water may affect the mineralogical structure of the material. However the amount of radionuclides in this safety assessment is too small to have any significant effect on the regolith and therefore this interaction does not need to be considered in the radionuclide modelling.

14:3 Radionuclides affect **primary producers** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. The effect of dose to organisms may cause cellular death and effect biomass and production and this interaction needs to be considered in the radionuclide modelling. Calculations of dose to non-human in SR-Site cover both auqtic and terrestrial species and are described in /Torudd 2010/.

14:4 Radionuclides affect **decomposers** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. The effect of dose to organisms may cause cellular death and effect biomass and production and this interaction needs to be considered in the radionuclide modelling Calculations of dose to non-human in SR-Site cover both auqtic and terrestrial species and are described in /Torudd 2010/.

14:5 Radionuclides affect **filter feeders** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. The effect of dose to organisms may cause cellular death and effect biomass and production and this interaction needs to be considered in the radionuclide modelling. Calculations of dose to non-human in SR-Site cover both auqtic and terrestrial species and are described in /Torudd 2010/.

14:6 Radionuclides affect **herbivores** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. The effect of dose to organisms may cause cellular death and effect biomass and production and this interaction needs to be considered in the radionuclide modelling. Calculations of dose to non-human in SR-Site cover both auqtic and terrestrial species and are described in /Torudd 2010/.

14:7 Radionuclides affect **carnivores** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. The effect of dose to organisms may cause cellular death and effect biomass and production and this interaction needs to be considered in the radionuclide modelling. Calculations of dose to non-human in SR-Site cover both auqtic and terrestrial species and are described in /Torudd 2010/.

14:8 Radionuclides affect **humans** by the process a) Exposure.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Evaluation of effects (in terms of dose) of radiation on humans is the main purpose of the safety assessment and this needs to be considered in the radionuclide modelling and is calculated in the radionuclide model (see /Avila et al. 2010/, and Chapter 10 in /Andersson 2010/).

14:9 There are no processes by which **radionuclides** affect **water in regolith** that are relevant to include in the radionuclide modelling.

14:10 There are no processes by which **radionuclides** affect **surface water** that are relevant to include in the radionuclide modelling.

14:11 Radionuclides affect **water composition** by the processes a) Decay, b) Radiolysis, and c) Reactions.

a) Decay – Decay of radionuclides to stable or other radioactive isotopes may affect the composition of the water in the different components of the biosphere system. However, the amounts of radionuclides considered in this safety assessment are probably too small to alter the water composition due to decay and this interaction does not need to be considered in the radionuclide modelling. However, since the distribution of radionuclides is important from a radionuclide perspective, the daughter nuclides that are formed during decay and that are of relevance to dose assessment are included in the radionuclide model (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

b) Radiolysis – During radiolysis, water dissociates under alpha radiation into hydrogen and oxygen. Thus, radiolysis can locally modify redox conditions, and thereby the speciation and solubility of compounds. However, the amounts of radionuclides considered in this safety assessment are too small to have any major effect on the water composition due to radiolysis and therefore, this interaction does not need to be considered in the radionuclide modelling.

c) Reactions – All reactions involving radionuclides in dissolved and in particulate form may affect the composition of the water in the different elements of the biosphere system. However, the amounts of radionuclides considered in this safety assessment are too small to have any significant effect and therefore this interaction does not need to be considered in the radionuclide modelling.

14:12 Radionuclides affect **gas and local atmosphere** by the process a) Phase transitions.

a) Phase transitions – Decay of some radionuclides form elements in the gas phase, e.g. Ra decaying to Rn. Radon is an example of a gas that can penetrate buildings and in some cases accumulate in areas with deficient ventilation. Doses from Radon inhalation could have a potential impact on LDFs for Ra-226 but it in SR-Site it is considered that in conditions where doses from "repository originated" Radon could be important, these will be outset by much higher doses from "natural" Radon and ingestion of other radionuclides (further discussed in /Avila et al. 2010/). However, radionuclides dissolved in water, e.g. C-14 may transform to gaseous form and be released to the local atmosphere. This interaction is important for the distribution of radionuclides between water and atmosphere but is treated interaction 12:11.

14:13 Radionuclides affect **temperature** by the process a) Decay.

a) Decay – Decaying radionuclides will generate heat that may influence the temperature in the different elements of the biosphere system. Other factors will influence temperature much more than decay of radionuclides and therefore this process does not need to be considered in the radionuclide modelling.

14:14 Radionuclides is a diagonal element with a radionuclide defined as an atom with an unstable nucleus. Radionuclides affect radionuclides by the process a) Decay.

a) Decay – The radionuclide undergoes radioactive decay, where one radionuclide transforms into another. Decay and half life of radionuclides are important for the calculation of radionuclides in the biosphere and decay is important to consider in the radionuclide modelling. Accordingly it is included in the radionuclide model through the half-lives of the different radionuclides (see /Nordén et al. 2010/ and Chapter 10 in /Andersson 2010/).

14:15 Radionuclides affect **external conditions** by the process a) Export.

a) Export – The export of radionuclides out of the system is partly included in the radionuclide modelling and has been studied in supporting simulations. The effect on the surrounding ecosystem is most probably small due to dilution (downstream in a catchment) unless the receiving system is very small or receives inputs from several upstream objects. This interaction needs to be considered to provide assurance that concentrations in receiving ecosystems are lower than in the exporting system in the radionuclide modelling. In the radionuclide model, this is considered by calculating the maximum release to all objects and by supporting calculations evaluating dose from downstream objects (see /Avila et al. 2010/, and Chapter 10 in /Andersson 2010/).

15:1 External conditions affect **geosphere** by the process a) Change in rock surface location.

a) Change in rock surface location – At large-scale glaciation influences the regolith and geosphere by isostatic compression and rebound. Presently interglacial conditions prevail and there is an isostatic rebound that results in land-rise and new land (regolith) emerging from the sea. The uplift of land results in shoreline-displacement which is an important interaction to consider in the radionuclide modelling. Accordingly, it is included and it is the driving force for the biosphere changes in the radionuclide model (see /Brydsten and Strömgren 2010, Lindborg 2010/, and Chapter 10 in /Andersson 2010/).Other examples of changes in rock surface location are earthquakes. These are treated as separate scenarios in the safety assessment /Munier et al. 2010/.

15:2 External conditions affect **the regolith** by the processes a) Change in rock surface location, b) Import, c) Saturation, d) Terrestrialisation.

a) Change in rock surface location – At large-scale glaciation influences the regolith and geosphere by isostatic compression and rebound. Presently interglacial conditions prevail and there is an isostatic rebound that results in land-rise and new land (regolith) emerging from the sea. The uplift of land results in shoreline-displacement which is an important interaction to consider in the radionuclide modelling. Accordingly, it is included and it is the driving force for the biosphere changes in the radionuclide model (see /Brydsten and Strömgren 2010, Lindborg 2010/, and Chapter 10 in /Andersson 2010/).Other examples of changes in rock surface location are earthquakes. These are treated as separate scenarios in the safety assessment /Munier et al. 2010/.

b) Import – The redistribution of regolith due to glacial processes is included in the radionuclide model as initial conditions in the model. Otherwise, the import of matter in this time perspective (interglacial) is assumed to be negligible except for human actions and thus, this interaction does not need to be considered in the radionuclide modelling. Human effects on the regolith are treated in 8:2.

c) Saturation – External factors may hypothetically influence the ground water level in the regolith. This may be important for the water flow and thereby transport and accumulation of radionuclides. Thus, this interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is considered in the hydrological models that generate parameter values applied to the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

d) Terrestrialisation – Reed growth leads to a mire expanding into the lake or marine bay altering the geometry of the basin. The final stage is when the lake ecosystem is transformed to mire. The transformation from aquatic to terrestrial ecosystem affects radionuclide distribution in the ecosystem, human utilisation of the ecosystem and human exposure and thus this interaction needs to be considered in the radionuclide modelling. Accordingly, the transformation from lake to land is included in the radionuclide model (see /Lindborg 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

15:3 External conditions affect **primary producers** by the processes a) Import, and b) Light related processes.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and is thus, needs to be considered in the radionuclide modelling. This is indirectly included in parameter values used in the radionuclide model for distribution, biomass and net community productivity for the aquatic and terrestrial (mire) ecosystems that are based on measurement *in situ* (and thereby include the effect of import, see Chapter 10 in /Aquilonius

2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/). Import of particles and nutrients which may influence primary producers is an indirect interaction via water composition 11:3.

b) Light related processes – The amount of solar irradiation influences photosynthesis and thereby the type and amount of primary producers. This interaction may be important for the accumulation and transport of radionuclides into the food web and needs to be considered in the radionuclide modelling. Accordingly, it is included in the radionuclide model as biomasses and net community productivity for the aquatic ecosystems and, biomass and primary production for the mire (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

15:4 External conditions affect **decomposers** by the process a) Import.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and is thus, needs to be considered in the radionuclide modelling. This is indirectly included in parameter values used in the radionuclide model for distribution, biomass and net community productivity for the aquatic and terrestrial (mire) ecosystems that are based on measurement *in situ* (and thereby include the effect of import, see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/). Import of particles and nutrients which may influence decomposers is an indirect interaction via water composition 11:4.

15:5 External conditions affect **filter feeders** by the process a) Import.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and is thus, needs to be considered in the radionuclide modelling. This is indirectly included in parameter values used in the radionuclide model for distribution, biomass and net community productivity for the aquatic and terrestrial (mire) ecosystems that are based on measurement *in situ* (and thereby include the effect of import, see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/). Import of particles and nutrients which may influence filter feeders is an indirect interaction via water composition 11:5.

15:6 External conditions affect **herbivores** by the process a) Import.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and is thus, needs to be considered in the radionuclide modelling. This is indirectly included in parameter values used in the radionuclide model for distribution, biomass and net community productivity for the aquatic and terrestrial (mire) ecosystems that are based on measurement *in situ* (and thereby include the effect of import, see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/). Import of particles and nutrients which may influence herbivores is an indirect interaction via water composition 11:6

15:7 External conditions affect **carnivores** by the process a) Import.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and is thus, needs to be considered in the radionuclide modelling. This is indirectly included in parameter values used in the radionuclide model for distribution, biomass and net community productivity for the aquatic and terrestrial (mire) ecosystems that are based on measurement *in situ* (and thereby include the effect of import, see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/). Import of particles and nutrients which may influence carnivores is an indirect interaction via water composition 11:7.

15:8 External conditions affect **humans** by the process a) Import.

a) Import – The import of uncontaminated material to the regional model area from external conditions may affect the transfer and accumulation of radionuclides and needs to be considered in the radionuclide modelling. In the radionuclide model, it is assumed that human behaviour is predefined to give the highest reasonably possible doses and the import of uncontaminated material is disregarded as a cautious assumption since it will dilute the contamination.

15:9 External conditions affect **water in regolith** by the processes a) Import and b) Saturation degree.

a) Import – Inflow of water to regolith from water in regolith outside the studied ecosystem is important for the water flow and thereby transport and accumulation of radionuclides. Thus this interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is considered in the hydrological models that generate parameter values to the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Saturation degree – External factor may hypothetically influence the ground water level in the regolith. This may be important for the water flow and thereby transport and accumulation of radionuclides. Thus, this interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is considered in the hydrological models that generate parameter values to the radionuclide model (see /Bosson et al. 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

15:10 External conditions affect **surface water** by the processes a) Convection, b) Import, c) Sea level changes, and d) Terrestrialisation.

a) Convection – The discharge from their catchments influences the water movements in lakes, wetlands and streams and, surrounding marine basins influence the advection in marine basins in the model area and this interaction needs to be considered in the radionuclide modelling. This is one of the major forces determining the water retention time and is therefore included in the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Import – Precipitation is a major force driving the discharge into streams, lakes and marine basins. This is one of the major forces determining the water retention time and therefore needs to be considered in the radionuclide modelling. Precipitation and discharge is included in the hydrological models that generate parameter values to the radionuclide model (see /Bosson et al. 2010/ (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

c) Sea level change – The alteration in height of the sea relative to the land will affect the amount and movement of surface waters. The distribution of surface water is important for transport and accumulation of radionuclides and this interaction needs to be considered in the radionuclide modelling. Sea-level changes can be caused by e.g. earth-quakes (tsunamis), global warming, land-slides, earth tides, weather and climatic changes. This has been addressed in the historical and future description in terms of development of the area and formation of lakes. The interaction is included in the radionuclide model by the representation of shore-line displacement, and the development of the landscape over time where sea-level changes on an inter annual basis are included (see /Lindborg 2010, Brydsten and Strömgren 2010/ and Chapter 10 in /Andersson 2010/).

d) Terrestrialisation – The transformation of lakes and sea bays into mires affects the amount of surface water in the biosphere object and the radionuclide distribution in the ecosystem, and thereby human utilisation of the ecosystem and human exposure and thus this interaction needs to be considered in the radionuclide modelling. This interaction is included in the radionuclide model by describing the succession of sea bays to mires for each biosphere object /Avila et al. 2010/ and Chapter 10 in /Andersson 2010/).

15:11 External conditions affect **water composition** by the process a) Import.

a) Import – The composition of surrounding waters outside the ecosystem may by import affect the composition of the surface waters and water in the regolith. The surrounding ecosystems have a large effect on the chemical composition of surface water and thus this interaction needs to be considered in the radionuclide modelling. Accordingly, this interaction is included by the use of site specific water composition data (*measured in situ* and thereby including the effect of external factors) in the calculation of parameter values applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

15:12 External conditions affect **gas and local atmosphere** by the processes a) Import, and b) Reactions.

a) Import – The local atmosphere is influenced by global wind conditions, large-scale weather systems and solar insolation. The interactions between external conditions and local atmosphere may have a large effect on the transport and accumulation of radionuclides and this interaction needs to be considered in the radionuclide modelling. Wind velocity and direction are important parameters for water turnover and shore erosion in the sea and lakes. These parameters are measured at Forsmark and are included in the radionuclide model through the oceanographic and sediment models and in calculations of gas flow between water and atmosphere (see /Karlsson et al. 2010, Brydsten and Strömgren 2010/, Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/). In addition, solar insolation is used as direct input in the calculations of primary production in the aquatic ecosystems, whereas it is indirectly included in the measure of primary production for terrestrial ecosystems.

b) Reactions – Photo-chemical reactions close to the surface will affect the gas composition e.g. ozone formation, smog formation and reactions in exhaust gases. This is assumed to be a non-site-specific effect and does not need to be considered in the radionuclide modelling.

15:13 External conditions affect **temperature** by the processes a) Import, and b) Light related processes.

a) Import – Import of heat by different materials entering the system will influence the temperature in the different elements of the system. This interaction is assumed to be a forcing function for the temperature in the system. This interaction needs to be considered in the radionuclide modelling. Accordingly, it is considered by the use of *in situ* temperature statistics used for calculations of parameter values applied to the radionuclide model and in direct estimates of processes affected by temperature, such as primary production that are also applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

b) Light related processes – Insolation and other sources of irradiation entering the system influence the temperature in the different parts of the system. This interaction needs to be considered in the radionuclide modelling, especially for the aquatic ecosystems. It is considered by using *in situ* temperature statistics in the calculations of parameter values applied to the radionuclide model and in direct estimate of processes affected by temperature, such as primary production that are also applied to the radionuclide model (see Chapter 10 in /Aquilonius 2010/, Chapter 13 in this report and Chapters 10 and 11 in /Andersson 2010/).

15:14 External conditions affect **radionuclides** by the process a) Import.

a) Import – It is assumed that the only source of radionuclides is internal and this interaction does not need to be considered in the radionuclide modelling. This has also been investigated in a separate supporting simulation presented in /Avila et al. 2010/, where it was shown that the direct source of the release caused the highest potential exposure.

15:15 External conditions are a diagonal element defined as all global conditions that affects local conditions that are considered in the biosphere matrix. The external conditions are situated at the boundary of the biosphere matrix and processes by which the external factors influence each other are not described here.

12.7 Concluding discussion

Not all processes between the components in the IM are expected to be quantitatively important for transport and accumulation of radionuclides from a deep repository in Forsmark. Thus, of the 51 identified processes, 34 were considered to be necessary to consider in the radionuclide modelling (Table 12-3, Figure 12-4). These processes may be necessary to consider in one specific process interaction but not in others. For a detailed description of where processes need to be considered the reader is referred to Section 12.6 above. A general description of these important processes for each group of processes is presented below.

There are many biological processes that are judged necessary to consider in the radionuclide model. This is because the most important exposure pathway for humans is via intake of water and food. Thus it is important to consider the distribution of biota and food-web interactions. In addition, biota may influence the distribution of radionuclides in abiotic pools by e.g. disturbing sediment or affecting water composition thereby influence long term accumulation and transport of radionuclides. However, other groups of processes are equally important to consider (further explored below).

Table 12-3. The 34 processes identified as necessary for the radionuclide modelling. * denotes biological processes that may involve humans in some interactions. The second column gives the number of the process in SKBs FEP database. Where the processes occur in the matrix are given in Table 12-2.

Biological processes	Numbering according to SKBs FEP database, see the FEP report. SR-Site FEP Bio:
Bioturbation	1
Consumption*	2
Death*	3
Decomposition	4
Excretion*	5
Food supply	6
Growth*	7
Habitat supply	8
Particle release/trapping	12
Primary production	13
Stimulation /inhibition*	14
Uptake*	15
Processes related to human behaviour	
Anthropogenic release	16
Species introduction/extermination	18
Water use	19
Chemical, mechanical and physical processes	
Element supply	22
Phase transitions	24
Physical properties change	25
Sorption/desorption	27
Wind stress	30
Transport processes	
Convection	32
Deposition	34
Import	36
Relocation	38
Resuspension	39
Radiological and thermal processes	
Decay	41
Exposure	42
Heat storage	43
Light-related processes	45
Radionuclide release	47
Landscape development processes	
Change in rock surface location	48
Sea-level changes	49
Terrestrialisation	50
Tresholding	51

Consumption, death, decomposition, excretion, food supply, habitat supply, stimulation/inhibition, and uptake, are biotic processes that may influence transport and accumulation of radionuclides in the food web. These processes are considered in the radionuclide model as biomass and net productivity of the ecosystems and production of litter in the terrestrial ecosystem. The processes bioturbation and particle release/trapping influence the abiotic compartment of the environment. Bioturbation influences the properties of the regolith and thereby influence the accumulation of radionuclides in the regolith. Particle release/trapping influence the amounts of particles in water and air which is important for the transport of radionuclides adhered to particles.

Human behavior may have large effect on the biosphere e.g. by introducing species or elements or by disturbing or removing material in large quantities. Water use, anthropogenic release, and species introduction/extermination are processes related to human behaviour that needs to be considered in the radionuclide modelling. Humans are not assumed to introduce species in aquaculture as this would decrease the dose from repository derived radionuclides, as aquaculture requires import of food for the cultured species (that would imply non-radioactive pellets from sites outside the model area). On the other hand, introduction of free-living edible species (e.g. crayfish) is included in the radionuclide model as these can increase the dose to humans.

Chemical, mechanical and physical processes can influence the state of elements and compounds, which can be important for the transport of radionuclides. For example, in some states elements are tightly bound to particles and in other states they may be easily dissolved and transported with water. Chemical, mechanical and physical processes necessary to consider in the radionuclide modelling are; phase transitions and sorption/desorption. The process phase transition is important for transport of C-14 from water to air. The process sorption/desorption determines whether radionuclides are bound to surfaces or dissolved in water and is crucial to consider when determining the transport and biological uptake of radionuclides.

Transport processes necessary to consider in the radionuclide modelling are; convection, deposition, import, resuspension, relocation and saturation. Convection includes e.g. surface water flow, discharge and recharge. Discharge and recharge are important for the transport upwards from a repository to surface systems and the pattern of discharge vs. recharge is important for the understanding of why and how transport of deep groundwater occurs. Surface water flow is also important for relocation of radionuclides since relativly fast transport through the landscape can take place in surface waters compared to groundwater and may affect the retention time in water bodies. In addition, flooding may cause a redistribution of radionuclides in the landscape. Radionuclides that have reached the surface system can, via flooding, go back to the groundwater system again. Import is the transport of radionuclides from surrounding ecosystems. This process may be of importance for the amounts of radionuclides in an ecosystem. The processes resuspension, relocation and deposition (e.g. sedimentation) are important for the transport from sediment to the water column and vice versa. Deposition is in addition to sedimentation also used to describe precipitation which is important for water balances and surface water flows.

Thermal and radiological processes necessary to consider in the radionuclide modelling are; decay, exposure, heat storage, and light related processes. Radionuclide-specific characteristics influence the transport of radionuclides and are of course important to consider in the radionuclide modelling. The amount of radionuclides released (radionuclide release), decay and exposure are crucial for the safety analysis. The process heat storage has a great influence on both biotic and abiotic components of aquatic ecosystems influencing e.g. distribution of biota, mixing of the water column, and ice coverage preventing exchange over the air-water interface. Light related processes include insolation, light absorption, light reflection and light scattering which in turn influence primary production.

Finally, the type of ecosystem greatly influences transport and accumulation of radionuclides. Landscape development processes that needs to be considered in the radionuclide modelling are change in rock surface location, sea level change, terrestrialisation, and tresholding. These processes determine the ecosystem at the site, e.g. terrestrial, limnic or marine.

Summarising the essence of this Chapter, it illustrates major process interactions and identifies processes that is necessary to consider in the radionuclide model. Moreover, it demonstrates that processes identified as important for transport and accumulation of radionuclides are considered in the radionuclide model.

13 Parameterisation of Forsmark and Laxemar-Simpevarp in terrestrial radionuclide modelling

13.1 Introduction

This chapter contains a description of how the parameters values for the terrestrial part of the radionuclide model have been calculated, the background data and the resulting parameter values. The model is hydrologically driven and the scenario is based on a below-ground release of radionuclides entering the biosphere.

In short, potential discharge areas affected by the release of radionuclides in the biosphere are identified from the modelling of deep groundwater discharge and from topography and ecosystem type /Lindborg 2010/. Each such area is called a biosphere object and is the smallest unit in the modelling of radionuclide transport and accumulation in the landscape. The model is divided into three more or less distinct stages: sea, lake and wetland (see /Andersson 2010/ for a description of the model). At the start of the modelling, all objects are marine. Over time they follow a successional path from a marine stage to a terrestrial stage, due to shoreline displacement. The criteria for this successional development are described in /Lindborg 2010/. The radionuclide modelling quantifies the potential annual effective dose to humans from a unit release to each each biosphere object in each time step, see /Avila et al. 2010/. During time most of the biosphere objects will reach a terrestrial stage that is represented by a forested wetland. Such wetlands may be further used for forestry or agricultural production after drainage, and the vegetation (wood, food products etc) may be contaminated with radionuclides in proportion to the inventory of radionuclides present in the ecosystem.

The parameters presented here are those describing biota, hydrology and regolith associated with wetlands, or agricultural use of drained wetlands, in the dose modelling. Parameters associated with lake ecosystems are presented in /Andersson 2010/, while parameters associated with marine ecosystems are presented in /Aquilonius 2010/. Regolith and object geometries are described in /Lindborg 2010/. Parameters describing element-specific properties, dose coefficients and human characteristics are presented in /Nordén et al. 2010/ (Table 13-1).

Below are some general aspects on the presentation of the parameters and the parameter values presented, followed by the parameters, the derivation of the parameter values and the parameter values for the Forsmark site. The subsequent section describing Laxemar-Simpevarp does only contain description of parameter values, where such deviate from the Forsmark parameter values.

13.1.1 Time span of the biosphere assessment and consequences for the ecosystems

The safety assessment is made over a period of 120,000 years and will therefore not only include successional changes, but also climate changes. Four different stages are distinguished in the modelling: a temperate, a periglacial, a glacial and a stage where the sites are below sea level (see Chapter 11). The temperate conditions prevail during an interglacial (defined as the warmer period between two glacial events), but it is preceded and followed by periglacial conditions (defined as occurrence of permafrost). An additional case is used to illustrate effects of global warming on the radionuclide modelling results.

Periglacial conditions have profound effects on the values of some parameters, such as primary production and the hydrological cycle (see Chapter 11). For some parameters, the estimate will be valid even under periglacial conditions, e.g. the porosity of peat in a mire or the density of soil used for agricultural purposes. In the calculation of annual effective dose to humans and other biota, periglacial conditions were handled by omitting agricultural products and the well from the potential exposure pathways. Global warming conditions was handled by prolonging the temperate conditions into the future (see /SKB 2010b/ for a detailed description). An alternative parameterization (presented below with separate heading under the parameters) was also made for alternative calculations or as a basis for a discussion of how changes in parameters caused by climate may affect the results of the radionuclide modelling under periglacial conditions and during a global warming case /Avila et al. 2010/.

Table 13-1. Parameters used in the radionuclide model. ^{a} each parameter estimated for 48 radionuclides, ^{b} each parameter estimated for 31 stable elements, ^{c} time-dependent parameters for which a separate parameter value is given for each time step and object (8 landscape geometry parameters, 4 regolith parameters, 8 aquatic ecosystem parameters and 1 surface hydrology and water exchange parameter). Total number of parameters listed in parenthesis. The references are given in the footnote below the table.

Type of parameter	N	Example	Source	Reference
Radionuclide specific[a]	1	Radionuclide half life	Literature	TR-10-07
Landscape geometries[c]	13	Size of biosphere objects and catchment areas, sedimentation and resuspension rates	Site investigation, site modelling	TR-10-05
Regolith properties[c]	27	Depth, density and porosity of sediments and soil	Site investigation, site modelling	TR-10-01, TR-10-02, TR-10-03
Aquatic ecosystem properties[c]	17	Biomass, productivity, gas exchange	Site investigation, site modelling	TR-10-02, TR-10-03
Terrestrial ecosystem properties	34	Biomass, productivity, gas exchange	Site investigation, site modelling	TR-10-01, TR-10-07
Surface hydrology and water exchange[c]	9	Runoff, vertical and horizontal advective fluxes, marine water exchange	Site investigation, site modelling	TR-10-01, TR-10-02, TR-10-03
Distribution coefficients and diffusivity[b]	10	Element-specific solid/liquid distribution coefficients (Kd) for regolith and particulate matter	Site investigation, literature	TR-10-07
Concentration ratios, retention and release[b]	19	Element-specific ratios between environmental media and organisms (CR)	Site investigation, literature	TR-10-07
Human characteristics	5	Life span, energy and water consumption	Literature	TR-10-07
Dose coefficients[a]	4	Radionuclide-specific factors for radiation exposure through external exposure, inhalation and ingestion	Literature	TR-10-07

References:
TR-10-01: This report
TR-10-02: /Andersson 2010/
TR-10-03: /Aquilonius 2010/
TR-10-05: /Lindborg 2010/
TR-10-07: /Nordén et al. 2010/

The periglacial estimate describes the properties of a treeless tundra environment. In the case of certain parameters, the same estimate is used for both the temperate domain and the periglacial domain since little change is expected to occur. In some instances (e.g. agricultural production) it has been difficult to find data that matches the periglacial case and an estimate as close as possible to periglacial conditions has then been derived. Global warming is an issue of increasing concern, and reports of potential effects on different properties have been published for different purposes, e.g. /Ministry of Environment 2007/. An alternative parameterization has been provided for properties associated with agricultural production and human food production for a global warming case. Under glacial or submerged conditions, the terrestrial environment is considered to be covered with ice or water all year round; hence no alternative parameterization has been done.

13.1.2 Parameter value representation

The model describes the most plausible "natural" succession path from sea to lake and further into wetland. Hence, there is no modelling of how the wetland may turn into other ecosystems such as bogs, forests or agriculture land after drainage (see detailed dose model description in /Andersson 2010/). However, the most important accumulation process in the terrestrial phase will occur during the wetland stage, and that is the accumulation of organic material (peat). The modelled wetland and its inventory of radionuclides in the peat can at any given time-step be drained for agricultural use or forestry. Therefore, estimates for animal production and other food-generating products have been calculated and compared for three terrestrial ecosystems: wetlands, forests and agricultural land. The highest estimate has then been used as the parameter estimate, for example the highest herbivore consumption in the three ecosystems is used to represent herbivore consumption in the model. This process of choosing the most cautious value is discussed below for each parameter estimate.

13.1.3 Parameter value statistics

Deterministic modelling has been based on the parameters estimated for the temperate case, where the climate stage has constrained the potential of human landuse, such as the potential of cultivating crops during a periglacial stage. In addition, a global warming case is acknowledged by extending the length of the temperate stage. These aspects are more specifically addressed and discussed in Chapter 11. Each parameter has been assigned a central value that was used in the deterministic modelling. Additionally, a potential range is presented for the central value estimate, which was used in a sensitivity analysis /Avila et al. 2010/.

Generally, the parameters in the model have been estimated using data from the site or from models populated with site data. In some cases when such data were lacking, the data were obtained from other areas as similar to our site as possible. The premises for parameter estimation are described below, along with statistical descriptions such as central value, maximum and minimum values, and standard deviation. For some data, such as for modelled or literature data, no statistical descriptions are available. The time resolution of the model is 1 year, and parameters are described as yearly averages. The parameter name within brackets is the name in the radionuclide model described in /Andersson 2010/.

The central value (arithmetic mean/median/geometric mean) for each parameter is representative of the property at the site. For example the central value describing the biomass of a wetland is a median based upon three forested wetlands, whereas the minimum and maximum values also take into consideration the fact that wetlands may be treeless and in some cases more productive/older than the three representatives investigated at the site. Therefore, the minimum is chosen from a treeless mire and the maximum is taken from a moist, productive, somewhat older forest site. The minimum and maximum values therefore represent a span that takes the different types of wetlands into account and thereby also the successional aspects of the wetlands.

Standard deviation, and minimum and maximum values, were used in a sensitivity analysis that describes the relative importance of different parameters for the model result /Avila et al. 2010/. In addition, a parameter distribution was suggested for each parameter, where mainly normal and lognormal distributions fit the actual data. In some cases no distribution is suggested, due to lack of data and/or no *a priori* anticipation. However, some of the field estimates have neither the spatial nor the temporal scope that is desirable for short-term modelling (e.g. 100 years). For example, modelling of climate parameters such as precipitation and runoff lacks a variation range. This means that the described variation for some site parameters does not cover the potential variation range, even though the estimated mean may be close to the true mean for a longer time period as well. Most of the parameters describing the regolith have a rather short span, reflecting a small number of samples in some cases but also a low variation.

13.2 The terrestrial biosphere objects in Forsmark

The biosphere objects considered in the dose modelling may be in one of four different stages following the successional trajectory marine basin – lake – wetland, and agricultural land. The wetland and the agricultural land are the terrestrial stages that are here parameterised based on the knowledge from the Forsmark site.

13.2.1 Wetland

Wetlands are frequent in the Forsmark area and cover more than 13% of the area (Table 3-3) and up to 25–35% of some sub-catchments. Most of the lakes in the regional model area are shallow and are surrounded by a more or less extensive reed (*Phragmites australis*) belt. As the lakes become increasingly shallow, the reed bed spreads until the lake becomes a wetland. Peat has developed in the more elevated areas with a thickness of less than one metre. Forested wetlands only cover 3.3% whereas open wetlands cover 10.1% of the regional model area. Many of these forested wetlands are located close to lakes and are often dominated by birch and/or alder, but they also contain more or less inundated areas dominated by Norway spruce and bogs with more or less sparse Scots pine forest. In the parameterization, the mire is assumed to be covered by trees and thereby has a potentially greater radionuclide inventory in biomass and radionuclide uptake (NPP) than a treeless mire. Bogs are not yet so numerous in this area, due in part to the young age of the terrestrial environment. The bog stage is not considered in the parameterization of the wetland due to the hydrological conditions that constrain the exchange between the accumulating bog peat and the lower regolith layers. In a bog the vegetation production is rain-fed.

13.2.2 Agricultural land

Arable land is currently found in the southeast on clayey till located fairly high in the landscape and is not considered to be a discharge area for groundwater, e.g. /Werner et al. 2007/. Instead, the arable land on discharge areas will be located on former lakes and mires that have to be drained before crop cultivation. The properties of the regolith that is cultivated are therefore parameterized accordingly. In each time-step it is possible to drain and use the mire for agricultural purposes, growing different crops, vegetables, etc.

13.3 Radionuclide model parameterization for the Forsmark site

This section contains descriptions of the site-specific terrestrial parameters. A description of the numerical model describing the transport and accumulation of radionuclides is presented in /Andersson 2010/. The abbreviation in parentheses below corresponds to the radionuclide model parameter name. The parameter values are presented at the end of each description.

In the following section, the terrestrial parameters in the dose model are divided into 1) regolith parameters, 2) hydrological parameters, 3) parameters related to radionuclide uptake by vegetation, 4) parameters related to radionuclide uptake by herbivores, 5) human food parameters and 6) parameters for simulating irrigation.

13.3.1 Regolith parameters

The regolith parameters describe properties of different generalized geological units found in the biosphere objects. The regolith in each biosphere object is described according to the conceptual model of the spatial distribution of regolith at Forsmark (Figure 13-2). The main input sources for assigning properties of the regolith are the surface map of Quaternary deposits, the depth and stratigraphy model of regolith, RDM, /Hedenström et al. 2008/, the soil type map /Lundin et al. 2004/ and models of future distribution of QD /Lindborg 2010/. Areas, volumes and depths of properties associated with the biosphere objects are defined and presented in /Lindborg 2010/ except for the root zone in arable land that is presented below.

The regolith is divided into four layers: regoUp, regoMid_PG, regoMid_GL and regoLow, representing peat (in the mire), postglacial deposits, glacial deposits and till, respectively (Figure 13-1). The lithological unit regoMid is divided into two sub-units: PG and GL. PG represents the postglacial organic sediments, i.e. gyttja and clay gyttja, whereas GL constitutes the glacial clay. Below follows a description of the derivation of parameter estimates describing the regolith.

Density of near-surface agricultural soil (Agri_dens_regoUp)

This parameter represents the dry bulk density of the upper 0.3 m of regolith in agricultural areas. In the dose modelling it is assumed that future agricultural land will be located on drained wetlands where the postglacial sediments will dominate /Lindborg 2010/. No such agricultural land areas are present in the investigation area today and literature data has therefore been used instead. In the calculations it has been assumed that the upper 0.3 m of the regolith contains equal amounts of fen peat and gyttja, and that they in regard to density have a recent history of agricultural use. This is a

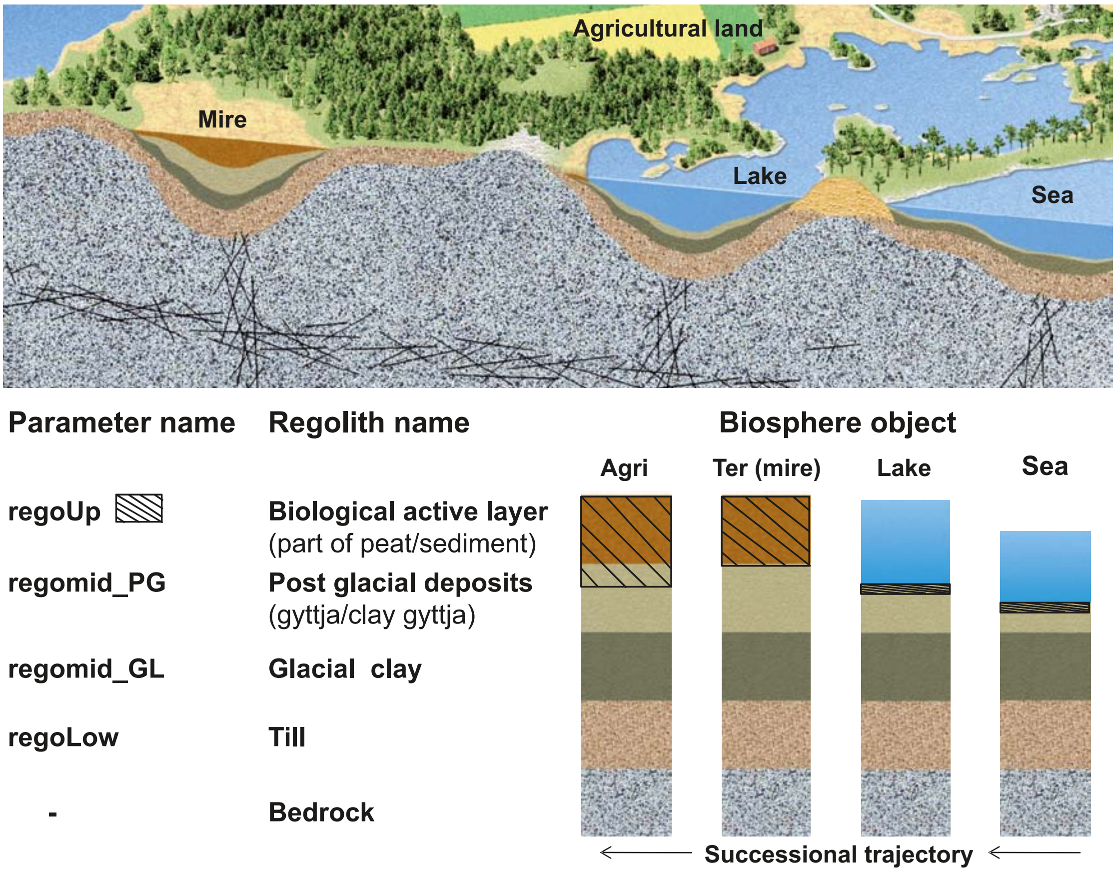


Figure 13-1. *The conceptual model of the generalized distribution of the regolith fordifferent types of biosphere objects at Forsmark. The parameter names in the Radionuclide model on the left are used together with the biosphere object prefix, e.g. Ter_z_regoUp to describe the thickness of peat layer or Ter_z_regomid_PG to describe the thickness of postglacial deposits below the mire . The thickness of the various regolith layers in soil profiles are also seen in the landscape pictures, which represent a generalized succession trajectory from sea to mire that is later converted to agricultural land by draining.*

cautious assumption because both soil types are heavily affected by the oxidized conditions after a drainage. Data for cultivated fen peat was taken from /Berglund and Persson 1996/, where densities from the layers between 0.2 and 0.5 m were used (213 kg m^{-3}, the upper part was heavily affected by minerogenic content). Data for cultivated gyttja was taken from /Berglund et al. 1989/ representing the upper 0.2 m (433 kg m^{-3}). A normal distribution was assumed and min and max values where assumed to represent densities from pure fen peat and pure gyttja, respectively. (Mean=323, min=213, max=433 kg m^{-3})

Porosity of near-surface agricultural soil (Agri_poro_regoUp)

This parameter represents the dry porosity of the upper 0.3 m of regolith in agricultural areas. In the dose modelling it is assumed that future agricultural land will be located on drained wetlands where the postglacial sediments will dominate /Lindborg 2010/. No such agricultural land areas are present in the investigation area today and literature data has therefore been used instead. In the calculations it has been assumed that the upper 0.3 m of the regolith contains equal amounts of fen peat and gyttja, and that they in regard to porosity have a recent history of agricultural use. This is a cautious assumption because both soil types are heavily affected by the oxidized conditions after a drainage. Data for cultivated fen peat was taken from /Berglund and Persson 1996/ (0.85 m^3 m^{-3}). Data for cultivated gyttja was taken from /Berglund et al. 1989/ representing the upper 0.2 m (0.77 m^3 m^{-3}). A normal distribution was assumed and min and max values where assumed to represent porosities from pure fen peat and pure gyttja, respectively. (Mean=0.81, min=0.77, max=0.85 m^3 m^{-3}).

Density of peat (Ter_dens_regoUp)

The parameter value represents the dry bulk density of peat from two studies. The mean is based on the means of the studies and represents in total 7 measurements from various depths at the Rönningarna mire on the Forsmark site /Sternbeck et al. 2006, Sheppard et al. 2009/ (Table 13-2). A normal distribution was assumed and min and max values were based on all individual samples representing the two studies. (Mean=86, SD=48, min=30, max=150 kg m^{-3})

Porosity of peat (Ter_poro_regoUp)

The parameter values represent the porosity of the peat layer. The values are based on measurements of water content from 4 studies and 38 peat samples at various depths of the peat layer from three mires in the Forsmark area: Stenrösmossen (0.91), Lersättermyran (0.86) /Fredriksson 2004/ and Rönningarna (0.91, 0.87) /Sternbeck et al. 2006, Sheppard et al. 2009/. A normal distribution was assumed and min and max values were based on all individual samples representing the four studies. (Mean=0.89, SD=0.03, min=0.76, max=0.95 m^3 m^{-3})

Density of glacial sediments (Ter_dens_regoMid_GL)

The parameter values represent the dry bulk density of the glacial clay found under the peat layer (Ter_regoUp) and postglacial sediments (Ter_regoMid_PG) in mires. This means that the properties of this layer are the same as those used for the aquatic systems layer 'regoMid_GL". The dry bulk density of glacial clay is based on calculations from analyses of water content and organic carbon content in three samples of glacial clay from the lakes Eckarfjärden, Fiskarfjärden and Norra Bassängen at Forsmark /Hedenström 2004/. The geological unit for this parameter is the same as for Aqua_dens_regoMid_GL. A uniform distribution was assumed and min and max values were from the three lakes. (Mean=663, min=662, max=664 kg m^{-3})

Density of postglacial sediments (Ter_dens_regoMid_PG)

This parameter value represents the dry bulk density of the postglacial sediments present before the basin was filled in with peat. This means that the properties of this layer are the same as those used for the aquatic systems layer 'regoMid_PG'. The values are based on measurements of the water content and organic content of gyttja and clay gyttja from lakes at the Forsmark site (Eckarfjärden, Fiskarfjärden, Stocksjön, Bolundsfjärden, Puttan and Norra Bassängen, /Brunberg described in SR Can, Hedenström 2004/) as well as measurements of the dry bulk density of samples of organic sediments from shallow coastal bays /Sternbeck et al. 2006/ Table 13-3. A mean was calculated based on the mean for each locality. A normal distribution was assumed and min and max values were based on the individual samples from the lakes/bays.The geological unit for this parameter is the same as for Aqua_dens_regoMid_PG. (Mean=138, SD=39, min=72, max=256 kg m^{-3})

Table 13-2. Input data and parameter values for Ter_dens_regoUp, representing the dry bulk density of peat.

IDCODE	Depth (m)	Dry bulk dens (kg m^{-3})
PFM006025	0.26–0.28	80.0
PFM006025	0.6–0.65	30.0
PFM006025	1.46–1.50	30.0
PFM006025	1.85–1.87	70.0
PFM006024	0.30	100.0
PFM006024	0.30	110.0
PFM006024	0.30	150.0

Table 13-3. Measured dry bulk density of coastal sediments /Sternbeck et al. 2006/.

Site	Idcode	Depth (m)	dry bulk dens kg/m^3
Tixelfjärden	PMF 005785	0.10–0.11	157.4
Tixelfjärden	PMF 005785	0.12–0.13	163.7
Tixelfjärden	PMF 005785	0.16–0.17	168.0
Tixelfjärden	PMF 005785	0.20–0.22	190.5
Tixelfjärden	PMF 005785	0.24–0.26	186.1
Tixelfjärden	PMF 005785	0.28–0.30	192.4
Tixelfjärden	PMF 005785	0.32–0.34	256.3
Tixelfjärden	PMF 005785	0.36–0.38	218.7
Tixelfjärden	PMF 005785	0.40–0.41	215.7
Kallrigafjärden	PMF 005784	0.10–0.11	179.6
Kallrigafjärden	PMF 005784	0.12–0.13	161.1
Kallrigafjärden	PMF 005784	0.14–0.15	180.1
Kallrigafjärden	PMF 005784	0.16–0.17	156.8
Kallrigafjärden	PMF 005784	0.18–0.20	180.7
Kallrigafjärden	PMF 005784	0.20–0.22	204.7
Kallrigafjärden	PMF 005784	0.24–0.26	170.5
Kallrigafjärden	PMF 005784	0.28–0.28	183.8
Kallrigafjärden	PMF 005784	0.32–0.34	219.8
Kallrigafjärden	PMF 005784	0.34–0.36	164.8
Kallrigafjärden	PMF 005784	0.38–0.39	187.9
Kallrigafjärden	PMF 005784	0.65–0.68	215.7

Porosity of glacial sediments (Ter_poro_regoMid_GL)

This parameter value represents the porosity of the glacial clay found under the peat layer (Ter_regoUp) and postglacial sediments (regoMid_PG) in mires. The values represent the porosity of the glacial clay found in the limnic and marine areas. This means that the lithological unit and properties of this layer are the same as those used for the aquatic systems layer “regoMid_GL”. The porosity values for glacial clay are based on secondary calculations from grain size distribution curves of clay collected offshore from Forsmark (N=7, within one sediment core) /Risberg 2005/ and calculations based on analyses of the water content and organic carbon content from the lakes Eckarfjärden, Fiskarfjärden and Norra Bassängen /Hedenström 2004/. (Mean=0.64, SD=0.08, min=0.55, max=0.75 m^3 m^{-3})

Porosity of postglacial sediments (Ter_poro_regoMid_PG)

This parameter value represents the porosity of the postglacial sediments present before the basin was filled in with peat (Table 13-2). This means that the properties of this layer are the same as those used for the aquatic systems layer ‘regoMid_PG’. The values are based on measurements of the water content and organic content of gyttja and clay gyttja from lakes at the Forsmark site (Eckarfjärden, Fiskarfjärden, Stocksjön, Bolundsfjärden, Puttan and Norra Bassängen Table 13-4, /Brunberg described in SR Can, Hedenström 2004/) as well as measurements of the dry bulk density of samples of organic sediments from shallow coastal bays /Sternbeck et al. 2006/ Table 13-3. Porosity was assumed to approximate the water content in the latter study. A mean was calculated based on the mean for each locality. A uniform distribution was assumed and min and max values were based on the samples from the lakes/bays. (Mean=0.93, min=0.90, max=0.96 m^3 m^{-3}).

Table 13-4. Input data used for calculations of the porosity of the postglacial sediments. */Hedenström 2004/, **Eckarfjärden /Hedenström and Risberg 2003/. * /Nordén 2007/. The water content of clay gyttja is based on values from Frisksjön, Oskarshamn.**

Stratum/lake	Stratum thickness (m)*	C** (% of dw)	Water content*** (% of wet sample)	Dry bulk dens kg/m^3	Porosity (m^3/m^3)
Eckarfjärden	(Σ 1.75 m)				
Gyttja	0.96	27	93	71.7	95.2
Clay gyttja	0.11	8	86	152.2	93.5
Clay	0.68	1	53	662.0	74.6
Fiskarfjärden	(Σ 3.52 m)				
Gyttja	1	17	93	72.6	96.5
Clay gyttja	0.61	5	86	152.7	93.8
Clay	1.91	1	53	661.7	74.6
Stocksjön	(Σ 0.49 m)				
Gyttja	0.4	27	86	149.5	91.8
Clay gyttja	0.03	8	86	152.2	93.5
Clay	0,06	1	53	662.0	74.6
Gällsboträsket	(Σ 1.41 m)				
Gyttja	0.34	27	86	149.5	91.8
Clay gyttja	0.37	8	86	152.2	93.5
Clay	0.7	1	53	662.0	74.6
Bolundsfjärden	(Σ 0.6 m)				
Gyttja	0.48	27	90	104.8	94.3
Clay gyttja	0.07	8	86	152.2	93.5
Clay	0.05	1	53	662.0	74.6
Puttan	(Σ 0.82 m)				
Gyttja	0.8	20	89	116.4	94.2
Clay gyttja	0.02	9	86	152.1	93.4
Clay	0	1	53	661.7	74.6
N:a Bassängen	(Σ 0.16 m)				
Gyttja	0.15	27	86	149.5	91.8
Clay gyttja	0.01	8	86	152.2	93.5
Clay	0	1	53	664.2	74.9

Density of till (dens_regoLow)

The values are based on the dry bulk density of till, i.e. sandy till to clayey till at depths below 0.3 m from five localities (Table 13-5) at the site /Lundin et al. 2005b, Sheppard et al. 2009/. The statistics are calculated from means for each locality. A normal distribution is assumed. (Mean=2,132, SD=87, min=1,980, max=2,200 kg m^{-3})

Porosity of till (poro_regoLow)

The parameter values represent the porosity of glacial till (Table 13-5). The porosity values for till are based on 15 measurements from > 0.3 m depth from four localities in the terrestrial area of the Forsmark site /Lundin et al. 2005b/. The statistics are based on the means for the four localities. A normal distribution is assumed. (Mean=0.21, SD=0.04, min=0.18, max=0.27 m^3 m^{-3})

Root zone in arable land (Agri_z_regUp)

This parameter represents the thickness of the layer in arable land that is regularly ploughed and is taken from /Karlsson et al. 2001/. This should be regarded as the layer where the majority of the crop roots are found. (Mean= 0.25, min=0.20, max=0.30 m)

Table 13-5. Data describing the different samples used to estimate till properties /Lundin et al. 2005b, Sheppard et al. 2009/.

ID CODE	Sampling depth (m)	QD	REL MATRIX VOL (%)	REL PORE VOL (%)	WATER CONTENT (%)	DRY BULK DENSITY (g cm^{-3})
PFM004455	0.50–0.55	sandy till	69.0	31.0	7.4	1.90
PFM004455	0.80–.085	sandy till	75.7	24.3	10.4	2.00
PFM004455	1.20–1.25	sandy till	72.9	27.1	11.7	2.00
PFM004455	1.70–1.75	sandy till	70.2	29.8	17.1	1.90
PFM004455	2.50–2.55	clayey sandy till	77.0	23.0	14.4	2.10
PFM004458	0.50–0.55	sandy till	77.4	22.6	15.6	2.10
PFM004458	0.80–0.85	gravelly till	77.8	22.2	15.3	2.10
PFM004458	1.20–1.25	gravelly till	81.7	18.3	14.9	2.20
PFM004458	1.70–1.75	sandy till	83.7	16.3	15.1	2.20
PFM004458	2.50–2.55	sandy till	83.0	17.0	13.3	2.20
PFM004459	3.50–3.55	clayey sandy silty till	80.2	19.8	18.9	2.20
PFM004460	0.50–0.55	sandy till	78.1	21.9	14.9	2.10
PFM004460	0.80–0.85	sandy till	79.3	20.7	16.0	2.10
PFM004460	1.20–1.25	sandy till	83.4	16.6	16.8	2.20
PFM004460	1.70–1.75	sandy till	86.0	14.0	15.9	2.30
AFM001076	0.35	clayey till	–	–	10.0	2.12
AFM001076	0.35	clayey till	–	–	8.8	2.10
AFM001076	0.35	clayey till	–	–	9.8	2.21

13.3.2 Hydrological parameters

The following is a description of parameters describing different water fluxes used in the dose modelling. The water fluxes between different soil/sediment layers have been modelled using MIKE SHE (DHI Software 2008). MIKE SHE is a dynamic, physically based modelling tool that describes the main processes in the land phase of the hydrological cycle. A brief outline of the MIKE SHE modelling follows below, but a more detailed description is presented in /Bosson et al. 2010/. Moreover, the two parameters “well capacity” and “wind velocity” at the end of this section have both been measured at the site.

In order to calculate the hydrological parameters for the dose model, water balances for today’s conditions have been analysed for different lakes. By simulating different time periods (i.e. different shoreline positions, regolith distribution,) and climate cases, the hydrological fluxes for future conditions have been described /Bosson et al. 2010/. A preliminary SR-Site MIKE SHE model was set up and calibrated based on a previous modelling /Bosson et al. 2008, Bosson et al. 2010/. The SR-Site model was set up at three different times: 2000 AD, 3000 AD and 5000 AD. Results from the preliminary SR-Site model for 5000 AD were used in order to calculate water fluxes to, from and between lake and mire areas in Forsmark /Bosson et al. 2010/. Six different lake objects were selected for the calculation of water balances in 5000AD. The main reason for choosing existing lakes is that the body of data is more extensive and the lakes are better described in the model. The lakes are of different sizes, with different vegetation and different thicknesses of underlying sediments. In this way the average value for the six lakes should represent an average lake within the model area. Each water balance is calculated for one year, i.e. the results are annual mean values. Three different water balances were calculated for each object: one for the lake area, one for the mire area, and one for the total area (lake+mire), resulting in a total of 18 water balances.

A schematic description of the fluxes considered in the lake/mire water balances is shown in Figure 13-2a. In the MIKE SHE model, 4 layers are identified: 1) Overland (OL) corresponds to lake water, 2) L1 is lake sediments (corresponds to Aqu_regoUp, Aqu_regoMid_Gl and Aqu_regoMid PG in section 13.3.1), 3) L2 is till (corresponds to regoLow in section 13.3.1) and 4) L3 is the bedrock. Fluxes between the different vertical layers (surface water, sediment, till and bedrock) are modelled as well as horizontal fluxes between the lake and the mire. In addition, the total horizontal fluxes into and out of the total lake+mire area are calculated. After calculations of water balances, all values are normalized with respect to the area, i.e. expressed in mm y^{-1}.

MIKE SHE and the radionuclide model divide the ecosystem components somewhat differently and the outputs from water balances in MIKE SHE had to be transformed in order to fit the set-up in the radionuclide model. A box model for the hydrological fluxes were set up (Figure 13-2b). The OL in Mike SHE corresponds to lake water in limnic ecosystem. L1 Mike SHE consists of lake sediments and corresponds to Aqu_regoUp, Aqu_regoMid_Gl and Aqu_regoMid PG. L2 consists of till and corresponds to regoLow and L3 is the bedrock i.e. belong to the geosphere and are not included in the radionuclide model for the biosphere. In the hydrological box model a fictive box (Ter_water) was introduced which is not present in the radionuclide model. This box was necessary to include in the hydrological modelling in order to get a correct water balance for each box and for the entire model. Finally, the hydrological parameter values are used in the Pandora model to calculate flows between different compartments in the ecosystems (Figure 13-2c).

In the model simulations, the radionuclide releases from the geosphere are directed to the lower regolith. Thereafter a vertical flux from the lower regolith to the Aqu_regoMid (lake_ adv_low_mid) and distribution of this flux between terrestrial area (i.e. mire) and lake is calculated (fract_mire). In the mire, a flux from Ter_regoMid (i.e. post-glacial and glacial deposits) to the Ter_regoUp (peat) is calculated. The vertical fluxes between the lake water and sediment are assumed to be equal in both directions. The same fluxes are used to represent the water exchange between Aqu_regoUp and Aqu_regoMid. Thus, in the radionuclide model, there is a flux from the middle regolith layer to surface water (Lake_Aqu_adv_mid_up_norm). The lateral fluxes between mire and lake are calculated as functions of area_subcatch (the sub-catchment areas of the object) and runoff (runoff) and by introducing a flooding coefficient (Flooding_coef). The runoff and flooding coefficient were estimated based on water balances in the MIKE SHE SDM-Site model /Bosson et al. 2008, Bosson et al. 2010/. Below follows the derivation of the hydrological fluxes for the radionuclide model and the empirically estimated parameter values describing well capacity and wind velocity.

Water flux from the till (adv_low_mid)

This parameter represents the total advective flux from the regoLow (till) to the Ter_regoMid and Aqu_regoMid (which are the postglacial and the glacial deposits) (m/y). This was estimated by summing the net fluxes from Ter_regoLow and Aqu_regoLow in Figure 13-2. (60–17) + (9–8) = 44 mm/y = 0,044 m/y (Table 13-6).

The fraction of the water flux that goes to the mire (fract_mire)

This parameter represents the fraction of the advective flux from the regoLow that goes to the mire. The fraction of the total flux from the regolith low that goes to the mire was estimated as: (60–17) / 44 = 0.98 (see Figure 13-2, Table 13-6).

Water flux from the postglacial/glacial deposits to the peat layer (Ter_adv_mid_up_norm)

This parameter represents the advective flux in the terrestrial object from the regoMid to the regoUp normalized by the net lateral advective fluxes from the mire. This flux was obtained as follows: The flux from the regoMid was set to (239+492+17) = 748 mm/y (see Figure 13-2). The flux from other compartments to the regoMid was set to (436 + 10) = 446 mm/y (see Figure 13-2). The normalized net flux was accordingly (748–446)/(972+17) = 0.31 (Table 13-6).

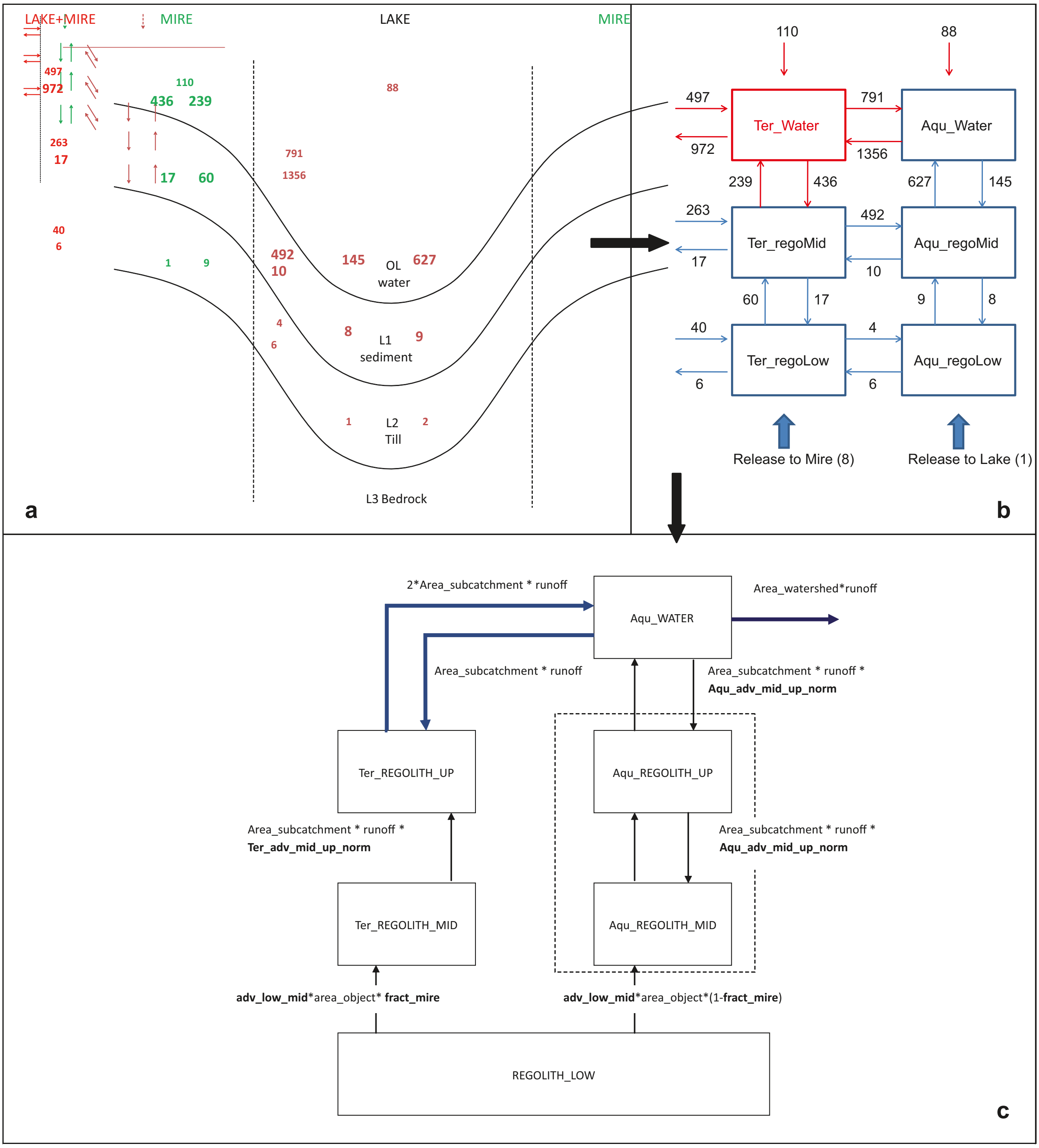


Figure 13-2. *Detailed hydrological models are used to parameterise water fluxes between compartments in the radionuclide model. a) Advective fluxes represent fluxes for the average lake-mire object obtained from the MIKE SHE simulations (n=6). The numbers are mean values for the six lakes (see Table 11-7) included in the modelling. Units are in mm y^{-1}. Net precipitation is included in the figure to obtain water balance in each compartment. b) Advective fluxes (units in mm y^{-1}) for an average lake-mire object obtained for MIKE SHE simulations and transformed to a box model. c) Conceptual representation of the water fluxes in the radionuclide model with parameter names in bold representing hydrological fluxes described in this section.*

Table 13-6. Parameter values describing hydrological fluxes estimated from MIKE SHE simulations /Bosson et al. 2010/. Adding the prefix Lake/Sea from column 3 or 4 to the names in column 1 will yield names that correspond to the parameter names used in the dose modelling. One exception is the Ter_adv_mid_up_norm that is only applicable in the lake-mire period and therefore lacks a prefix.

Parameter	Unit	Lake-Mire period	Sea period*
Adv_low_mid	m/y	0.044	0.008
fract_mire	unitless	0.98	0
Ter_adv_mid_up_norm	unitless	0.31	0
Aqu_adv_mid_up_norm	unitless	0.64	0
Flooding_coef	unitless	1.3	–

*For the sea period it is assumed that there a net upward flux equal to the flux from the geosphere to the regolith-low. This flux is assumed to be constant though the regolith_low and sediment layer, because there is no influence of lateral surface fluxes as in the terrestrial period. The fluxes are directed to the aquatic part, so the fraction to mire in this case is zero.

Water flux to and from lake sediments normalized by the flux from the mire (Aqu_adv_mid_up_norm)

This parameter represents the advective flux in the aquatic object between the regoMid and the regoUp and between the regoUp and the water normalized by the net lateral advective fluxes from the mire. This flux was obtained by adding all fluxes to and from the lake sediment and normalizing by the fluxes out from the mire (sub-catchment area *runoff). Total flux to the lake sediment is set to (145 + 492)/(972+17) = 637/(989) = 0.64 and total flux from the lake sediment is set to (627+10)/(972+17) = 637/(989) = 0.64 (Table 13-6).

Water flux describing the lake flooding (Flooding_coef)

This coefficient describes the part of the gross annual lateral flux of water entering the biosphere object that also is transported from the lake to the mire (Figure 13-2c). In the model the flux from the mire to the lake is represented by runoff*area_catchment*(1+Flooding coefficient) (see Figure 13-2c). The MIKE-SHE results suggest that the flux leaving the biosphere object is represented by (972+17) (Figure 13-2a and b), which is synonymous to runoff*area_catchment. The MIKE-SHE results also suggest that the flux from the mire to the lake is (791+492+972+17). Accordingly, this gives the expression runoff*area_catchment*(1+Flooding coefficient)=791+492+972+17. By assuming that runoff*area_catchment is equal to (972+17) and rearranging the expression, flooding_coef is equal to (791+492+972+17)/(972+17)–1=1.3 (Table 13-6).

Alternative calculations – Periglacial domain estimate

For the alternative calculation describing radionuclide behaviour during permafrost, values were derived from a separate MIKE SHE modelling for biosphere object 114 (Table 13-7) and are further described in /Bosson et al. 2010/.

Table 13-7. Parameter values describing hydrological fluxes during a periglacial domain estimated from MIKE SHE simulations /Bosson et al. 2010/. These values were used in a supporting calculation studying the effect of periglacial conditions in radionuclide modelling.

Parameter	Unit	Lake-Mire period
Lake_adv_low_mid	m/y	0.003
Lake_fract_mire	unitless	0.33
Ter_adv_mid_up_norm	unitless	0.0014
Lake_aqu_adv_mid_up_norm	unitless	0.03
Flooding_coef	unitless	1.1

Runoff (Runoff)

The runoff parameter represents the total mean annual runoff for the SDM-site model area in MIKE SHE. Of the total mean annual runoff of 0.186 m, 0.144 m is runoff from surface streams and 0.042 m is direct runoff from the surface to the sea. The runoff was estimated by calculating a water balance based on three years of simulation. The calculation was based on the final MIKE SHE SDM-site model /Bosson et al. 2008/. Minimum, maximum and the standard deviation for runoff were taken from long time regional measurements at Vattholma (SMHI station 50110). The statistics was based on a time series of monthly mean discharge from 1,917 to 2,000. The long time series was also compared to results from the MIKE SHE model of the Forsmark area describing the hydrological conditions at different time periods (2000AD, 5000AD and 10000AD). The model results are similar to the long term data set from Vattholma. Hydrological data from the Vattholma station are described in /Larsson-McCann et al. 2002b/. (Mean=0.186, SD= 0.08, min= 0.07, max= 0.45 my^{-1})

Alternative calculations – Periglacial domain estimate

Runoff was estimated from a separate MIKE SHE modelling for a potential talik in biosphere object 114 presented in /Bosson et al. 2010/. (Mean=0.217 my^{-1})

Well capacity (wellCapac)

This is a description of the potential water yield, or well capacity, from wells in the Forsmark candidate area. The water yield of the percussion-drilled boreholes in the Forsmark candidate area is exceptional compared with the water yield of domestic bedrock wells in northern Uppland. The parameter estimate derives from 22 percussion boreholes located in the area close to or directly above the repository /Gentzschein et al. 2007/. The median value for the well capacity of the data set for the percussion boreholes is about 20 times greater than the values for the surrounding domestic wells outside the candidate area. The reason for this is that these wells penetrate sheet joints located deep within the investigation area. Drilled wells located farther away could result in elevated activity concentrations in the well water. However, it is considered to be unlikely that a low capacity well outside or inside the investigation area would receive 100% of released radionuclides. The difference between the water yield inside and outside the candidate area is further discussed in /Gentzschein et al. 2007/. The complete data set is found in the SKB database Sicada. Data are taken from the HFM wells numbers HFM1–HFM22. (Geometric mean= 82,502, geometric SD= 4.3, min=1,892, max=630,720 $m^3\ y^{-1}$)

Wind velocity (vel_vind)

Data from the local meteorological station Högmasten were used to determine the wind speed at the Forsmark site. The data set was obtained from the SKB database Sicada (the Sicada delivery ID is *Sicada_09_054_windspeed)*. The wind speed is registered every 30 minutes and calculations are based on data for the period May 2003 to July 2007. Monthly means were calculated for the whole period, and the monthly means were used for the missing months in 2003 and 2007 so the data set would represent five years. The statistics based on annual mean values are presented in Table 13-8.

Table 13-8. Parameter values for annual mean wind speed.

	Wind speed ($m\ s^{-1}$)	Wind speed ($m\ y^{-1}$)
Mean	1.93	60,919,000
Min	1.82	63,876,000
Max	2.03	57,509,000
Std	0.08	2,558,000
n	5	5

13.3.3 Parameters related to uptake by wetland vegetation

The concentration of radionuclides in biota is calculated using concentration ratios (further described in /Nordén et al. 2010/) and ecosystem specific parameters.

Average biomass of plants (Ter_biom_pp)

The wetland biomass estimates includes both above- and below-ground biomass for trees, vascular plants and bryophytes for three localities, two of which are wetlands and one is a moist drained peatland with planted forest (Table 6-9). The reason for choosing a wetland with a tree layer is that higher biomasses will lead to a higher total content accumulated in biomass of certain radionuclides with specific properties (i.e. Cl-36). This is regarded as a cautious assumption. The minimum estimate is from an open mire in Forsmark dominated by brown mosses, herbs and reed /Löfgren 2005/ and the maximum value is from a 90–100 year old productive Norway spruce forest in Forsmark. The maximum estimate is regarded as a cautious assumption, since a swamp forest or a Scots pine bog generally has a lower biomass than woodlands with a lower groundwater level. (Mean=5.990, min=2.186, max=10.027 kgC m^{-2}).

Alternative calculations – Periglacial domain estimate

This estimate is based upon data presented in a review by /Wielgolaski et al. 1981/ (ref. 14–20, 23 and 24). The median total biomass was based on nine different studies from arctic and alpine tundra communities classified as wet sedge-moss communities. (Median=0.819 min=0.480, max=1.884 kgC m^{-2}).

Productivity of primary producers as a function of biomass (Ter_prodBiom_pp)

Wetland net primary production (NPP) is used as a function of biomass, i.e. production per unit biomass. Generally, the estimate decreases as perennial tissue, such as wood, increases. This estimate includes both above and below-ground biomass and production for trees, vascular plants and bryophytes. The same wetlands were used as in the calculations of Ter_biom_pp (Table 4-5 and 6-9). A lognormal distribution was assumed and a geometric mean was therefore presented. (Geometric mean=0.081, min=0.058, max=0.130 kgC kgCbiomass y^{-1}).

Alternative calculations – Periglacial domain estimate

This estimate is based upon data presented in a review by /Wielgolaski et al. 1981/. A geometric mean, based on nine different studies from arctic and alpine tundra communities classified as wet sedge-moss communities, was calculated for the ratio between the NPP and the biomass. (ref. 14–20, 23 and 24 in /Wielgolaski et al. 1981/ gave the following estimates that was used to calculated the productivity; NPP median=93, min=36, max=419 kgC m^{-2} y^{-1}; biomass median=819, min=480, max=1,884 kgC m^{-2}). (Geometric mean=0.099, min=0.019, max=0.511 kgC kgCbiomass y^{-1}).

Annual fractional loss of litter by decomposition (Ter_decomp)

Wetlands exhibit anaerobic conditions throughout most of the peat profile. However, most of the decomposition occurs in the uppermost layer (the acrotelm) that is periodically enriched with oxygen /Malmer and Wallén 2004/. The lower layer, the catotelm, which offers constant anaerobic conditions, also is subjected to decomposition, but at much lower rate. Generally, the variation in heterotrophic respiration may be great due to differences in temperature and precipitation from year to year /Waddington and Roulet 2000/. Long-term estimates are therefore used in the calculations. Primary production and the litter production also affect respiration, but in general heterotrophic respiration is restricted by other parameters in this type of anaerobic environment with an excess of organic material. The estimate calculated here is a combined estimate of the decomposition occurring in the acrotelm and the catotelm and is based on long-term (1,600 years) mean accumulation from the bog Rönningarna in Forsmark /Sternbeck et al. 2006/ (38±11 gC m^{-2} y^{-1} , min 4.6 m^{-2} y^{-1}, max 86 gCm^{-2} y^{-1}). By subtracting the mean accumulation in peat from the NPP of the median wetland (of the three used to calculate Ter_biom_pp and Ter_prob_pp above), a fraction can be calculated representing the long-term annual decomposition. It was implicitly assumed in this calculation that the long-term accumulation in the vegetation was close to zero. The minimum was calculated using the open wetland NPP (253 gCm^{-2} y^{-1}) and the maximum accumulation from /Sternbeck et al. 2006/, where the maximum accumulation is well above the expected long-term range of about 20–50 gC $m^{-2}y^{-1}$ e.g. /Turunen et al. 2002, Malmer and Wallén 2004/. The maximum decomposition can be greater than 1 when the wetland is a net source of carbon during warm and dry years or during years with a prolonged vegetation period. However, here the maximum is set to 1. (Mean=0.91, min=0.66, max=1.0).

Alternative calculations – Periglacial domain estimate

This estimate is based on calculations from a subalpine bog in northern Sweden /Malmer and Wallén 2004/. The net carbon balance of the bog was calculated for two different periods, approximately 800 y BP and the nineteenth century, which gave a mean accumulation of 18.5 kgC m^{-2} y^{-1} (min=17, max=20). They had also calculated the litter input of carbon to be 50 gC m^{-2} y^{-1}, which is much lower than the calculated mean NPP (from the parameter "Productivity of primary producers as a function of biomass" above) used as the long-term litter input. Here we assume an accumulation of 18.5 gC m^{-2} y^{-1}, and use the median NPP (93 gC $m^{-2}y^{-1}$) from the above-calculated periglacial productivity to calculate the fractional loss of litter. The peat accumulation estimate is made in a *Sphagnum*-dominated bog and is not an exact match to the communities with more sedges representing the biomass and the NPP estimate in periglacial wetlands /Wielgolaski et al. 1981/. However, the calculation suggests that a greater fraction of the production is accumulated under periglacial conditions compared with temperate conditions, although the actual amount is less. (Mean=0.80, min=0.78 and max=0.82).

Fraction of decomposed matter that enters the atmosphere (frac_C_atmos)

This is the fraction of the carbon (as CO_2) originating from decomposition of litter that enters the atmosphere. The rest is dissolved in the soil water and both include DOC and DIC. In the parameter above there is an estimate of the fraction that is decomposed and it is therefore necessary to estimate the part that is decomposed and lost in solution. The dissolved carbon (CO_2, CH_4 and DOC) is dominated by DOC 83% followed by DIC 12% and CH_4 6% /Waddington and Roulet 1997/. The mass fluxes within the wetland are greater than the export, and the origin of the DOC seemed to depend on the depth. Surface water contained more allochthonous carbon than deeper water. This was attributed to the shallow water passing through the wetland, whereas the deeper water is more stagnant. /Waddington and Roulet 2000/ estimated the DOC export as 6 gC $m^{-2}y^{-1}$ as a mean of two consecutive years. Here it represents the potential export of carbon (CO_2, CH_4 and DOC), although there are higher concentrations to be found within the wetland. The DOC found within a wetland has both an allochthonous and an autochthonous origin, but here the DOC export figure is set to represent loss of carbon of autochthonous origin from the mire by means other than respiration. The fraction being decomposed but remaining dissolved was calculated by dividing the export of DOC (6 gC $m^{-2}y^{-1}$) by the decomposed part (391 gC $m^{-2}y^{-1}$, calculated for the parameter above). This gives the fraction that could be considered to be decomposed and dissolved, and later transported from the mire. The minimum value was calculated using a high estimate of carbon export from a northern peatland (20 gC $m^{-2}y^{-1}$ /Gorham 1995/). The maximum value was when all carbon entered the atmosphere. (Mean=0.98, min=0.95, max=1.0).

Alternative calculations – Periglacial domain estimate

This estimate is calculated using the same approach as in the temperate case, but using the same primary production as in the periglacial estimate of "Productivity of primary producers as a function of biomass" and the periglacial estimate of carbon accumulation (see the periglacial estimate under "Annual fractional loss of litter by decomposition"). (Mean=0.92, min 0.73, max=1.0).

Release of carbon (Ter_degass_C)

This parameter describes the release of inorganic carbon (as carbon dioxide) that originates from the pool of dissolved inorganic carbon in the wetland to the atmosphere. This flux is depending upon pH, porosity and organic content of the soil. No such studies have been found describing this flux for wetland ecosystems. Unfortunately, an old preliminary calculation was by mistake used in the modelling. This data instead described the total carbon degassing from the three forested wetland soils, including both autotrophic and heterotrophic respiration, which is an overestimate of the degassing by one order of magnitude compared to the figure derived for a lake ecosystem (0.079 kgC $m^{-2}y^{-1}$). Furthermore, the true value is probably somewhat lower for a mire than for a lake. Mainly, because of the CO_2 source (heterotrophic respiration) that is located in the aerobic layer of the peat (and CO_2 does only to a small extent dissolve and becomes a part of the pool of dissolved CO_2 in the anaerobic layer of the peat) and that the peat itself slows down the diffusion and transport of CO_2 to the atmosphere. The implication of this error is that a larger part of the C-14 that enters the wetland will be degassed from the mire and assimilated by the mire vegetation instead of being transported to the lake and assimilated there. Generally, the highest LDFs for C-14 are generated in the lake stage and this suggests that the LDF for C-14 has been underestimated by one or two orders of magnitude. In the SR-Site assessment, C-14 contributes only a very small portion to the final dose estimate and consequently the underestimate of the LDF for C-14 will not affect the final dose estimate. (Total carbon degassing, mean=0.73, min=0.45,max=0.85 kgC y^{-1}).

Concentration of dissolved inorganic carbon in peat (Ter_conc_C_regoUp)

The parameter value represents the concentration of dissolved inorganic carbon (DIC) in a wetland. The parameter estimate is based on a study from northern Sweden, where one depth profile was sampled in a rich flark fen (Kallkällsmyran) during summer /Nilsson and Bohlin 1993/. The mean for the depth profile was used to represent the Forsmark wetlands. A minimum and a maximum value were taken from the same study, where further 12 mires were described. DIC is sensitive to pH in the water and therefore the mean and maximum estimate were back calculated using a higher pH representing the Forsmark region (pH=6.7 representing a Norway spruce wetland) using the following relationship, $C\_soil[\mu mol/l]=pCO_2*(10^{-1.46}+10^{pH-7.76})$. The pH for the mire with the maximum value in the study was assumed to be 6. A normal distribution is assumed. (Mean=0.086, min=0.012, max=0.182 kgC m^{-3}).

The height of the atmospheric layer where CO_2 is taken up by the forested wetland vegetation (Ter_z_mixlay)

This parameter decribes the height of the atmospheric layer from which the vegetation on the forested wetland takes up CO_2 for photosynthesis. C-14 entering the atmosphere from the ground will be mixed with C-12 in a certain volume that here represents the potential CO_2 uptake by the vegetation. The area is determined by the area of the biosphere object, whereas this parameter determines the height. It was calculated according to the equation:

z_mixlay=Daily demand of C(kgC m^{-2})/conc_Air_C (kgC m^{-3})

The daily demand was assumed to be the median annual net primary production divided by the number of days in the vegetation period. The concentration of carbon in the atmosphere was taken from a parameter described below (conc_C_atmos). The height was somewhat lower than the median height of the three forested wetlands described above. This seems to be a cautious estimate because the actual height is at least the height of the vegetation that takes up carbon dioxide. Moreover, this range of values is likely to underestimate the mixed layer height from which carbon dioxide is taken, as turbulent processes will tend to mix air up to the inversion height (100 to 1,000 m) on timescales of less than one hour. (Mean=9.5, min=8.7, max=17.8 m).

Alternative calculations – Periglacial domain estimate

The periglacial estimate is considered to represent a treeless tundra environment. If the z_mixlayer is calculated in a similar way as above using the production estimate cited above and a length of the vegetation period of 100 days this estimate becomes extremly large. Instead a cautious estimate was used describing the maximum hight of vegetation that otherwise generally is lower in a tundra environment. (Mean=0.9. min=0.4, max=1.2 m)

The height of the atmospheric layer where CO_2 is taken up by the crop on the agricultural field (Agri_z_mixlay)

The above-mentioned equation was also applied to the agricultural field, where the total production was calculated using the standard yield of Barley for Forsmark (Table 4-11, including threshing loss and straw yield) and adding root biomass as 19% of total biomass /Andrén et al. 1990/. The daily demand was calculated by dividing the total production by the number of days in the vegetation period /204 days, Table 3-2). A minimum value was calculated by using the minimum value for Forsmark, whereas a maximum value was calculated using the maximum actual yield for Uppsala County for the same period as for the yield in Forsmark.(Mean=4.8. min=4.7, max=8.0 m).

Air concentration of dust (Ter_conc_dust)

No site-specific data on dust concentrations are available from the Forsmark area. Instead a value recommended for assessments of dose to the public in /UNSCEAR 2000/ was used (0.05 mg m^{-3}). The value is of the same order of magnitude as dust concentrations recommended for outdoor environments in risk assessments for contaminated ground by the Swedish Environmental Protection Agency /Liljelind and Barregård 2008, Naturvårdsverket 2009/. The same dust concentration was assigned to agricultural areas (Agri_conc_Dust) and other terrestrial areas (Ter_conc_Dust). The same value is also used to represent a periglacial case. In the probabilistic calculations a maximum value 10% higher than the best estimate was used, while half of the best estimate is used as a minimum value. The parameters were given uniform distributions.

Roughness length (Ter_z_roughness, Agri_z_roughness)

The roughness length is defined as the height at which the wind speed becomes zero when the wind profile above the canopy is extrapolated down through the vegetation. This parameter is used in the radionuclide model for estimating the variation of wind speed with height and the average wind speed in the above-ground mixing layer where photosynthesis is assumed to take place.

/Seinfeld 1986, Mayall 2003/ presented data describing the relationship between vegetation height and roughness length. Data are also presented in Table 3-2 in /Avila and Pröhl 2008/. To represent a forested wetland the value for forests was chosen. Their vegetation height was only 2 m, however. A variation of 10% was assumed to cover the minimum and maximum interval. Normal distribution was assumed. (Ter_z_roughness, mean=1, min=0.9, max=1.1 m).

For the alternative calculation investigating the effect of long-term irrigation /see Avila et al. 2010/ this parameter was also used for an agricultural field representing a farmland with a vegetation height of 1 m. (Agri_z_roughness, mean=0.25, min=0.23, max=0.28 m).

Carbon concentration in the atmosphere (conc_C_atmos)

The behaviour of C in the biosphere is somewhat different from the behaviour of most other elements. As is common practise /IAEA 2001/ a specific activity model /Andersson 2010/ is used for C-14 as is motivated by the strong influence that the C cycle has on the environmental behaviour of this radionuclide. In this model the C-14 specific activity in air is calculated and for this the total C concentration (all isotopes) of the atmosphere (conc_C_atmos) is used.

The Global Monitoring Division of NOAA/Earth System Research Laboratory has measured CO_2 and other greenhouse gases for several decades at a globally distributed network of air sampling sites. A global average was calculated /Tans 2009/. The data were reported as the dry air mole fraction and was converted into mol CO_2 at +5°C using the Ideal gas law. This estimate was then converted to kgC m^{-3}. The measured CO_2 concentration for 2008 was used as a mean. A standard deviation was calculated using the residual variance around the regression line of yearly means between 1980 and 2008. (Mean=2.0E–04, SD=5.9E–07 kg m^{-3}).

Alternative calculations – Periglacial domain estimate

The estimate for the periglacial case was also taken from /Kjellström et al. 2009/, where it was based on ice-core records spanning the last 800,000 years /Kjellström et al. 2009 and references within/.

Values used for the parameter "C concentration in the atmosphere" (conc_C_atmos) in the different climate cases/domains simulated in SR-Site. The values are assumed to be normally distributed. For definitions of the climate concept see /SKB 2010b/. (Mean=1.1E–04, SD=1.4E–02 kg m^{-3}).

Alternative calculations – Global warming estimate

The global warming estimate was based on assumptions made in /Kjellström et al. 2009/. Greenhouse gas concentrations were inferred from ice-core records spanning the last 800,000 years /Kjellström et al. 2009 and references within / The CO_2 level for the warm case was chosen as a compromise between a high level (needed to simulate a warm climate that melts the Greenland ice sheet) and a not too high level (that remains in the atmosphere a long time after emissions have ceased). According to /Lenton et al. 2006/, a 750 ppm level still means that all "conventional" fossil fuel resources (including coal, oil and gas) need not have been used. The same standard deviation as for the temperate case was assumed. (Mean=3.9E–04, SD=5.9E–07 kg m^{-3}).

13.3.4 Parameters related to herbivore uptake

Biomass of herbivores (biom_herb)

In order to derive transfer factors and calculate doses of radionuclides to biota, a number of species characteristics have to be used. Table 13-9 shows biomasses for a number of common herbivores found in the Forsmark regional model area (see section 4.2.).

Herbivore life time (t_life_herb)

In order to derive transfer factors and calculate doses of radionuclides to biota, a number of species characteristics have to be used. Table 13-10 shows the longevity of a number of common herbivores found in the Forsmark regional model area (see Section 4.2.).

Table 13-9. Biomass of an individual for a number of common herbivore species in the Forsmark regional model area.

Species	Biomass (kgC)			Ref
	Mean	min	max	
Roe deer	2.9	1.6	3.5	http://www.jagareforbundet.se accessed 2009-05-28. The min biomass is from a one year old individual
Moose	35.1	23.4	93.6	min weight from http://www.jagareforbundet.se accessed 2009-05-28
European hare	0.44	–	–	R-05-36
Mountain hare	0.35	0.29	0.59	R-05-36, http://www.viltfakta.se, 090404)
Wild boar	7.0	0.1	17.6	R-05-36, max from http://www.jagareforbundet.se accessed 2009-05-28
Capercaillie	0.34	0.06	0.82	Appendix 4

Table 13-10. Duration of life for some herbivore species in the Forsmark regional model area.

	Mean longevity (d)			Ref
	Mean	min	max	
Roe deer	1,095	1	6,205	www.viltfakta.se
Moose	1,351	1	9,125	www.viltfakta.se
European hare	730	1	3,650	Assumed to be the same as for mountain hare below
Mountain hare	730	1	3,650	www.viltfakta.se
Wild boar	584	1	9,855	www.viltfakta.se
Capercaillie	5	1	3,650	www.viltfakta.se

Ingestion rate by different herbivores (IngRate_herb)

In order to derive transfer factors and calculate doses of radionuclides to biota, a number of species characteristics have to be used. Table 13-11 shows ingestion rates for a number of common herbivores found in the Forsmark regional model area (see Section 4.2.). Table 13-12 shows the main components in their diet.

Fraction of mushrooms in the diet of herbivores (frac_mush_Herbiv)

When estimating uptake of radionuclides in terrestrial herbivores in the mire ecosystem the parameter "fraction of mushrooms in the diet of terrestrial herbivores" (frac_mush_Herbiv) is used. The parameter is dimensionless. The value is based on diet data from /Avila 1998, Avila et al. 1999/ presented in Table 13-13 and abundance data as biomass per square metre from Table 4-31. A value was calculated for both Moose and roe deer, which are the two dominating species in the region. The mean value was assumed to be the value weighted for the relative abundance of the two species. The value describing the fraction of mushrooms in the diet of moose, which is the less abundant species, was used as the minimum value. The estimate for roe deer was assigned the maximum fraction in the diet. The parameter was given a uniform distribution. (Mean=0.06, min=0.01, max=0.14).

Table 13-11. Ingestion rates for some common species in the Forsmark regional model area.

Ingestion rate kgC(feed)/kgC(animal)/y	Mean	Ref
Roe deer	27.3	Table 4-31
Moose	11.0	Table 4-31
Mountain hare	55.0	Table 4-31
Wild boar	16.7	Table 4-31
Capercaillie	126.3	Excel sheet for calculation of bird consumption in Simone

Table 13-12. Diet broken down among four groups of food types for common species present in the Forsmark regional model area.

Species	Diet (fraction)				Reference
	Primary producers	Fungi	Animals	Insects	
Roe deer	0.86	0.14	0	0	/Cederlund et al. 1980/
Moose	0.99	0.01	0	0	/Cederlund et al. 1980/
Mountain hare	1	0	0	0	www.viltfakta.se
Wild boar	0.91	0	0.08	0	fraction of volume /Truvé and Cederlund 2005/
Eurasian woodcock	0	0	0	1	www.viltfakta.se
Black grouse	0.9	0	0	0.1	Juveniles eat insects and larvae http://www.sofnet.org/ (accessed 090408)
Capercaillie	0.9	0	0	0.1	Juveniles eat insects and larvae http://www.sofnet.org/ (accessed 090408)
Common Wood-pigeon	0.9	0	0	0.1	Mostly seeds etc http://www.sofnet.org/ (accessed 090408)

Table 13-13. Fraction of mushrooms in the diet of the two most common herbivore species in the Forsmark regional model area and their abundance as standing stock per square metre. Diet data are taken from /Avila 1998, Avila et al. 1999/ and abundance data from Table 4-31.

Herbivore species	Fraction mushrooms in the diet (%)			Abundance (mgC m^{-2})
	Mean	Min	Max	Mean
Moose	0.9	0.25	1.1	36
Roe deer	13.7	4.5	20	21

13.3.5 Human food parameters

Production of berries (prod_edib_berry)

This is an estimate of the berry yield in terrestrial areas of Forsmark. A comparison of the potential yield on mires, on agricultural land and in the forest (Table 13-14) reveals that the forest yield is highest. The high berry yield of cranberry and cloudberry (Landscape type Peatland, Table 4-56) on the mire is close to, but somewhat lower than, the average production per unit area in the forest, represented by bilberry (category Medium which represents the fertility of the ground using an empirical model developed for Finish conditions, Table 4-56), lingonberry (category Other, Table 4-56), raspberry, cloudberry and cranberry (category Woodland, see Table 4-56). The berry yield in agricultural areas is represented here by the rosehip, but this estimate was even lower than that for the mire. Forest berry production was used to represent both wetlands and the drained mire, where the later could be used both for forest production and arable land.

Both bilberry and lingonberry production were positively correlated to tree height/diameter, and tree production on a drained mire is expected to be high. It is therefore assumed that the berry yield is also high, although this must be seen as a cautious assumption as the berry yield is low in former peatlands. Moreover, the collected amount is generally around 5% of the actual yield. (Mean=0.000127, min=0.000089, max=0.000211 kgCm^{-2} y^{-1}).

Alternative calculations – Periglacial domain estimate

One estimate was found from a "foothill tundra" locality in northern Canada /Murray et al. 2005/. Here, cranberry dominated together with crowberry, but cloudberry and some blueberry were also present. They estimated both an "actual" and a maximum yield (0.00012 and 0.00023 kgC m^{-2} y^{-1}). This estimate was close to the temperate estimate (see Table 13-14) and the temperate estimate can therefore also represent the periglacial case.

Production of fungi (prod_edib_mush)

This estimate describes the fungi yield in both woodland and wetlands (Section 4.3.2). Few studies have estimated the production of fungi in wetlands, but /Salo 1979/ investigated fungi yield on drained and fertilized wetlands in Finland and reported a maximum value on a drained and fertilized mire of 0.11 gCm^{-2}y^{-1}. The edible fraction was not presented, however. The yield is generally expected to be lower at Forsmark, and most species that are edible are found in more minerogenic "wetlands", such as Norwegian spruce swamp forests or around streams. However, it is assumed here that the edible fungi yield on woodlands also represents the yield of edible fungi on wetlands, which is therefore a cautious assumption. (Mean=0.000122, min=0.000063, max=0.00021 kgC m^{-2} y^{-1}).

Alternative calculations – Periglacial domain estimate

No estimates of edible fungi yields in tundra environments have been found. The temperate estimate is therefore used. This is probably an overestimate because the yield in Sweden seems to be lower in the northern part than in the southern part of the country /Eriksson and Kardell 1987/, which suggests a declining fungi yield going from the south to the north in boreal areas.

Table 13-14. Berry yield calculated for three different ecosystems in Forsmark.

Ecosystem	Berry yield (kgC m^{-2} y^{-1})			Based on
	Central value	Minimum	Maximum	
Mire	0.000096	0.00007	0.000109	Table 4-56
Forest land	0.000127	0.000089	0.000211	Table 4-56
Agricultural land	0.000081	0.000062	0.000093	Table 4-56

Production of game meat (Prod_edib_game)

This parameter represents the production of wild game that is hunted to some degree in the area or the region. The production estimates are based on the population sizes and their energy budget in terms of consumption, respiration and egestion (see Section 4.2.1). This production was assumed to represent the long-term potential harvest that would keep the game populations near the sizes that are found today. The estimates for the forest and the wetland ecosystems are the same (Table 13-15). As no distinction was made between wetland and forest during the inventories, it is difficult to assign specific feeding habitats to some of the animals (see discussion in Section 4.3). The estimate of game production in forest was chosen to represent the potential production of animals on wetlands and agricultural land as well, since it was higher in the forest and therefore regarded as more cautious (Table 13-15). In the forest, roe deer and moose represent over 90% of production, and accordingly these two species represent the production of wild game with regard to diet selection, life time etc. Roe deer and moose population figures were adjusted, as the densities were estimated after the hunting season, by increasing the density figures by a value corresponding to the loss from hunting in the area based on local hunting statistics (Section 4.2.1). The production estimate comprises the whole animal, whereas the carcass weight, that is the body without the head, intestines and the lower parts of the legs, is normally 55% of the total living weight according to Svensk Viltförvaltning AB /Cederlund 2003, personal communication/. The utilized carcass weight (bones excluded) for moose has not been found in any publication. According to Svensk Viltförvaltning AB, approximately 80% of the carcass weight can be utilized. This means that approximately 44% of the animal is normally eaten, and this estimate is termed prod_edible _game. In the calculation it has been assumed that the utilized carcass weight approach is valid for all animals listed in Table 13-15.

A maximum value was calculated for the production of game meat based on hunting statistics describing the number of moose felled in Uppsala County. Statistics were taken from the National game database (www.viltdata.se) describing statistics from 1994 to 2008. The regional estimate for Uppsala County was close to the Östhammar estimate for 2008 (2.85 and 2.68 moose felled per 1,000 ha, respectively), and the regional statistics were therefore assumed to represent the local population in Forsmark (mean 3.28 moose felled per 1,000 ha). The maximum number of felled moose per 1,000 ha (3.84 in Uppsala County for 1995/96) was 17% higher than the regional mean and the minimum number (2.68 in Forsmark for 2008) was 32% lower than the regional mean. This span was applied to the total woodland game production value (prod_ edible_game) in Table 13-15.

Table 13-15. Data describing the total production of populations of game species. The utilized carcass was calculated based on data from Table 4-31 and 4-43. Production estimates for birds were based on the calculation of consumption described in Section 4.2.2.

Wild game species	Production (kgC m^{-2} y^{-1}) Woodland	 Wetland	 Agricultural land	Comments
Roe deer	1.00E–05	1.00E–05	1.00E–05	
Moose	7.00E–06	7.00E–06	7.00E–06	
European hare	3.00E–07	3.00E–07	3.00E–07	
Mountain hare	4.00E–07	4.00E–07	–	
Wild boar	1.10E–07	1.10E–07	1.10E–07	
Eurasian woodcock	2.15E–09	–	–	
Black grouse	2.91E–09	–	–	
Capercaillie	7.41E–09	–	–	
Common Wood-pigeon	9.58E–07	–	–	
Rodents	3.12E–06	[1)]9.20E–06	2.55E–06	Not utilized as food today
Amphibians and reptiles	2.32E–05	3.60E–06	2.32E–05	Not utilized as food today
Common snipe	–	9.99E–10	–	
Pheasant	–	–	6.58E–09	
Total	1.88E–05	1.78E–05	7.66E–06	

1) Water vole.

Assuming that hunting success is related to population size, the generated span reflects the potential density of a moose population in Forsmark. Moose production is somewhat lower than roe deer production, which together represent approximately 90% of the total production. Although variation in population size is undoubtedly greater for roe deer than moose (due to life history characteristics),the estimated range in production is probably a representative value for a sustainable yield of meat from hunting. (Mean= 0.00000826, min=0.00000561, max=0.00000967 $kgCm^{-2}y^{-1}$).

Alternative calculations – Periglacial domain estimate

In a periglacial environment the same functional groups will be present, but by other species, such as reindeer (*Rangifer tarandus*) and muskox (*Ovibos moschatus*), both of which are herbivores. Reindeer migrate over large areas, whereas muskox is less mobile and spend the summers in the valleys and the winter on higher ground. Such migratory patterns are more pronounced in tundra environments and may have implications on the potential of requiring dose from a specific area. Nevertheless, the periglacial estimate is set equal to the temperate estimate, even though it is considered to be an overestimate of the actual terrestrial animal production.

Domestic animal meat production (prod_edib_meat)

Domestic animals account for meat production in the agricultural areas. Cattle represent 79% of the animal meat produced in Forsmark parish (disregarding milk, which is discussed below), and cattle is therefore chosen as the representative species with regard to species characteristics (Table 13-16). The production of different products as a function of fodder intake was determined to evaluate the productivity of the most common products (Table 13-16). Fodder intake by cattle was calculated based on data from /SLU 1996, Table 229/. Total daily fodder intake was calculated to be 4.0 kgC (min 3.0 kgC and max 5.0 kgC) for meat production and 7.1 kgC (min 6.2 kgC and max 7.9 kgC) for dairy cows (see also description in /Nordén et al. 2010/). Total production in the Forsmark parish (Table 13-16) was then divided by the total consumption of fodder in the parish (number of individuals×fodder intake) to generate figures for beef in Table 13-17. The same procedure was carried out for the other products based on the intake of fodder from /SLU 1996/. Unless stated otherwise, the fodder was assumed to have a water content of 15% and a carbon content of 46%. Minimum and maximum values for meat production were based on differences in the age of the animals at slaughter and in fodder composition (Table 229 /SLU 1996/). Minimum and maximum values for milk production were based on the difference in mean production in 1994 between four common dairy cow breeds /SLU 1996, Table 165/. The difference was divided by the mean production for all breeds (31%). This figure was used on the actual production for the Forsmark Parish to generate a minimum and a maximum value. This span may not capture the full range of differences between individual diary cows, but may serve as a good approximation.

The production of different meat products is characterized by differences in the relation between fodder intake and the meat produced (Table 13-17). Production of chicken meat and eggs has a high efficiency regarding fodder intake, but represents a small part of the total meat production. This higher production efficiency may be approximated by using the milk production efficiency.

Table 13-16. Estimates of animal production in Forsmark parish (Table 4-29 /Miliander et al. 2004a/). Units are kg fresh weight ha^{-1}.

Product	1990	1995	1999	Average	% of total
Milk	487,175	337,275	479,680	434,710	97.2
Beef	7,115	8,870	8,918	8,301	1.9
Mutton	551	422	436	470	0.1
Pork	827	0	0	276	0.1
Chicken meat	1,804	1,353	1,082	1,413	0.3
Eggs	2,805	2,104	1,683	2,197	0.5

Table 13-17. Estimated production of different products as a function of fodder intake (kgC kgCfodder^{-1} y^{-1}). See the text for an explanation of how the figures were calculated.

Product	Central value	Min	Max
Beef	0.006	0.0045	0.008
Milk	0.148	0.102	0.194
Egg	0.138	–	–
Chicken	0.139	–	–

The parameter describing beef production per unit fodder intake should be combined with prod_milk because these parameters are describing an animal husbandry representative for the Forsmark region where a certain number of the animals is used for meat production and another is used for milk production (see 8.3.3). This estimate is also used in a periglacial case, where the fodder production is much less than in a temperate environment. (Mean=0.006, min=0.005, max=0.008 kgCmeat kgCfodder^{-1}). To give an estimate of the production per unit area this estimate has to be multiplied with the parameter prod_fodder (kg m^{-2}, described below). However, this was not done in the radionuclide modelling /Avila et al. 2010/ and the estimate above was instead used directly, meaning that the actual meat production per unit area of suitable land was underestimated by a factor 5. The effect of this underestimation is discussed in /Avila et al. 2010/.

Production of milk (prod_milk)

See under prod_meat above for a description.

(Mean=0.148, min=0.102, max=0.194 kgCmilk kgCfodder^{-1})

To give an estimate of the production per unit area this estimate has to be multiplied with the parameter prod_fodder (kg m^{-2}, described below). However, this was not done in the radionuclide modelling /Avila et al. 2010/ and the estimate above was instead used directly, meaning that the actual meat production per unit area of suitable land was underestimated by a factor 5. The effect of this underestimation is discussed in /Avila et al. 2010/.

Production of cereals (prod_edib_cereals and prod_cereals)

Barley is the most commonly used crop in the area today. The yield is the standard yield estimated for the Forsmark yield area (SKO-0322) 2000–2007 (Table 4-11 excluding threshing loss and straw yield). The minimum value is a minimum value based on the standard yield from the same period and the same area, while the maximum is the highest mean yield from the same period describing the actual yield but from Uppsala County /SCB 2009/. The difference between the standard yield and the actual yield is that the standard yield is normalized with regard to effects of weather. The standard yield may be usable as it is calculated for small regions and thereby gives a reliable estimate for the particular region in comparison with other regions. The actual yield for Uppsala County was used to describe a maximum yield that in most cases is a function of favorable weather. Water content was estimated to be 14% /SCB 2000b/ and carbon content to be 50% of the dry weight. (Mean=0.114, SD=0.003, min=0.112, max=0.189 kgC m^{-2} y^{-1}).

The total above-ground yield including threshing loss (1.05 representing the spike and husks) and straw yield (1.4 representing the straw) was also estimated (prod_cereals). (Mean=0.168, SD=0.004, min=0.165, max=0.278 kgC m^{-2} y^{-1}).

Alternative calculations – Periglacial domain estimate

This estimate is based on data on the production of spring barley in Norrbotten County in the far north of Sweden situated on the boreal taiga between 1965 and 2008 /SCB 2009/. Most of the agricultural areas are situated in the coastal regions in that area. These areas do not have permafrost and crop production must be regarded as much higher than expected under periglacial conditions. (Mean=0.091, SD=0.024, min=0.014, max=0,137 kgC m^{-2} y^{-1}).

The total above-ground yield including threshing loss (1.05) and straw yield (1.4) was also estimated (prod_cereals). (Mean=0.134, SD=0.035, min=0.021, max=0.202 kgC m^{-2} y^{-1}).

Alternative calculations – Global warming estimate

An estimate of cereal production was taken from the very south of Sweden (Skåne) /SCB 2009/ with an annual mean temperature of between +7 and +8° C and a precipitation of 700–800 mm (1951–80) /Eckersten et al. 2007/. Spring barley is the most commonly grown cereal crop, closely followed by winter wheat. The yield is higher for the latter and is therefore chosen to represent the yield in a global warming case. (Mean=0.318, SD=0.022, min=0.256, max=0.337 kgC m^{-2} y^{-1}).

The total above-ground yield including threshing loss (1.05) and straw yield (1.4) was also estimated (prod_cereals). (Mean=0.467, SD=0.032, min=0.376, max=0.495 kgC m^{-2} y^{-1}).

Production of root crops (prod_edib_tuber)

Potatoes are the most widely cultivated root crop in Sweden and also in the Forsmark region. Statistics for yield were taken from Uppsala County /SCB 2009/ for the years 2000 to 2005 (except 2001). Carbon content was set to 6.9% based on the content of proteins, lipids and carbohydrates /Altman and Dittmer 1964, Dyson 1978, Rouwenhorst et al. 1991/ (see also Section 4.3.2). (Mean=0.127, SD=0.011, min=0.117, max=0.144 kgC m^{-2} y^{-1}).

Alternative calculations – Periglacial domain estimate

This estimate is based on data on the production of spring barley in Norrbotten County in the far north of Sweden situated on the boreal taiga /SCB 2009/. Most of the agricultural areas are situated in the coastal regions in that area. These areas do not have permafrost and crop production must be regarded as much higher than expected under periglacial conditions. (Mean=0.108, SD=0.027, min=0.0457, max=0.172).

Alternative calculations – Global warming estimate

An estimate of potato production was taken from the south of Sweden (Skåne) /SCB 2009/ with an annual mean temperature of between +7 and +8° C and a precipitation of 700–800 mm (1951–80) /Eckarsten et al. 2007/. (Mean=0.225, SD=0.042, min=0.180, max=0.318).

Production of vegetables (prod_edib_vegetables)

Cabbage was chosen as a representative vegetable. It is not common in the region but is widely cultivated in Sweden. The yield statistics represent the nation and were taken from /Jordbruksverket 2006/ for the years 1999, 2002 and 2004. The dry matter content was set to 12% of wet weight /IAEA 2010/ and the carbon content was set to 33% based on the content of proteins, lipids and carbohydrates /Altman and Dittmer 1964, Dyson 1978, Rouwenhorst et al. 1991/ (see also page 121). (Mean=0.135, min=0.115, max=0.146 kgC m^{-2} y^{-1}).

Alternative calculations – Periglacial domain estimate

Production of vegetables is low due to limitations imposed by climatic conditions in the Arctic such as lack of warmth and moisture, and short growing seasons. At present, agriculture in the north consists mostly of growing cool-season vegetables such as turnips, cabbage, broccoli, carrots and spinach. No estimates of yields of such vegetables have been found for tundra or northern areas. A cautious estimate was made by using the relative yield decrease for fodder (hay, –14%) between Uppsala and Norrbotten to approximate the decreased cabbage yield. (Mean=0.116, min=0.099, max=0.126 kgC m^{-2} y^{-1}).

Alternative calculations – Global warming estimate

The lack of data for yield from vegetables in different parts of Sweden /Jordbruksverket 2006/ makes it difficult to make a direct estimate of the increased yield due to increased temperature. Another approach was used instead where the relative yield increase for fodder (hay, +34%) was applied to the temperate cabbage mean national yield to approximate the increase due to global warming. (Mean=0.181, min=0.154, max=0.196 kgC m^{-2} y^{-1}).

Production of fodder for animal production (prod_fodder)

This parameter is an estimate of the potential animal fodder yield (haymaking). Fodder production for milk and meat production is the most common use of agricultural land in the region. Approximately 80% of the agricultural land area is used for this type of production. Fodder includes hay (grass species) and clover. Data are from /SCB 2007b/ and are based on production estimates from Uppsala County from 2003 to 2006 (see also Figure 4-11). Historically, haymaking was common in wetter ecosystems such as wetlands and sea shore meadows or in drier meadows. Later, more intensified cultivation was common, supported by ploughing, cultivation and fertilization. Table 13-18 shows yield for three different ecosystems. The estimate represents the total above-ground production of herbs/grasses/sedges on a treeless mire in Forsmark (Table 4-1 /Löfgren 2005/ and on a sea shore meadow in Tullgarn south of Sweden /Wallentinus 1973/. The third estimate consists of agricultural statistics on the actual harvest in a meadow. A combined estimate is made for the potential yields representing the ecosystems that can be used for fodder harvest. (Mean=0.200, min=0.078, max=0.594 kgC m^{-2} y^{-1}).

Alternative calculations – Periglacial domain estimate

This estimate is based on data on the production of hay in Norrbotten County in the far north of Sweden situated on the boreal taiga. Most of the agricultural areas are situated in the coastal regions in that area. These areas do not have permafrost and fodder production must be regarded as higher than expected under periglacial conditions. (Mean=0.172, SD=0.025, min=0.124, max=0.177).

Alternative calculations – Global warming estimate

An estimate of hay production was taken from the south of Sweden (Skåne) /SCB 2009/ with an annual mean temperature between +7 and +8˚ C and a precipitation of 700–800 mm (year 1951–80) /Eckarsten et al. 2007/. (Mean=0.268, SD=0.017, min=0.242, max=0.291).

13.3.6 Parameters used to simulate irrigation

In SR-Site, irrigation of agricultural fields with contaminated water is modelled (see /Avila et al. 2010/ for further description). Five different parameters are used in the modelling: the annual number of irrigation events, the total water volume used per year, the water storage capacity of the irrigated vegetation, the average integration time and the fraction of irrigation water derived from a well.

Table 13-18. Production/yield estimates from three different ecosystems that may be used to produce fodder for animal production. A-G is Above-ground.

Ecosystem	Production (kgC m^{-2} m^{-1})	Min	Max	Comment	Reference
Forsmark mire	0.078	0.050		A-G production	/Löfgren 2005/
Sea shore meadow	0.594			A-G production	/Wallentinus 1973/
Agricultural yield of hay	0.200	0.189	0.223	Actual harvest	Table 4-11, Uppsala County

Irrigation events (numb_irrig)

Data on the annual number of irrigation events were taken from Table 8-1 in /Karlsson et al. 2001/ where no references to these values are presented. A sensitivity analysis of the importance of different parameters for the results for modelling irrigation was performed in /Bergström and Barkefors 2004/. The number of irrigation events contributed approximately 10–15% of the variation in results. A uniform distribution was assumed. (Mean=5, min=3, max=7).

Water volume used for irrigation (vol_irrig)

Data on the total water volume used for irrigation during one year were taken from /Karlsson et al. 2001/. They presented an annual irrigation water amount of c. 0.15 m^3m^{-2} for Swedish conditions and this value was used as a best estimate in SR-Site as well. It agrees with the mean annual value for Sweden estimated from figures on irrigated area and water volumes in /Brundell et al. 2008/ (0.12 m^3m^{-2}). A combination of the number of irrigation events and the water volume at each irrigation occasion given in /Karlsson et al. 2001/ was used to determine minimum and maximum values, and a uniform distribution was assumed. (Mean=0.15, min=0.1, max=0.2 my^{-1}).

Water storage capacity of vegetation (leaf_StoreCapac)

In earlier safety assessments by SKB (SR 97, SAFE) interception of irrigation water was described by a lumped parameter that was independent of element-specific behaviours. /Bergström and Barkefors 2004/ identified a need to split this factor into three parameters, one of which (coefRetent, see Section 9.3 in /Nordén et al. 2010/) is element-specific. The other parameters used to simulate retention of irrigation water are the leaf area index (LAI, see below) and the water storage capacity on the vegetation surfaces per LAI. The later parameter is expressed as m^3 m^{-2}. The values used in SR-Site were taken from /Bergström and Barkefors 2004/ who recommend using a value of 0.3 mm per LAI based on /Pröhl 1990/. The minimum and maximum values are also given in /Bergström and Barkefors 2004/ but without references. A uniform distribution was assumed. (Mean= 3.0E–04, min=2.0E–04, max=4.0E–04 m^3m^{-2}).

Leaf area index of crops (Leaf_areaIndex)

The leaf area index is defined as the ratio of the total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. In the SR-Site radionuclide model this parameter is used only for crops to calculate the amount of radionuclide retained by irrigation. The unit used is m^2 m^{-2}. Data for the parameter is from a review of 83 studies describing leaf area index for crops world wide /ORNL DAAC 2009/. (Mean=3.62, SD=2.06, min=0.2, max=8.7 m^2m^{-2}).

Alternative calculations – Periglacial domain estimate

For the periglacial case the estimate was based on 11 studies describing vegetation in tundra environments /ORNL DAAC 2009/. (Mean=1.88, SD=1.47, min=0.18, max=5.3 m^2 m^{-2}).

Average integration time

The time interval over which concentration in vegetables from radionuclides accumulated in soil as a consequence of irrigation with contaminated water is described by the parameter "AverTime". A value of 50 years was used, which is the same value used by ICRP /2007/ in the derivation of dose coefficients used in calculation of average dose during the life time of adults. This parameter was kept at a constant value in the probabilistic simulations.

13.4 Radionuclide model parameterization for the Laxemar-Simpevarp site

This section contains descriptions of the site-specific terrestrial parameters for the Laxemar-Simpevarp area. In the text below are only those parameters for which the values differ from the Forsmark site (described above) are addressed. Moreover, no additional parameter values describing conditions during a periglacial domain or a global warming variant are presented for Laxemar-Simpevarp. For Laxemar-Simpevarp only deterministic radionuclide modelling was done using the central value for each parameter. The results from the radionuclide modelling for the Laxemar-Simpevarp site are presented in /SKB 2010c/. For a review of the characteristics of the Laxemar-Simpevarp area the reader is referred to Chapter 4.

13.4.1 Regolith parameters

Density of glacial sediments (Ter_dens_regoMid_GL)

The parameter values represent the dry bulk density of the glacial clay. The glacial clay is often overlain by peat (Ter_regoUp) and postglacial sediments (Ter_regoMid_PG). The lithological unit and properties of this layer are the same as those used for the aquatic systems layer 'regoMid_GL". The dry bulk density of glacial clay is based on calculations from analyses of water content and content of organic material. For these calculations it was assumed that the organic and minerogenic material have densities of 1 and 2.65 g/cm^3 respectively. Altogether 11 samples from /Sohlenius et al. 2006/ and /Nilsson 2004/ were used for estimating the dry bulk density. The samples were taken from lakes and shallow bays, but also from machine dug trenches in the terrestrial part of the Laxemar area. (Mean=696, SD=171, min=446, max=1,053kg m^{-3}).

Density of postglacial sediments (Ter_dens_regoMid_PG)

The parameter values represent the dry bulk density of the postglacial clay which has been and still is deposited in lakes and bays. In the terrestrial areas post glacial clay is found at the floor of valleys. In the aquatic system, the corresponding deposit is found on accumulation bottoms in lakes and bays. The properties of this layer are the same as those used for the aquatic systems layer 'regoMid_PG'. The postglacial clay in the Laxemar area contains a significant amount of organic material and is therefore referred to as clay gyttja (see /Sohlenius and Hedenström 2008/). The calculation of dry bulk density is based on results from analyses of water content and organic carbon content of clay gyttja. For these calculations it was assumed that the organic carbon and minerogenic material have densities of 1 and 2.65 g cm^{-3} respectively. Altogether 42 samples from lakes and shallow bays /Nilsson 2004/ were used to determine the density of postglacial clay. (Mean=181, SD=65, min=76, max=394 kg m^{-3}).

Porosity of glacial sediments (Ter_poro_regoMid_GL)

The parameter values represent the porosity of the glacial clay which often is overlain by peat (Ter_regoUp) and postglacial sediments (regoMid_PG). The lithological unit and properties of this layer are the same as those used for the aquatic systems layer 'regoMid_GL. The porosity of glacial clay is based on calculations from analyses of water content and content of organic material. For these calculations it was assumed that the pore volume is water saturated, and the organic and minerogenic material have densities of 1 and 2.65 g cm^{-3} respectively. Altogether 11 samples from /Sohlenius et al. 2006/ and /Nilsson 2004/ were used for estimating the porosity. The samples were taken from lakes and shallow bays, but also from machine-dug trenches in the terrestrial part of the Laxemar area. (Mean=0.74, SD=0.07, min=0.60, max=0.83 m^3 m^{-3}).

Porosity of postglacial sediments (Ter_poro_regoMid_PG)

The parameter values represent the porosity of the postglacial clay which has been and still is deposited in lakes and bays. In the terrestrial areas postglacial clay is found at the floor of valleys. In the aquatic system the corresponding deposit is found on accumulation bottoms in lakes and bays. This means that the properties of this layer are the same as those used for the aquatic systems layer 'regoMid_PG'. The postglacial clay in the Laxemar area contains a significant amount of organic material and is therefore referred to as clay gyttja (see /Sohlenius and Hedenström 2008/). The calculation of porosity is based on results from analyses of water content and organic carbon content of clay gyttja. For these calculations it was assumed that the pore volume is water saturated, and the organic carbon and minerogenic material have densities of 1 and 2.65 g cm^{-3} respectively. Altogether 42 samples from lakes and shallow bays /Nilsson 2004/ were used to determine the porosity of postglacial clay. (SD 0.03). (Mean=0.90, SD=0.03, min=0.75, max=0.94 m^3 m^{-3}).

Density of till (dens_regoLow)

This parameter value represents the dry bulk density of till. The till in the Laxemar area has a relatively high content of gravel and stones. It has therefore not been possible to take samples with a known volume and the density of till was consequently not measured. Instead, typical bulk density values of till were taken from the literature. According to /Pusch 1973/ the dry bulk density of typical Swedish till varies between 1,850 and 2,300 kg cm^{-3}. Based on these values the average dry density of till is assumed to be 2,075 kg/m^3. (Mean=2,075, min=1,850, max=2,300 kg m^{-3}).

Porosity of till (poro_regoLow)

This parameter value represents the porosity of till. The till in the Laxemar area has a relatively high content of gravel and stones. It has therefore not been possible to take samples with a known volume and the porosity of till was consequently not measured. Instead, typical porosity values of till were taken from the literature. According to /Pusch 1973/ the porosity of typical Swedish till varies between 0.10 and 0.25 m^3 m^{-3}. Based on these values the average porosity of till is assumed to be 0.18 m^3 m^{-3}. (Mean=0.18, min=0.10, max=0.25 m^3 m^{-3}).

13.4.2 Hydrological parameters

The hydrological parameter values describing water fluxes within biosphere objects for Laxemar-Simpevarp were modelled using MIKE-SHE (Table 13-19). These were derived using the same approach as described above for Forsmark and is described in detail for Laxemar by /Bosson et al. 2010, Andersson 2010/. Some additional parameters were estimated directly using measurements at the site.

Runoff (Runoff)

The runoff parameter represents the total mean annual runoff for the SDM-site model area in MIKE SHE. Of the total mean annual runoff 0.145 my^{-1} is runoff in surface streams and the rest is direct runoff to the sea via the surface or the saturated zone. The runoff was estimated by calculating a water balance based on three years of simulation, October 1, 2004 to September 30, 2007. The calculation was based on the final MIKE SHE SDM-site model /Bosson et al. 2009/. Data describing minimum, maximum and standard deviation was taken from long term regional measurements at the

Table 13-19. Values of the parameter values estimated from the MIKE SHE simulations for Laxemar-Simpevarp. Adding the prefix Lake/Sea from column 3 or 4 to the names in column 1 will yield names that correspond to the parameter names used in the dose modelling. One exception is the Ter_adv_mid_up_norm that is only applicable in the lake-mire period and therefore lacks a prefix. The modelling and derivation of the values is further described under the section describing the values for Forsmark.

Parameter	Unit	Lake-Mire period	Sea period*
Adv_low_mid	m/y	0.057	0.008
fract_mire	unitless	0.25	0
Ter_adv_mid_up_norm	unitless	0.62	0
Aqu_adv_mid_up_norm	unitless	0.99	0
Flooding_coef	unitless	0.87	–

*For the sea period it is assumed that there a net upward flux equal to the flux from the geosphere to the regolith-low. This flux is assumed to be constant though the regolith_low and sediment layer, because there is no influence of lateral surface fluxes as in the terrestrial period. The fluxes are directed to the aquatic part, so the fraction to mire in this case is zero.

station in Forshultesjön nedre (SMHI station 1619). The annual mean values, based on daily mean discharge during the period 1955 to 2000, were used when calculating the statistics of the runoff in the area. The calculated runoff from the MIKE SHE SDM-site model and the long term mean annual runoff in Forshultesjön nedre is only 5%. (Mean=0.17, SD=0.07, min=0.06, max=0.40 my^{-1}).

Well capacity (wellCapac)

This is a description of the potential water yield, or well capacity, from percussion drilled boreholes in the Laxemar-Simpevarp area. The well capacities from private wells in the surrounding area have not been included in the statistics. The well capacity in Forsmark was derived using only data from percussion drilled boreholes, thus the same methodology was used for the Laxemar area. The water yield of 43 percussion-drilled boreholes from wells in Laxemar, Ävrö and Simpevarp has been used when calculating the statistics of the well capacity. The specific capacity Q, m^2/(m drawdown*s), was used to calculate the capacity in $m^3/s = Q*si$, with an estimated value of si = 20 m. (Geometric mean= 8,426, geometric SD= 3.1, min=10, max=332,389 $m^3\ y^{-1}$).

Wind velocity (vel_vind)

Data from the local meteorological station at Äspö were used to determine the wind speed at the Laxemar-Simpevarp site. The data set was obtained from the SKB database Sicada (the Sicada delivery ID is 1238587 – Data Delivery SICADA_10_057_1.pdf). The wind speed is registered every 30 minutes and calculations are based on data for the period October 2003 to October 2007. Monthly means were calculated for the whole period, and the monthly means were used for the missing months in 2003 and 2007 so the data set would represent five years. The statistics based on annual mean values are presented in Table 13-20.

13.4.3 Parameters related to uptake by wetland vegetation

Release of carbon (Ter_degass_C)

This parameter describes the release of inorganic carbon (as carbon dioxide) that originates from the pool of dissolved inorganic carbon in the wetland to the atmosphere. This flux is depending upon pH, porosity and organic content of the soil. No such studies have been found describing this flux for wetland ecosystems. The same degassing value was used as for the lake Frisksjön, which was described by a mean from 4 years (see description of the derivation of the lake values in /Andersson 2010/). This estimate is probably an overestimate of the actual degassing, see discussion under the parameter description for the Forsmark value. (Mean=0.044 kgC $m^{-2}y^{-1}$).

Concentration of dissolved inorganic carbon in peat (Ter_conc_C_regoUp)

The parameter value represents the concentration of dissolved inorganic carbon (DIC) in a wetland. The parameter estimate is a mean from two depths from one mire within a larger comparison of mires from northern Sweden /Nilsson and Bohlin 1993/. This value was close to the overall mean among the 12 investigated mires. A minimum and a maximum value were taken from the same study and the lowest and highest values of all samples were used. DIC is sensitive to pH in the water and the study represented mires with a relative low pH, where the vast majority of the dissolved CO_2 is expected not to be in other forms, such as carbonates. (Mean=0.023, min=0.012, max 0.078 kgC m^{-3}).

Table 13-20. Statistics describing annual wind speed in Laxemar-Simpevarp.

	Wind speed (m s^{-1})	Wind speed (m y^{-1})
Mean	1.66	52,659,305
Max	1.74	58,896,371
Min	1.56	49,203,277
Std	0.06	2,042,600
n	5	5

The height of the atmospheric layer where CO_2 is taken up by the crop on the agricultural field (Agri_z_mixlay)

This parameter decribes the height of the atmospheric layer from which the crop on the drained wetland takes up CO_2 for photosynthesis. C-14 entering the atmosphere from the ground will be mixed with C-12 in a certain volume that here represents the potential CO_2 uptake by the vegetation. The area is determined by the area of the biosphere object, whereas this parameter determines the height. It was calculated according to the equation:

z_mixlay=Daily demand of C(kgC m^{-2})/conc_Air_C (kgC m^{-3})

The daily demand was assumed to be the mean annual net primary production divided by the number of days in the vegetation period (224 days, Table 3-5). The total production was calculated using the standard yield of Barley for Laxemar-Simpevarp (Table 4-11). By adding threshing loss and straw yield, and adding root biomass by assuming that root biomass is 19% of total biomass /Andrén et al. 1990/, the total production was calculated. A minimum value was calculated by using the minimum value for Laxemar-Simpevarp, while a maximum value was calculated using the maximum actual yield for Kalmar County for the same period as for the yield in Laxemar-Simpevarp. The concentration of carbon in the atmosphere was taken from from the parameter described above for Forsmark (conc_C_atmos). (Mean=5.0 min=4.5, max=6.7 m).

13.4.4 Parameters related to herbivore uptake

Ingestion rate by different herbivores (IngRate_herb)

In order to derive transfer factors and calculate doses of radionuclides to biota, a number of species characteristics have to be used. Table 13-21 shows ingestion rates for a number of common herbivores found in the Laxemar-Simpevarp regional model area (see Section 4.2.). Table 13-22 shows the main components in their diet. These rates are almost identical to the rates presented for Forsmark and consequently the same rates may used.

13.4.5 Human food parameters

Production of berries (prod_edib_berry)

This is an estimate of the berry yield in terrestrial areas of Laxemar-Simpevarp. A comparison of the potential yield on mires, on agricultural land and in the forest (Table 13-23) reveals that the forest yield is highest. The high berry yield of cranberry and cloudberry (Landscape type Peatland, Table 4-56) on the mire is close to, but somewhat lower than, the average production per unit area in the forest, represented by bilberry (category Medium which represents the fertility of the ground using an empirical model developed for Finish conditions, Table 4-56), lingonberry (category Other, Table 4-56), raspberry, cloudberry and cranberry (category Woodland, see Table 4-56). The berry yield in agricultural areas is represented here by the rosehip, but this estimate was even lower than that for the mire. Forest berry production was used to represent both wetlands and the drained mire, where the later could be used both for forest production and arable land.

Table 13-21. Ingestion rates for some common species in the Simpevarp regional model area.

Ingestion rate kgC (feed) kgC^{-1} (animal) y^{-1}	Mean	Ref
Roe deer	26.3	Table 4-31
Moose	11.1	Table 4-31
Mountain hare	56,7	Table 4-31
Wild boar	14.7	Table 4-31
Capercaillie	126.3	Excel sheet for calculation of bird consumption in Simone

Table 13-22. Diet broken down among four groups of food types for common species present in the Laxemar-Simpevarp regional model area.

Species	Diet (fraction)				Reference
	Primary producers	Fungi	Animals	Insects	
Roe deer	0.86	0.14	0	0	/Cederlund et al. 1980/
Moose	0.99	0.01	0	0	/Cederlund et al. 1980/
Mountain hare	1	0	0	0	www.viltfakta.se
Wild boar	0.91	0	0.08	0	Fraction of volume /Truvé and Cederlund 2005/
Eurasian woodcock	0	0	0	1	www.viltfakta.se
Black grouse	0.9	0	0	0.1	Juveniles eat insects and larvae http://www.sofnet.org/ (accessed 090408)
Capercaillie	0.9	0	0	0.1	Juveniles eat insects and larvae http://www.sofnet.org/ (accessed 090408)
Common Wood-pigeon	0.9	0	0	0.1	Mostly seeds etc http://www.sofnet.org/ (accessed 090408)

Table 13-23. Berry yield calculated for three different ecosystems in the Simpevarp area.

Ecosystem	Berry yield (kgC m^{-2} y^{-1})			Based on
	Central value	Minimum	Maximum	
Mire	0.000096	0.00007	0.000109	Table 4-56
Forest land	0.00012	0.000088	0.00019	Table 4-56
Agricultural land	0.000081	0.000062	0.000093	Table 4-56

Both bilberry and lingonberry production were positively correlated to tree height/diameter, and tree production on a drained mire is expected to be high. It is therefore assumed that the berry yield is also high, although this must be seen as a cautious assumption as the berry yield is low in former peatlands. Moreover, the collected amount is generally around 5% of the actual yield. The estimate calculated for the Simpevarp area (Table 13-23) is almost identical to the estimate for Forsmark and the Forsmark estimate was therefore used. (Mean=0.000127, min=0.000089, max=0.000211 kgCm^{-2} y^{-1}).

Production of game meat (Prod_edib_game)

This parameter represents the production of wild game that is hunted to some degree in the area or the region. The production estimates are based on the population sizes and their energy budgets in terms of consumption, respiration and egestion (see Section 4.2.1). The production was assumed to represent the long-term potential harvest that would keep the game populations near the sizes that are found today. The estimates for the forest and the wetland ecosystems are similar (Table 13-24). As no distinction was made between wetland and forest during the inventories, it is difficult to assign specific feeding habitats to some of the animals (see discussion in Section 4.3). The estimate of game production in forest was chosen to represent the potential production of animals on wetlands and agricultural land as well, since it was higher in the forest and therefore regarded as more cautious (Table 13-24). In the forest, roe deer and moose represent over 90% of production, and accordingly these two species represent the production of wild game with regard to diet selection, life time etc. Roe deer and moose population figures were adjusted, as the densities were estimated after the hunting season, by increasing the density figures by a value corresponding to the loss from hunting in the area based on local hunting statistics (Section 4.2.1). The production estimate comprises the whole animal, whereas the carcass weight, that is the body without the head, intestines and the lower parts of the legs, is normally 55% of the total living weight according to Svensk Viltförvaltning AB /Cederlund 2003, personal communication/. The utilized carcass weight (bones excluded) for moose has not been found in any publication. According to Svensk Viltförvaltning AB, approximately 80%

of the carcass weight can be utilized. This means that approximately 44% of the animal is normally eaten, and this estimate is termed prod_edible _game. In the calculation it has been assumed that the utilized carcass weight approach is valid for all animals listed in Table 13-24.

A maximum value was calculated for the production of game meat based on hunting statistics describing the number of moose felled in Kalmar County. Statistics were taken from the National game database (www.viltdata.se) describing statistics from 1996 to 2010. The regional estimate for Kalmar County was close to the Oskarshamn estimate for 2010 (2.92 and 4.47 moose felled per 1,000 ha, respectively), and the regional statistics were therefore assumed to represent the local population in Laxemar-Simpevarp (mean 2.4 moose felled per 1,000 ha). The maximum number of felled moose per 1,000 ha (considering both the regional and the Oskarshamn estimates for the period 1996 to 2010) was 86% higher than the regional mean and the minimum number was 20% lower than the mean. This span was applied to the total woodland game production value (prod_edible_game) in Table 13-24. Assuming that hunting success is related to population size, the generated span reflects the potential density of a moose population in Laxemar-Simpevarp. Moose production is somewhat lower than roe deer production, which together represent approximately 90% of the total production. Although variation in population size is undoubtedly greater for roe deer than moose (due to life history characteristics), the estimated range in production is probably a representative value for the sustainable yield of meat from hunting. (Mean= 0.00000768, min=0.00000617, max=0.0000143 kgC$m^{-2}y^{-1}$).

Production of cereals (prod_edib_cereals and prod_cereals)

Barley is the most commonly used crop in the area today. The yield is the standard yield estimated for the Simpevarp yield area 2000–2007 (See Table 4-11). The minimum value is the minimum standard yield from the same period and the same area, while the maximum is the highest mean yield from the same period describing the actual yield but from Kalmar county for the same period /SCB 2007b/. Water content was estimated to be 14% /SCB 2000a/ and carbon content to be 50% of the dry weight. (Mean=0.129, SD=0.006, min=0.117, max=0.173 kgC m^{-2} y^{-1}).

The total above-ground yield including threshing loss (1.05) and straw yield (1.4) was also estimated (prod_cereals). (Mean=0.190, SD=0.009, min=0.172, max=0.254 kgC m^{-2} y^{-1}).

Table 13-24. Data describing the total production of populations of different game species. The utilized carcass was calculated based on data from Table 4-32 and 4-44. Production estimates for birds were based on the calculation of consumption described in Section 4.2.2.

Wild game species	Production (kgC m^{-2} y^{-1})			Comments
	Woodland	Wetland	Agricultural land	
Roe deer	7.8E–06	7.8E–06	7.8E–06	
Moose	7.3E–06	7.3E–06	7.3E–06	
Red/Fallow deer	5.0E–07	5.0E–07	5.0E–07	
European hare	1.0E–06	1.0E–06	1.0E–06	
Mountain hare	3.0E–07	3.0E–07		
Wild boar	5.6E–07	5.6E–07	5.6E–07	
Eurasian woodcock	5.7E–10	–	–	
Black grouse	7.7E–10	–	–	
Capercaillie	2.0E–09	–	–	
Common Wood-pigeon	2.5E–10	–	–	
Rodents	1.4E–05	1)1.0E–05	1.4E–05	Not utilized as food today
Amphibians and reptiles	2.8E–05	2.7E–06	2.8E–05	Not utilized as food today
Common snipe	–	9.83E–10	–	
Pheasant	–	–	4.3E–09	
Total	1.8E–05	1,8E–05	1.7E–05	

2) Water vole

Production of root crops (prod_edib_tuber)

Potatoes are the most widely cultivated root crop in Sweden and also in the Simpevarp region. Statistics for yield were taken from Kalmar County /SCB 2007b/ for the years 2000 to 2006. Carbon content was set to 6.9% based on the content of proteins, lipids and carbohydrates /Altman and Dittmer 1964, Dyson 1978, Rouwenhorst et al. 1991/ (see also Section 4.3.2). (Mean=0.163, SD=0.020, min=0.133, max=0.184 kgC m^{-2} y^{-1}).

Production of fodder for animal production (prod_fodder)

This parameter is an estimate of the potential animal fodder yield (haymaking). Fodder production for milk and meat production is the most common use of agricultural land in the region. Approximately 80% of the agricultural land area is used for this type of production. Fodder includes hay (grass species) and clover. Data are from Statistics Sweden and are based on production estimates from Kalmar County from 2003 to 2006 (see Figure 4-11). (Mean=0.231, SD=0.031 kgC m^{-2} y^{-1}).

13.5 Uncertainties in the parameterization

The site-generic parameterization is in most cases derived from investigations conducted at the site. This ensures that local conditions are used to constrain the potential output of the biosphere radionuclide modelling. However, some aspects of uncertainty associated with spatial and temporal variation and with the extrapolation of present-day site properties to the future are discussed below.

13.5.1 Spatial and temporal variation

In the parameterization, most of the parameters include, in addition to an estimate of the central value, estimates of the standard deviation and minimum and maximum values as well in order to describe the potential variation under present-day conditions. These estimates serve as a basis for a sensitivity analysis to identify the relative importance of different parameters under present-day conditions (see /Avila et al. 2010/). However, some of the field estimates have neither the spatial nor, perhaps more importantly, the temporal scope that would be desirable in a short-term perspective (e.g. 100 years). This means that the described variation for some parameters at the site does not cover the potential variation range, even though the estimated mean may be close to the true mean for a longer time period as well. For example, the modelling of climate parameters, such as precipitation and runoff, lacks a variation range. In the case of runoff the variation range has been shown to be rather small, around 10% /Larsson-McCann et al. 2002b/. Similarly, most of the parameters describing the regolith have a rather small range, which further supports the use of site-generic parameters rather than parameters describing a specific biosphere object. For those parameters where variation is presented, a sensitivity analysis is used to explore how this variation could influence the result of the dose modelling /Avila et al. 2010/. Generally, the variation or range in the site-generic parameter statistics can be regarded as small in comparison with the uncertainties associated with the radionuclide-specific parameterization that is presented in /Nordén et al. 2010/.

13.5.2 Future conditions

The parameterization presented above is used for future conditions up to 120,000 AD covering the three climate domains: temperate, periglacial and glacial. In the glacial domain, the terrestrial area is assumed to be covered by ice /SKB 2010b/. In the radionuclide modelling, the temperate estimates are also used for periglacial and global warming conditions (see Section 13.1.2). The change in some parameter values in connection with shifts between temperate and periglacial domains are potentially large. In some cases, the estimated parameters together with their measures of variation will undoubtedly be valid even under permafrost conditions, e.g. the porosity of peat in a mire or the density of soil used for agriculture purposes. In other cases, the estimates will be overestimates for permafrost conditions, such as tree net primary production. However, as pointed out above, the variation generated by a changing climate will probably be subordinate to the large range found in radionuclide-specific parameterization /SKB 2010a, Avila et al. 2010/. Nevertheless, a alternative calculation was made using the alternative parameter values presented above for periglacial conditions /Avila et al. 2010/. This exercise did not result in higher estimates of annual effective dos to humans suggesting that the results are robust to introduction of further variability in parameters related to climate change.

14 Concluding and generalizing description of the terrestrial ecosystems in Forsmark and Laxemar-Simpevarp

14.1 Introduction

In this chapter, a number of important features of the terrestrial ecosystem are generalised and discussed for each site. These features are all regarded as important input to the safety assessment to which this work is a basic input. There are five major aims with this report; 1) to characterise and describe the terrestrial ecosystems of today and how these were distributed in the past for the Forsmark and the Laxemar-Simpevarp areas, and, moreover, put the descriptive data into a larger context of other regions, 2) to describe major pools, fluxes and sinks of elements within the terrestrial ecosystems, 3) to describe the human impact on the terrestrial ecosystems of both areas, 4) to compare the processes included in the radionuclide model with the site knowledge using a interaction matrix, and finally 5) to present parameter values for the radionuclide modelling in the SR-Site assessment.

Modelling the fate of long-lived radionuclides released from an underground nuclear waste repository entering the surface ecosystems is partly constrained by the fact that a number of generalizations and simplifications have to be made. In this chapter, the attempt is to make generalizations of the terrestrial ecosystems that may underpin assumptions and/or be used directly in the dose modelling in the safety assessment. Reliable descriptions and generalizations of the present-day ecosystems may be more easily made in comparison with the more long-term predictions that have to be made when modelling the fate of radionuclides entering the surface ecosystems. Similarly, the knowledge of how natural analogues/isotopes behave in ecosystems may be used to describe constraints to the potential doses to humans and biota. In this perspective, some aspects of long-term variability and uncertainty are discussed. In the last part of this chapter an attempt is made to evaluate the importance of different processes to the radionuclide modelling.

14.2 Generalization of the terrestrial ecosystems

Generally, there are a number of similarities between the two sites Forsmark and Laxemar-Simpevarp. Both sites are close to the sea and the shoreline displacement has resulted in relatively young terrestrial ecosystems. This is manifested in a low carbon content of soils, generally poorly developed soils, in a thin peat layer in wetlands close to the coast, and in that bogs are found only in the inner parts of the investigation areas or further inland. The vegetation is also similar although Forsmark is situated further north with a somewhat different climate, making e.g. the oak a rare species in this area. However, there are factors, e.g. moisture and nutrient content that may be more important at the local scale than the regional factors for e.g. net primary production (NPP).

The generalization of properties includes a generalization in both space and in time. The spatial extension is restricted to the regional model area (Appendix 1 and 2). The temporal extension is to tens of years, where the ambition is to smooth out extreme values and find an appropriate mean for the sites under present-day conditions that is built upon the site investigations. In some cases, long-term estimates have been used, e.g. for accumulation in the soil organic carbon pool, due to a large variation between years and a continued mineralization of older organic material. In other cases, there have been few site data available and the estimate may be from a specific locality. In most cases the reader is directed to the reference that is presented with the property in the tables.

14.2.1 Wetlands

The flat topography in Forsmark has resulted in a large number of shallow wetlands, whereas Laxemar-Simpevarp with a more pronounced topography has wetlands along the larger valleys. In Laxemar-Simpevarp most of these wetlands have been drained and used as agricultural land.

Wetlands may be split into a number of subcategories (see Section 4.1), but are here presented as two categories, where the presence of trees is one important difference and the presence of a well-developed bottom layer is another. A number of estimates of properties are presented in Table 14-1. These estimates are built upon data presented in previous sections. The forested wetland representing Forsmark is mainly derived from a locality having peaty mor rather than peat soils, and therefore the SOC is a mean of two localities having peaty mor.

Long-term variability and uncertanities

Wetlands have been heavily exploited during the last few centuries, where an increased need for productive land areas has turned wetlands into agricultural land and forests by drainage activities. From the perspective of a safety assessment it is of utmost importance to be able to understand and predict the continuous accumulation of organic material and accompanying elements in wetlands. The organic material is oxidized when the water table is lowered, resulting in a net release of other elements bound to the peat. The estimates of long-term accumulation of organic material in wetlands at the sites presented in this report (Section 4.1.1) are in the higher part of the range of corresponding estimates from literature. Moreover, the long-term accumulation rates are expected to be lower than the short-term or per year values, due to a more or less continuous mineralization in the more deep-lying anoxic layers of the wetland e.g. /Malmer and Wallén 2004/.

14.2.2 Agricultural land

The more pronounced topography in Laxemar-Simpevarp has made wetlands along larger valleys more abundant and many of these wetlands have later been drained and used as agricultural land. This also means that partially peaty soils dominate the agricultural land. The agricultural land is therefore more abundant and evenly dispersed along valleys in Laxemar-Simpevarp than in Forsmark, where the main agricultural area is situated on clayey till in the south east. Arable land, pastures and clear cuts dominate the open land. Many pastures were earlier intensively used but are today a part of the abandoned farmland following the nation-wide general regression of agricultural activities.

Table 14-1. Generalized ecosystem properties for an open wetland and a forested wetland found in Forsmark and Laxemar–Simpevarp, respectively.

Properties	Forsmark		Laxemar-Simpevarp	
	Rich fen	Forested wetland	Poor fen	Forested wetland
Area (m^2)[a]	10,766	10,766	3,400	3,400
Catchment area (m^2)[a]	102,900	102,900	30,100	30,100
Biomass (gC m^{-2})	2,186±1,102[b]	5,971[c]	1,453±419[b]	6,226[c]
NPP (gC m^{-2} y^{-1})	253±59[b]	429±122[c]	342±102[b]	360±102[c]
SOC (gC m^{-2} to 1 m)	43,280[d]	5,960[d]	15,600[e]	44,200[e]
Peat depth (m)	1.4[f]	–	0.85[g]	0.85[g]
Acc. (gC m^{-2} y^{-1})[h]	38±11	38±11	29± 4	29± 4

a) Median from Appendix 10, Table A7-1. No attempt was made to separate between wetland categories.
b) Table 4-5, Section 4.1.1.
c) From Table 6-10.
d) Mean from /Lundin et al. 2004/.
e) Mean from Table 6-32 /Sohlenius and Hedenström 2008/.
f) Regolith depth model, Table 5-8 /Hedenström and Sohlenius 2008/.
g) Regolith depth model, Table 6-8 /Sohlenius and Hedenström 2008/.
h) /Sternbeck et al. 2006/.

Table 14-2. Generalized ecosystem properties for an arable land and a grassland found in Forsmark and Laxemar–Simpevarp, respectively. Grain is produced on arable land whereas pastures include both former arable land and seminatural grassland.

Properties	Forsmark		Laxemar-Simpevarp	
	Arable land	Pasture	Arable land	Pasture
Area (m^2)[a]	4,516	4,516	4,900	4,900
Catchment area (m^2)[a]	21,900	21,900	56,000	56,000
Biomass (gC m^{-2})	199±5[b]	383±86[c]	226±11[b]	445±157[c]
NPP (gC m^{-2} y^{-1})	199±5[b]	380±113[c]	226±11[b]	250±93[c]
SOC[d]	13,884	13,884	20,460	27,600
QD	Clayey till	Till	Clay-gyttja	Till
Soil depth to bedrock (m)	5.8[e]	3.6[e]	5.7[f]	2.1[f]

a) Median Appendix table A7-2. No attempt was made to separate between different agricultural land categories.
b) Table 4-11, above- and below ground. Assuming 19% of total biomass and NPP is allocated to roots.
c) Table 4-15 and 4-16, above- and below-ground. Carbon content is 0.46 of dry weight.
d) Table 8-4 and 8-5.
e) Table 5-8 /Hedenström and Sohlenius 2008/.
f) Table 6-10 /Sohlenius and Hedenström 2008/.
d) Table 5-8 /Hedenström and Sohlenius 2008/.
e) Table 6-10 /Sohlenius and Hedenström 2008/.

Long-term variability and uncertanities

This land use class is characterized by being sustained by human land use. The socio-economic situation in combination with the technical development has mainly determined the regional development of agricultural land so far. Since the 1940s the trend has been to aggregate and rationalize the agricultural land use, where less fertile soils have been abandoned in favour of larger more fertile areas. In the different land use scenarios developed in Chapter 8, the largest variation in terms of yield from the agricultural land would be created by changes in how much of that is used for crop or fodder production. With increasing area, this means that more and more low-fertile soils would be incorporated in the category of agricultural land. However, this incorporation would be restricted by a number of different factors such as the boulder frequency and/or the soil.

The technical development of machinery, plant breeding, nutrient addition and crop rotation have all increased yields several-fold during the last century. This development may be expected to go on and especially a future implementation of genetically modified organisms may further increase potential future yields.

14.2.3 Forests

Both sites are dominated by the coniferous trees Scots pine and Norway spruce, and have a long history of forestry. The forestry management is evident today as a fairly high percentage of younger and older clear-cuts are found in the landscape. Table 14-3 presents data for forests at both sites representing forest on ground with a fairly deep soil depth, excluding Scots pine forest found in areas with a shallow or non-existing soil layer.

Long-term development of forests has been modeled using both the COUP model (Table 4-25) and LPJ-GUESS (Table 14-4). The modeled mean biomasses as an average over a 100 year period, beginning from a clear-cut, are similar, although the NPP estimates obtained using LPJ-GUESS are approximately 140 and 120 gC m^{-2} y^{-1} higher for Forsmark and Laxemar-Simpevarp, respectively.

Table 14-3. Generalized ecosystem properties for a forest located on ground with medium to large soil depth found in Forsmark and Laxemar-Simpevarp, respectively.

Properties Dominant species	Forsmark Needle-leaved trees	Laxemar-Simpevarp Needle-leaved trees
Catchment area (m^2)[a]	200	200
Biomass (gC m^{-2})	9,758[b]	8,821[c]
NPP (gC m^{-2} y^{-1})	603[b]	568[c]
SOC (incl. litter)	8,051[b]	9,015[c]
Soil type	Till	Till
Soil depth to bedrock (m)	3.6[d]	2.1[e]

a) Appendix 7.
b) Table 8-3.
c) Table 8-4.
d) Table 5-8 /Hedenström and Sohlenius 2008/.
e) Table 6-10 /Sohlenius and Hedenström 2008/.

Table 14-4. Mean biomass and net primary production with standard deviation for a forest stand during a 100 year period starting after a clear-cut in Forsmark and Laxemar-Simpevarp, respectively. Results are output from the model LPJ-GUESS, using site data for driving variables. The numbers include both field and tree layer and above and below-ground (From Table 7-7).

Properties	Forsmark	Laxemar-Simpevarp
Biomass (gC m^{-2})	6,767±3,536	6,377±2,945
NPP (gC m^{-2} y^{-1})	478±110	484±94

Long-term variability and uncertanities

Short-term variability in biomass and NPP of forest vegetation is high due to a number of factors, such as age, nutrient availability, moisture, exposure and combinations of these. Model results in Chapter 7 also suggest a large variation. Generally, the variability dominates over many of the regional differences that may be described in most of Sweden. However, comparisons between localities in the south to the north of Sweden has been made e.g. /Berggren Kleja et al. 2007/. They found that a decrease in biomass and NPP for the tree layer was compensated by a similar increase in the field layer when going from the south to the north in Sweden.

In models covering longer time scales, it would be important to include parameters of climatic change and its effect on vegetation. Such a modelling attempt was presented in /Kjellström et al. 2009/, where the vegetation was modelled during both a warmer and a colder climate using the dynamic vegetation model LPJ-GUESS /Smith et al. 2001/ (see Chapter 11). This modelling exercise gave estimates of a number of parameters, such as vegetation type, biomass and NPP. Shifts between vegetation zones, due to a climate change, may have important consequences for cultivation and forestry.

14.2.4 Fauna

There are some differences in the species pools between the sites, mainly due to the more northern location of Forsmark. The most abundant free-living herbivores at both sites are moose and roe deer. When livestock are present they have a higher consumption than other large herbivores, although part of their food generally is imported fodder. At present, the red fox is the largest and most common predator at both sites, altough the Forsmark region also has the lynx, which currently is found only in low abundance. Generally, the density estimates at the two sites are similar. The calculations of total consumption by herbivores suggested that the consumption was somewhat higher in Laxemar-Simpevarp, mainly due to a higher abundance of rodents at the time when the density estimates were made.

Long-term variability and uncertanities

The ungulate population densities are mainly restricted by hunting, predators and severe winter conditions. The importance of these may depend on the species in focus. Today, the moose population is under extensive management and will probably be kept within certain boundaries (5–15 ind·$10km^{-2}$), due to hunting /Truvé 2007/. The roe deer population is also influenced by hunting, but is also affected by the presence of red fox and lynx that both have increasing populations today. Generally, a lower hunting pressure on both herbivores and predators could initially mean higher ungulate populations, but would also imply increasing and expanding predator populations. These would probably restrict the ungulate populations below population densities found today.

14.2.5 Land use

Without exception, human land use has to be regarded the most important factor structuring the landscape. In present-day Europe there are hardly any habitats or landscapes that have not been more or less influenced by human activities /Bakker 1989, Berglund 1991/. People have influenced the landscape in south eastern Sweden more or less intensively since the last Ice Age. A rich diversity of habitats containing large numbers of plant species, including many that probably did not occur in the original natural landscape, has developed as a result of varying natural conditions combined with different land uses. Major factors affecting the flora and fauna are clear-cutting, agricultural management, abandonment resulting in a natural succession, and intensified management.

The amount of resources in the area that humans can utilise is described in Section 8.4.3. This information can be distributed over the different ecosystems in order to estimate how much food that can be obtained from each ecosystem for a sustainable population of humans. This also enables estimation of the maximum sustainable population at the site i.e. /Jansson et al. 2006/.

Long-term variability and uncertanities

Physical properties, e.g. soil properties, bedrock type and topography, are important constraints on land use. Historical maps reveal a close connection between land use intensity and land-cover distribution. The more fertile soils were used for agricultural purposes whereas the less fertile soils were used more extensively for grazing. As management intensity and population increased, more of the medium fertile soils were used for agriculture whereas the poorest soils were assigned to the livestock /Rosén and Borgegård 1999/. Physical properties are important controls on land use but on the other hand, land use can alter biophysical properties both in a short and long time perspective. For example, drainage of soils, straightening of rivers, nutrient depletion, and plantation of conifers or broad-leafed trees may alter the soil properties within a generation.

The identification of how historical and present-day land use is correlated with factors such as Quaternary deposits and vegetation makes it possible to predict landscape changes in the future if we know the land use intensity. One approach may be to model four major scenarios: abandonment, intensification due to cultivation, intensification due to forest management and *status quo* of the present-day land use. This would generate a full-scale picture of how the landscape configuration could vary depending on land use intensity and type of management. Three of these scenarios have been analysed and the results are presented in /Lindborg 2010/.

14.3 Element pools and fluxes

Elements are transported and accumulated in the biosphere to different extents depending on the properties of the element and on the context to which it is exposed. Descriptions of pools and fluxes presented in Chapter 8 and 9 underpin the understanding of accumulation and turnover of elements in different pools in terrestrial ecosystems. Some stable elements can be used to predict the behaviour of radionuclides in the ecosystems i.e. analogues. Also /Tröjbom and Grolander 2010/ made mass balance calculations, but included both terrestrial and limnic data in thier descriptions of element transport and accumulation at the landscape level.

14.3.1 Energy, carbon or organic matter

In the description of fluxes of matter entering the food web, as well as of fluxes within the food web, energy, carbon and organic matter may be regarded as interchangeable quantities. These quantities are also suitable for describing sinks of matter that in a first step is incorporated into biota, and that later is accumulated, more or less decomposed, in the form of e.g. humus or peat in certain parts of the landscape. Many other bioavialable elements follow the same pathway as organic carbon, but accumulation rates may differ between elements, partly due to different mineralization rates. As an example, limiting macro- and micronutrients are generally mineralized at a faster rate than non-limiting elements.

Pools

The field- and model-estimated carbon pools and fluxes for a large number of vegetation types revealed some general patterns common to both sites. The largest carbon pool was found in the humus and mineral soil, followed by the vegetation. Vegetation types developed on water-logged soils gave rise to higher carbon content in the soil due to a thicker organic horizon or a dominating peat layer. The potential size of the pool may serve as a limit to how much that may be accumulated with regard to other elements that follows carbon in a stoichiometric relationship.

Fluxes

The largest carbon flux is the uptake of carbon by primary producers, where approximately half is transformed into biomass. This net primary production creates a demand for a number of macro- and micro-nutrients that are incorporated into the biomass according to more or less well-described stoichiometric relationships, e.g. /Sterner and Elser 2002/. The majority of these elements are taken from the soil via the fine roots, e.g. /Greger 2004/. Along with this uptake of necessary elements, a number of other elements are also incorporated into the biomass in small amounts. Consequently, NPP will set the upper limit to the potential incorporation of different elements into biomass. The NPP may vary over time as an effect of changing properties of the vegetation, but also due to differences in climatic variables between years. Long-term estimates, as in Table 10-4, may therefore serve as an approximation for long-term uptake in e.g. forest stands subjected to clear-cutting. Biomass eventually reaches the soil compartment as litter, where it is mineralized. The balance between litter production and heterotrophic respiration determines to what extent organic material (and incorporated elements) may be accumulated in the soil.

Sinks and sources of carbon

The accumulation of carbon was, however, dominated by accumulation in vegetation. The comparative approach revealed that some of the studied ecosystems were more or less reluctant to emit or accumulate organic material. For example, a clear-cut initiates an increased soil respiration and a release of organically bound elements, whereas some wetland types have a long-term accumulation of organic matter. Especially wetlands dominated by reed in close connection to lakes had both a high production and a high accumulation in the soil organic matter pool.

Both the young soils and the water-logged soils in wetlands are today subjected to a continuous accumulation of carbon. In water-logged soils, the mineralization may be restricted by the anaerobic conditions, whereas in well-drained soils litter production and heterotrophic respiration may be closer to equilibrium. In the more well-drained forests, the organic matter pool in the humus layer seems to build up of over shorter time periods. The humus layer is easily released by fire and seems to vary with the age of the forest /Liski et al. 1998/.

The results in Chapter 10 indicate that the total carbon and nitrogen stocks in Podzol soils reach equilibrium after approximately 2,500 years, which is similar to the approximately 2,000 years reported by /Liski et al. 1998/. However, in deeper soil layers, the carbon concentration seems to increase for c 6,000 years and then level off, indicating a slower dynamic in soil forming processes in deeper horizons. Except for decomposition of organic matter, soil forming processes result in leaching and enrichment of elements within the soil profile. Eventually, these processes will cause a lower pH and relocalisation of elements within the soils. Probably, this relocalisation will go faster in the Laxemar-Simpevarp area, due to the higher buffering capacity in the lime-enriched Forsmark soils. The water-logged soils are today in most cases described as fens, which are fed with water from a catchment area, and accumulate peaty soil. The organic matter originates, in large part, from autochthonous production within the fen. The water-logged peaty soils may further be subjected to accumulation of elements transported with water that adhere to organic material e.g. DOC.

Agricultural land that has a history as a drained peatland will be subject to continuous oxidation of peat, where other elements bound to the organic material also will be released when peatland is transformed to agricultural land. A previous sink will suddenly turn into a source not only for carbon but also for elements earlier accumulated in biomass and later accumulated by adhesive forces to the organic matter.

Food web

Calculated fluxes to free-living mammals, livestock, birds, amphibians and reptiles revealed that the largest flux in the food web was found between agricultural land and livestock. The most important herbivore with regard to consumption and production (except for livestock) is in Forsmark roe deer, closely followed by moose, whereas the opposite is true in Laxemar-Simpevarp. Livestock consumption is the largest flux of carbon from the vegetation, but there is a greater difference between livestock and wild game consumption in Laxemar-Simpevarp than in Forsmark, due to higher abundances of livestock in Laxemar-Simpevarp. In some catchments where livestock was absent, the consumption of vegetation was low. Herbivore consumption (disregarding livestock) is close to 0.5% of the NPP at both sites. Humans were mainly utilizing crops and products from livestock, such as milk, eggs and meat.

Output from the terrestrial system

Export of carbon is mainly in the form of dissolved organic carbon. In relation to the internal fluxes of carbon in the terrestrial ecosystems the export is generally low.

14.3.2 Phosphorous, Thorium, Uranium and Iodine

The mass balances of four elements illustrated some different behavioural patterns, where the water-soluble micronutrient iodine to a large extent was incorporated into the vegetation and also transported further downstream into the lakes. The distribution of the macronutrient phosphorus was similar, but only a small quantity was transported from the terrestrial areas. The mass balance suggested a large retention of phosphorus at the catchment level, where a large part is retained in the vegetation e.g. /Tröjbom and Grolander 2010/. The heavy isotopes of thorium and uranium had their largest pools in the mineral soil and to a lesser extent in the humus layer. They showed a less mobile pattern with small amounts found in the vegetation or transported downstream. However, uranium was the element that had the highest export in relation to input of atmospheric deposition, suggesting a high weathering rate compared with thorium. Generally, it would be expected that weathering on these fairly young soils would be somewhat higher than the average for Sweden.

All of the elements show a higher export from the terrestrial ecosystems in the Laxemar-Simpevarp area than in the Forsmark area, except for uranium. Both phosphorus and iodine are known to precipitate in reactions with $CaCO_3$-rich soils /Greger 2004/, which dominate in the Forsmark area. Moreover, agricultural land is more abundant in Laxemar-Simpevarp, which may explain a higher export of phosphorus in Laxemar-Simpevarp.

14.3.3 Patterns of element distribution in ecosystems

The element distribution among the four compartments mineral soil, humus layer, producers and consumers showed consistent patterns between the sites. Most of the elements found in a higher content in the vegetation were nutrients. The nutrients are found amongst both the non-metals and in the group of metals. Many of the other elements found within the vegetation have analogous behaviour to nutrients and are therefore found accordingly. Other elements seem to be restricted to the fine roots within the producer compartment, such as U, Cd and Hg. Generally, small amounts were found in the consumer compartment and many elements were found to be below the detection limit within this compartment.

14.3.4 Long-term accumulation

The terrestrial vegetation type having the largest potential for long-term accumulation of elements is the wetland, where peat may accumulate for thousands of years. Comparisons suggest that the accumulation of organic material is somewhat higher at both the sites compared with national and boreal averages. With time, this higher accumulation rate will probably declineto average and later on decline further as the wetland gets older. However, the accumulation of organic matter in bogs will, in a safety assessment perspective, be of less importance due to the fact that the vegetation in bogs uses water from precipitation and not groundwater.

14.4 Terrestrial ecosystem processes of importance to a safety assessment

The identification and handling of features, events and processes that are important for transport and accumulation of radionuclides in the environment are also of importance in the assessment of human health and the safety of the environment. Ecosystems are complex, with a large number of structures and functions, and the number of interactions within an ecosystem is immense. A large number of ecosystem properties have been described (Chapter 5) and quantified for a number of ecosystems at both Forsmark and Laxemar-Simpevarp (Chapter 4, 6 and 7). These describe the present conditions at the Forsmark and Laxemar-Simpevarp sites, where field estimates in many cases neither have the spatial, nor, and perhaps more important, the temporal extension that would be desirable in a short-term perspective (e.g. 10 years). This implicates that the estimated variation for many parameters describing the site does not comprise the potential variation range, even though the estimated mean may be close to the true mean even for a longer time period. One way to compensate for this has been to consistently try to compare site data with other data found in the literature or to compare with modelled results. Additionally, an historic aspect has also been included in order to deepen the understanding of the present configuration of the landscape and its land use (Chapter 10). This has resulted in a cross-validated site description of Forsmark and Laxemar-Simpevarp.

The terrestrial ecosystem in focus for the radionuclide modelling is the wetland that is identified as the potential target for discharge of deep groundwater and in most cases is preceeded by a lake stage /Lindborg 2010/. The mire is also potentially used for agricultural purposes after draining. In the time perspective of the safety assessment changes in climate conditions is expected, both naturally occurring and human-induced. During colder climate conditions than today, it is expected that NPP and accumulation of peat in mires will decrease and also the potential yield from agricultural land, until permafrost conditions ultimately sets both NPP, accumulation of organic material and agricultural landuse to a minimum. During warmer conditions i.e. in a global warming case, it is expected that NPP would increase and the peat accumulation would be similar to today or decrease, whereas potential yield would increase until drier conditions sets limits to NPP.

The interaction matrix (IM), described in Chapter 12, is a practical tool to display components and pathways that may potentially affect radionuclide accumulation and exposure. The systematic approach of using an interaction matrix (IM) to identify relevant processes and interactions may save valuable time in an assessment context and also ensure that relevant processes are included, both in site investigations as well as in the radionuclide modelling. The comparison in Chapter 12 includes subjects that are only partly or not treated at all in this report. For example hydrological fluxes have only been briefly handeled in this report and are described elsewhere e.g. /Johansson 2008, Werner 2009, Bosson et al. 2010/, and sorption and desorption processes are handled by /Nordén et al. 2010/. This exercise suggested that all important identified interactions were considered in the radionuclide model. Figure 14.1 is a compilation of the most important processes that were identified from the descriptions of ecosystems at the site and the IM for a mire ecosystem at a given point in time.

Ecosystem characteristics, such as biomass, net primary production, consumption and accumulation of soil organic matter, have been in focus since they are considered to be of interest in a safety assessment perspective because of their direct implications for food web transfer and long-term accumulation in the landscape. In this report, these properties have been quantified, discussed and compared to national or international literature using both data from the site investigations and quantitative modelling approaches (also based on site data as far as possible). A number of other processes that are important are related to water fluxes and have direct consequences for biological processes such as decomposition and for transporting elements to and from a mire ecosystem.

The ecosystems have also been presented in a context of developmental/successional trajectories (Chapter 10), in order to support the assumptions concerning spatial delimitation and distribution of ecosystems and ecosystem succession during an interglacial in the safety assessment, but this is not illustrated in Figure 14.1.

In Chapter 13 the parameter values in the radionuclide modelling associated with terrestrial ecosystems are presented. The estimation of parameter values is based on relevant site data and /or literature data. In many cases, the correspondence between the process in Figure 14-1 and the parameters is not direct and the reader is refered to /Andersson 2010/ for a comprehensive description of how different parameters are used to represent the different processes.

For the long-term perspective, SR-Site uses a reconstruction of the last glacial cycle to give one example of possible future changes in climate and climate-related processes. In the base case, periglacial conditions and globally warmed conditions are modelled using adjustments, such as omitting agricultural pathways, excluding wells and extending the temperate climate to year 60,000AD. Many terrestrial ecosystem parameters are likely to change as the climate changes (Chapter 11) and it was therefore considered nesseccary to calculate alternative values for periglacial and global warming conditions for appropriate parameters (Chapter 11). These alternative parameter values were used to make alternative calculations to investigate the effects of a changed climate on the LDFs in the case of periglacial conditions and as a basis for further discussion of the effects of global warming.

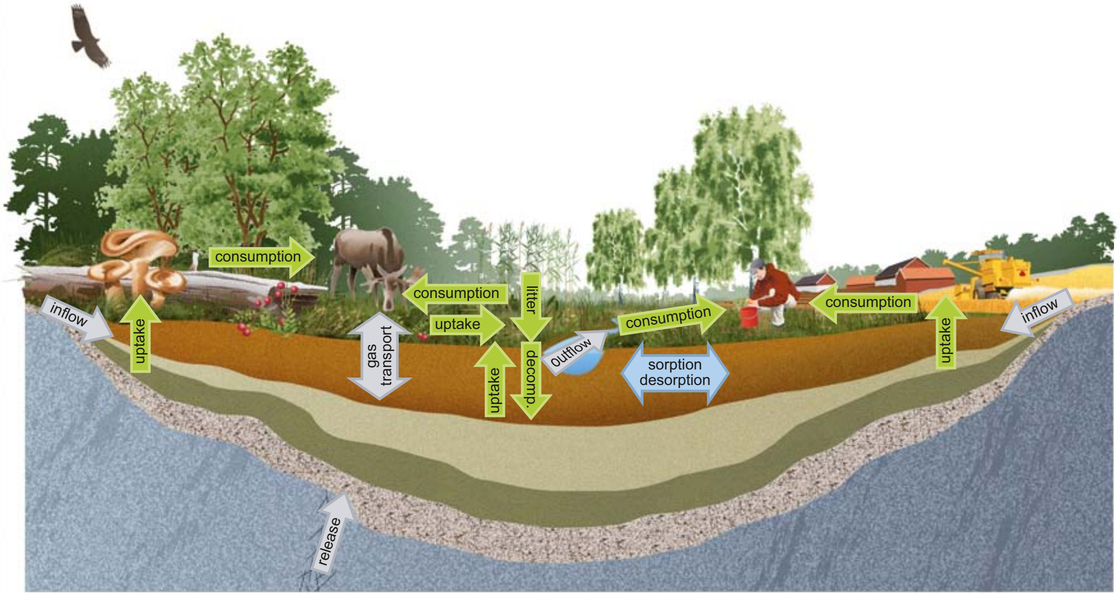


Figure 14-1. *A conceptual description of important fluxes affecting the transport and accumulation of elements in a wetland ecosystem and in an arable land on a drained part of a mire, where the human exposure in a safety assessment is in focus. Green arrows are fluxes mediated by biota, grey arrows are water and gas fluxes, blue arrow represents sorption/desorption processes, consumption also includes water for drinking. The mire was preceded by a lake and a marine stage in which gyttja/clay and postglacial clay were deposited prior to the peat.*

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Abrahamsson T, 2003. Forsmark site investigation. Vegetation inventory in part of the municipality of Östhammar. SKB P-03-81, Svensk Kärnbränslehantering AB.

Ahl D E, Gower S T, Mackay D S, Burrows S N, Norman J M, Diak G R, 2004. Heterogeneity of light use efficiency in a northern Wisconsin forest: implications for modelling net primary production with remote sensing. Remote Sensing of Environment, 93, pp 168–178.

Ahlén I, 2004. Fladdermusfaunan i Sverige. Arternas utbredning och status. Kunskapsläget 2004 (in Swedish). Fauna och flora, 99, pp 2–11.

Albaugh T J, Allen H L, Dougherty P M, Johnsen K H, 2004. Long term growth responses of loblolly pine to optimal nutrient and water resource availability. Forest Ecology and Management, 192, pp 3–19.

Alexandersson H, 2003. Korrektion av nederbörd enligt enkel klimatologisk metodik (in Swedish). Norrköping: SMHI. (SMHI meterologi 111).

Alexandersson H, Moberg A, 1997. Homogenization of Swedish temperature data. Part 1: Homogeneity test for linear trends. International Journal of Climatology, 17, pp 25–34.

Alley R B, Mayewski P A, Sowers T, Stuiver M, Taylor K C, Clark P U, 1997. Holocene climatic instability: a prominent widespread event 8,200 years ago. Geology, 25, pp 483–486.

Alling V, Andersson P, Fridriksson G, Rubio Lind C, 2004a. Forsmark site investigation. Validation of GIS-maps and inventory of vegetation types in Forsmark. Validation and inventory of marshland, swamp forest, fertile land & woodland. SKB P-04-314, Svensk Kärnbränslehantering AB.

Alling V, Andersson P, Fridriksson G, Rubio Lind C, 2004b. Oskarshamn site investigation. Biomass production of Common reed (Phragmites australis), in fauna, epiphytes, sessile epifauna and mobile epifauna. Common reed biotopes in Oskarshamn's model area. SKB P-04-316, Svensk Kärnbränslehantering AB.

Alling V, Andersson P, Fridriksson G, Rubio Lind C, 2004c. Estimation of biomass and primary production of birch. Birch biotopes in Forsmark and Oskarshamn. SKB P-04-315, Svensk Kärnbränslehantering AB.

Alm J, Schulman L, Walden J, Nykänen H, Martikainen P J, Silvola J, 1999. Carbon balance of a boreal bog during a year within an exceptional dry summer. Ecology, 80, pp 161–174.

Alriksson A, Eriksson H M, 1998. Variations in mineral nutrient and C distribution in the soil and vegetation compartments of five temperate tree species in NE Sweden. Forest Ecology and Management, 108, pp 261–273.

Altman P L, Dittmer D S (eds), 1964. Biology data book. Washington: Federation of American Societies for Experimental Biology.

Andersson E (ed), 2010. The limnic ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere. SKB TR-10-02, Svensk Kärnbränslehantering AB.

Andersson E, Tudorancea M-M, Tudorancea C, Brunberg A-K, Blomqvist P, 2003. Water chemistry, biomass and production of biota in lake Eckarfjärden during 2002. SKB R-03-27, Svensk Kärnbränslehantering AB.

Andersson E, Karlsson S, Söderbäck B, Wijnbladh E, 2006. Oskarshamn and Forsmark site investigation. Biomass of benthic and planktonic bacteria in Laxemar and Forsmark and biomass of Reed (Phragmites australis) in Lake Frisksjön. SKB P-06-232, Svensk Kärnbränslehantering AB.

Andersson J, 2004a. Vegetation inventory in part of the municipality of Oskarshamn. SKB P-04-20, Svensk Kärnbränslehantering AB.

Andersson J, 2004b. Forsmark site investigation. Investigation of the amount of dead wood. SKB P-04-124, Svensk Kärnbränslehantering AB.

Andersson J, 2005. Oskarshamn site investigation. Investigation of the amount of dead wood. SKB P-05-87, Svensk Kärnbränslehantering AB.

Andrén C, 2004a. Forsmark site investigation. Amphibians and reptiles. SKB P-04-07, Svensk Kärnbränslehantering AB.

Andrén C, 2004b. Oskarshamn site investigation. Amphibians and reptiles in SKB special area of investigation at Simpevarp. SKB P-04-36, Svensk Kärnbränslehantering AB.

Andrén O, Lindberg T, Paustian K, Rosswall T (eds), 1990. Ecology of arable land: Organisms, carbon and nitrogen cycling. Copenhagen: Munksgaard. (Ecological Bulletins 40), pp 85–126.

Angelstam P, 1992. Conservation of communities. The importance of edges, surroundings and landscape mosaic structure. In: Hansson L (ed). Ecological principles of nature conservation. London: Elsevier Applied Science, pp 4–6.

Aquilonius K (ed), 2010. The marine ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere. TR-10-03, Svensk Kärnbränslehantering AB.

Aquilonius K, Karlsson S, 2003. Forsmark site investigation. Snow depth, frost in ground and ice cover during the winter 2002/2003. SKB P-03-117, Svensk Kärnbränslehantering AB.

Archegova I B, 2007. Thermal regime of tundra soils under reclamation and restoration of natural vegetation. Eurasian Soil Science, 40, pp 854–859.

Arnesson A, 2001. Välskötta vallar ger produktiva ekokor (in Swedish). Uppsala: Sveriges Lantbruksuniversitet. (Fakta Jordbruk 14/2001)

Asaeda T, Karunaratne S, 2000. Dynamic modeling of the growth of Phragmites australis: model description. Aquatic Botany, 67, pp 301–318.

Asaeda T, Hung Nam L, Hietz P, Tanaka N, Karunaratne S, 2002. Seasonal fluctuations in live and dead biomass of Phragmites australis as described by a growth and decomposition model: implications of duration of aerobic conditions for litter mineralization and sedimentation. Aquatic Botany, 73, pp 223–239.

Avery S V, 1996. Fate of caesium in the environment: distribution between abiotic and biotic components of aquatic and terrestrial ecosystems. Journal of Environmental Radioactivity, 30, pp 139–171.

Avila R, 1998. Radiocaesium transfer to roe deer and moose. Modelling and experimental studies. Agraria 136, Uppsala, Sweden.

Avila R, Bergström U, 2006. Methodology for calculation of doses to man and implementation in Pandora. SKB R-06-68, Svensk Kärnbränslehantering AB.

Avila R, Moberg L, 1999. A systematic approach to the migration of 137Cs in forest ecosystems using interaction matrices. Journal of Environmental Radioactivity, 45, pp 271–282.

Avila R, Pröhl G, 2008. Models used in the SFR 1 SAR-08 and KBS-3H safety assessments for calculation of ^{14}C doses, R-08-16, Svensk Kärnbränslehantering AB, Stockholm, Sweden.

Avila R, Johansson K J, Bergström R, 1999. Model of the seasonal variations of fungi ingestion and 137Cs activity concentrations in roe deer. Journal of Environmental Radioactivity, 46, pp 99–112.

Avila R, Ekström P-A, Åstrand P-G, 2010. Landscape Dose conversion Factors used in the safety assessment SR-Site. SKB TR-10-06, Svensk Kärnbränslehantering AB.

BACC, 2008. Assessment of climate change for the Baltic Sea basin. The BACC (BALTEX Assessment of Climate Change for the Baltic Sea basins) author team. Berlin: Springer.

Bachelet D, Neilson R P, Hickler T, Drapek R J, Lenihan J M, Sykes M T, Smith B, Sitch S, Thonicke K, 2003. Simulating past and future dynamics of natural ecosystems in the United States. Global Biogeochemical Cycles, 17, pp 1045–1065.

Badeck F-W, Lischke H K, Bugmann , Hickler T, Hönninger K, Lasch P, Lexer M J, Mouillot F, Schaber J, Smith B, 2001. Tree species composition in European pristine forests: comparison of stand data to model predictions. Climatic Changes, 51, pp 307–347.

Baes C F, Sharp R D, 1983. A proposal for estimation of soil leaching and leaching constants for use in assessment models. Journal of Environmental Quality, 12, pp 17–28.

Baird D, Ulanowicz R E, 1989. The seasonal dynamics of the Chesapeake Bay ecosystem. Ecological Monographs, 59, pp 329–364.

Baker J M, Ochsner T E, Venterea R T, Griffis T J, 2007. Tillage and soil carbon sequestration – what do we really know? Agriculture, Ecosystems and Environment, 118, pp 1–5.

Bakker J P, 1989. Nature management by grazing and cutting: on the ecological significance of grazing and cutting regimes applied to restore former species-rich grassland communities in the Netherlands. Dordrecht: Kluwer Academic Publishers.

Balboa M A, 2005. Biomasa arbórea y estabilidad nutricional de los sistemas forestales de Pinus pinaster Ait., Eucalyptus globulus Labill. y Quercus robur L. en Galicia. Ph.D. thesis. Univesidad de Santiago de Compostela, Spain.

BBC, 2004. European water vole [Online]. Available at: http://www.bbc.co.uk/nature/wildfacts/factfiles/268.shtml. [29 November 2004].

Begon M, Harper J L, Townsend C R, 1996. Ecology: individuals, populations and communities. Boston: Blackwell Scientific.

Benediktsson G, Feldhusen K, Mjureke D, Pettersson S, Sandberg T, Staaf H, Svensson U, Östberg K, 2005. Sweden's National Inventory Report 2005 – submitted under the Monitoring Mechanism of Community greenhouse gas emissions. Swedish Environmental Protection Agency.

Berg B, Ekbohm G, Johansson M B, McClaugherty C, Rutigliano F, Virzo De Santo A, 1996. Maximum decomposition limits of forest litter types: a synthesis. Canadian Journal of Botany, 74, pp 659–672.

Berg B, Johansson M B, Tjarve I, Gaitniekes T, Rokjanis B, Beier C, Rothe A, Bolger T, Göttlein A, Gertsberger P, 1999a. Needle litterfall in a north european spruce forest transect. Report 80, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Berg B, Albrektson A, Berg M, Cortina J, Johansson M B, Gallardo A, Madeira M, Pausas J, Kratz W, Vallejo R, McClaugherty C, 1999b. Amounts of litter fall in some pine forests in a European transect, in particular Scots pine. Annals of Forest Science, 56, pp 625–639.

Berg J, Jansson U, Wästfelt A, 2006. Landscape, history and people in a geographical perspective. Studies of land-use, settlement and livelihood in Oskarshamn and Forsmark. SKB R-06-37, Svensk Kärnbränslehantering AB.

Bergeron Y, 2000. Species and stand dynamics in the mixed woods of Quebec's southern boreal forest. Ecology, 81, pp 1500–1516.

Berggren D, Fröberg M, Bergkvist B, 2003. Transport and leaching of DOC as affected by site properties and climate – a synthesis based on LUSTRA data. A report from LUSTRA, Uppsala.

Berggren D, Bergkvist B, Johansson M-B, Langvall O, Majdi H, Melkerud P-A, Nilsson Å, Weslien P, Olsson M, 2004. A description of LUSTRA's common field sites. Report 87, Swedish University of Agriculture Sciences, Uppsala, Sweden.

Berggren J, Kyläkorpi L, 2002a. Ekosystemen i Forsmarksområdet. Sammanställning av befintlig information (Ecosystems in the Forsmark area. A list of available information) (in Swedish). SKB R-02-08, Svensk Kärnbränslehantering AB.

Berggren J, Kyläkorpi L, 2002b. Ekosystemen i Simpevarpsområdet. Sammanställning av befintlig information (Ecosystems in the Simpevarp area. A list of available information) (in Swedish). SKB R-02-10, Svensk Kärnbränslehantering AB.

Berggren Kleja D, Svensson M, Majdi H, Jansson P-E, Langvall O, Bergkvist B, Johansson M-B, Weslien P, Truusb L, Lindroth A, Ågren G I, 2007. Pools and fluxes of carbon in three Norway spruce ecosystems along a climatic gradient in Sweden. Biogeochemistry, 89, pp 7–25.

Bergkvist M, Ekström L, Eriksson K, Hammarlund E, Hollsten M, Lind A-L, Lundholm K, 2003. Kallrigafjärden, NO Uppland. Områdets historia, nuläge samt framtida landskapsutveckling (in Swedish). SKB R-03-26, Svensk Kärnbränslehantering AB.

Berglund B, 1966. Late-Quaternary vegetation in eastern Blekinge, south-eastern Sweden: a pollen-analytical study. II. Post-glacial time. Stockholm. (Opera Botanica 12)

Berglund B E, 1991. The Late Bronze Age landscape: landscape, land use and vegetation. Ecological Bulletins, 41, p 73.

Berglund B E, Digerfeldt G, Engelmark R, Gaillard M-J, Karlsson S, Miller U, Risberg J, 1996a. Palaeoecological events during the last 15,000 years: regional syntheses of palaeoecological studies of lakes and mires in Europe – Sweden. In: Berglund B E, Birks H J B, Ralska-Jasiewiczowa M, Wright H E (eds). New York: Wiley. (International Geological Correlation Programme, Project 158B), pp 233–280.

Berglund B E, Björse G, Liljegren R, 1996b. Från istid till nutid (in Swedish). In: Gustafsson L, Ahlén I (eds). Sveriges nationalatlas. Växter och djur. Stockholm: Sveriges nationalatlas, pp 14–24.

Berglund K, Persson L, 1996. Water repellence of cultivated organic soils. In: Berglund K, 1996. Cultivated organic soils in Sweden: properties and amelioration. Swedish university of Agricultural Sciences. Department of Soil Sciences. Reports and dissertations 28.

Berglund K, Miller U, Persson J, 1989. Gyttjejordar, deras sammansättning och egenskaper. The composition and properties of gyttja soils. Swedish university of Agricultural Sciences. Department of Soil Sciences. Hydrotechnics Report160.

Bergström E, 2001. Late Holocene distribution of lake sediment and peat in NE Uppland, Sweden. SKB R-01-12, Svensk Kärnbränslehantering AB.

Bergström U, Barkefors C, 2004. Irrigation in dose assessments models. SKB R-04-26, Svensk Kärnbränslehantering AB.

Binkley D, Stape J L, Ryan M G, Barnard H R, Fownes J, 2002. Age-related decline in forest ecosystem growth: an individual tree, stand-structure hypothesis. Ecosystems, 5, pp 58–67.

Birkeland P W, Shroba R R, Burns S F, Price A B, Tonkin P J, 1999. Integrating soils and geomorphology in mountains – an example from the Front Range of Colorado. Geomorphology, 55, pp 329–344.

Björck J, 1999. The Allerød-Younger Dryas pollen zone boundary in an 800-year varve chronology from southeastern Sweden. GFF, 121, pp 287–292.

Björck S, Kromer B, Johnsen S, Bennike O, Hammarlund D, Lemdahl G, Possnert G, Lander Rasmussen T, Wohlfarth B, Hammer C H, Spurk M, 1996. Synchronized terrestrial-atmospheric deglacial records around the North Atlantic. Science, 274, pp 1155–1160.

Björkman L, 1996. The Late Holocene history of beech Fagus sylvatica and Norway spruce Picea abies at stand-scale in southern Sweden. Ph.D. thesis. Lund University, Sweden. (Lundqa Thesis 39).

Black T A, Harden J W, 1995. Effect of timber harvest on soil carbon storage at Blodgett Experimental Forest, California. Canadian Journal of Forest Research, 25, pp 1385–1396.

Black T A, den Hartog G, Neumann H H, Blanken P D, Yang P C, Rusell C, Nesic Z, Lee X, Chen S G, Staebler R, Novak M, 1996. Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest. Global Change Biology, 2, pp 219–229.

Bolinder M A, Janzen H H, Gregorisch E G, Angers D A, Vandenbygaart A J, 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agriculture, Ecosystems and Environments, 118, pp 29–42.

Bolstad P V, Davis K J, Martin J, Cook B D, Wang W, 2004. Component and whole-system respiration fluxes in northern deciduous forests. Tree Physiology, 24, pp 493–504.

Bonan G, 1993. Importance of leaf area index and forest type when estimating photosynthesis in boreal forests. Remote Sensing of Environment, 43, pp 303–314.

Bondeau A, Smith P C, Zaehle S, Schapoff S, Lucht W, Cramer W, Gerten D, Lotze-Campen H, Muller C, Reichstein M, Smith B, 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology, 13, pp 1–28.

Boresjö L, 1989. Multitemporal analysis of satellite data for vegetation mapping in Sweden. Ph.D. thesis. Stockholm University, Sweden.

Boresjö Bronge L, 2004. Satellite remote sensing for estimating leaf area index, FPAR and primary production. A literature review. SKB R-04-24, Svensk Kärnbränslehantering AB.

Boresjö Bronge L, Wester K, 2002. Vegetation mapping with satellite data of the Forsmark and Tierp regions. SKB R-02-06, Svensk Kärnbränslehantering AB.

Boresjö Bronge L, Wester K, 2003. Vegetation mapping with satellite data of the Forsmark, Tierp and Oskarshamn regions. SKB P-03-83, Svensk Kärnbränslehantering AB.

Borgegård S-O, 1994. Förändring och konstans i odlingslandskapet – excemplet Krusenberg, Uppland (in Swedish). Svenska botanisk tidskrift, 88, pp 109–125.

Borgmark A, 2005a. The colour of climate: changes in peat decomposition as a proxy for climate change – a study of raised bogs in south-central Sweden. Ph.D. thesis. Stockholm University, Sweden.

Borgmark A, 2005b. Holocene climate variability and periodicities in south-central Sweden, as interpreted from peat humification analysis. The Holocene, 15, pp 387–395.

Borgmark A, Wastegård S, 2008. Regional and local patterns of peat humification in three raised peat bogs in Värmland, south-central Sweden. GFF, 130, pp 161–176.

Bosatta E, Ågren G I, 1996. Theoretical analyses of carbon and nutrient dynamics in soil profiles. Soil Biology and Biochemistry, 28, pp 1523–1531.

Bosson E, Gustafsson L-G, Sassner M, 2008. Numerical modelling of surface hydrology and near-surface hydrogeology at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-09, Svensk Kärnbränslehantering AB.

Bosson E, Sassner M, Gustafsson L-G, 2009. Numerical modelling of surface hydrology and near-surface hydrogeology at Laxemar-Simpevarp. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-72, Svensk Kärnbränslehantering AB.

Bosson E, Sassner M, Sabel U, Gustafsson L-G, 2010. Modelling of present and future hydrology and solute transport at Forsmark. SR-Site Biosphere. SR Site Biosphere. SKB R-10-02, Svensk Kärnbränslehantering AB.

Botch M S, Kobak K I, Vinson T S, Kolchugina T P, 1995. Carbon pools and accumulation in peatlands of the former Soviet Union. Global Biogeochemical Cycles, 9, pp 37–46.

Bradshaw R H W, Lindbladh M, 2005. Regional spread and stand-scale establishment of Fagus Sylvatica and Picea abies in Scandinavia. Ecology, 86, pp 1679–1686.

Bradshaw R H W, Zackrisson O, 1990. A two thousand year history of a northern Swedish boreal forest stand. Journal of Vegetation Science, 1, pp 519–528.

Bradshaw R H W, Holmqvist B H, Cowling S A, Sykes M T, 2000. The effects of climate change on the distribution and management of Picea abies in southern Scandinavia. Canadian Journal of Forest Research, 30, pp 1992–1998.

Bray J R, Gorham E, 1964. Litter production in forests of the world. Advances in Ecological Research, 2, pp 101–157.

Bridgham S C, Ping C-L, Richardson J L, Updegraff K, 2001. Soils of northern peatlands: histosols and gelisols. In: Richardson J L, Vepraskas M J (eds). Wetland soils: genisis, hydrology, landscapes and classification. Boca Raton, FL: CRC Press, pp 343–370.

Brinson M M, Lugo A E, Brown S, 1981. Primary productivity, decomposition and consumer activity in freshwater wetlands. Annual Review of Ecological Systems, 12, pp 123–161.

Broberg A, Andersson E, 1991. Distribution and circulation of ^{137}Cs in lake ecosystems. In: Moberg L (ed). The Chernobyl fallout in Sweden: from a research programme on environmental radiology. Stockholm: Swedish Radiation Protection Institute, pp 151–175.

Brown J H, Gillooly J F, Allen A P, Savage V M, West G B, 2004. Toward a metabolic theory of ecology. Ecology, 85, pp 1771–1789.

Brunberg A-K, Blomqvist P, 1998. Vatten i Uppsala län 1997. Beskrivning, utvärdering, åtgärdsförslag (in Swedish). Rapport nr 8/1998, Upplandsstiftelsen, Uppsala.

Brunberg A-K, Blomqvist P, 2000. Post-glacial, land rise-induced formation and development of lakes in the Forsmark area, central Sweden. SKB TR-00-02, Svensk Kärnbränslehantering AB.

Brunberg A-K, Carlsson T, Blomqvist P, Brydsten L, Strömgren M, 2004a. Forsmark site investigation. Identification of catchments, lake-related drainage parameters and lake habitats. SKB P-04-25, Svensk Kärnbränslehantering AB.

Brunberg A-K, Carlsson T, Brydsten L, Strömgren M, 2004b. Oskarshamn site investigation. Identification of catchments, lake-related drainage parameters and lake habitats. SKB P-04-242, Svensk Kärnbränslehantering AB.

Brundell P, Kanlén F, Westö A-K, 2008. Water use for irrigation. Report on Grant Agreement No 71301.2006.002–2006.470, Statistiska centralbyrån (Statistics Sweden).

Brydsten L, 2004. A mathematical model for lake ontogeny in terms of filling with sediments and macrophyte vegetation. SKB TR-04-09, Svensk Kärnbränslehantering AB.

Brydsten L, Strömgren M, 2005. Digital elevation models for site investigation programme in Oskarshamn. Site description version 1.2. SKB R-05-38, Svensk Kärnbränslehantering AB.

Brydsten L, Strömgren M, 2010. A coupled regolith-lake development model applied to the Forsmark site. SKB TR-10-56, Svensk Kärnbränslehantering AB.

Bugmann H K M, 1994. On the ecology of mountainous forest in a changing climate: A simulation study. Ph.D. thesis. Swiss Federal Institute of Technology, Zürich.

Burrough P A, Van Der Perk M, Howard B J, Prister B S, Sansone U, Voitsekhovitch O V, 1999. Environmental mobility of radiocaesium in the Pripyat catchment, Ukraine/Belarus. Water, Air, and Soil Pollution, 110, pp 35–55.

Burrows S N, Gower S T, Norma J M, Diak G, Mackay D S, Ahl D E, Clayton M K, 2003. Spatial variability of aboveground net primary production for a forested landscape in northern Wisconsin. Canadian Journal of Forest Research, 33, pp 2007–2018.

Byrne K A, Kiely G, Leahy P, 2005. CO_2 fluxes in adjacent new and permanent temperate grasslands. Agricultural and Forest Meteorology, 135, pp 82–92.

Caldwell M M, Dawson T E, Richards J H, 1998. Hydraulic Lift: consequences of water efflux for the roots of plants. Oecologia, 113, pp 151–161.

Campbell N A, 1993. Biology. 3rd ed. Redwood City, CA: Benjamin/Cummings.

Camill P, Clark J S, 1998. Climate change disequilibrium of boreal permafrost peatlands caused by local processes. The American Naturalist, 151, pp 207–222.

Camps M, Hillier S, Vidal M, Rauret G, 2003. Laboratory experiments to predict changes in radiocaesium root uptake after flooding events. Journal of Environmental Radioactivity, 67, pp 247–259.

Canham C D, Pace M L, Papaik M J, Primack A G B, 2004. A spatially explicit watershed-scale analysis of dissolved organic carbon in Adirondack lakes. Ecological Application, 14, pp 839–854.

Carlsson T, Brunberg A-K, Brydsten L, Strömberg M, 2005. Forsmark site investigation. Characterisation of running waters, including vegetation, substrate, and technical encroachments. SKB P-05-150, Svensk Kärnbränslehantering AB.

Carrer S, Halling-Sorensen B, Bendoricchio G, 2000. Modelling the fate of dioxins in a trophic network by coupling an ecotoxicological and an Ecopath model. Ecological Modelling, 126, pp 201–223.

Cederlund G, 2008a. Platsundersökning Forsmark. Älgstammens ålderssammansättning och reproduktion i Forsmark (in Swedish). SKB P-08-35, Svensk Kärnbränslehantering AB.

Cederlund G, 2008b. Platsundersökning Forsmark. Älgstammens ålderssammansättning och reproduktion i Saxmarken-Hållnäs. (in Swedish). SKB P-08-36, Svensk Kärnbränslehantering AB.

Cederlund G, 2008c. Platsundersökning Oskarshamn. Älgstammens ålderssammansättning och reproduktion i Oskarshamn (in Swedish). SKB P-08-40, Svensk Kärnbränslehantering AB.

Cederlund G, 2009a. Platsundersökning Forsmark. Älgstammens ålderssammansättning och reproduktion i Forsmark (in Swedish). SKB P-09-23, Svensk Kärnbränslehantering AB.

Cederlund G, 2009b. Platsundersökning Forsmark. Älgstammens ålderssammansättning och reproduktion i Saxmarken-Hållnäs (in Swedish). SKB P-09-24, Svensk Kärnbränslehantering AB.

Cederlund G, 2009c. Platsundersökning Oskarshamn. Älgstammens ålderssammansättning och reproduktion i Oskarshamn (in Swedish). SKB P-09-25, Svensk Kärnbränslehantering AB.

Cederlund G, Broman E, 2010a. Monitering Forsmark. Älgstammens ålderssammansättning, reproduktion och hornutveckling i Forsmark jaktåret 2009 (in Swedish). SKB P-10-26, Svensk Kärnbränslehantering AB.

Cederlund G, Broman E, 2010b. Monitering Forsmark. Älgstammens ålderssammansättning, reproduktion och hornutveckling i Hållnäs jaktåret 2009 (in Swedish). SKB P-10-27, Svensk Kärnbränslehantering AB.

Cederlund G, Lemel J, 2007a. Platsundersökning Forsmark. Älgstammens ålderssammansättning och reproduktion i Forsmark (in Swedish). SKB P-07-132, Svensk Kärnbränslehantering AB.

Cederlund G, Lemel, J, 2007b. Platsundersökning Oskarshamn. Älgstammens ålderssammansättning och reproduktion i Oskarshamn (in Swedish). SKB P-07-136, Svensk Kärnbränslehantering AB.

Cederlund G, Lemel J, 2007c. Platsundersökning Forsmark. Älgstammens ålderssammansättning och reproduktion i Saxmarken-Hållnäs (in Swedish). SKB P-07-133, Svensk Kärnbränslehantering AB.

Cederlund G, Truvé J, 2007. Översiktlig bedömning av konsekvenser för jakten som inkapslingsanläggning och slutförvar för använt kärnbränsle medför (in Swedish). SKB P-07-09, Svensk Kärnbränslehantering AB.

Cederlund G, Ljungkvist H, Markgren G, Stålfelt F, 1980. Foods of moose and roe deer at Grimsö in central Sweden – results of rumen content analyses. Viltrevy (Swedish Wildlife Research), 11, pp 167–247.

Cederlund G, Hammarström A, Wallin K, 2003. Surveys of mammal populations in the areas adjacent to Forsmark and Tierp. SKB P-03-18, Svensk Kärnbränslehantering AB.

Cederlund G, Hammarström A, Wallin K, 2004. Surveys of mammal populations in the areas adjacent to Forsmark and Oskarshamn. Results from 2003. SKB P-04-04, Svensk Kärnbränslehantering AB.

Cederlund G, Hammarström A, Wallin K, 2005a. Oskarshamn site investigation. Survey of small rodent populations in the areas adjacent to Simpevarp. Results from 2004. SKB P-05-84, Svensk Kärnbränslehantering AB.

Cederlund G, Hammarström A, Wallin K, 2005b. Forsmark site investigation. Surveys of mammal populations in Forsmark. Results from 2004. SKB P-05-151, Svensk Kärnbränslehantering AB.

Cederlund G, Lemel J, Wallin K, 2006a. Forsmark site investigation. Älgstammens ålderssammansättning och reproduktion i Saxmarken-Hållnäs (in Swedish). SKB P-06-218, Svensk Kärnbränslehantering AB.

Cederlund G, Lemel J, Wallin K, 2006b. Forsmark site investigation. Älgstammens ålderssammansättning och reproduktion i Forsmark (in Swedish). SKB P-06-219, Svensk Kärnbränslehantering AB.

Cederlund G, Lemel J, Wallin K, 2006c. Platsundersökning Oskarshamn. Älgstammens ålderssammansättning och reproduktion i Oskarshamn (in Swedish). SKB P-06-228, Svensk Kärnbränslehantering AB.

Chapin F S, Matson P, Mooney H A, 2002. Principles of terrestrial ecosystem ecology. New York: Springer.

Chen J M, Cihlar J, 1995. Plant canopy gap-size analysis theory for improving optical measurements of leaf area index. Applied Optics, 34, pp 6211–6222.

Chen J M, Rich P M, Gower S T, Norman J M, Plummer S, 1997. Leaf area index of boreal forests: theory, techniques, and measurements. Journal of Geophysical Research, 102, pp 29429–29443.

Chen J M, Ju W, Cihlar J, Price D, Liu J, Chen W, Pan J, Black A, Barr A, 2003. Spatial distribution of carbon sources and sinks in Canda's forests. Tellus B, 55, pp 622–641.

Chen S B, Zhu Y G, Hu Q H, 2005. Soil to plant transfer of ^{238}U, ^{226}Ra and ^{232}Th on a uranium mining-impacted soil from southeastern China. Journal of Environmental Radioactivity, 82, pp 223–236.

Clarhäll A, 2011. SKB studies of the periglacial environment – Report from field studies in Kangerlussuaq, Greenland 2008 and 2010. SKB P-11-05, Svensk Kärnbränslehantering AB.

Clark D A, Brown S, Kicklighter D W, Chambers J Q, Thomlinson J R, Ni J, 2001. Measuring net primary production in forests: concepts and field methods. Ecological Applications, 11, pp 356–370.

Cleveland C C, Jason C N, Townsend A R, Hood E, 2004. Composition, dynamics, and fate of leached dissolved organic matter in terrestrial ecosystems: results from a decomposition experiment. Ecosystems, 7, pp 275–285.

Clymo R S, 1984. The limit to peat bog growth. Philosophical Transsactions of the Royal Society of London, B303, pp 605–654.

Coble D W, Milner K S, Marshall J D, 2001. Above – and below – ground production of trees and other vegetation on contrasting aspects in western Montana: a case study. Forest Ecology and Management, 142, pp 231–241.

Coupe M D, Cahill J F J, 2003. Effects of insects on primary production in temperate herbaceous communities: a meta-analysis. Ecological Entomology, 28, pp 511–521.

Cousins S A O, 2001. Analysis of land cover transitions based on 17th and 18th century cadastral maps and aerial photographs. Landscape Ecology, 16, pp 41–54.

Cowardin L M, Carter V, Golet F C, LaRoe E T, 1979. Classification of wetlands and deepwater habitats of the United States. FWS/OBS-79/31, U.S. Fish and Wildlife Service, Washington, D.C.

Cowling S A, Shin Y, 2006. Simulated ecosystem threshold responses to co-varying temperature, precipitation and atmospheric CO_2 within a region of Amazonia. Global Ecology and Biogeography, 15, pp 553–566.

Craft C B, Richardson C J, 1993. Peat accretion and N, P, and organic C accumulation in nutrient-enriched and unenriched Everglades peatlands. Ecological Applications, 3, pp 446–458.

Craft C, Washburn C, Parker A, 2008. Latitudinal trends in organic accumulation in temperate freshwater peatlands. In: Vymazal J (ed). Wastewater treatment, plant dynamics and management in constructed and natural wetlands. Dordrecht: Springer, pp 23–31.

Cramer V A, Hobbs R J, Standish R J, 2008. What's new about old fields? Land abandonment and ecosystem assembly. Trends in Ecology & Evolution, 23, pp 104–112.

Cramer W, 1986. Vegetation dynamics on rising sea shores in eastern central Sweden. Ph.D. thesis. Uppsala University, Sweden.

Cramer W, Bondeau A, Woodward F, Prentice I, Betts R, Brovkin V, Cox P, Fisher V, Foley J, Friend A, Kucharik C, Lomas M, Ramankutty N, Sitch S, Smith B, White A, Young-Molling C, 2001. Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models. Global change biology, 7, pp 357–373.

Crawley M J, 1983. Herbivory: the dynamics of animal-plant interactions. Oxford: Blackwell Scientific.

Cyr H, Pace M L, 1993. Magnitude and patterns of herbivory in aquatic and terrestrial ecosystems. Nature, 361, pp 148–150.

Davidson E A, Belk E, Boone R D, 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Global Change Biology, 4, pp 217–227.

Davis B A S, Brewer S, Stevenson A C, Guiot J, Data Contributors, 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews, 22, pp 1701–1716.

DeAngelis D L, Gardner R H, Shugart H H, 1981. Productivity of forest ecosystems studied during the IBP: The woodlands data set. In: Reichle D E (ed). Dynamic properties of forest ecosystems. Cambridge: Cambridge University Press, pp 567–672.

de Jong J, Gylje S, 2005. Forsmark site investigation. Abundance and distribution of bat (Chiroptera) species in the Forsmark area. SKB P-05-61, Svensk Kärnbränslehantering AB.

Del Grosso S J, Parton W J, Mosier A R, Ojima D S, Kulmala D S, Phongpan S, 2000. General model for N_2O and N_2 gas emissions from soils due to dentrification. Global Biogeochemical Cycles, 14, pp 1045–1060.

Detling J K, 1988. Grasslands and savannas: regulation of energy flow and nutrient cycling by herbivores. In: Pomeroy L R, Alberts J J (eds). Concepts of ecosystem ecology: a comparative view. New York: Springer, pp 131–148.

Dionisio Pires L M, Bontes B M, Van Donk E, Ibelings B W, 2005. Grazing on colonial and flamentous, toxic and non-toxic cyanobacteria by the zebra mussel Dreissena polymorpha. Journal of Plankton Research, 27, pp 331–339.

DOF, 2007. Natur og fugle. [Online]. Available at: http://www.dofbasen.dk/ART/. Dansk Ornitologisk Forening. [15 August 2007].

Dyer, M I, Turner C L, Seastedt T R, 1993. Herbivory and its consequences. Ecological Applications, 3, pp 10–16.

Dyson R D, 1978. Cell biology: a molecular approach. 2nd ed. Boston: Allyn & Bacon.

Eckersten H, Andersson L, Holstein F, Mannerstedt Fogelfors B, Lewan E, Sigvald R, Torsell B, 2007. Bedömningar av klimatförändringars effekter på växtproduktion inom jordbruket i Sverige. Appendix B 24 in: Sverige inför klimatförändringarna – hot och möjligheter (in Swedish with English summary). SOU 2007:60, Ministry of Environment, pp 26–277.

Edberg R (ed), 2006. Gutefårägarens handbok (in Swedish). Åby: Föreningen Gutefåret.

Eklund S, 2004. Nyckelbiotoper och högre naturvärden inom prioriterade områden i Uppsala län. Sammanställning av inventeringsresultat samt fördjupad inventering i Forsmark (in Swedish). SKB P-04-33, Svensk Kärnbränslehantering AB.

Ekman M, 1996. A consistent map of the postglacial uplift of Fennoscandia. Terra Nova, 8, pp 158–165.

Ekstam U, Forshed N, (eds), 2000. Swedish semi-natural grasslands—history and ecology (In Swedish: Svenska naturbetesmarker—historia och ekologi). Naturvårdsverket Förlag, Stockholm, Sweden.

Eliasson P, 1992. Genom helvetes port, men… Skogsdikning som mål och medel (in Swedish). Aktuellt om historia, 3–4, pp 46–60.

Elveland J, 1978. Skötsel av Norrländska rikkärr. Studier av vegetationsförändringar vid olika skötselåtgärder och annan påverkan (Management of rich fens in North Sweden: studies of various factors influencing the vegetational dynamics) (in Swedish). Solna: Naturvårdsverket. (SNV PM 1007).

Emsley J, 1998. The Elements. 3rd ed. Oxford: Clarendon.

Engdahl A, Ternsell A, Hannu S, 2006. Oskarshamn site investigation. Chemical characterisation of deposits and biota. SKB P-06-320, Svensk Kärnbränslehantering AB.

Engelmark O, Hytteborn H, 1999. Coniferous forests. In: Rydin H, Snoeijs P, Diekmann M (eds). Swedish plant geography: dedicated to Eddy van der Maarel on his 65th birthday. Uppsala: Svenska växtgeografiska sällskapet. (Acta Phytogeographica Suecica 84), pp 55–74.

Ericson L, Wallentinus H-G, 1979. Sea-shore vegetation around the Gulf of Bothnia. Wahlenbergia, 5, pp 1–142.

Eriksson H, 1991. Sources and sinks of carbon dioxide in Sweden. Ambio, 20, pp 146–150.

Eriksson J, Hammar O, Högborg E, Jansson S Vahtras K, Wallén C H, 1970. Växtodlingslära. Del 1, Marken (in Swedish). Stockholm: LT.

Eriksson L, Ingelög T, Kardell L, 1979. Blåbär, lingon, hallon: förekomst och bärproduktion i Sverige 1974–1977 (Bilberry, lingonberry, raspberry: occurrence and production in Sweden 1974–1977) (in Swedish). Rapport 16, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Esseen P A, Ehnström B, Ericson L, Sjöberg K, 1992. Boreal forests – the focal habitats. In: Hansson L (ed). Ecological principles of nature conservation: applications in temperate and boreal environments. London: Elsevier Applied Science, pp 252–325.

Euskirchen E S, Chen J, Gustafson E J, Ma S, 2003. Soil respiration at dominant patch types within a managed northern Wisconsin landscape. Ecosystems, 6, pp 595–607.

Fassnach K S, Gower S T, 1997. Interrelationships among the edaphic and stand characteristics, leaf area index, and aboveground net primary production of upland forest ecosystems in North central Wisconsin. Canadian Journal of Forest Research, 27, pp 1058–1067.

Fineli, 2007. Rowan berry. [Online]. Available at: http://www.fineli.fi/food.php?foodid=457&lang=en. National Institute for Health and Welfare, Finland. [15 May 2007].

Finér L, 1989. Biomass and nutrient cycle in fertilized and unfertilized pine, mixed birch and pine and spruce stands on a drained mire. Acta Forestalia Fennica 208, pp 1–63.

Firmino A, 1999. Agriculture and landscape in Portugal. Landscape and Urban Planning, 46, pp 83–91.

Fisher J T, Wilkinson L, 2005. The response of mammals to forest fire and timber harvest in the North American boreal forest. Mammal Review, 35, pp 51–81.

Fitter A H, Heinemeyer A, Staddon P L, 2000. The impact of eleveated CO_2 and global climate change on arbuscular mycorrhizas: a myocentric approach. New Phytologist, 147, pp 179–187.

Flanagan L B, Weaver L A, Carlson P J, 2002. Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate grassland. Global Change Biology, 8, pp 599–615.

Flinn K, Vellend M, Marks P, 2005. Environmental causes and consequences of forest clearance and agricultural abandonment in central New York, USA. Journal of Biogeography, 32, pp 439–452.

Flygare I, Isacson M, 2003. Det svenska jordbrukets historia. Band 5. Jordbruket i välfärdssamhället 1945–2000 (in Swedish). Örebro: Natur och kultur/LT.

Foster D R, 1992. Land-use history (1730–1990) and vegetation dynamics in central New England, USA. Journal of Ecology, 80, pp 753–772.

Fredén C (ed), 2002. Sveriges nationalatlas. Berg och jord (in Swedish). 3rd ed. Stockholm: SNA Förlag.

Fredriksson D, 2004. Forsmark site investigation. Peatland investigation Forsmark. SKB P-04-127, Svensk Kärnbränslehantering AB.

Fridriksson G, Öhr J, 2003. Assessment of plant biomass of the ground, field and shrub layers of the Forsmark area. SKB P-03-90, Svensk Kärnbränslehantering AB.

Fuge R, Johnson C C, 1986. The geochemistry of iodine – a review. Environmental Geochemistry and Health, 8, pp 31–54.

Fulton M R, 1991. Adult recruitment as a function of juvenile growth rate in size-structured plant populations. Oikos, 62, pp 102–105.

Gellrich M, Baur P, Koch B, Zimmermann N E, 2007. Agricultural land abandonment and natural forest re-growth in the Swiss mountains: A spatially explicit economic analysis. Agriculture, Ecosystems and Environment, 118, pp 93–108.

Gentzschein B, Levén J, Follin S, 2007. A comparison between well yield data from the site investigation in Forsmark and domestic wells in northern Uppland. SKB P-06-53, Svensk Kärnbränslehantering AB.

Gerten D, Schappoff S, Haberlandt U, Lucht W, Sitch S, 2004. Terrestrial vegetation and water balance-hydrological evaluation of a dynamic global vegetation model. Journal of Hydrology, 286, pp 249–270.

Giese L A B, Aust W M, Kolka R K, Trettin C C, 2003. Biomass and carbon pools of disturbed riparian forests. Forest Ecology and Management, 180, pp 493–508.

Gill R, Jackson R B, 2000. Global patterns of root turnover for terrestrial ecosystems. New Phytologist, 147, pp 13–31.

Goldschmidt T, Witte F, Wanink J, 1993. Cascading Effects of the Introduced Nile Perch on the Detritivorous/Phytoplanktivorous Species in the Sublittoral Areas of Lake Victoria. Conservation Biology, 7, pp 686–700.

Golley F B, 1961. Energy values of ecological material. Ecology, 42, pp 581–584.

Goudriaan J, Groot R J J, Uithol P W J, 2001. Productivity of Agro-ecosystems. In: Roy J, Saugier B, Mooney H A (eds). Terrestrial global productivity. London: Academic Press, pp 301–313.

Goulden M L, Daube B, Fan S M, Sutton D J, Bazzaz A, Munger J W, Wofsy S C, 1997. Physiological responses of a black spruce forest to weather. Journal of Geophysical Research (BOREAS Special issue), 102, pp 28987–28996.

Gorham E, 1991. Northern peatlands: Role in the carbon cycle and probable responses to climate warming. Ecological Applications, 1, pp 182–195.

Gorham E, 1995. The biogeochemistry of northern peatlands. In: Woodwell G, MacKenzie F T, (eds). Biotic feedbacks in the global climatic system: will the warming feed the warming? Oxford: Oxford University Press, pp 169–187.

Gower S T, McMurtrie R E, Murty D, 1996. Aboveground net primary production decline with stand age: potential causes. Trends in Ecology and Evolution, 11, pp 378–382.

Gower S T, Krankina O, Olson R J, Apps M, Linder S, Wang C, 2001. Net primary production and carbon allocation patterns of boreal forest ecosystems. Ecological Applications, 11, pp 1395–1411.

Green M, 2003a. Platsundersökning Simpevarp. Fågelundersökningar inom SKB:s platsundersökningar 2002 (in Swedish). SKB P-03-31, Svensk Kärnbränslehantering AB.

Green M, 2003b. Fågelundersökningar inom SKB:s platsundersökningar 2002 (in Swedish). Forsmark. SKB P-03-10, Svensk Kärnbränslehantering AB.

Green M, 2004a. Forsmark site investigation. Bird monitoring in Forsmark 2002–2003. SKB P-04-30, Svensk Kärnbränslehantering AB.

Green M, 2004b. Oskarshamn site investigations. Bird surveys in Simpevarp 2003. SKB P-04-21, Svensk Kärnbränslehantering AB.

Green M, 2005a. Forsmark site investigation. Bird monitoring in Forsmark 2002–2004. SKB P-05-73, Svensk Kärnbränslehantering AB.

Green M, 2005b. Oskarshamn site investigations. Bird monitoring in Simpevarp 2002–2004. SKB P-05-42, Svensk Kärnbränslehantering AB.

Green M, 2006a. Oskarshamn site investigations. Bird monitoring in Simpevarp 2002–2006. SKB P-06-298, Svensk Kärnbränslehantering AB.

Green M, 2006b. Forsmark site investigation. Bird monitoring in Forsmark 2005. SKB P-06-46, Svensk Kärnbränslehantering AB.

Green M, 2006c. Oskarshamn site investigations. Bird monitoring in Simpevarp 2002–2005. SKB P-06-43, Svensk Kärnbränslehantering AB.

Green M, 2007a. Forsmark site investigations. Bird monitoring in Forsmark 2006. SKB P-07-02, Svensk Kärnbränslehantering AB.

Green M, 2007b. Oskarshamn site investigation. Bird monitoring in Simpevarp 2002–2007. SKB P-07-226, Svensk Kärnbränslehantering AB.

Green M, 2008a. Forsmark site investigations. Bird monitoring in Forsmark 2007. SKB P-08-25, Svensk Kärnbränslehantering AB.

Green M, 2008b. Forsmark site investigation. Bird monitoring in Forsmark 2008. SKB P-08-84, Svensk Kärnbränslehantering AB.

Green M, 2008c. Oskarshamn site investigations. Bird monitoring in Simpevarp 2002–2008. SKB P-08-89, Svensk Kärnbränslehantering AB.

Green M, 2009. Site investigations Forsmark. Bird monitoring in Forsmark 2009. SKB P-09-71, Svensk Kärnbränslehantering AB.

Green M, 2010. Oskarshamn site investigations. Bird monitoring in Simpevarp 2002–2009. SKB P-10-11, Svensk Kärnbränslehantering AB.

Greger M, 2004. Uptake of nuclides by plants. SKB TR-04-14, Svensk Kärnbränslehantering AB.

Griffin M P A, Cole M L, Kroeger K D, Cebrian J, 1998. Dependence of herbivory on autotrophic nitrogen content and on net primary production across ecosystems. The Biological Bulletine, 195, pp 233–234.

Griffiths R W, Schloesser D W, Leach J H, Kovalak W P, 1991. Distribution and dispersal of zebra mussel (Dreissena polymorpha) in the Great lakes region. Canadian Journal of Fisheries and Aquatic Sciences, 48, pp 1381–1388.

Gunnarsson U, Malmer N, Rydin H, 2002. Dynamics or constancy in Sphagnum dominated mire ecosystems? A 40-year study. Ecography, 25, pp 685–704.

Gustafsson D, Jansson P-E, Gärdenäs A, Eckersten H, 2006. Simulated carbon and water processes of forest ecosystems in Forsmark and Oskarshamn during a 100-year period. SKB TR-06-45, Svensk Kärnbränslehantering AB.

Göthberg A, Wahlman H, 2006. Forsmark site investigation. Inventory of vascular plants and classification of calcareous wetlands in the Forsmark area. SKB P-06-115, Svensk Kärnbränslehantering AB.

Hamrén U, Collinder P, 2010. Vattenverksamhet i Forsmark. Ekologisk fältinventering och naturvärdesklassificering samt beskrivning av skogsproduktionsmark. SKB R-10-16, Svensk Kärnbränslehantering AB. (In Swedish, with Summary in English.)

Hannu S, Karlsson S, 2006. Forsmark site investigation. Chemical characterisation of deposits and biota. SKB P-06-220, Svensk Kärnbränslehantering AB.

Hansson L, 2002. Mammal movements and foraging at remnant woodlands inside coniferous forest landscapes. Forest Ecology and Management, 160, pp 109-114.

Hanson P J, Edwards N T, Garten C T, Andrews J A, 2000. Separating root and soil microbial contributions to soil respiration: A review of methods and observations. Biogeochemistry, 48, pp 115–146.

Haxeltine A, Prentice I C, 1996. BIOME3: an equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. Global Biogeochemical Cycles, 10, pp 693–709.

Heal O W, Flanagan P W, French D D, MacLean S F, 1981. Decomposition and accumulation of organic matter. In: Bliss L C, Heal O W, Moore J J (eds). Tundra ecosystems: a comparative analysis. Cambridge: Cambridge University Press.

Heath R C, 1987. Basic ground-water hydrology. Water-Supply Paper 2220, U.S Geological Survey.

Hedenström A, 2004. Forsmark site investigation. Investigation of marine and lacustrine sediments in lakes. Stratigraphical and analytical data. SKB P-04-86, Svensk Kärnbränslehantering AB.

Hedenström A, Risberg J, 2003. Shore displacement in northern Uppland during the last 6,500 calendar years. SKB TR-03-17, Svensk Kärnbränslehantering AB.

Hedenström A, Sohlenius G, 2008. Description of the regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-04, Svensk Kärnbränslehantering AB.

Hedenström A, Sohlenius G, Strömgren M, Brydsten L, Nyman H, 2008. Depth and stratigraphy of regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-07, Svensk Kärnbränslehantering AB.

Heginbottom J A, Dubreuil M A, Harker P A, 1995. Canada – Permafrost. In: The national atlas of Canada. 5th ed. National Atlas Information Service, Natural Resources Canada, MCR 4177.

Heimann M, Esser G, Haxeltine A, Kaduk J, Kicklighter D W, Knorr W, Kohlmaier G H, McGuire A D, Kelillo J, Moore B, Otto R D, Prentice I C, Sauf W, Schloss A, Sitch S, Wittenberg U, Wurth G, 1998. Evaluation of terrestrial carbon cycle models through simulations of the seasonal cycle of atmospheric CO_2 – First results of a model intercomparison study. Global Biogeochemical Cycles, 12, pp 1–24.

Hély C, Bremond L, Smith B, Sykes M T, Guiot J, 2006. Sensitivity of African biomes to changes in precipitation regime. Global Ecology and Biogeography, 15, pp 258–270.

Hendricks J J, Mitchell R J, Kuehn K A, Pecot S D, Sims S E, 2006. Measuring external mycelia production of ectomycorrhizal fungi in the field: the soil matrix matters. New Phytologist, 171, pp 179–186.

Heneryd N, 2004. Forsmark site investigation. Snow depth, ground frost and ice cover during the winter 2003/2004. SKB P-04-137, Svensk Kärnbränslehantering AB.

Heneryd N, 2005. Forsmark site investigation. Snow depth, ground frost and ice cover during the winter 2004/2005. SKB P-05-134, Svensk Kärnbränslehantering AB.

Heneryd N, 2006. Forsmark site investigation. Snow depth, ground frost and ice cover during the winter 2005/2006. SKB P-06-97, Svensk Kärnbränslehantering AB.

Heneryd N, 2007a. Snow depth, snow water content and ice cover during the winter 2006/2007. SKB P-07-81, Svensk Kärnbränslehantering AB.

Heneryd N, 2007b. Forsmark site investigation. Measurements of ground respiration, primary production and NEE in terrestrial habitats. SKB P-07-23, Svensk Kärnbränslehantering AB.

Hickler T, Smith B, Sykes M T, Davis M B, Sugita S, Walker K, 2004. Using a generalized vegetation model to simulate vegetation dynamics in the western Great Lakes region, USA, under alternative disturbance regimes. Ecology, 2, pp 519–530.

Hickler T, Prentice I C, Smith B, Sykes, M T, Zaehle S, 2006. Implementing plant hydraulic architecture within the LPJ Dynamic Global Vegetation Model. Global Ecology and Biogeography, 15, pp 567–577.

Hilbert D A, Roulet N T, Moore T R, 2000. Modelling and analysis of peatlands as dynamical systems, Journal of Ecology, 88, pp 230–242.

Hilton J, Livens F R, Spezzano P, Leonardo D R P, 1993. Retention of radioactive caesium by different soils in the catchment of a small lake. The Science of the Total Environment, 129, pp 253–266.

Holland R E, 1993. Changes in planktonic diatoms and water transparency in Hachery Bay, Bass Island area, Western Lake Erie, since establishment of the zebra mussle. Journal of Great Lakes Research, 19, pp 617–624.

Holland B, Welch A A, Unwin I D, Buss D H, Paul A A, Southgate D A T, 1991. The composition of foods. MAFF and the Royal Society of Chemistry.

Hollinger S E, Bernacchi C J, Meyers T P, 2005. Carbon budget of mature no-till ecosystem in North Central Region of the United States. Agricultural and Forest Meteorology, 130, pp 59–69.

Horne A J, Goldman C R, 1994. Limnology. 2nd ed. New York: McGraw-Hill.

Horrill A D, 1984. Radionuclide levels and distribution in grazed saltmarsh in West Cumbria. Environmental Pollution, Series B, 8, pp 265–280.

Humborg C, Smedberg E, Blomqvist S, Mörth C-M, Brink J, Rahm L, Danielsson Å, Sahlberg J, 2004. Nutrient variations in boreal and subarctic Swedish rivers: Landscape control of land-sea fluxes. Limnology and Oceanography, 49, pp 1871–1883.

Humphreys W F, 1979. Production and respiration in animal populations. Journal of Animal Ecology, 48, pp 427–453.

Hunter M D, 2001. Out of sight, out of mind: the impacts of of root-feeding insects in natural and managed systems. Agricultural and Forest Entomology, 3, pp 1–8.

Huntley B, Birks H J B, 1983. An atlas of past and present pollen maps for Europe: 0–13,000 years ago. Cambridge: Cambridge University Press.

Hyvönen R, Ågren G I, Linder S, Persson T, Cotrufo M F, et al, 2007. The likely impact of elevated [CO2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystem: a literature review. New Phytologist, 173, pp 463–480.

Hägglund B, 1973. Om övre höjdens utveckling för gran i södra Sverige (in Swedish). Rapport 24, Skogshögskolan, Stockholm, Sweden.

Hägglund B, Lundmark J-E, 1987a. Handledning i bonitering med Skogshögskolans boniteringssystem. Del 2. Diagram och tabeller (in Swedish). Jönköping: Skogsstyrelsen.

Hägglund B, Lundmark J-E 1987b. Handledning i bonitering med Skogshögskolans boniteringssystem. Del 1. Defenitioner och anvisningar (in Swedish). Jönköping: Skogsstyrelsen.

Högberg P, Nordgren A, Buchmann N, Taylor A F S, Ekblad A, Högberg M N, Nyberg G, Ottosson-Löfvenius M, Read D J, 2001. Large-scale forest girdling shows that current photosynthesis drives soil respiration. Nature, 411, pp 789–792.

IAEA, 2001. Literature models for use in assessing the impact of discharges of radioactive substances to the environment. Safety Reports Series 19, International Atomic Energy Agency, Vienna.

IAEA, 2010. Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments. Technical Reports Series 472, International Atomic Energy Agency, Vienna.

Ignell H, 2004. Oskarshamn site investigation. Investigations on mammals – bats. Investigation of the fauna of mammals in selected places within SKB investigation area. SKB P-04-237, Svensk Kärnbränslehantering AB.

Ignell H, Karlsson J, Lundkvist E, Ramstedt H, Wahlman H, 2006. Naturmiljöbeskrivning och preliminär bedömning av konsekvenser för naturmiljö. Slutförvar för använt kärnbränsle vid Simpevarp/Laxemar. SKB P-06-102, Svensk Kärnbränslehantering AB.

Ihalainen M, Pukkala T, 2001. Modelling cowberry (Vaccinium vitis-idaea) and bilberry (Vaccinium myrtillus) yields from mineral soils and peatlands on the basis of visual field estimates. Silva Fennica, 35, pp 329–340.

Ihalainen M, Salo K, Pukkala T, 2003. Empirical prediction models for Vaccinium myrtillus and V. vitis-idaea berry yields in North Karelia, Finland. Silva Fennica, 37, pp 95–108.

Ingmar T, 1963. Från havsvik till mosse – något om Florornas utveckling (in Swedish). Sveriges Natur, Årsbok 1963, pp 120–132.

Ingmar T, Moreborg K, 1976. The leaching and original content of calcium carbonate in till in northern Uppland, Sweden. Geologiska Föreningens i Stockholm Förhandlingar, 98, pp 120–132.

ICRP 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103, Annals of the ICRP Volume 37 (2-4).

IVL, 2009. IVL startsida. [Online]. Available at: http://www.ivl.se/. IVL Svenska Miljöinstitutet. [4 April 2009].

Jackson R B, Canadell J, Ehleringer J R, Mooney H A, Sala O E, Schultze E D, 1996. A global analysis of root distributions for terrestrial biomes. Oecologia, 108, pp 389–411.

Jakobsen I, Rosendahl L, 1990. Carbon flow into soil and external hyphae from roots of mycorrhizal cucumber plants. New Phytologist, 115, pp 77–83.

Janssens I A, Lankreijer H, Matteuchi G, Kowalski A S, Buchmann N, Epron D, Pilegaard K, Kutsch W, Longdoz B, Grunwald T, Montagnani L, Dore S, Rebmann C, Moors E J, Grelle A, Rannik U, Morgenstern K, Oltechev S, Clement R, Gudmundsson J, Minerbi S, Berbigier P, Ibrom A, Mongrieff J, Aubinet M, Bernhofer C, Jensen N O, Vesala T, Granier A, Schulze E-D, Lindroth A, Dolman A J, Jarvis P G, Ceulemans R, Valentini R, 2001. Productivity overshadows temperature in determining soil and ecosystem respiration across European forests. Global Change Biology, 7, pp 269–278.

Jansson P-E, Karlberg L, 2004. Coupled heat and mass transfer model for soil-plant-atmosphere systems. Trita-AMI report 3087, Royal Institute of Technology, Stockholm, Sweden.

Jansson U, Berg J, Björklund A, 2004. A study on landscape and the historical geography of two areas – Oskarshamn and Forsmark. SKB R-04-67, Svensk Kärnbränslehantering AB.

Jansson U, Kautsky U, Miliander S, 2006. Rural landscape, production and human consumption: past, present and future. Ambio, 35, pp 505–512.

Jarvis P G, Saugier B, Schulze D E, 2001. Chapter 10. Productivity of boreal forests. In: Roy J, Saugier B, Mooney H A (eds). Terrestrial global productivity. London: Academic Press, pp 211–244.

Jauhiainen S, Pitkainen A, Vasander H, 2004. Chemostratigraphy and vegetation in two boreal mires during the Holocene. The Holocene, 14, pp 768–779.

Jeffries R, Darby S E, Sear D A, 2002. The influence of vegetation and organic debris on flood-plain sediment dynamics: case study of a low-order stream in the New Forest, England. Geomorphology, 1291, pp 1–20.

Jerling L, 1999. Sea shores. In: Rydin H, Snoeijs P, Diekmann M (eds). Swedish plant geography: dedicated to Eddy van der Maarel on his 65th birthday. Uppsala: Svenska växtgeografiska sällskapet. (Acta Phytogeographica Suecica 84).

Jerling L, Isaeus M, Lanneck J, Lindborg T, Schüldt R, 2001. The terrestrial biosphere in the SFR region. SKB R-01-09, Svensk Kärnbränslehantering AB.

Johanson K, Nikolova I, Taylor A F S, Vinichuk M, 2004. Uptake of elements by fungi in the Forsmark area. SKB TR-04-26, Svensk Kärnbränslehantering AB.

Johansson M B, Grälls C, 1989. Quantity, decomposition and nutrient dynamics of litterfall in some forest stands at Hålebäck, southern Sweden. Report 62, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Johansson M B, Lundmark J E, 1986. Markmiljön i gran- och björkbestånd. Skogsvårdsförbundets tidskrift, SST 2/86, pp 31–37.

Johansson M B, Kögel I, Zech W, 1986. Changes in the lignin fraction of spruce and pine needle litter during decomposition as studied by some chemical methods. Soil Biology and Biochemistry, 18, pp 611–619.

Johansson P-O, 2003. Forsmark site investigation. Drilling and sampling in soil. Installation of groundwater monitoring wells and surface water level gauges. SKB P-03-64, Svensk Kärnbränslehantering AB.

Johansson P-O, 2008. Description of surface hydrology and near-surface hydrogeology at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-08, Svensk Kärnbränslehantering AB.

Johansson P-O, Werner K, Bosson E, Berglund S, Juston J, 2005. Description of climate, surface hydrology, and near-surface hydrogeology. Preliminary site description Forsmark area – version 1.2. SKB R-05-06, Svensk Kärnbränslehantering AB.

Johansson S, 2005. The Swedish Foodprint: An agroecological study of food consumption. Ph.D. thesis. Uppsala: Swedish University of Agricultural Sciences. (Acta Universitatis agriculturae Sueciae 2005:56)

Johansson T, 2000. Biomass equations for determining functions of common and grey alder growing on abandoned farmland and some practical implications. Biomass and Bioenergy, 18, pp 147–159.

Johnson D W, Curtis P S, 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management, 140, pp 227–238.

Jones T H, Bradford M A, 2002. Assessing the functional implications of soil biodiversity in ecosystems. Ecological Research, 16, pp 845–858.

Jones G, Hollier G, Forbes J, Robinson A, 1992. The HarperCollins dictionary of environmental science. New York: HarperPerennial.

Jonsell B, Jonsell L, 1995. Floran i Hållnäs socken (in Swedish). Svensk botanisk tidskrift, 89, pp 257–312.

Jonsson L, 1992. Fåglar i Europa med Nordafrika och Mellanöstern (Birds of Europe: with North Africa and the Middle East) (in Swedish). Wahlström & Widstrand.

Jordbruksverket, 2006. Jordbruksstatistisk årsbok 2006 (Yearbook of agricultural statistics 2006 including food statistics) (in Swedish). Stockholm: SCB.

Jose S, Gillespie R, 1997. Leaf area-productivity relationships among mixed-species hardwood forest communities of the central hardwood region. Forest Science, 43, pp 56–64.

Jung M, Le Maire G, Zaehle S, Luyssaert S, Vetter M, Churkina G, Ciais P, Viovy N, Reichstein M, 2007. Assessing the ability of three ecosystem models to simulate gross carbon uptake of forests from boreal to Mediterranean climate in Europe. Biogeosciences, 4, pp 647–656.

Kardell L, 1993. Produktion av skogsbär och matsvampar på Ekenäs gård i Södermanland (in Swedish). Rapport 56, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Kardell L, 2003. Svenskarna och skogen. D. 1. Från ved till linjeskepp (in Swedish). Jönköping: Skogsstyrelsen.

Kardell L, Carlsson E, 1982. Hjortron, tranbär, lingon: förekomst och bärproduktion i Sverige 1978–1980 (Cloudberry, cranberry, lingonberry: occurrence and production in Sweden 1978–1980) (in Swedish). Rapport 25, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Kardell L, Eriksson L, 1987. The effect of forest operations on the production of edible mushrooms. Sveriges skogsvårdsförbunds tidskrift, 85, pp 3–23.

Karlberg L, Gustafsson D, Jansson P-E, 2006. Modelling carbon and water flows in terrestrial ecosystems in the boreal zone – examples from Oskarshamn. SKB R-06-121, Svensk Kärnbränslehantering AB.

Karlén W, Bodin A, Kuylenstierna J, Näslund J-O, 1995. Climate of Northern Sweden during the Holocene. Journal of Coastal Research, Special Issue, 17, pp 49–54.

Karlsson P-A, 1990. Järnbruken och ståndssamhället. Institutionell och attitydmässig konflikt under Sveriges tidiga industrialisering (Iron industry and the society of estates: conflicts between institutions and attitudes during the early industrialization of Sweden 1700–1770) (in Swedish). Stockholm: Jernkontoret. (Jernkontorets bergshistoriska skriftserie 25)

Karlsson S, 2007. Stone age vegetation in Uppland, Southeastern Svealand, Sweden. GFF, 129, pp 295–305.

Karlsson S, Bergström U, Meili M, 2001. Models for dose assessments. Models adapted to the SFR-area, Sweden. SKB TR-01-04, Svensk Kärnbränslehantering AB.

Karlsson A, Eriksson C, Borell Lövstedt C, Liungman O, Engqvist A, 2010. High-resolution hydrodynamic modelling of the marine environment at Forsmark between 6500 BC and 9000 AD. SKB R-10-09, Svensk Kärnbränslehantering AB.

Kashian D M, Turner M G, Romme W H, 2005. Variability in leaf area and stemwood increment along a 300-year lodgepole pine chronosequence. Ecosystems, 8, pp 48–61.

Kautsky U, 1995. Ecosystem processes in coastal areas of the Baltic Sea. Ph.D. thesis. Stockholm University, Sweden.

Kellner E, 2003. Wetlands – different types, their properties and functions. SKB TR-04-08, Svensk Kärnbränslehantering AB.

Khudyakov O I, Kononenko A V, Kudryavtseva L Yu, Kerzhentseva V V, 1999. Hydrothermic fields of surface-gley tundra soils and their changes upon soil cultivation. Eurasian Soil Science, 32, pp 1105–1114.

Kjellström E, Brandefelt J, Näslund J-O, Smith B, Strandberg G, Wohlfart B, 2009. Climate conditions in Sweden in a 100,000 year time perspective. SKB TR-09-04, Svensk Kärnbränslehantering AB.

Knape S, 2001. Natural hydrochemical variations in small catchments with thin soil layers and crystalline bedrock: hydrochemical data from two catchments at Äspö Island and two others in the Lake Gårdsjön area, collected 1997 to 1999. Chalmers University of Technology, Göteborg, Sweden.

Knorr W, Heimann M, 2001. Uncertainties in global terrestrial biosphere modeling, Part II: global constraints for a process-based vegetation model. Global Biogeochemical Cycles, 15, pp 227–246.

Knorr W, Smith B, Widlowski J L, Pinty B, Gobron N, 2004. Combining remote sensing techniques with productivity models: a case study for monitoring carbon stocks in northern European forests. In: Stamatiadis S, Lynch J M, Schepers J S (eds). Remote sensing for agriculture and the environment. Larissa, Greece: OECD Publications, pp 52–64.

Koca D, Smith B, Sykes M, 2006. Modelling regional climate change effects on potential natural ecosystems in Sweden. Climatic Change, 78, pp 381–406.

Kolari P, Pumpanen J, Rannik U, Ilvesniemi H, Hari P, Berningen F, 2004. Carbon balance of different aged Scots pine forests in Southern Finland. Global Change Biology, 10, pp 1106–1119.

Korhola A, Tolonen K, 1996. The natural history of mires in Finland and the rate of peat accumulation. In: Vasander H (ed). Peatlands in Finland. Helsinki: Finnish Peatland Society, pp 20–26.

Koulouri M, Giourga C 2007. Land abandonment and slope gradient as key factors of soil erosion in Mediterranean terraced lands. Catena, 69, pp 274–281.

Kuhry P, 1994. The role of fire in the development of Sphagnum-dominated peatlands in the western boreal Canada. Journal of Ecology, 82, pp 899–910.

Kumblad L, 2004. Radionuclides in the Baltic Sea – Ecosystem models and experiments on transport and fate. Ph.D. thesis. Stockholm University, Sweden.

Kumblad L, Kautsky U, Næslund B, 2006. Transport and fate of radionuclides in aquatic environments – the use of ecosystem modeling for exposure assessments of nuclear facilities. Journal of Environmental Radioactivity, 87, pp 107–129.

Kutsch W L, Staack A, Wötzel J, Middelhoff U, Kappen L, 2001. Field measurements of root respiration and total soil respiration in an alder forest. New Phytologist, 150, pp 157–168.

Kyläkorpi L, 2004. Nature values and site accessibility maps of Forsmark and Simpevarp. Version 1.2. SKB R-04-12, Svensk Kärnbränslehantering AB.

Kyläkorpi L, Berggren J, Larsson M, Liberg M, Rydgren B, 2000. Biological variables for the site survey of surface ecosystems – existing data and survey methods. SKB R-00-33, Svensk Kärnbränslehantering AB.

Küttel M, 1985. Biostratigraphische und paläoökologische Untersuchungen in SE-Småland, Schweden. Uppsala: Societas Upsaliensis pro geologia quaternaria. (Striae 21).

Lagerbäck R, Sundh M, Svedlund J-O, 2004. Oskarshamn site investigation. Searching for evidence of late- or postglacial faulting in the Oskarshamn region. Results from 2003. SKB P-04-192, Svensk Kärnbränslehantering AB.

Lagerbäck R, Sund M, Svedlund J-O, Johansson H, 2005. Forsmark site investigation. Searching for evidence of late- or postglacial faulting in the Forsmark region. Results from 2002–2004. SKB R-05-51, Svensk Kärnbränslehantering AB.

Lagergren F, Eklundh L, Grelle A, Lundblad M, Mölder M, Lankreijer H, Lindroth A, 2005. Net primary production and light use efficiency in a mixed coniferous forest in Sweden. Plant, Cell and Environment, 28, pp 412–423.

Lagergren F, Lindroth A, Dellwik E, Ibrom A, Lankreijer H, Launiainen S, Mölder M, Kolare P, Pilegaard K, Vesala T, 2008. Biophysical controls on CO_2 fluxes of three Northern forests based on long-term eddy covariance data. Tellus B, 60, pp 143–152.

Laine J, Vasander H, 1996. Ecology and vegetation gradients of peatlands. In: Vasander H (ed). Peatlands in Finland. Helsinki: Finnish Peatland Society, pp 10–20.

Lal R, 2007. Carbon management in agricultural soils. Mitigation and Adaptation Strategies for Global Change, 12, pp 303–322.

Landin J, 2002. Våtmarker av många slag (in Swedish). In: Tonderski K, Weisner S, Landin J, Oscarsson H (eds). Våtmarksboken. Skapande och nyttjande av värdefulla våtmarker. VASTRA rapport 3, Vattenstrategiska forskningsprogrammet (Swedish Water Management Research Programme).

Larcher W, 1995. Physiological plant ecology. 3rd ed. Berlin: Springer.

Larsson S, Tenow O, 1980. Needle-eating insects and grazing dynamics in a mature Scots pine forest in central Sweden. In: Persson T (ed). Structure and function of northern coniferous forests: an ecosystem study. Stockholm: Naturvetenskapliga forskningsrådet. (Ecological Bulletins 32), pp 269–306.

Larsson-McCann S, Karlsson A, Nord M, Sjögren J, Johansson L, Ivarsson M, Kindell S, 2002a. Meteorological, hydrological and oceanographical information and data for the site investigation program in the community of Oskarshamn. SKB TR-02-03, Svensk Kärnbränslehantering AB.

Larsson-McCann S, Karlsson A, Nord M, Sjögren J, Johansson L, Ivarsson M, Kindell S, 2002b. Meteorological, hydrological and oceanographical information and data for the site investigation program in the communities of Östhammar and Tierp in the northern part of Uppland. SKB TR-02-02, Svensk Kärnbränslehantering AB.

Le Dantec V, Dufrêne E, Saugier B, 2000. Interannual and spatial variation in maximum leaf area index of temperate deciduous stands. Forest Ecology and Management, 134, pp 71–81.

Lemel J, 1999. Populationstillväxt, dynamik och spridning hos vildsvinet, Sus scrofa, i mellersta Sverige: slutrapport (in Swedish). Uppsala: Svenska Jägareförbundet.

Li Z, Kurz W A, Apps M J, Beukema S J, 2003. Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: recent improvement and implications for the estimation of NPP and NEP. Canadian Journal of Forest Research, 33, pp 126–136.

Lidman F, 2009. Radionuclide profile from Klarebäcksmossen (PSM006562) analysed by gamma spectrometry and ICP-AES. SKB TR-06-37, Svensk Kärnbränslehantering AB.

Likens G E, Borman F H, 1995. Biogeochemistry of a forested ecosystem. 2nd ed. New York: Springer.

Liljelind I, Barregård L, 2008. Hälsoriksbedömning vid utredning av förorenade områden (in Swedish). Rapport 5859, Naturvårdsverket.

Limpens J, Berendse1 F, Blodau C, Canadell J G, Freeman C, Holden J, Roulet N, Rydin H, Schaepman-Strub G, 2008. Peatlands and the carbon cycle: from local processes to global implications – a synthesis. Biogeosciences, 5, pp 1475–1491.

Linkie M, Smith R J, Leader-Williams N, 2004. Mapping and predicting deforestation patterns in the lowlands of Sumatra. Biodiversity and Conservation, 13, pp 1809–1818.

Lindbladh M, 2004. När granen kom till byn – några tankar kring granens invandring i södra Sverige. Svensk botanisk tidskrift, 98, pp 249–262.

Lindbladh M, Niklasson M, Nilsson S G, 2003. Long-time record of fire and open canopy in a high biodiversity forest in southeast Sweden. Biological Conservation, 114, pp 231–243.

Lindborg T (ed), 2005. Description of surface systems. Preliminary site description Forsmark area – version 1.2. SKB R-05-03, Svensk Kärnbränslehantering AB.

Lindborg T (ed), 2006. Description of surface systems. Preliminary site description Laxemar subarea – version 1.2. SKB R-06-11, Svensk Kärnbränslehantering AB.

Lindborg T (ed), 2010. Landscape Forsmark – data, methodology and results for SR-Site. SKB TR-10-05, Svensk Kärnbränslehantering AB.

Lindborg T, Kautsky U, 2000. Variabler i olika ekosystem, tänkbara att beskriva vid platsundersökning för ett djupförvar (in Swedish). SKB R-00-19, Svensk Kärnbränslehantering AB.

Lindborg T, Kautsky U (eds), 2004. Ecosystem modelling in the Forsmark area – proceedings from two workshops modelling Eckarfjärden and Bolundsfjärden catchment areas. SKB R-04-71, Svensk Kärnbränslehantering AB.

Lindborg T, Löfgren A, 2005. A strategy for biosphere descriptions during site investigations for a repository of spent nuclear fuel. Conference proceeding ECORAD 2004, Aix en Provence, France, Radioprotection, Suppl. 1, 40, pp 707–712.

Lindroos H, Isaksson H, Thunehed H, 2004. The potential for ore and industrial minerals in the Forsmark area. SKB R-04-18, Svensk Kärnbränslehantering AB.

Lindroth A, Grelle A, Morén A-S, 1998. Long-term measurements of boreal forest carbon balance reveal large temperature sensitivity. Global Change Biology, 4, pp 443–450.

Lindroth A, Lund M, Nilsson M, Aurela M, Christensen T R, Laurila T, Rinne J, Riutta T, Sagerfors J, Ström L, Tuovinen J-P, Vesala T, 2007. Environmetal controls on the CO_2 exchange in north European mires. Tellus B, 59, pp 812–825.

Liski J, Ilvesniemi H, Mäkelä A, Starr M, 1998. Model analysis of the effects of soil age, fires and harvesting on the carbon storage of boreal forests. European Journal of Soil Science, 49, pp 407–416.

Liu J, Chen J M, Cihlar J, Chen W, 1999. Net primary productivity distribution in the BOREAS region from a process model using satellite and surface data. Journal Geophysical Research, 104, pp 27735–27754.

Lohm U, Persson T, 1978. Levande jord (in Swedish). Stockholm: Esselte studium. (Aktuell biologi 3)

Lovett G M, Cole J J, Pace M L, 2006. Is net ecosystem production equal to ecosystem carbon accumulation. Ecosystems, 9, pp 1–4.

Lucht W, Prentice I C, Myneni R B, Sitch S, Friedlingstein P, Cramer W, Bousquet P, Buermann W, Smith B, 2002. Climatic control of the high-latitude vegetation greening trend and Pinatubo effect. Science, 296, pp 1687–1689.

Lund M, Lindroth A, Christensen T, Ström L, 2007. Annual CO_2 balance of a temperate bog. Tellus B, 59, pp 804–811.

Lundin L, Lode E, Stendahl J, Melkerud P A, Björkvald L, Thorstensson A, 2004. Soils and site types in the Forsmark area. SKB R-04-08, Svensk Kärnbränslehantering AB.

Lundin L, Lode E, Stendahl J, Björkvald L, Hansson J, 2005a. Oskarshamn site investigation. Soils and site types in the Oskarshamn area. SKB R-05-15, Svensk Kärnbränslehantering AB.

Lundin L, Stendahl J, Lode E, 2005b. Forsmark site investigation. Soils in two large trenches. SKB P-05-166, Svensk Kärnbränslehantering AB.

Lundin L, Lode E, Stendahl J, 2006. Oskarshamn site investigation. Extended soil chemistry in three site types. SKB P-06-321, Svensk Kärnbränslehantering AB.

Lundin L, Snäll S, Jonsson E, Hannu S, Selnert E, Engdahl A, 2007. Oskarshamn site investigation. Characterization of soil samples from three valleys in the Laxemar area. SKB P-07-222, Svensk Kärnbränslehantering AB.

Lundkvist E, 2006. Oskarshamn site investigation. Production and respiration measurements in different vegetation types. Comparisons between a young pine stand, a wet forest, a fen, and an agricultural field. SKB P-06-278, Svensk Kärnbränslehantering AB.

Lundmark J E, 1988. Skogsmarkens ekologi. Ståndortsanpassat skogsbruk. Del 2. Tillämpning (in Swedish). Jönköping: Skogsstyrelsen.

Lundmark J E, Berg B, Nilsson Å, 1982. Contortatallens inflytande på mark och markvegetation i jämförelse med sylvestristallens. Sveriges skogsvårdsförbunds tidskrift, 1–2, pp 43–48.

Lundqvist L, 2006. Inledande kulturhistoriska studier i Simpevarpsområdet. Småland, Misterhults socken, Oskarshamn kommun (in Swedish). SKB R-06-65, Svensk Kärnbränslehantering AB.

Lunt D J, Ross I, Hopley P J, Valdes P J, 2007. Modelling Late Oligocene C_4 grasses and climate. Palaeogeography, Palaeoclimatology, Palaeoecology, 251, pp 239–253.

Lärke A, Hillgren R, Wern L, Jones J, Aquilonius K, 2005. Oskarshamn site investigation. Hydrological and meteorological monitoring at Oskarshamn during 2003–2004. SKB P-05-227, Svensk Kärnbränslehantering AB.

Löfgren A, 2005. Oskarshamn/Forsmark site investigation. Estimation of biomass and net primary production in field and ground layer, and biomass in litter layer in different vegetation types in Forsmark and Oskarshamn. SKP P-05-80, Svensk Kärnbränslehantering AB.

Löfgren A (ed), 2008. The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp. Site descriptive modelling, SDM-Site. SKB R-08-01, Svensk Kärnbränslehantering AB.

Löfgren A, Jerling L, 2002. Species richness, extinction and immigration rates of vascular plants on islands in the Stockholm archipelago, Sweden, during a century of ceasing management. Folia Geobotanica, 37, pp 297–308.

Löfgren A, Lindborg T, 2003. A descriptive ecosystem model – a strategy for model development during site investigations. SKB R-03-06, Svensk Kärnbränslehantering AB.

Löfgren A, Miliander S, Truvé J Lindborg T, 2006. Carbon budgets for catchments across a manged landscape mosaic in southeast Sweden: Contributing to the safety assessment of a nuclear waste repository. Ambio, 35, pp 459–468.

Löfquist I, 2005. Fullfoder till får. Kristianstad: Hushållningssällskapet.

MacDonald D, Crabtree J R, Wiesinger G, Dax T, Stamou N, Fleury P, Lazpita J G, Gibon A, 2000. Agricultural Abandonment in Mountain Areas of Europe: Environmental Consequences and Policy Response. Journal of Environmental Management, 59, pp 47–69.

Magnusson C, Sohlenius B, 1980. Root consumption in a 15–20 year old Scots pine stand with special regard to phytophagus nematodes. In: Persson T (ed). Structure and function of Northern coniferous forests: an ecosystem study. Stockholm: Naturvetenskapliga forskningsrådet. (Ecological Bulletins 32), pp 261–268.

Maljanen M, Martikainen P J, Walden J, Silvola J, 2001. CO_2 exchange in an organic field growing barley or grass in eastern Finland. Global Change Biology, 7, pp 679–692.

Malmer N, Wallén B, 2004. Input rates, decay losses and accumulation rates of carbon in bogs during the last millennium: internal processes and environmental change. The Holocene, 14, pp 111–117.

Marklund L G, 1988. Biomassafunktioner för tall, gran och björk i Sverige (Biomass functions for Scots pine, Norway spruce and birch in Sweden) (in Swedish). Rapport 45, Swedish University of Agricultural Sciences, Umeå, Sweden.

Marshall J D, Waring R H, 1985. Predicting fine root production and turnover by monitoring root starch and soil temperature. Canadian Journal of Forest Research, 15, pp 791–800.

Martin, J G, Kloeppel B D, Schaefer T L, Kimbler D L, McNuity S G, 1998. Above-ground biomass and nitrogen allocation of ten deciduous southern Appalachian tree species. Canadian Journal of Forestry Research, 28, pp 1648–1659.

Matamala R, González-Meler M A, Jastrow J D, Norby J R, Schlesinger W H, 2003. Impacts of fine root turnover on forest NPP and soil C sequestration potential. Science, 302, pp 1385–1387.

Matamala W, Schlesinger W H, 2000. Effects of elevated atmospheric CO_2 on fine root production and activity in an intact temperate forest ecosystem. Global Change Biology, 6, pp 967–979.

Mattson L, Stridberg E, 1980. Skogens roll i i svensk markanvändning: en utvecklingsstudie (in Swedish). Rapport 32, Swedish Institute of Agriculture Sciences, Umeå, Sweden.

Mattson W J, Addy N D, 1975. Phytophagous insects as regulators of forest primary production. Science, 190, pp 515–522.

Mayall A, 2003. Modelling the dispersion of radionuclides in the atmosphere; In: Scott E M (ed). Modelling of radioactivity in the environment. Amsterdam: Elsevier, pp 13–54

McCloy K R, Lucht W, 2001. Comparison of the fraction absorbed photosynthetically active radiation (FAPAR) data derived from AVHRR NVDI data with that estimated by the LPJ global dynamic vegetation model, for the period July 1981 – June 1998. In: Geoscience and Remote Sensing Symposium, 2001. IGARSS ‘01. IEEE 2001 International 3, pp 1335–1337.

McGuire A D, Sitch S, Clein J S, 2001. Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO_2, climate and land use effects with four process-based ecosystem models. Global Biogeochemical Cycles, 15, pp 183–206.

Meehl G A, Stocker T F, Collins W D, Friedlingstein P, Gaye A T, Gregory J M, Kitoh A, Knutti R, Murphy J M, Noda A, Raper S C B, Watterson I G, Weaver A J, Zhao Z-C, 2007. Global Climate Projections. In: Climate Change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel of Climate Change, 2007. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K B, Tignor M, Miller H L (eds). Cambridge: Cambridge University Press.

Miliander S, Punakivi M, Kyläkorpi L, Rydgen B, 2004a. Human population and activities at Forsmark. Site description. SKB R-04-10, Svensk Kärnbränslehantering AB.

Miliander S, Punakivi M, Kyläkorpi L, Rydgren B, 2004b. Human population and activities at Simpevarp. Site description. SKB R-04-11, Svensk Kärnbränslehantering AB.

Ministry of Environment, 2007. Sverige inför klimatförändringarna – hot och möjligheter (in Swedish). SOU 2007:60, Ministry of Environment, Sweden.

Mitsch W J, Gosselink J G, 2000. Wetlands. New York: Wiley.

Mitsch W J, Dorge C L, Wiemhoff J R, 1979. Ecosystem dynamics and a phosphorus budget of an alluvial cypress swamp in southern Illinois. Ecology, 60, pp 1116–1124.

Mjöfors K, Johansson M B, Nilsson Å, Hyvönen R, 2007. Input and turnover of forest tree litter in the Forsmark and Oskarshamn areas. SKB R-07-23, Svensk Kärnbränslehantering AB.

Morales P, Sykes M T, Prentice I C, Smith P, Smith B, Bugmann H, Zierl B, Friedlingstein P, Viovy N, Sabaté S, Sanchez A, Pla E, Gracia C A, Sitch S, Arneth A, Ogee J, 2005. Comparing and evaluating process based ecosystem predictions of carbon and water fluxes in major European forest biomes. Global Change Biology, 11, pp 2211–2233.

Morales P, Hickler T, Rowell D P, Smith B, Sykes M T, 2007. Changes in European ecosystem productivity and carbon balance driven by Regional Climate Model output. Global Change Biology, 13, pp 108–122.

Mossberg B, Stenberg L, 2003. Den nya nordiska floran (in Swedish). Stockholm: Wahlström & Widstrand.

Mossberg B, Nilsson S, Persson O, 1979. Svampar i naturen. Del 1 och del 2 (in Swedish). Stockholm: Wahlström & Widstrand.

Mungur A S, Shutes R B E, Rewitt D M, House M A, 1995. An assessment of metal removal from highway runoff by a natural wetland. Water Science and Technology, 32, pp 169–175.

Munthe J, Johanson K J, Skyllberg U, Tyler G, 2001. Effekter på tungmetallers och cesiums rörlighet av markförsurning och motåtgärder (in Swedish). Rapport 2001:11G, Skogsstyrelsen, Jönköping, Sweden.

Munier R, 2010. Full perimeter intersection criteria. Definitions and implementations in SR-Site. SKB TR-10-21, Svensk Kärnbränslehantering AB.

Murray G, Boxall P C, Wein R W, 2005. Distribution, abundance, and utilization of wild berries by the Gwich'in people in the Mackenzie river delta region. Economic Botany, 59, pp 174–184.

Myers-Smith I H, Harden J W, Wilmking M, Fuller C C, McGuire A D, Chapin III F S, 2008. Wetland succession in a permafrost collapse: interactions between fire and thermokarst. Biogeosciences, 5, 1273–1286.

Myllys M, 1996. Agriculture on peatlands. In: Vasander H (ed). Peatlands in Finland. Helsinki: Finnish Peatland Society, pp 64–71.

Mäkilä M, Goslar T, 2008. The carbon dynamics of surface peat layers in southern and central boreal mires of Finland and Russian Karelia. Suo, 59, pp 49–69.

Nabuurs G J, Päivinen R, Sikkema R, Mohren G M J, 1997. The role of the European forests in the global carbon cycle – a review. Biomass Bioenergy, 13, pp 345–358.

Nabuurs G J, Schelhaas M J, Mohren G M J, Field C B, 2003. Temporal evolution of the European forest sector carbon sink from 1950 to 1999. Global Change Biology, 9, pp 152–160.

Nagy K A, 1987. Field metabolic rate and food requirement scaling in mammals and birds. Ecological Monographs, 57, pp 111–128.

Nagy K A, Girard I A, Brown T K, 1999. Energetics of free-ranging mammals, reptiles and birds. Annual Review of Nutrition, 19, pp 247–277.

Naito W, Miyamoto K-I, Nakanishi J, Masunaga S, Bartell S M, 2002. Application of an ecosystem model for aquatic ecological risk assessment of chemicals for a Japanese lake. Water Research, 36, pp 1–14.

Naturhistoriska riksmuseet, 1997. Den virtuella floran. [Online]. Available at: http://linnaeus.nrm.se/flora/. [7 August 2007].

Naturvårdsverket, 2007. Levande sjöar och vattendrag. Underlagsrapport till fördjupad utvärdering av miljömålsarbetet. Rapport 5769, Naturvårdsverket (Swedish Environmental Protection Agency). (In Swedish.),

Naturvårdsverket, 2009. Riktvärden för förorenad mark. Modellbeskrivning och vägledning. Rapport 5976, Naturvårdsverket.

Neff J C, Ashner G P, 2001. Dissolved organic carbon in terrestrial ecosystems. Ecosystems, 4, pp 29–48.

Nemani R R, Keeling C D, Hashimoto H, Jolly W M, Piper S C, Tucker C J, Myneni, R B, Running S W, 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. Science, 300, pp 1560–1563.

Ni J, Harrison S P, Prentice I C, Kutzbach J E, Sitch S, 2006. Impact of climate variability on present and Holocene vegetation: A model study. Ecological Modeling, 191, pp 469–486.

Niering W A, 1989. Wetland vegetation development. In: Majumdar S K, Brooks R P, Brenner F J, Tiner J R W (eds). Wetlands ecology conservation: emphasis in Pennsylvania. Easton, PA: Pennsylvania Academy of Science, pp 103–113.

Nikula A, Heikkinen S, Helle E, 2004. Habitat selection of adult moose Alces alces at two spatial scales in central Finland. Wildlife Biology, 10, pp 121–135.

Nilsson G, 2004. Oskarshamn site investigation. Investigation of sediments, peat lands and wetlands. Stratigraphical and analytical data. SKB P-04-273, Svensk Kärnbränslehantering AB.

Nilsson M, Bohlin E, 1993. Methane and carbon dioxide concentrations in bogs and fens – with special reference to the effects of the botanical composition of the peat. Journal of Ecology, 81, pp 615–625.

Nilsson T, Lundin L, 2006. Prediction of bulk density in Swedish forest soils from the organic carbon content and soil depth. Report 91, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Nordén S, 2007. Forsmark site investigation. Collection of archive samples. SKB P-07-196, Svensk Kärnbränslehantering AB.

Nordén S, Söderbäck B, Andersson E, 2008. The limnic ecosystems at Forsmark and Laxemar-Simpevarp. Site descriptive modelling, SDM-Site. SKB R-08-02, Svensk Kärnbränslehantering AB.

Nordén S, de la Cruz I, Grolander S, Stenberg K, Avila R, 2010. Element-specific and constant parameters used for dose calculations in SR-Site. SKB TR-10-07, Svensk Kärnbränslehantering AB.

Novick K A, Stoy P C, Katul G G, Ellsworth D S, Siqueira M B S, Juang J, Oren R, 2004. Carbon dioxide and water vapor exchange in a warm temperate grassland. Oecologica, 138, pp 259–274.

Nylén T, Grip H, 1991. Transport of caesium-137 in a forest catchment. In: Feldt W (ed). Proceedings of the XVth Congress of IRPA. Progress in Radiation Protection, pp 221–226.

Næsser E, 1999. Decomposition rate constants of Picea abies logs in southeastern Norway. Canadian Journal of Forest Research, 29, pp 372–381.

Odum H T, Odum E P, 1955. Trophic structure and productivity of a winward coral reef community on Eniwetok Atoll. Ecological Monographs, 35, pp 291–320.

Oleksyn J, Reisch P B, Chalupka W, Tjoelker M G, 1999. Differential above- and below-ground biomass accumulation of European Pinus sylvestris populations in a 12-year-old provenance experiment. Scandinavian Journal of Forest Research, 14, pp 7–17.

Olsson M, 2000a. Bidrar marken till växthuseffekten – eller kan den hjälpa oss att lösa problemen? (in Swedish). Kungliga Skogs- och Lantbruksakademins tidsskrift, 139, pp 41–50.

Olsson K, 2000b. Hammarsjön Dykungens sjö. Svensk botanisk tidskrift, 95, pp 71–80.

Olsson M, Melkerud P A, 1989. Chemical and mineralogical changes during genesis of a podzol from till in southern Sweden. Geoderma, 45, pp 267–287.

Olsson M, Erlandsson M, Lundin L, Nilsson T, Nilsson Å, Stendahl J, 2008. Organic carbon stocks in Swedish Podzol soils in relation to soil hydrology and other site characteristics. Silva Fennica, 43, pp 209–222.

Olofsson P, Eklundh L, Lagergren F, Jönsson P, Lindroth A, 2006. Estimating net primary production for Scandinavian forest using data from Terra/MODIS. Advances in Space Research, 39, pp 125–130.

Olsthoorn A F M, 1991. Fine root density and root biomass of two Douglas-fir stands on sandy soils in the Netherlands. 1. Root biomass in early summer. Netherlands Journal of Agricultural Science, 39, pp 49–60.

ORNL DAAC, 2009. Global leaf area index data from field measurements, 1932–2000. [Online]. Web page. Available at: http://daac.ornl.gov/VEGETATION/LAI_support_images.html#table. Oak Ridge National Laboratory Distributed Active Archive Centre (ORNL DAAC), Oak Ridge, Tennessee. [07 June 2009].

Ottosson P, 2006a. Nulägesbeskrivning av rekreation och friluftsliv i Oskarshamn (in Swedish). SKB P-06-114, Svensk Kärnbränslehantering AB.

Ottosson P, 2006b. Nulägesbeskrivning av rekreation och friluftsliv i Forsmark (in Swedish). SKB P-06-113, Svensk Kärnbränslehantering AB.

Parmalee P W, Klippel W E, 1974. Freshwater mussels as a prehistoric food resource. American Antiquity, 39, pp 421–434.

Partanen K, Siljander-Rasi H, Hokavaara M, Ruusunen M, 2007. Effects of finishing diet and pre-slaughter fasting time on meat quality in crossbred pigs. Agricultural and Food Science, 16, pp 245–258.

Pennock D J, van Kessel C, 1997. Clear-cut forest harvest impacts on soil quality indicators in the mixedwood forest of Saskatchewan, Canada. Geoderma, 75, pp 13–32.

Persson E, Mattsson B, 2002. Strategi för uppfödning av slaktsvin. Rapport 29, PIG – Praktiskt Inriktade Grisförsök.

Persson H, 1975. Deciduous woodland at Andersby, eastern Sweden: field-layer and belowground production. Uppsala: Svenska växtgeografiska sällskapet. (Acta phytogeographica suecica 62).

Persson H, 1978. Spatial distribution of fine root growth, mortality and decomposition in a young Scots pine stand in Central Sweden. Oikos, 34, pp 77–87.

Persson H, 1983. The distribution and productivity of fine roots in boreal forests. Plant and Soil, 71, pp 87–101.

Persson H, 2000. Adaptive tactics and characteristics of tree fine roots. Development in Plant and Soil Sciences, 33, pp 337–346.

Persson H, 2002. Root systems of arboreal plants. In: Waisel Y, Eshel A, Kafkafi U (eds). Plant roots: the hidden half. 3rd ed. New York: Marcel Dekker.

Persson T, Nilsson L-O (eds), 2001. Skogabyförsöket – Effekter av långvarig kväve- och svavel tillförsel till ett skogsekosystem (in Swedish). Rapport 5173, Naturvårdsverket (Swedish Environmental Protection Agency).

Persson H, Stadenberg I, 2007a. Distribution of fine roots in forest areas close to the Swedish Forsmark and Oskarshamn nuclear power plants. SKB R-07-01, Svensk Kärnbränslehantering AB.

Persson H, Stadenberg I, 2007b. Growth dynamics of fine roots in a coniferous fern forest site close to Forsmark in the central part of Sweden. SKB TR-07-11, Svensk Kärnbränslehantering AB.

Persson H, Majdi H, Clemensson-Lindell A, 1995. Effect of acid deposition on tree roots. Ecological Bulletin, 44, pp 158–167.

Persson T, Lenoir L, Taylor A, 2007. Bioturbation in different ecosystems at Forsmark and Oskarshamn. SKB R-06-123, Svensk Kärnbränslehantering AB.

Petanidou T, Kizos T, Soulakellis N, 2008. Socioeconomic Dimensions of Changes in the Agricultural Landscape of the Mediterranean Basin: A Case Study of the Abandonment of Cultivation Terraces on Nisyros Island, Greece. Environmental Management, 41, pp 250–266.

Petersson H, Ståhl G, 2006. Functions for below-ground biomass of Pinus sylvestris, Picea Abies, Betula pendula and Betula pubescens in Sweden. Scandinavien Journal of Forest Research, 21, pp 84–93.

Petrusewicz K (ed), 1967. Secondary productivity of terrestrial ecosystems (principles and methods). Vol II. Warszawa: Panstwowe Wydawnictwo Naukowe.

Pihl Karlsson G, Blomgren H, Pettersson K, Svensson A, Sjöberg K, 2003. Nationell miljöövervakning av luft- och nederbördskemi 2002 (in Swedish). IVL Rapport U 852, IVL Svenska Miljöinstitutet AB (IVL Swedish Environmental Research Institute Ltd.).

Pihl Karlsson G, Nettelbladt A, Akselsson C, Hellsten S, Karlsson P E, Kronnäs V, Malm G, 2008. För Kalmar läns Luftvårdsförbund. Övervakning av luftföroreningar i Kalmar län – mätningar och modellering. Resultat till och med september 2007 (in Swedish). IVL Rapport B 1777, IVL Svenska Miljöinstitutet AB (IVL Swedish Environmental Research Institute Ltd.).

Pitt V H (ed), 1977. The Penguin dictionary of physics. Harmodsworth: Penguin.

Porteous A, 2000. Dictionary of environmental science and technology. 3rd ed. Chichester: Wiley.

Pregitzer K S, Euskirschen E S, 2004. Carbon cycling and storage in world forests: biome patterns related to forest age. Global Change Biology, 10, pp 2052–2077.

Pregitzer K S, Laskowski M J, Burton A J, Lessard V C, Zak D R, 1998. Variation in sugar maple root respiration with root diameter and soil depth. Tree Physiology, 18, pp 665–670.

Prentice I C, Helmisaari H, 1991. Silvics of north European trees: Compilation, comparisons and implications for forest succession modelling. Forest Ecology and Management, 42, pp 79–93.

Pröhl G, 1990. Modellierung der Radionuklidausbreitung in Nahringsketten nach Deposition von Strontium-90, Cäsium-137 ind Jod-131 auf landwirtschaftlich genutzte Flächen Institut für Strahlenschutz, GSF-Bericht 29/90. GSF-Forschungszentrum für Umvelt und Gesundheit, Neuherberg.

Pusch R, 1973. Densitet vattenhalt och portal: förslag till geoteknisk laboratoriehänvisning, del 7 (in Swedish). Stockholm: Statens institut för byggnadsforskning. (Byggforskningsrådets informationsblad B5:1973)

Påhlsson L (ed), 1994. Vegetationstyper i Norden (in Swedish). Köpenhamn: Nordiska ministerrådet. (TemaNord 1994:665)

Påhlsson L (ed), 1998. Vegetationstyper i Norden (in Swedish). 3rd ed. København: Nordisk Ministerråd. (TemaNord 1998:510)

Påsse T, 1997. A mathematical model of past, present and future shore level displacement in Fennoscandia. SKB TR 97-28, Svensk Kärnbränslehantering AB.

Påsse T, 2001. An empirical model of glacio-isostatic movements and shore-level displacement in Fennoscandia. SKB R-01-41, Svensk Kärnbränslehantering AB.

Rahme L, Hartman D, 2006. Fiskskinn: garvning och sömnad med traditionella metoder. Sigtuna: Lottas garfveri. (In Swedish.)

Raisch J W, Schlesinger W H, 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus B 44, pp 81–99.

Ranheden, 1989. Barknåre och Lingnåre, human impact and vegetational development in an area of subrecent landuplift. Uppsala: Societas Upsaliensis pro Geologia Quaternaria. (Striae 33).

Raulo J, Hokkanen T, 1989. Litter fall of Alnus incana and Alnus glutinosa. Folia Forestalia, 738, pp 1–25.

Rayment M B, Jarvis P G, 2000. Temporal and spatial variation of soil CO_2 efflux in a Canadian boreal forest. Soil Biology and Biochemistry, 32, pp 35–45.

Read D J, 1991. Mycorrhizas in ecosystems. Experientia, 47, pp 376–391.

Read D J, 1994. Plant-microbe mutualisms and community structure. In: Schulze E-D, Mooney H-A (eds). Biodiversity and Ecosystem Function. Berlin: Springer.

Reid J M, Monaghan P, Ruxton G D, 2000. The consequences of clutch size for incubation conditions and hatching success in starlings. Functional Ecology, 14, pp 560–565.

Renting A, 1996. I skuggan av Lövsta bruk: järnbruksrörelsens inverkan på agrarsamhället i norra Uppland 1630–1930 (in Swedish). (Meddelanden från Kulturgeografiska institutionen vid Stockholms universitet 96).

Richardson C J, 1994. Ecological functions and human values in wetlands: a framework for assessing impacts. Wetlands, 14, pp 1–9.

Richardson C J, 1995. Wetlands ecology. In: Nierenberg W A (ed). Encyclopedia of environmental biology. San Diego, CA: Academic Press, pp 535–550.

Risberg J, 2005. Forsmark site investigation. Bio- and lithostratigraphy in offshore sediment core PFM004396. Salinity variations in the Bothnian Sea offshore Forsmark. SKB P-05-139, Svensk Kärnbränslehantering AB.

Robinson S D, Moore T R, 2000. The influence of permafrost and 2fire upon carbon accumulation in high boreal peatlands, Northwest Territories, Canada. Arctic, Antarctic, and Alpine Research, 32, pp 155–166.

Rosén E, Borgegård S-O, 1999. The open cultural landscape. In: Rydin H, Snoeijs P, Diekmann M (eds). Swedish plant geography: dedicated to Eddy van der Maarel on his 65th birthday. Uppsala: Svenska växtgeografiska sällskapet. (Acta Phytogeographica Suecica 84), pp 113–134.

Rouwenhorst R J, Jzn J F, Scheffers W A, van Dijken J P, 1991. Determination of protein concentration by total organic carbon analysis. Journal of Biochemical and Biophysical Methods, 22, pp 119–128.

Rudmark L, 2004. Oskarshamn site investigation. Investigation of Quaternary deposits at Simpevarp peninsula and the islands of Ävrö and Hålö. SKB P-04-22, Svensk Kärnbränslehantering AB.

Rudmark L, Malmberg-Persson K, Mikko H, 2005. Oskarshamn site investigation. Investigation of Quaternary deposits 2003–2004. SKB P-05-49, Svensk Kärnbränslehantering AB.

Ruimy A, Saugier B, Dedieu G, 1994. Methodology for the estimation of terretrial net primary production from remotely sensed data. Journal of Geophysical Research, 99, pp 5263–5283.

Runyon J, Waring R H, Goward S N, Welles J M, 1994. Environmental limits on net primay production and light use efficiency across the Oregon transect. Ecological Applications, 4, pp 226–237.

Rydin H, Borgegård S O, 1991. Plant characteristics over a century of primary succession on islands: Lake Hjälmaren. Ecology, 72, pp 1089–1101.

Rydin H, Sjörs H, Löfroth M, 1999. Mires. Acta Phytogeographica Suecica, 84, pp 91–112.

Rühling Å, 1997. Floran i Oskarshamns kommun. Lund: Svensk Botanisk Förening.

Saarsalmi A, Starr M, Hokkanen T, Ukonmaanaho L, Kukkola M, Nöjd P, Sievänen R, 2007. Predicting annual canopy and litterfall production for Norway spruce (Picea abies (L.) Karst.) stands. Forest Ecology and Management, 242, pp 578–586.

Saiz G, Black K, Reidy B, Lopez S, Farrell E P, 2007. Assessment of soil CO_2 efflux and its components using a process-based model in a young temperate forest site. Geoderma, 139, pp 79–89.

Sala O E, van Vuuren D, Pereira H M, Lodge D, Alder J, Cumming G, Dobson A, Volters W, Xenopoulos M, Zaitsev A S, 2005. Biodiversity across scenarios. In: Carpenter S R, Pingali P (eds). Ecosystem services and human well-being: scenarios. Vol 2. Washington, D.C.: Island Press.

Salo K, 1979. Mushrooms and mushroom yield on transitional peatlands in central Finland. Annales Botanici Fennici, 16, pp 181–192.

Salonen K, Sarvala J, Hakala I, Viljanen M-L, 1976. The relation of energy and organic carbon in aquatic invertebrates. Limnology and Oceanography, 21, pp 724–730.

Samuelson L J, Johnsen K, Stokes T, 2004. Production, allocation, and stemwood growth efficiency of Pinus taeda L. stands in response to 6 years of intensive management. Forest Ecology and Management, 192, pp 59–70.

Santantonio D, Hermann R K, 1985. Standing crop, production, and turnover of fine roots on dry, moderate, and wet sites of mature Douglas-fir in western Oregon. Annales des Sciences Forestières, 42, pp 113–142.

Saugier B, Roy R, Mooney H A, 2001. Estimations of global terrestrial productivity: Converging toward a single number? In: J Roy, Saugier B, Mooney H A (eds). Terrestrial global productivity. London: Academic Press, pp 543–557.

Sawhney B L, 1972. Selective sorption and fixation of cations by clay minerals: a review. Clays and Clay Minerals, 20, pp 93–100.

Saxén R, 1994. Transport of Cs-137 in large Finnish drainage basins. In: Dahlgaard H (ed). Nordic radioecology: the transfer of radionuclides through Nordic ecosystems to man. Amsterdam: Elsevier, pp 63–78.

Scarascia-Mugnozza G, Bauer G A, Persson H, Matteucci G, Masci A, 2000. Tree biomass, growth and nutrient pools. In: Schulze E-D (ed). Carbon and nitrogen cycling in European forest ecosystems. Berlin: Springer. (Ecological Studies 142)

SCB, 1998. Markanvändningen i Sverige (Land use in Sweden) (in Swedish). 3rd ed. Örebro: Statistiska centralbyrån.

SCB, 2000a. Naturmiljön i siffror 2000 (The Natural Environment in Figures 2000) (in Swedish). Stockholm: Statistiska centralbyrån (SCB) och Naturvårdsverket Sweden.

SCB, 2000b. Standard yields for yield survey districts, counties and the whole country in 2000 (in Swedish). Statistiska meddelanden JO 15 SM 0001, Statistiska centralbyrån.

SCB, 2001. Standard yields for yield survey districts, counties and the whole country in 2001 (in Swedish). Statistiska meddelanden JO 15 SM 0101, Statistiska centralbyrån.

SCB, 2002. Standard yields for yield survey districts, counties and the whole country in 2002 (in Swedish). Statistiska meddelanden JO 15 SM 0201, Statistiska centralbyrån.

SCB, 2003. Standard yields for yield survey districts, counties and the whole country in 2003 (in Swedish). Statistiska meddelanden JO 15 SM 0301, Statistiska centralbyrån.

SCB, 2004. Standard yields for yield survey districts, counties and the whole country in 2004 (in Swedish). Statistiska meddelanden JO 15 SM 0401, Statistiska centralbyrån.

SCB, 2005. Standard yields for yield survey districts, counties and the whole country in 2005 (in Swedish). Statistiska meddelanden JO 15 SM 0501, Statistiska centralbyrån.

SCB, 2006. Standard yields for yield survey districts, counties and the whole country in 2006 (in Swedish). Statistiska meddelanden JO 15 SM 0601, Statistiska centralbyrån.

SCB, 2007a. Standard yields for yield survey districts, counties and the whole country in 2007 (in Swedish). Statistiska meddelanden JO 15 SM 0701, Statistiska centralbyrån.

SCB, 2007b. Yield per hectar and total production in regions for different crops. Yearly data. [Online]. Available at: http://www.ssd.scb.se/databaser/makro/Visavar.asp?yp=tansss&xu=C9233001&huvudtabell=SkordarL&deltabell=01&deltabellnamn=Yield+per+hectar+and+total+production+in+regions+for+different+crops.+Yearly+data.&omradekod=JO&omradetext=Agriculture%2C+forestry+and+fishery&preskat=O&innehall=HektarSkord&starttid=1965&stopptid=2009&Prodid=JO0601&fromSok=&Fromwhere=S&lang=2&langdb=2. [4 December 2007].

SCB, 2007c. Vattenuttag och vattenanvändning i Sverige 2005 (Water withdrawal and water use in Sweden 2005) (in Swedish). Statistiska Meddelanden MI 27 SM 0701, Statistiska centralbyrån.

SCB, 2009. Yield per hectar and total production in regions for different crops. Yearly data. [Online]. Available at: http://www.ssd.scb.se/databaser/makro/Visavar.asp?yp=tansss&xu=C9233001&huvudtabell=SkordarL&deltabell=01&deltabellnamn=Yield+per+hectar+and+total+production+in+regions+for+different+crops.+Yearly+data.&omradekod=JO&omradetext=Agriculture%2C+forestry+and+fishery&preskat=O&innehall=HektarSkord&starttid=1965&stopptid=2009&Prodid=JO0601&fromSok=&Fromwhere=S&lang=2&langdb=2. [15 September 2009].

Schlesinger W H, 1977. Carbon balance in terrestrial detritus. Annual Review of Ecology and Systematics, 8, pp 51–81.

Schlesinger W H, 1990. Evidence from chronosequence studies for a low carbon potential of soils. Nature, 348, pp 232–234.

Schlesinger W H, 1997. Biogeochemistry: an analysis of global change. 2nd ed. San Diego, CA: Academic Press.

Schowalter T D, 2000. Insect ecology: an ecosystem approach. San Diego, CA: Academic Press.

Schowalter T D, Hargrove W W, Crossley D A, 1986. Herbivory in forested ecosystems. Annual Review of Entomology, 31, pp 177–196.

Schulze E-D (ed), 2000. Carbon and nitrogen cycling in European forest ecosystems. Berlin: Springer.

Schuur E A, G, Bockheim J, Canadell J G, Euskirchen E, Field C B, Goryachkin S V, Hagemann S, Kuhry P, Lafleur P, Lee H, Mazhitova G, Nelson F E, Rinke A, Romanovsky V, Shiklomanov N, Tarnocai C, Venevsky S, Vogel J G, Zimov S A, 2008. Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. BioSciences, 58, pp 701–714.

Scott J A, French N R, Leetham J W, 1979. Patterns of consumption in grasslands. In: French N R (ed). Perspectives in grassland ecology. New York: Springer, pp 89–105.

Seinfeld J H, 1986. Atmospheric chemistry and physics of air pollution. New York: Wiley.

Sheppard M I, Shepard S C, Sanipelli B, 2002. Recommended biosphere model values for iodine. Report 06819-REP-01200-10090. Ontario Power Generation, Nuclear Waste Management Division, Canada.

Sheppard S C, Sheppard M I, Tait J C, Sanipelli B L, 2006. Revision and meta analysis of selected biosphere parameter values for chlorine, iodine, neptunium, radium, radon and uranium. Journal of Environmental Radioactivity, 89, pp 115–137.

Sheppard S, Long J, Sanipelli B, Sohlenius G, 2009. Solid/liquid partition coefficients (Kd) for selected soils and sediments at Forsmark and Laxemar-Simpevarp. SKB R-09-27, Svensk Kärnbränslehantering AB.

Silvola J, Alm J, Ahlholm U, Nykänen H, Martikainen P J, 1996. CO_2 fluxes from peat in boreal mires under varying temperature and moisture conditions. Journal of Ecology, 84, pp 219–228.

Sitch S, Smith B, Prentice I C, Arneth A, Bondeau A, Crameer W, Kaplans J O, Levis S, Lucht W, Sykes M T, Thonicke K, Venevsky S, 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Global Vegetation Model. Global Change Biology, 9, pp 161–185.

Sjörs H, 1967. Nordisk växtgeografi (in Swedish). 2nd ed. Stockholm: Bonnier.

SKB, 2001. Project SAFE. Scenario and system analysis. SKB R-01-13, Svensk Kärnbränslehantering AB.

SKB, 2006. FEP report for the safety assessment SR-Can. SKB TR-06-20, Svensk KärnbränslehanteringAB.

SKB, 2008. Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark. SKB TR-08-05, Svensk Kärnbränslehantering AB.

SKB, 2009. Site description of Laxemar at completion of the site investigation phase. SDM-Site Laxemar. SKB TR-09-01, Svensk Kärnbränslehantering AB.

SKB, 2010a. Biosphere analyses for the safety assessment SR-Site – synthesis and summary of results. SKB TR-10-09, Svensk Kärnbränslehantering AB.

SKB, 2010b. Climate and climate-related issues for the safety assessment SR-Site. SKB TR-10-49, Svensk Kärnbränslehantering AB.

SKB, 2010c. Comparative analysis of safety related site characteristics. SKB TR-10-54, Svensk Kärnbränslehantering AB.

SKB, 2010d. Fud-program 2010. Program för forskning, utveckling och demonstration av metoder för hantering och slutförvaring av kärnavfall. Svensk Kärnbränslehantering AB.

SKB, 2010e. Components, processes and interactions in the biosphere. SR-Site Biosphere. SKB R-10-37, Svensk Kärnbränslehantering AB.

SKB, 2010f. FEP report for the safety assessment SR-Site. SKB TR-10-45, Svensk Kärnbränslehantering AB.

SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB.

Skogsstyrelsen, 2000. Skogliga konsekvensanalyser 1999 (in Swedish). Jönköping: Skogsstyrelsen.

Skre O, 1972. High temperature demands for growth and development in Norway spruce (Picea abies (L.) Karst.) in Scandinavia. Meldinger fra Norges Landbrukshøgskole, 51, pp 1–29.

SLU, 1996. Databok för driftsplanering 1996 (in Swedish). Uppsala: Sveriges lantbruksuniversitet. (Speciella skrifter 62)

SLU, 2001. Skogsdata 2001: aktuella uppgifter om de svenska skogarna från riksskogstaxeringen (in Swedish). Umeå: Department of Forest Resource Management and Geomatics, Swedish University of Agricultural Sciences.

SLU, 2002. Skogsdata: aktuella uppgifter om de svenska skogarna från riksskogstaxeringen (in Swedish). Umeå: Swedish University of Agricultural Sciences.

SMHI, 2003. NORDKLIM [Online]. http://www.smhi.se/hfa_coord/nordklim/. Swedish Meteorological and Hydrological Institute. [1 September 2006].

Smith B, Prentice I C, Sykes M T, 2001. Representation of vegetation dynamics in the modeling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. Global Ecology & Biogeography, 10, pp 621–637.

Smith B, Knorr W, Widlowski J L, Pinty B, Gobron N, 2008. Combining remote sensing data with process modelling to monitor boreal forest carbon balances. Forest Ecology and Management, 255, pp 3985–3994.

Smith F W, Long J N, 2001. Age-related decline in forest growth: an emergent property. Forest Ecology and Management, 144, pp 175–181.

SNV, 1984. Våtmarksinventering inom fastlandsdelen av Kalmar Län: Del 1 Allmän beskrivning och catalog over särskilt värdefulla object. Rapport PM 1787, Statens Naturvårdsverk (Swedish Environmental Protection Agency).

Soegaard H, Jensen N O, Boegh E, Hasager C B, Schelde K, Thomsen A, 2005. Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modelling. Agricultural and Forest Meteorology, 114, pp 153–173.

SOF, 2007. Sveriges fåglar. [Online]. Available at: http://www.sofnet.org/index.asp?lev=718&typ=1. Sveriges ornitologiska förening. [15 August 2007].

Soto D, Mena G, 1999. Filter feeding by the freshwater mussel, Diplodon chilensis, as a biocontrol of salmon farming eutrophication. Aquaculture, 171, pp 65–81.

Sohlenius G, Hedenström A, 2008. Description of the regolith at Laxemar. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-05, Svensk Kärnbränslehantering AB.

Sohlenius G, Bergman T, Snäll S, Lundin L, Lode E, Stendahl J, Riise A, Nilsson J, Johansson T, Göransson M, 2006. Oskarshamn site investigation. Soils, Quaternary deposits and bedrock in topographic lineaments situated in the Laxemar subarea. SKB P-06-121, Svensk Kärnbränslehantering AB.

Sonesten L, 2005. Chemical characteristics of surface waters in the Forsmark area. Evaluation of data from lakes, streams, and coastal sites. SKB R-05-41, Svensk Kärnbränslehantering AB.

Sporrong U, Ekstam U, Samuelsson K (ed), 1995. Swedish landscapes. Stockholm: Swedish Environmental Protection Agency.

Stark K, Wallberg P, Nylén T, 2006. Post-depositional redistribution and gradual accumulation of ^{137}Cs in a riparian wetland ecosystem in Sweden. Journal of Environmental Radioactivity, 87, pp 175–187.

Sternbeck J, Land M, Nilsson Ö, 2006. Oskarshamn and Forsmark site investigations. ^{210}Pb and ^{14}C dating of sediments and peat. Accumulation rates of carbon, nitrogen and phosphorus. SKB P-06-301, Svensk Kärnbränslehantering AB.

Sterner R W, Elser J J, 2002. Ecological stoichiometry: the biology of elements from molecules to the biosphere. Princeton, NJ: Princeton University Press.

Strijker D, 2005. Marginal lands in Europe – causes of decline. Basic and Applied Ecology, 6, pp 99–106.

Strömgren M, Brydsten L, 2008. Digital elevation models of Forsmark. Site-descriptive modelling, SDM-Site Forsmark. SKB R-08-62, Svensk Kärnbränslehantering AB.

Strömgren M, Brydsten L, Lindgren F, 2006. Oskarshamn site investigation. Measurements of brook gradients. SKB P-06-05, Svensk Kärnbränslehantering AB.

Stumm W, 2004. Chemical processes regulating the composition of lake waters. In: O'Sullivan P E, Reynolds C S (eds). The lakes handbook. Vol. 1. Limnology and limnetic ecology. Malden, MA: Blackwell Science, pp 79–106.

Sturesson E, 2003. Platsundersökning Oskarshamn. Nyckelbiotopsinventering i Simpevarpsområdet. SKB P-03-78, Svensk Kärnbränslehantering AB.

Suyker A E, Verma S B, 2001. Year-round observations of the net ecosystem exchange of carbon dioxide in a native tallgrass prairie. Global Change Biology, 7, pp 279–289.

Suyker A E, Verma S B, Burba G G, 2003. Interannual variability in net CO_2 exchange of a native tallgrass prairie. Global Change Biology, 9, pp 255–265.

Svanberg O, Vilborg I, 2001. Från surhål och mygghelvete till myllrande våtmarker. Utvärdering av arbetet mot ett miljökvalitetsmål (in Swedish). Rapport 5146, Naturvårdsverket (Swedish Environmental Protection Agency).

Sveaskog, 2007. Silviculture and production. [Online]. Available at: http://www.sveaskog.se/en/Forestry-and-Environment/Active-forestry-for-sustainable-development/. Sveaskogs Förvaltnings AB. [27 February 2007].

Svenska Jägareförbundet, 2004. Viltvetande, detaljerad artfakta om rödrävsstammen. [Online]. Available at: http://www.jagareforbundet.se/Viltet/ViltVetande/Artpresentationer/Rav/. [30 November 2004].

Svenska Jägareförbundet, 2007. Viltvetande. Älg – population. [Online]. Available at: http://www.jagareforbundet.se/Viltet/ViltVetande/Artpresentationer/Alg/. [20 August 2007].

Svensson J, Jeglum J K, 2000. Primary succession and dynamics of Norway spruce coastal forests on land-uplift ground moraine. Uppsala: Swedish University of Agricultural Sciences. (Studia Forestalia Suecica 209)

Swanson R V, Flanagan L B, 2001. Environmental regulation of carbon dioxide exchange at the forest floor in a boreal black spruce ecosystem. Agricultural and Forest Meteorology, 108, pp 165–181.

Swedish Dairy Association, 2007. Description of fodder consumption for diary cows. Available at: http://www.svenskmjolk.se/Global/Dokument/EPi-tr%C3%A4det/Aktuellt%20och%20Opinion/Seminarier%20och%20konferenser/DU%202005/Rolf%20Sp%C3%B6rndly%20%20Fullfoder%20-%20Blandfoder%20-%20F%C3%A5r%20vi%20det%20att%20fungera%20i%20praktiken.pdf [2011]

Sykes M T, Prentice I C, 1995. Boreal forest futures: modelling the controls on tree species range limits and transient responses to climate change. Water, Air and Soil Pollution, 82, pp 415–428.

Sykes M T, Prentice I C, Cramer W, 1996. A bioclimatic model for the potential distribution of north European tree species under present and future climates. Journal of Biogeography, 23, pp 203–233.

Söderbäck B (ed), 2008. Geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas, Site descriptive modelling, SDM-Site. SKB R-08-19, Svensk Kärnbränslehantering AB.

Tagesson T, 2006a. Indirect estimations and spatial variation in leaf area index of coniferous, deciduous and mixed forest stands in Forsmark and Simpevarp. SKB TR-06-29, Svensk Kärnbränslehantering AB.

Tagesson T, 2006b. Seasonal variation and controlling factors of soil carbon effluxes in six vegetation types in southeast of Sweden. SKB TR-06-28, Svensk Kärnbränslehantering AB.

Tagesson T, 2006c. Aspects of the carbon cycle in the terrestrial ecosystems of Northeastern Småland. SKB R-06-41, Svensk Kärnbränslehantering AB.

Tagesson T, 2006d. Calibration and analysis of soil carbon efflux estimates with closed chambers at Forsmark and Laxemar. SKB R-06-125, Svensk Kärnbränslehantering AB.

Tagesson T, 2007. Soil carbon effluxes in ecosystems of Forsmark and Simpevarp. SKB TR-07-13, Svensk Kärnbränslehantering AB.

Tagesson T, Lindroth A, 2007. High soil carbon efflux rates in several ecosystems in southern Sweden. Boreal Environment Research, 12, pp 65–80.

Tagesson T, Eklundh L, Lindroth A, 2009a. Applicability of leaf area index products for boreal regions of Sweden. International Journal of Remote Sensing, 30, pp 5619–5632.

Tagesson T, Smith B, Löfgren A, Rammig A, Eklundh L, Lindroth A, 2009b. Estimating net primary production of Swedish forest landscapes by combining mechanistic modeling and remote sensing. Ambio, 38, pp 316–324.

Tannerfeldt M, Thiel L, 2004. Oskarshamn site investigation. Survey of mammal populations at Simpevarp. Spotlight survey 2004. SKB P-04-238, Svensk Kärnbränslehantering AB.

Tans P, 2009. Trends in carbon dioxide. [Online] Available at: http://www.cmdl.noaa.gov/ccgg/trends/. National Oceanic & Atmospheric Administration/Earth System Research Laboratoty, U.S. Department of Commerce. [16 April 2009].

Tarnocai C, 1988. Wetlands in Canada: distribution and characteristics. In: Schiff H I, Barrie L A, (eds). Global change, Canadian wetlands study, workshop report and research plan. Toronto: Canadian Institutle for Research in Atmospheric Chemistry, York University, pp 21–25.

Thibault D H, Sheppard M I, Smith P A, 1990. A critical compilation and review of default soil solid/liquid partition coefficients, Kd, for use in environmental assessments. AECL-10125, Atomic Energy of Canada Limited.

Thulin B, Hahn H J, 2008. Ecology and living conditions of groundwater fauna. SKB TR-08-06, Svensk Kärnbränslehantering AB.

Tipping E, 1996. Hydrochemical modeling of the retention and transport of metallic radionuclides in the soils of an upland catchment. Environmental Pollution, 94, pp 105–116.

Tolonen K, Turunen J, 1996. Accumulation rates of carbon in mires in Finland and implications for climate change. The Holocene, 6, pp 171–178.

Torudd J, 2010. Long term radiological effects on plants and animals of a deep geological repository. SR-Site Biosphere. SKB TR-10-08, Svensk Kärnbränslehantering AB.

Trumbore S E, Gaudinski J B, 2003. The secret lives of roots. Science, 302, pp 1344–1345.

Truvé J, 2007. Oskarshamn and Forsmark site investigation. Surveys of mammal populations in the areas adjacent to Forsmark and Oskarshamn. Results from 2007, compared with results from 2002/2003. SKB P-07-122, Svensk Kärnbränslehantering AB.

Truvé J, Cederlund G, 2005. Mammals in the areas adjacent to Forsmark and Oskarshamn. Population density, ecological data and carbon budget. SKB R-05-36, Svensk Kärnbränslehantering AB.

Tröjbom M, Grolander S, 2010. Chemical conditions in present and future ecosystems in Forsmark – implications for selected radionuclides in the safety assessment SR-Site. SKB R-10-27, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, 2006a. Chemical characteristics of surface systems in the Forsmark area. Visualisation and statistical evaluation of data from shallow groundwater, precipitation, and regolith. SKB R-06-19, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, 2006b. Chemical characteristics of surface systems in the Simpevarp area. Visualisation and statistical evaluation of data from surface water, precipitation, shallow groundwater, and regolith. SKB R-06-18, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, Johansson P-O, 2007. Hydrochemistry in surface water and shallow groundwater. Site descriptive modelling, SDM-Site Forsmark. SKB R-07-55, Svensk Kärnbränslehantering AB.

Tröjbom M, Söderbäck B, Kalinowski B, 2008. Hydrochemistry of surface water and shallow groundwater. Site descriptive modelling, SDM-site Laxemar. SKB R-08-46, Svensk Kärnbränslehantering AB.

Turunen J, Tomppo E, Tolonen K, Reinikainen A, 2002. Estimating carbon accumulation rates of undrained mires in Finland–application to boreal and subarctic regions. The Holocene, 12, pp 69–80.

Tyler G, Olsson T, 2006. The importance of atmospheric deposition, charge and atomic mass to the dynamics of minor and rare elements in developing, ageing, and wilted leaves of beech (Fagus sylvatica L.). Chemosphere, 65, pp 250–260.

Tyree M C, Seiler J R, Aust W M, Sampson D A, Fox T R, 2006. Long-term effects of site preparation and fertilization on total soil CO_2 efflux and heterotrophic respiration in a 33-year-old Pinus taeda L. plantation on the wet flats of the Virginia Lower Coastal Plain. Forest Ecology and Management, 234, pp 363–369.

Ulén B, Snäll S, 1998. Biogeochemistry and weathering in a forest catchment and an arable field in central Sweden. Acta Agricultræ Scandinavica, Section B, Soil and Plant Science, 48, pp 201–211.

United Nations Scientific Committee on the Effects of Atomic Radiation, 2000. Report to the General Assembly, with scientific annexes. Volume I: Sources.

USDA, 2004. National Nutrient Database, Release 17. [Online]. Available at: http://www.usda.gov/wps/portal/usdahome. U.S. Department of Agriculture. [3 March 2006].

USDA, 2007. National Nutrient Database, Release 18. [Online]. Available at: http://www.usda.gov/wps/portal/usdahome. U.S. Department of Agriculture. [17 December 2007].

van der Heijden M G A, Sanders I R, (eds) 2002. Mycorrhizal ecology. Berlin: Springer. (Ecological Studies 157)

Van der Perk M, Slávik O, Fulajtár E, 2002. Assessment of spatial variation of cesium-137 in small catchments. Journal of Environmental Quality, 31, pp 1930–1939.

Vardy S R, Warner B G, Turunen J, Aravena R, 2000. Carbon accumulation in permafrost peatlands in the Northwest Territories and Nunavut, Canada. The Holocene, 10, pp 273–280.

Vellend M, Verheyen K, Flinn K M, Jacquemyn H, Kolb A, Van Calster H, Peterken G, Graae B J, Bellemare J, Honnay O, Brunet J, Wulf M, Gerhardt F, Hermy M, 2007. Homogenization of forest plant communities and weakening of species-environment relationships via agricultural land use. Journal of Ecology, 95, pp 565–573.

Vera F W M, 2000. Grazing ecology and forest history. Wallingford: CABI Publishing.

Vera Tome F, Blanco Rodriguez M P, Lozano J C, 2003. Soil-to-plant transfer factors for natural radionuclides and stable elements in a Mediterranean area. Journal of Environmental Radioactivity, 65, p 161.

Vikström M, Gustafsson L-G, 2006. Modelling transport of water and solutes in future wetlands in Forsmark. SKB R-06-46, Svensk Kärnbränslehantering AB.

Viro P J, 1952. Kivisyyden määrittämisestä (in Finnish). Summary: On the determination of stoniness. Communicationes Instituti Forestalis Fenniae, 40, p 23.

Viro P J, 1955. Investigations on forest litter. Communicationes Instituti Forestalis Fenniae, 45, pp 1–65.

Vogt K A, Persson H, 1991. Measuring growth and development of roots. In: Lassoie J P, Hinkley T M (eds). Techniques and approaches in forest tree ecophysiology. Boca Raton, FL: CRC Press.

Vogt K A, Grier C C, Meier C E, Edmonds R L, 1982. Mycorrhizal role in net primary production and nutrient cycling in Abies amabilis ecosystems in western Washington. Ecology, 63, pp 370–380.

Vogt K A, Vogt D J, Palmiotto P A, Boon P, O'Hara J, Asbjornson H, 1996. Review of root dynamics in forest ecosystems grouped by climate, climatic forest type and species. Plant and Soil, 187, pp 159–219.

von Post L, Granlund E, 1926. Södra Sveriges torvtillgångar (The supply of peat in southern Sweden) (in Swedish). Stockholm. (Sveriges geologiska undersökning. Serie C, Avhandlingar och uppsatser 335)

Waddington J M, Roulet N T, 1997. Groundwater flow and dissolved carbon movement in a boreal peatland. Journal of Hydrology, 191, pp 122–138.

Waddington J M, Roulet N T, 2000. Carbon balance of a boreal patterned peatland. Global Change Biology, 6, pp 87–97.

Wahlman H, Ramstedt H, Lundkvist E, 2006. Bedömning av en inkapslingsanläggnings konsekvenser för naturmiljön. Oskarshamn och Forsmark (in Swedish). SKB P-06-109, Svensk Kärnbränslehantering AB.

Walker D, 1970. Direction and rate in some British post-glacial hydroseres. In: Walker D, West R G (eds). Studies in the vegetational history of the British Isles. Cambridge: Cambridge University Press, pp 117–139.

Wallander H, Göransson H, Rosengren U, 2004. Production, standing biomass and natural abundance of ^{15}N and ^{13}C in ectomycorrhizal mycelia collected at different soil depths in two forest types. Oecologia, 139, pp 89–97.

Wallenius T H, 1999. Yield variations of common wild berries in Finland in 1956–1996. Annales Botanici Fennici, 36, pp 299–314.

Wallentinus H G, 1973. Above-ground primary production of a Juncetum gerardi on a Baltic seashore meadow. Oikos, 24, pp 200–219.

Walling D E, Bradley S B, 1988. Transport and redistribution of Chernobyl fallout radionuclides by fluvial processes: some preliminary evidence. Environmental Geochemistry and Health, 10, pp 35–39.

Watson I, Burnett A D, 1993. Hydrology: an environmental approach. Cambridge, FL: Buchanan Books.

Weisser W W, Siemann E, 2004. The various effects of insects on ecosystem functioning. In: Weisser W W, Siemann E (eds). 2004. Insects and ecosystem functioning. Berlin: Springer. (Ecological studies 173)

Welinder S, Pedersen E A, Widgren M, 1998. Det svenska jordbrukets historia. Band 1. Jordbrukets första femtusen år: 4000 f. Kr.–1000 e. Kr. (in Swedish). Örebro: Natur och kultur/LT.

Werner K, 2009. Description of surface hydrology and near-surface hydrogeology at Laxemar-Simpevarp. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-71, Svensk Kärnbränslehantering AB.

Werner K, Lundholm L, 2004. Forsmark site investigation. Supplementary drilling and soil sampling, installation of groundwater monitoring wells, a pumping well and surface water level gauges. SKB P-04-139, Svensk Kärnbränslehantering AB.

Werner K, Johansson P-O, Brydsten L, Bosson E, Berglund S, Tröjbom M, Nyman H, 2007. Recharge and discharge of near-surface groundwater in Forsmark. Comparison of classification methods. SKB R-07-08, Svensk Kärnbränslehantering AB.

Werner K, Öhman J, Holgersson B, Rönnback K, Marelius K, 2008. Meteorological, hydrological and hydrogeological monitoring data and near-surface hydrogeological properties data from Laxemar-Simpevarp. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-73, Svensk Kärnbränslehantering AB.

West T O, Post W M, 2002. Division S-6- soil & water management & conservation soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Science Society of America Journal, 66, pp 1930–1946.

Whicker F W, Schultz V, 1982. Radioecology: Nuclear energy and the environment. Boca Raton, FL: CRC Press.

Widén B, Majdi H, 2001. Soil CO_2 efflux and root respiration at three sites in a mixed pine and spruce forest: Seasonal and diurnal variation. Canadian Journal of Forest Research, 31, pp 786–796.

Wielgolaski F E, Bliss L C, Svoboda J, Doyle G, 1981. Primary production of tundra. In: Bliss L C, Heal O W, Moore J J (eds). Tundra ecosystems: a comparative analysis. Cambridge: Cambridge University Press, pp 813.

Wijnbladh E, Aquilonius K, Floderus S, 2008. The marine ecosystems at Forsmark and Laxemar-Simpevarp. Site descriptive modelling, SDM-Site. SKB R-08-03, Svensk Kärnbränslehantering AB.

Willson M F, Gende S M, Marston B H, 1998. Fishes and the forest. BioScience, 48, pp 455–462.

Wilkinson S B, Zheng W, Allen J R, Fielding N J, Wanstall V C, Russell G, Hawkins S J, 2008. Water quality improvements in Liverpool docks: the role of filter feeders in algal and nutrient dynamics. Marine Ecology, 17, pp 197–211.

Zackrisson O, 1977. Influence of forest fires on the North Swedish boreal forest. Oikos, 29, pp 22–32.

Zaehle S, Sitch S, Smith B, Hatterman F, 2005. Effects of parameter uncertainties on the modeling of terrestrial biosphere dynamics. Global Biogeochemical Cycles, 19, pp 1–16.

Zheng D, Prince S, Häme T, 2004. Estimating net primary production of boreal forests in Finland and Sweden from field data and remote sensing. Journal Vegetation Science, 15, pp 161–170.

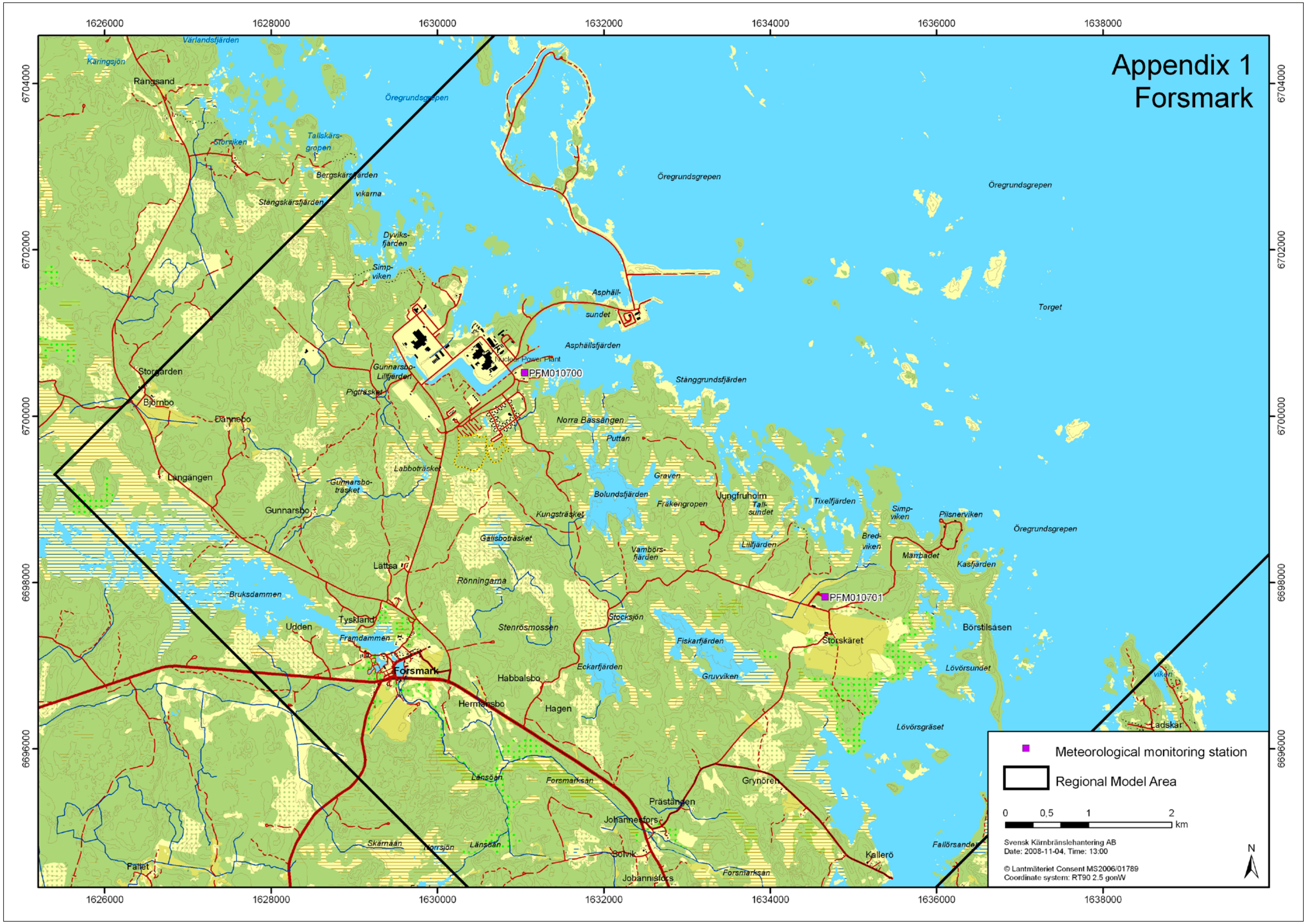
Zlotin R I, Khodashova K S, 1980. The role of animals in biological cycling of forest-steppe ecosystems. Stroudsburg, PA: Dowden, Hutchinson & Ross.

Yamaya K, Branch T, 1968. On the influence of alder (Alnus inkumae) on soil properties in northern Japan. In: Trappe J M, Franklin J F, Tarrant R F and Hausen, G M (eds). Biology of Alder: proceedings from a symposium held at Northwest Scientific Association 40th annual meeting, Pullman, Washington, 14–15 April 1967. Portland, OR: Pacific Northwest Forest and Range Experiment Station, U.S. Department of Agriculture.

Ågren G I, Bosatta E, 1998. Theoretical ecosystem ecology: understanding element cycles. Cambridge: Cambridge University Press.

Ågren G, Axelsson B, Flower-Ellis J G K, Linder S, Persson H, Staaf H, Troeng E, 1980. Annual carbon budget for a young Scots pine. Ecological Bulletin, 32, pp 307–313.

Detailed map of Forsmark



Detailed map of Laxemar-Simpevarp

Appendix 3

A compilation of ecological studies performed in the Forsmark and Laxemar-Simpevarp investigation areas

A list of published studies that have been performed in the Forsmark (F) and Laxemar-Simpevarp (L) regional model areas. These are all available for download on the SKB website (www.skb.se).

Main subject	Specific subject	Site	Report	Reference
Vegetation	Vegetation map	F	R-02-06	/Boresjö Bronge and Wester 2002/
	Vegetation map	F/L	P-03-83	/Boresjö Bronge and Wester 2003/
	Validation of GIS	F	P-04-314	/Alling et al. 2004a/
	Remote sensing and LAI		R-04-24	/Boresjö Bronge 2004/
Key habitats	Nature values	F/L	R-04-12	/Kyläkorpi 2004/
	Survey	L	P-03-78	/Sturesson 2003/
	Survey	F	P-04-33	/Eklund 2004/
	Consequences	L	P-06-102	/Ignell et al. 2006/
	Consequences	F/L	P-06-109	/Wahlman et al. 2006/
Tree layer	Litter fall and litter decomposition	F/L	R-07-23	/Mjöfors et al. 2007/
	Birch on clear-cuts	F/L	P-04-315	/Alling et al. 2004c/
	LAI-index and tree stand data	F/L	TR-06-29	/Tagesson 2006a/
	Tree parameters and field layer composition	F	P-03-81	/Abrahamsson 2003/
	Tree parameters and field layer composition	L	P-04-20	/Andersson 2004a/
	Dead wood	F	P-04-124	/Andersson 2004b/
	Dead wood	L	P-05-87	/Andersson 2005/
Field layer	Biomass	F	P-03-90	/Fridriksson and Öhr 2003/
	Biomass and production	F/L	P-05-80	/Löfgren 2005/
	Fungi	F	TR-04-26	/Johanson et al. 2004/
Root zone	Depth of roots	F	P-05-166	/Lundin et al. 2005b/
	Depth of roots	L	R-05-15	/Lundin et al. 2005a/
	Biomass and depth of fine roots	F/L	R-07-01	/Persson and Stadenberg 2007a/
	Turnover of fine roots	F	TR-07-11	/Persson and Stadenberg 2007b/
Respiration	Analysis 2003–2004	L	TR-06-28	/Tagesson 2006b/
	Analysis spring 2003 and LPJ-GUESS modelling	L	TR-06-41	/Tagesson 2006a/
	Method of calibration and analysis	F/L	R-06-125	/Tagesson 2006d/
	Measurements	L	P-06-278	/Lundkvist 2006/
	Measurements	F	P-07-23	/Heneryd 2007b/
	Analysis 2004–2005	F/L	TR-07-13	/Tagesson 2007/
Wetlands	Properties and function		TR-04-08	/Kellner 2003/
	Inventory of vascular plants	F	P-06-115	/Göthberg and Wahlman 2006/
	Biomass estimates of *Phragmites australis*	L	P-04-316	/Alling et al. 2004b/
Mammals	Mammal monitoring	F	P-03-18	/Cederlund et al. 2003/
	Mammal monitoring	F/L	P-04-04	/Cederlund et al. 2004/
	Bat monitoring	L	P-04-237	/Ignell 2004/
	Mammal monitoring	L	P-04-238	/Tannerfeldt and Thiel 2004/
	Bat monitoring	F	P-05-61	/de Jong and Gylje 2005/
	Rodent monitoring	L	P-05-84	/Cederlund et al. 2005a/
	Ecological data and carbon budget	F/L	R-05-36	/Truvé and Cederlund 2005/
	Mammal monitoring	F	P-05-151	/Cederlund et al. 2005b/
	Moose monitoring	F	P-06-218	/Cederlund et al. 2006a/
	Moose monitoring	F	P-06-219	/Cederlund et al. 2006b/
	Moose monitoring	L	P-06-228	/Cederlund et al. 2006c/

Main subject	Specific subject	Site	Report	Reference
	Consequences on hunting	L	P-07-09	/Cederlund and Truvé 2007/
	Surveys of mammal populations	F/L	P-07-122	/Truvé 2007/
	Moose monitoring	F	P-07-132	/Cederlund and Lemel 2007a/
	Moose monitoring	F	P-07-133	/Cederlund and Lemel 2007c/
	Moose monitoring	L	P-07-136	/Cederlund and Lemel 2007b/
	Moose monitoring	F	P-08-35	/Cederlund 2008a/
	Moose monitoring	F	P-08-36	/Cederlund 2008b/
	Moose monitoring	L	P-08-40	/Cederlund 2008c/
	Moose monitoring	F	P-09-23	/Cederlund 2009a/
	Moose monitoring	F	P-09-24	/Cederlund 2009b/
	Moose monitoring	L	P-09-25	/Cederlund 2009c/
	Moose monitoring	F	P-10-26	/Cederlund and Broman 2010a/
	Moose monitoring	L	P-10-27	/Cederlund and Broman 2010b/
Birds	Monitoring	F	P-03-10	/Green 2003a/
	Monitoring	L	P-03-31	/Green 2003b/
	Monitoring	L	P-04-21	/Green 2004a/
	Monitoring	F	P-04-30	/Green 2004b/
	Monitoring	L	P-05-42	/Green 2005a/
	Monitoring	F	P-05-73	/Green 2005b/
	Monitoring	L	P-06-43	/Green 2006a/
	Monitoring	F	P-06-46	/Green 2006b/
	Monitoring	L	P-06-298	/Green 2006c/
	Monitoring	F	P-07-02	/Green 2007a/
	Monitoring	L	P-07-226	/Green 2007b/
	Monitoring	F	P-08-25	/Green 2008a/
	Monitoring	F	P-08-84	/Green 2008b/
	Monitoring	L	P-08-89	/Green 2008c/
	Monitoring	L	P-09-71	/Green 2009/
	Monitoring	L	P-10-11	/Green 2010/
Invertebrates	Bioturbation	F/L	R-06-123	/Persson et al. 2007/
Groundwater fauna		F/L	TR-08-06	/Thulin and Hahn 2008/
Soils	Description	F	R-04-08	/Lundin et al. 2004/
	Description	L	R-05-15	/Lundin et al. 2005a/
Chemical characterisation	Deposits	F	P-05-166	/Lundin et al. 2005b/
	Biota and deposits	F	P-06-220	/Hannu and Karlsson 2006/
	Biota and deposits	L	P-06-320	/Engdahl et al. 2006/
	Deposits	L	P-06-321	/Lundin et al. 2006/
	Deposits	L	P-07-222	/Lundin et al. 2007/
Ecosystem modelling	Workshop proceedings	F	R-04-71	/Lindborg and Kautsky 2004/
	LPJ-GUESS modelling of carbon	L	R-06-41	/Tagesson 2006a/
	Coup modelling of forest ecosystems	F/L	R-06-45	/Gustafsson et al. 2006/
	Coup modelling of carbon and water in terrestrial ecosystems	L	R-06-121	/Karlberg et al. 2006/
Description of surface systems	General description of biosphere	F	R-05-03	/Lindborg 2005/
	General description of biosphere	L	R-06-11	/Lindborg 2006/
A descriptive ecosystem model	Terrestrial biosphere model	F	R-01-09	/Jerling et al. 2001/
	Strategy description		R-03-06	/Löfgren and Lindborg 2003/
Ecosystem description	Literature survey	F	R-02-08	/Berggren and Kyläkorpi 2002a/
	Literature survey	L	R-02-10	/Berggren and Kyläkorpi 2002b/
	Variables for surface ecosystems		R-00-33	/Kyläkorpi et al. 2000/
	Variables for surface ecosystems		R-00-19	/Lindborg and Kautsky 2000/

Appendix 4

Biomass and consumption of birds at the two sites.

These data are presented also in Section 4.2.2 and have been used to calculate the bird consumption in the food webs. Data are based on inventories of the regional model area during the breeding season for the Forsmark area 2002–2004 and the Laxemar-Simpevarp area 2003 and 2004 /Green unpubl./. The species were divided into five different functional groups in the first column according to their main food preference (Figure 4-33). Food selection by different species was found on the website of the Swedish Ornithological Association /SOF 2007/ and the Danish Ornithological Association /DOF 2007/ and /Jonsson 1992/. The different bird species were divided into groups depending on which habitat they mainly gather their food from: woodland (W), open land (O), lake (L), sea 1 (S1) or sea 2 (S2; S= S1+S2) (see Table 4-36 for definitions). The number of eggs laid were found on the website of the Danish Ornithological Association /DOF 2007/. The breeding period in days was calculated based on the number of months (30 days for all months) given in /Jonsson 1992/ or on the website of the Swedish Ornithological Association. The breeding period varied between 120 days, for species migrating to the south of Sahara or a similar distance, and 365 days for non-migratory bird species. The body mass of the species was mainly taken from /Green unpubl./, but in some cases body mass was taken from the Danish ornithological association website /DOF 2007/. Constants for the equation describing the field metabolic ratio were provided for the systematic/functional groups: passerines, Charadriiformes, Galliformes, marine birds, insectivores and omnivores and temperate forest birds. The group carnivores was assigned values representative for the category “All birds” in lieu of better estimates.

	Number of territories						
Species	**Forsmark**	**Laxemar-Simpevarp**	**Habitat**	**Number of eggs**	**Breeding period (days)**	**Body mass (g)**	**Systematic group/ order (in /Nagy et al. 1999/)**
Carnivores							
Marsh Harrier (Brun kärrhök)	5	2	L+S1	5	150	585	All birds
Sparrow Hawk (Sparvhök)	12	19	W	4	365	204	All birds
Northern Goshawk (Duvhök)	3	7	W	3.5	365	1,140	All birds
Common Buzzard (Ormvråk)	14	22	W	3.5	240	856	All birds
Pygmy Owl (Sparvuggla)	15	13	W	6	365	58	All birds
Ural Olw (Slaguggla)	4		W	4	365	730	All birds
Tengmalms Owl (Pärluggla)	1	2	W	5	365	143	All birds
Tawny Owl (Kattuggla)	16	56	O	4	365	472	All birds
Raven (Korp)	13	30	W	5	365	1,100	All birds
Insectivores							
Velvet Scoter (Svärta)	7	5	S	11	210	1,588	Marine birds
Common Shelduck (Gravand)	5	1	L+S1	9	210	1,152	Marine bird
Honey Buzzard (Bivråk)	6	9	O	1.5	120	626	Insectivores
Eurasian Hobby (Lärkfalk)	7	8	O	2.5	150	236	Insectivores
Northern Lapwing (Tofsvipa)	25	1	O	4	240	218	Charadriiform^{es}
Eurasian Oystercatcher (Strandskata)	25	10	L+S1	3	210	526	Charadriiformes

Species	Number of territories Forsmark	 Laxemar-Simpevarp	Habitat	Number of eggs	Breeding period (days)	Body mass (g)	Systematic group/ order (in /Nagy et al. 1999/)
Common Ringed Plover (Större strandpipare)	18	5	L+S1	4	210	64	Charadriiformes
Common Snipe (Enkelbeckasin)	182	100	L+S1	4	210	116	Charadriiformes
Common Redshank (Rödbena)	37	5	L+S1	4	180	122	Charadriiformes
Green Sandpiper (Skogssnäppa)	54	100	L+S1	4	180	80	Charadriiformes
Curlew (Storspov)	3		L+S1	4.5	105	725	Charadriiformes
Common Sandpiper (Drillsnäppa)	35	120	L+S1	4	210	48	Charadriiformes
Eurasian Woodcock (Morkulla)	91		W	4	240	312	Charadriiformes
Wryneck (Göktyta)	45	25	W	8	150	40	Insectivores
Grey-headed Woodpecker (Gråspett)	1		W	6.5	365	128	Insectivores
Black Woodpecker (Spillkråka)	13	30	W	4.5	365	380	Insectivores
Lesser Spotted Woodpecker (Mindre hackspett)	13	19	W	5	365	23	Insectivores
Three-toed Woodpecker (Tretåig hackspett)	2		W	4	365	66	Insectivores
Great spotted woodpecker (Större hackspett)	54	330	W	6	365	85	Passeriformes
Green Woodpecker (Gröngöling)	20	65	W	6	365	218	Passeriformes
River Warbler (Flodsångare)	1		W	6	90	18	Passeriformes
Greenish Warbler (Lundsångare)	1		W	5	120	10	Passeriformes
Red-breasted Flycatcher (Mindre flugsnappare)	5	5	W	4.5	120	9	Passeriformes
Song Thrush (Taltrast)	1,050	2,500	W	5.5	180	64	Passeriformes
Tree Pipit (Trädpiplärka)	460	2,900	W	5	150	23	Passeriformes
Winter Wren (Gärdsmyg)	410	800	W	7	240	9	Passeriformes
Dunnock (Järnsparv)	550	910	W	4.5	210	19	Passeriformes
Common Redstart (Rödstjärt)	45	400	W	6.5	180	15	Passeriformes
European robin (Rödhake)	2,500	5,500	W	6	210	17	Passeriformes
Redwing (Rödvingetrast)	270		W	5.5	210	68	Passeriformes
Garden Warbler (Trädgårdssångare)	680	1,200	W	4.5	150	19	Passeriformes
Blackcap (Svarthätta)	200	1,500	W	5	180	18	Passeriformes
Icterine Warbler (Härmsångare)	15	10	W	5	150	13	Passeriformes
Wood Warbler (Grönsångare)	180	1,000	W	6	150	11	Passeriformes
Common Chiffchaff (Gransångare)	91		W	6	180	8	Passeriformes

Species	Number of territories		Habitat	Number of eggs	Breeding period (days)	Body mass (g)	Systematic group/ order (in /Nagy et al. 1999/)
	Forsmark	Laxemar-Simpevarp					
Willow Warbler (Lövsångare)	3,900	12,000	W	6.5	150	9	Passeriformes
Goldcrest (Kungsfågel)	1,320	3,500	W	18	365	6	Passeriformes
European Pied Flycatcher (Svartvit flugsnappare)	230	600	W	6	150	13	Passeriformes
Spotted Flycatcher (Grå flugsnappare)	460	2,000	W	4.5	150	15	Passeriformes
Eurasian Treecreeper (Trädkrypare)	540	1,200	W	5.5	365	9	Passeriformes
Long-tailed Tit (Stjärtmes)	50	60	W	9.5	365	8	Passeriformes
Red-backed Shrike (Törnskata)	60	100	O	5.5	120	28	Insectivores
Wheatear (Stenskvätta)	6	12	O	1.5	150	24	Passeriformes
Grashopper Warbler (Gräshoppsångare)	1	1	O	5	120	13	Passeriformes
Common Cuckoo (Gök)	29	100	O	5	150	112	Passeriformes
Common Swift (Tornseglare)	100	500	O	2.5	120	42	Passeriformes
Barn swallow (Ladusvala)	10	150	O	4.5	180	19	Passeriformes
House Martin (Hussvala)	50	200	O	4.5	180	18	Passeriformes
Meadow Pipit (Ängspiplärka)	7		O	6	180	18	Passeriformes
White Wagtail (Sädesärla)	270	500	O	6	180	21	Passeriformes
Black Redstart (Svart rödstjärt)	1		O	5	210	16	Passeriformes
Thrush Nightingale (Näktergal)	4	40	O	5	150	24	Passeriformes
Whinchat (Buskskvätta)	34	10	O	6	150	17	Passeriformes
Eurasian Reed-Warbler (Rörsångare)	180	400	O	4	150	12	Passeriformes
Sedge Warbler (Sävsångare)	180	5	O	4.5	150	10	Passeriformes
Marsh Warbler (Kärrsångare)	1	1	O	4	150	12	Passeriformes
Greater Whitethroat (Törnsångare)	45	250	O	5	150	14	Passeriformes
Lesser Whitethroat (Ärtsångare)	270	600	O	4	150	12	Passeriformes
Eurasian Nightjar (Nattskärra)		70	O	2	150	85	Passeriformes
Rock Pipit (Skärpiplärka)		7	O	5	180	23	Passeriformes
Herbivores							
Mute Swan (Knölsvan)	69	55	L+S1	7	365	10,750	All birds
Greylag Goose (Grågås)	49	120	L+S1	4.5	240	3,464	All birds
Canada Goose (Kanadagås)	26	3	L+S1	6	365	3,450	All birds
Mallard (Gräsand)	104	150	L+S1	11	365	1,024	All birds

Species	Number of territories		Habitat	Number of eggs	Breeding period (days)	Body mass (g)	Systematic group/ order (in /Nagy et al. 1999/)
	Forsmark	Laxemar-Simpevarp					
Eurasian Wigeon (Bläsand)	1		L+S1	9	180	700	All birds
Green-winged Teal (Kricka)	30	10	L+S1	10	180	360	All birds
Stock dove (Skogsduva)	10	13	W	2	210	301	Temperate forest
Eurasian Bullfinch (Domherre)	230	150	W	5	365	31	Passeriformes
Hawfinch (Stenknäck)	10	9	W	4.5	365	54	Passeriformes
Red Crossbill (Mindre korsnäbb)	200	100	W	4	365	38	Passeriformes
Parrot Crossbill (Större korsnäbb)	50	10	W	4	365	52	Passeriformes
Rock Pigeon (Stadsduva)	10	20	O	2	365	304	Passeriformes
Piscivorer							
Blackthroated Diver (Storlom)	6	2	L+S	2	150	2,806	Marine bird
Bittern (Rördrom)	4		L+S1	5	240	1,231	Marine bird
Gray Heron (Häger)		85	L+S1	4	210	1,800	Charadriiformes
White-tailed Eagel (Havsörn)	4	2	L+S	2	365	4,793	Marine bird
Osprey (Fiskgjuse)	8	4	L+S	3.5	150	1,528	Marine bird
Common Merganser (Storskrake)	168	50	L+S1	9.5	365	1,355	Marine bird
Great Crested Grebe (Skäggdopping)	37	65	L+S1	3.5	180	875	Marine bird
Red-breasted Merganser (Småskrake)	5	11	L+S1	8.5	365	1,129	Marine bird
Great Cormorant (Storskarv)	121		S	4	365	2,184	Pelecaniformes
Lesser Black-backed Gull (Sillltrut)	97	27	L+S	3	210	715	Charadriiformes
Herring gull (Gråtrut)	272	98	L+S1	2.5	365	1,060	Charadriiformes
Common gull (Fiskmås)	184	75	L+S1	3	210	386	Charadriiformes
Parasitic Jaeger (Labb)	4	1	S	3	180	384	Charadriiformes
Razorbill (Tordmule)	3	4	S	1	210	717	Charadriiformes
Black Gillemot (Tobisgrissla)	50		L+S1	1	365	378	Charadriiformes
Common Tern (Fisktärna)	95	30	L+S1	2.5	105	126	Charadriiformes
Artic Tern (Silvertärna)	234	167	S	2	120	110	Charadriiformes
Caspian Tern (Skräntärna)		1	L+S	2	150	675	Charadriiformes
Omnivores (herbivores/insectivores)							
Common Eider (Ejder)	144	150	S1	5.5	210	2,066	Marine bird
Turnstone (Roskarl)	10	5	S1	3.5	120	113	Charadriiformes
Black-headed Gull (Skrattmås)	143	56	L+S1	3	240	266	Charadriiformes
Little Gull (Dvärgmås)	2		L	3	180	120	Charadriiformes
Great Black-backed Gull (Havstrut)	29	27	L+S1	3	365	1,606	Charadriiformes

Species	Number of territories Forsmark	 Laxemar-Simpevarp	Habitat	Number of eggs	Breeding period (days)	Body mass (g)	Systematic group/ order (in /Nagy et al. 1999/)
Shoveler (Skedand)	6	1	L+S1	8.5	120	560	Omnivore
Pochard (Brunand)	1		L+S1	8.5	213	869	Omnivore
Spotted Crake (Småfläckig sumphöna)	3	1	L	10.5	120	90	Omnivore
Whooper Swan (Sångsvan)	5	4	L+S1	4	240	9,375	Omnivore
Gadwall (Snatterand)	4	1	L+S1	10	210	775	Omnivore
Tufted Duck (Vigg)	52	35	L+S1	9	365	750	Omnivore
Common Goldeneye (Knipa)	83	50	L+S1	9	365	962	Omnivore
Water Rail (Vattenrall)	8	2	L+S1	2	240	116	Omnivore
Eurasian Coot (Sothöna)	1		L+S1	7.5	365	732	Omnivore
Hazelhen (Järpe)	30	10	W	7.5	365	370	Galliformes
Black Grouse (Orre)	20	20	W	7	365	1,106	Galliformes
Capercaillie (Tjäder)	6	10	W	7.5	365	2,931	Galliformes
Marsh Tit (Entita)	20	400	W	8	365	12	Passeriformes
Nutcracker (Nötkråka)	7	15	W	4	365	192	Passeriformes
Eurasian Blackbird (Koltrast)	1,100	3,200	W	4	365	93	Passeriformes
Chaffinch (Bofink)	4,300	11,000	W	4	210	24	Passeriformes
Fieldfare (Björktrast)	50	42	W	5.5	365	105	Passeriformes
Mistle Thrush (Dubbeltrast)	23	300	W	5	210	118	Passeriformes
Great tit (Talgoxe)	860	2,200	W	9	365	18	Passeriformes
Eurasian Blue Tit (Blåmes)	100	1,200	W	10	365	11	Passeriformes
Coal Tit (Svartmes)	360	1,200	W	9	365	9	Passeriformes
Crested Tit (Tofsmes)	500	900	W	6.5	365	11	Passeriformes
Willow Tit (Talltita)	460	450	W	7.5	365	11	Passeriformes
Common Wood-Pigeon (Ringduva)	180	1,000	W	2	210	510	Omnivore
Eurasian Siskin (Grönsiska)	1,050	1,200	W	5	365	12	Passeriformes
European Greenfinch (Grönfink)	320	600	W	5	365	30	Passeriformes
Eurasian Nuthatch (Nötväcka)	120	700	W	6.5	365	23	Passeriformes
Eurasian Jay (Nötskrika)	90	200	W	6.5	365	170	Passeriformes
Hooded crow (Kråka)	45	50	W	4.5	365	550	Passeriformes
Quail (Vaktel)	1		O	9	105	99	Galliformes
Ring-necked Pheasant (Fasan)	1	60	O	14	365	1,000	Galliformes
Scarlet Rosefinch (Rosenfink)	50	7	O	4.5	120	23	Passeriformes
Linnet (Hämpling)	5	6	O	5.5	180	19	Passeriformes
Ortolan Bunting (Ortolansparv)	1		O	4.5	120	25	Passeriformes
Wood Lark (Trädlärka)	2	40	O	4	180	30	Passeriformes
Skylark (Sånglärka)	11	7	O	4	240	36	Passeriformes

Species	Number of territories Forsmark	 Laxemar-Simpevarp	Habitat	Number of eggs	Breeding period (days)	Body mass (g)	Systematic group/ order (in /Nagy et al. 1999/)
Crane (Trana)	20	29	O	2	150	5,300	Omnivore
Eurasian Jackdaw (Kaja)	50	100	O	5	365	226	Passeriformes
Eurasian Magpie (Skata)	10	30	O	7	365	210	Passeriformes
European Starling (Stare)	50	500	O	4	365	80	Passeriformes
House Sparrow (Gråsparv)	20	100	O	4.5	365	28	Passeriformes
Eurasian Tree Sparrow (Pilfink)	50	200	O	4	365	20	Passeriformes
European Goldfinch (Steglits)	3	2	O	5.5	365	16	Passeriformes
Reed Bunting (Sävsparv)	180	200	O	5	365	20	Passeriformes
Yellowhammer (Gulsparv)	500	1,500	O	4.5	365	30	Passeriformes

Appendix 5

Data for calculation of energy budgets of amphibians and reptiles (in Swedish)

Underlag till
Energiflöden i ekosystem med grod- och kräldjur
2004-10-27

Claes Andrén
Nature – Artbevarande & Foto
Västergården 170, 446 91 Alvhem
0303-33 64 33, 070-771 5361
claes.andren@nature.se

A5.1 Beskrivning av arbetsuppgiften

För arter av grod- och kräldjur inom Simpevarp och Forsmark särskilda undersökningsområden (12 st, se tidigare rapporter) lämnas här uppgifter rörande;

1/ Genomsnittsvikt hos en vuxen individ. Normalt finns inte dessa uppgifter i litteraturen utan enbart storlek i form av längd. Jag har kollat runt med folk som håller dessa arter i fångenskap. Jag har utgått från en jämn könsfördelning i populationen, vilket stämmer ungefär för kräldjuren men inte alltid lika väl hos groddjuren. I allmänhet finns lite fler hanar eftersom dessa blir könsmogna vid lägre ålder. Ofta är honan betydligt större än hanen, särskilt hos vanlig snok, huggorm, och vanlig padda. Den angivna vikten är ett mått där jag försökt väga in dessa förhållanden för respektive art.

2/ Täthet av individer/ha. Mycket svårt att ge en riktigt bra siffra främst beroende på att dessa djur inte finns jämt fördelade i landskapet utan är knutna till speciella mikromiljöer eller finns radiärt i fläckar med rätt biotop runt en lekdamm, eller längs kantzoner i landskapet. För de flesta arterna finns det inga undersökningar gjorda som ger stöd för min uppskattning. Här är alltså osäkerheten ganska stor.

3/ Typ av föda. Relativt enkelt. Dessa uppgifter finns normalt i litteraturen.

4/ Energibehov/dag under den aktiva säsongen. Beakta att alla arterna har en aktiv säsong av varierande längd. Under denna tid har de en relativt hög energiomsättning. Under övervintringen sänker de sin metabolism till nästan 0 och i sammanhanget kan denna energiförbrukning negligeras. Alla upptagna arter är rovdjur och man räknar med att 90% av energin i födan kan utnyttjas (för växtätare är siffran mindre än 60%). Jag har lämnat uppgift om ungefärligt antal dagar per år som arterna är aktiva.

5/ Fortplantningskapacitet. Antalet ungar per hona och år. Vissa reptiler får ungar enbart vartannat år men siffran anger genomsnitt per år. Många groddjur lägger extremt många ägg, av vilka en mycket stor andel dör innan metamorfos till landliv (ofta 95–99%). Därefter dör cirka 30% av de metamorfoserade per år fram till vuxen ålder (2–3 år normalt). Grodorna reproducerar sig i snitt en eller två gånger under sin livstid. Paddor och salamandrar 3–4 gånger. Ödlorna 2–3 gånger och ormarna 3–4 gånger under sitt liv. Antalet ungar eller ägg hos en hona beror i stor utsträckning på hennes storlek (ålder) och den mängd energi hon lyckats samla i sina fettkroppar (ett speciellt organ) inför varje reproduktiv säsong.

A5.1.1 Förhållanden som ytterligare komplicerar arbetsuppgiften

Längden på den aktiva perioden varierar mellan arterna, med avseende på vilken breddgrad vi är och mellan år beroende på vädersituation (främst temperatur). Hos groddjuren är det extra komplicerat att ange rimliga värden, dels beroende på att det i stor utsträckning saknas sådan information i litteraturen, dels därför att de även som vuxna tillbringar en kortare eller längre del av säsongen i vatten och resterande tid på land. Hur lång tid de jagar i dessa två miljöer beror på tillgången på lämplig föda som varierar mellan år och typer av vatten och landmiljö. Typen av bytesdjur är också olika i vatten- respektive landmiljön.

En ytterligare komplikation är att både grod- och kräldjur har en mycket oregelbunden förekomst i landskapet. Dels måste man känna till vilken typ av landmiljö som är optimal eller i alla fall godtagbar. För groddjur måste man veta hur långt arten maximalt vandrar radiärt från lekdammen och på vilket avstånd lämplig miljö finns och hur stora dessa fläckar är. Många arter av kräldjur finns främst längs kanter i landskapet eller där solinstrålningen är tillräckligt hög för att ge optimal kroppstemperatur. Många kräldjur fungerar så att om temperaturen ett år är ovanligt låg (tillåter inte optimal energiomsättning vid bytesfångst till exempel), så sänker de sin metabolism och går under mark. På samma sätt kan det vara om bytestätheten sjunker kraftigt så ställer de ner metabolismen kraftigt och går under mark (en motsvarighet till vintervila men beroende på födobrist). En huggorm kan t ex svälta ett år utan problem, det finns ofta stora fettreserver att ta av eller så resorberas ägg och ungar.

Hos ödlor generellt beräknas energiförbrukningen vara 4–30 mg torr vikt foder per gram levande ödla per dag. Den högre siffran avser perioder av hög aktivitet. Biomassa hos populationer av småödlor i ett Nordamerikanskt landskap var 27 (12–49) g per ha, och hos en annan art 61–97 g per ha. Biomassa hos ormar i ett savannområde var 150 g per ha. Denna typ av uppgifter saknas för svenska arter och jag har inte funnit motsvarande uppgifter för vår landskapstyp heller.

I beräkningen nedan har energiförbrukningen hos ormar beräknats vara 10 mg torrvikt foder per dag per gram levande vikt av ormen. Motsvarande siffror för ödlor beräknas vara 20 mg och hos groddjuren 5 mg. Skillnaderna beror främst på olika kroppstemperatur hos de olika djurgrupperna som är högst hos ödlor och betydligt lägre hos groddjur. Undersökningar visar att energiomsättningen påverkas starkt av aktivitetstemperaturen hos ett djur.

A5.2 Arter

A5.2.1 Mindre vattensalamander

Vuxenvikt 3 gram, byten i vattnet är större djurplankton och diverse vattenlevande insekter och spindeldjur, byten på land är främst mjuka ryggradslösa djur som daggmask och sniglar eller insektslarver. Det finns inga beräkningar av täthet men i medeltal i fiskfria småvatten så leker cirka 200 vuxna/100 m^2 vattenyta. Populationerna varierar normalt mellan några hundra och upp till cirka 10 000 individer. När de sedan går upp på land sprider de sig radiärt från några tiotals meter till cirka 300 m från vattnet och förekommer i ganska varierad landmiljö. Hur långt de går beror ofta på födotillgång. Tätheten kan uppskattas om man utgår från befintliga småvatten och drar en cirkel runt vattnet med en radie av 300 m (räknat från vattenlinjen). Räkna ut ytan och dela med antalet djur som uppskattas till 200/100 m^2 vattenyta (dock max 10 000 ind). Det finns alltså inte salamandrar spridda jämt i landskapet, dock finns enstaka individer som vandrar längre sträckor mellan dammar. Antal aktiva dagar/år är cirka 200 (varav 60–90 i lekvattnet och resterande i fuktig landmiljö). Vuxna djur är nattaktiva. Förekommer främst i fiskfria vatten. Populationsstorleken kan variera med flera tiopotenser beroende på närvaro eller avsaknad av rovfisk. Energibehov hos ett vuxet djur under en säsong motsvarar 3×5 mg×200 dagar = 3 000 mg torrvikt foder per individ. Antalet ägg i snitt 350 per säsong.

A5.2.2 Större vattensalamander

Vuxenvikt 9 gram, byten i vattnet är vattenlevande insekter och spindeldjur, men också grodlarver och larver av den mindre vattensalamandern, byten på land daggmask, sniglar och insektslarver. Beräkning av täthet görs enligt samma modell men här räknas med endast 100 ind/100 m^2 och en spridningszoon som är 500 m från dammens vattenkant. Totalpopulationen är sällan över några tusen djur. Denna art har större krav på landmiljön och finns främst i områden med gammal skog med förmultnande ved på marken och gärna blockrik och öppen terräng mellan gamla träd. Antal aktiva dagar/år är cirka 170. Energibehov motsvarar 9×5 mg×170 dagar = 7 650 mg torrvikt foder per individ under säsongen. Antalet ägg i snitt 400 per säsong, men endast 50% överlever till larv beroende på genetisk defekt hos arten, det vill säga antalet ägg bör justeras till 200.

A5.2.3 Vanlig padda

Vuxenvikt hona 80 gram, hane 40 gram, i genomsnitt 60 gram. Äter alla smådjur (insekter, spindlar, maskar mm) som rör sig. Ungefärligt antal vuxna per hektar cirka 40 per hektar och utspridda mer jämt i landskapet jämfört med grodorna och salamandrarna, även i lite torrare marker. Antal aktiva dagar/år är cirka 220. Energibehov motsvarar 80×5 mg×220 dagar = 123 200 mg torrvikt foder per individ under säsongen. Antalet ägg i snitt 4 000 per säsong.

A5.2.4 Åkergroda

Vuxenvikt cirka 20 gram. Äter alla smådjur (insekter, spindlar, maskar mm) som rör sig. Ungefärligt antal vuxna per hektar är 30 st inom 100 m från lekdammens strandkant, 10 st inom 100–300 m från damm och 1–5 inom 300–500 m från lekdamm. Antal aktiva dagar/år är cirka 200. Energibehov motsvarar 20×5 mg×200 dagar = 20 000 mg torrvikt foder per individ under säsongen. Antalet ägg i snitt 1 500 per säsong.

A5.2.5 Vanlig groda

Vuxenvikt 25 gram. Äter alla smådjur (insekter, spindlar, maskar mm) som rör sig. Obs! Förekommer endast i Forsmark. Ungefärligt antal vuxna per hektar är 20 st inom 100 m från lekvattnets strand, 10 st inom 100–300 m och 5 inom 300–500 m. Antal aktiva dagar/år är cirka 220. Energibehov motsvarar 25×5 mg×220 dagar = 27 500 mg torrvikt foder per individ under säsongen. Antalet ägg i snitt 2 000 per säsong.

A5.2.6 Gölgroda

Vuxenvikt 20 gram. Äter alla smådjur (insekter, spindlar, maskar mm) som rör sig. Finns endast i Forsmark och helt knuten till dammar. I rapporten finns angivet fyra dammar där arten påträffats och ungefärliga antalet vuxna djur varierar mellan 50 och 100 per damm. Antal aktiva dagar/år är cirka 170. Energibehov motsvarar 20×5 mg×170 dagar = 17 000 mg torrvikt foder per individ under säsongen. Antalet ägg i snitt 1 700 per säsong.

A5.2.7 Sandödla

Vuxenvikt 8 gram. Äter spindlar och olika insekter. Lever i små isolerade kolonier med 10–30 vuxna inom en yta av cirka ett hektar. Dessa små kolonier ligger glest utspridda och i Simpevarp kom jag i kontakt med en sådan koloni. Utslaget på hela området 0.1–0.2 vuxna per hektar. Antal aktiva dagar/år är cirka 170. Energibehov motsvarar 8×20 mg×170 dagar = 27 200 mg torrvikt foder per individ under säsongen. Antalet ägg i snitt cirka 10 per säsong.

A5.2.8 Skogsödla

Vuxenvikt 5 gram. Äter spindlar och olika insekter. Täthet uppskattas till 5 vuxna per hektar. Antal aktiva dagar/år är cirka 210. Energibehov motsvarar 5×20 mg×210 dagar = 21 000 mg torrvikt foder per individ under säsongen. Föder levande ungar, cirka 7 per säsong.

A5.2.9 Kopparödla

Vuxen vikt 15 gram. Äter främst daggmask och sniglar. Täthet uppskattas till 10 vuxna per hektar. Antal aktiva dagar/år är cirka 200. Energibehov motsvarar 15×20 mg×200 dagar = 60 000 mg torrvikt foder per individ under säsongen. Föder levande ungar, cirka 8 per säsong.

A5.2.10 Hasselsnok

Vuxenvikt 70 gram. Äter främst andra reptiler såsom kopparödla. Täthet uppskattas till 0.2 vuxna per hektar. Antal aktiva dagar/år är cirka 200. Energibehov motsvarar 70×10 mg×200 dagar = 140 000 mg torrvikt foder per individ under säsongen. Föder levande ungar, cirka 12 vid varje födsel vartannat år, det vill säga cirka 6 per säsong.

A1.2.11 Snok

Vuxenvikt 50–80 gram hos hane och 100–300 gram hos hona. Utgående från ett litet överskott av hanar anges medelvikten till 175 gram per vuxen. Äter främst grodor, paddor, salamandrar och fisk. Täthet uppskattas till 2 vuxna/hektar i områden med fuktiga marker (där många bytesobjekt finns) och 1 vuxen/hektar i torrare marker. Antal aktiva dagar/år är cirka 200. Energibehov motsvarar 175×10 mg×200 dagar = 350 000 mg torrvikt foder per individ under säsongen. Lägger ägg varje år, cirka 13 ägg per säsong.

A1.2.12 Huggorm

Vuxenvikt 100 gram hos hane och 200 gram hos honan, genomsnitt per vuxen 150 gram (jämn könskvot), äter främst sork och möss (cirka 1 gnagare/15 dagar under 150 dagar). Huggormen äter inte hela den aktiva perioden utan endast under cirka 70% av den aktiva perioden om 220 dagar per år. Täthet uppskattas till 1vuxen/hektar, i igenväxande ängsmarker med hög tthet av smågnagare upp till 4 vuxna per hektar. Energibehov motsvarar 150×10 mg×220 dagar = 330 000 mg torrvikt foder per individ under säsongen. Föder levande ungar, cirka 10 vartannat år, det vill säga 5 per säsong i genomsnitt.

Species list Forsmark

The mammals, birds, amphibians and reptiles are well-described for the sites (see references in table). However, the plant lists should not be regarded as complete and is put together using mainly the reports /Andersson 2004b, Göthberg and Wahlman 2006, Johanson et al. 2004/. These cover primarily the common and typical species for the area.

Latin	Swedish
Mammals	**Däggdjur**
See Table 4-24 and 4-29	
Birds	**Fåglar**
See Appendix 4	
Amphibians and reptiles	**Grod- och kräldjur**
See Table 4-43	
Vascular plants	**Kärlväxter**
Acer platanoides	Lönn
Achillea millefolium	Rölleka
Agrimonia eupatoria	Småborre
Agrostis canina	Brunven
Agrostis capillaris	Rödven
Agrostis stolonifera	Krypven
Alchemilla sp	Daggkåpor
Alnus glutinosa	Klibbal
Andromeda polifolia	Rosling
Anemone nemorosa	Vitsippa
Angelica sylvestris	Strätta
Anthoxanthum odoratum	Vårbrodd
Anthriscus sylvestris	Hundkex
Arrhenatherum elatius	Knylhavre
Athyrium filix-femina	Majbräken
Berberis vulgaris	Berberis
Betula pendula	Vårtbjörk
Betula pubescens	Glasbjörk
Brachypodium sylvaticum	Lundskafting
Briza media	Darrgräs
Calamagrostis arundinacea	Piprör
Calamagrostis canescens	Grenrör
Calamagrostis epigejos	Bergrör
Calamagrostis purpurea	Brunrör
Calamagrostis stricta	Madrör
Callitriche stagnalis	Dikeslånke
Calluna vulgaris	Ljung
Caltha palustris	Kabbeleka
Campanula patula	Ängsklocka
Campanula persicifolia	Stor Blåklocka
Cardamine pratensis	Ängsbräsma
Carex acuta	Vasstarr
Carex appropinquata	Tagelstarr
Carex buxbaumii	Klubbstarr
Carex canescens	Gråstarr
Carex capillaris	Hårstarr
Carex caspitosa	Tuvstarr
Carex cuprina	Blankstarr
Carex diandra	Trindstarr
Carex digitata	Vispstarr
Carex disticha	Plattstarr

Latin	Swedish
Carex elata	Bunkestarr
Carex elongata	Rankstarr
Carex flacca	Slankstarr
Carex flava	Knagglestarr
Carex globularis	Klotstarr
Carex lasiocarpa	Trådstarr
Carex lepidocarpa	Näbbstarr
Carex limosa	Dystarr
Carex nigra	Hundstarr
Carex nigra/juncella	Styltstarr
Carex ovalis	Harstarr
Carex pallescens	Blekstarr
Carex panicea	Hirsstarr
Carex pseudocyperus	Slokstarr
Carex pulicaris	Loppstarr
Carex pulicaris	Loppstarr
Carex rostrata	Flaskstarr
Carex vesicaria	Blåsstarr
Centarium littorale	Kustarun
Centaurea jacea	Rödklint
Cerastium fontanum	Hönsarv
Chrysosplenium alternifolium	Gullpudra
Circaea alpina	Dvärghäxört
Cirsium arvense	Åkertistel
Cirsium helenioides	Brudborste
Cirsium palustre	Kärrtistel
Cirsium vulgare	Vägtistel
Coeloglossum viride	Grönkulla
Convallaria majalis	Liljekonvalj
Crepis paludosa	Kärrfibbla
Cypripedium calceolus	Guckusko
Dactylis glomerata	Hundäxing
Dactylorhiza fuchsii	Skogsnycklar
Dactylorhiza incarnata	Ängsnycklar
Danthonia decumbens	Knägräs
Daphne mezereum	Tibast
Dapne mezereum	Tibast
Deschampsia cespitosa	Tuvtåtel
Deschampsia flexuosa	Kruståtel
Drosera anglica	Storsileshår
Drosera rotundifolia	Rundsileshår
Dryopteris carthusiana	Skogsbräken
Dryopteris cristata	Granbräken
Dryopteris filix-mas	Träjon
Eleocharis quinqueflora	Tagelsäv
Eleocharis uniglumis	Agnsäv
Elymus caninus	Lundelm
Elytrigia juncea	Strandkvickrot
Elytrigia repens	Kvickrot
Empetrum nigerum	Kråkbär
Epilobium adenocaulon	Amerikansk dunört
Epilobium angustifolium	Mjölkört
Epilobium palustre	Kärrdunört
Epipactis helleborine	Skogsknipprot
Epipactis palustris	Kärrknipprot
Equisetum arvense	Åkerfräken

Latin	**Swedish**
Equisetum fluviatile	Sjöfräken
Equisetum palustre	Kärrfräken
Equisetum pratense	Ängsfräken
Equisetum scirpoides	Trådfräken
Equisetum sylvaticum	Skogsfräken
Equisetum variegatum	Smalfräken
Eriophorum angustifolium	Ängsull
Eriophorum vaginatum	Tuvull
Eupatorium cannabinum	Hampflockel
Euphrasia frigida	Fjällögontröst
Festuca arundinacea	Rörsvingel
Festuca ovina	Fårsvingel
Festuca rubra	Rödsvingel
Filipendula ulmaria	Älggräs
Filipendula vulgaris	Brudbröd
Fragaria vesca	Smultron
Frangula alnus	Brakved
Fraxinus excelsior	Ask
Galeopsis bifida	Toppdån
Galium album	Stormåra
Galium boreale	Vitmåra
Galium palustre	Vattenmåra
Galium uliginosum	Vattenmåra
Galium verum	Gulmåra
Gentianella uliginosa	Sumpgentiana
Geranium robertianum	Stinknäva
Geranium sanguineum	Blodnäva
Geranium sylvaticum	Midsommarblomster
Geum rivale	Humleblomster
Glaux maritima	Strandkrypa
Glechoma hederacea	Jordreva
Glyceria fluitans	Mannagräs
Goodyera repens	Knärot
Gymnocarpium dryopteris	Ekbräken
Hepatica nobilis	Blåsippa
Hieracium grp silvaticiforma	Skogsfibbla
Hieracium umbellatum	Flockfibbla
Hierocloë odorata	Ängsmyskgräs
Hippophae rhamnoides	Havtorn
Huperzia selago	Lopplummer
Hypericum maculatum	Fyrkantig Johannesört
Hypericum perforatum	Äkta johannesört
Hypochoeris maculata	Slåtterfibbla
Inula salicina	Krissla
Iris pseudacorus	Svärdslilja
Juncus articulatus	Ryltåg
Juncus balticus	Östersjötåg
Juniperus communis	En
Knautia arvensis	Åkervädd
Lactuca sativa	Skogssallat
Lathyrus linifolius	Gökärt
Lathyrus pratensis	Gulvial
Lathyrus vernus	Vårärt
Ledum palustre	Skvattram
Lemna minor	Andmat

Latin	Swedish
Leontodon autumnalis	Höstfibbla
Leucanthemum vulgare	Prästkrage
Linaria vulgaris	Gulmåra
Linnaea borealis	Linnea
Listera ovata	Tvåblad
Lithospermum officinale	Stenfrö
Lonicera xylosteum	Skogstry
Luzula pallescens	Blekfryle
Luzula pilosa	Vårfryle
Lycopodium annotinum	Revlummer
Lycopus europaeus	Strandklo
Lysimachia thyrsiflora	Topplösa
Lysimachia vulgaris	Videört
Lythrum salicaria	Fackelblomster
Maianthemum bifolium	Ekorrbär
Malus sylvestris	Vildapel
Melampyrum nemorosum	Natt och dag
Melampyrum sylvaticum	Skogskovall
Melica nutans	Bergsslok
Mentha aquatica	Vattenmynta
Mentha arvensis	Åkermynta
Menyanthes trifoliata	Vattenklöver
Milium effusum	Hässlebrodd
Molinia caerulea	Blåtåtel
Monotropa hypopitys	Tallört
Myosotis sylvatica	Skogsförgätmigej
Myrica gale	Pors
Ophioglossum vulgatum	Ormtunga
Origanum vulgare	Kungsmynta
Orthilia secunda	Björkpyrola
Oxalis acetosella	Harsyra
Paris quadrifolia	Ormbär
Parnassia palustris	Slåtterblomma
Pedicularis palustris	Kärrspira
Peucedanum palustre	Kärrsilja
Phegopteris connectilis	Hultbräken
Phleum pratense	Timotej
Phragmites australis	Vass
Picea abies	Gran
Pimpinella saxifraga	Bockrot
Pinguicula vulgaris	Tätört
Pinus sylvestris	Tall
Plantago lanceolata	Svartkämpar
Plantago maritima	Gulkämpar
Platanthera bifolia	Nattviol
Plathanthera chlorantha	Grönvit nattviol
Poa nemoralis	Lundgröe
Poa palustris	Sengröe
Poa pratensis	Ängsgröe
Poa trivialis	Kärrgröe
Polygala vulgaris	Jungfrulin
Polygonatum multiflorum	Storrams
Polygonatum odoratum	Getrams
Polypodium vulgare	Stensöta
Populus tremula	Asp
Potentilla anserina	Gåsört

Latin	**Swedish**
Potentilla erecta	Blodrot
Potentilla palustris	Kråkklöver
Potentilla reptans	Revfingerört
Primula farinosa	Majviva
Primula veris	Gullviva
Prunella vulgaris	Brunört
Prunus padus	Hägg
Pteridium aquilinum	Örnbräken
Puccinellia capillaris	Saltgräs
Puccinellia distans	Grått saltgäs
Pulmonaria obscura	Lungört
Pyrola chlorantha	Grönpyrola
Pyrola rotundifolia	Vitpyrola
Quercus robur	Ek
Ranunculus acris	Vanlig Smörblomma
Ranunculus flammula	Ältranunkel
Ranunculus lingua	Sjöranunkel
Ranunculus repens	Revsmörblomma
Rhododendron tomentosum	Skvattram
Rhynchospora alba	Vitag
Ribes alpinum	Måbär
Roegneria canina	Lundelm
Rosa canina	Nyponros
Rubus caesius	Blåhallon
Rubus chamaemorus	Hjortron
Rubus idaeus	Hallon
Rubus saxatilis	Stenbär
Rumex acetosa	Ängssyra
Sagittaria natans	Trubbpilblad
Salix aurita	Bindvide
Salix caprea	Sälg
Salix cinerea	Gråvide
Salix myrsinifolia	Svartvide
Salix pentandra	Jolster
Salix repens	Krypvide
Sanicula europaea	Sårläka
Satureja vulgare	Bergmynta
Satureja vulgaris	Bergmynta
Schoenoplectus lacustris	Säv
Schoenus ferrugineus	Axag
Scrophulaira nodosa	Flenört
Sedum telephium	Kärleksört
Selaginella selaginoides	Dvärglummer
Sesleria caerulea	Älväxing
Silene dioica	Rödblära
Solanum dulcamara	Besksöta
Solidago virgaurea	Gullris
Sonchus arvensis	Åkermolke
Sorbus aucuparia	Rönn
Sorbus intermedia	Oxel
Sparganium natans	Dvärgigelknopp
Stachys sylvatica	Stinksyska
Stellaria graminea	Grässtjärnblomma
Stellaria longifolia	Skogsstj.blomma
Stellaria nemorum ssp nemorum	Nordlundarv

Latin	**Swedish**
Succisa pratensis	Ängsvädd
Taraxacum sp	Maskros
Thalictrum flavum	Ängsruta
Thalictrum simplex	Backruta
Thelypteris palustris	Kärrbräken
Trichophorum alpinum	Snip
Trientalis europaea	Skogsstjärna
Trifolium medium	Skogsklöver
Trifolium pratense	Rödklöver
Triglochin maritima	Havssälting
Triglochin palustre	Kärrsälting
Tussilago farfara	Tussilago
Typha latifolia	Bredkaveldun
Ulmus glabra	Alm
Utricularia intermedia	Dybläddra
Utricularia vulgaris	Vattenbläddra
Vaccinium myrtillus	Blåbär
Vaccinium oxycoccos	Tranbär
Vaccinium uliginosum	Odon
Vaccinium vitis-idaea	Lingon
Valeriana sambucifolia	Strandvänderot
Veronica chamaedrys	Teveronika
Veronica officinalis	Ärenpris
Veronica scutellata	Dyveronika
Viburnum opulus	Olvon
Vicia cracca	Kråkvicker
Vicia sepium	Häckvicker
Vicia sylvatica	Skogsvicker
Viola canina	Ängsviol
Viola mirabilis	Underviol
Viola palustris	Kärrviol
Viola riviniana	Skogsviol
Bryophytes	Mossor
Aneura pinguis	Fetbålmossa
Antitrichia curtipendula	Fällmossa
Brachythecium sp	Gräsmossor
Calliergion sp	Skedmossor
Calliergionella sp	Spjutmossor
Campylium sp	Spärrmossor
Climacium dendroides	Palmmossa
Dichelyma sp	Klomossor
Dicranum sp	Kvastmossor
Drepanocladus sp	Krokmossor
Helodium blandowii	Kärrkammossa
Herzogiella striatella	Spretmossor
Hylocomium splendens	Husmossa
Hypnum cupressiforme	Cypressfläta (Bergklomossa)
Lophozia sp	Flikmossor
Mnium sp	Stjärnmossor
Plagiochila asplenioides	Praktbräkenmossa
Pleurozium schreberi	Väggmossa
Polytrichum sp	Björnmossor
Pseudotaxiphyllum elegans	Platt skimmermossa
Ptilidium pulcherrinum	Tät franslevermossa
Ptilium crista-castrensis	Kammossa

Latin	Swedish
Rhytidiadelphus triquetrus	Kranshakmossa
Scorpidium scorpioides	Korvspionmossa
Sphagnum sp	Vitmossor
Thuidium sp	Tujamossor
Tomentypnum nitens	Gyllenmossa
Warnstorfia exannulata	Kärrkrokmossa
Lichens	**Lavar**
Cladonia arbuscula	Gulvit renlav
Cladonia rangiferina	Grå renlav
Cladonia stellaria	Fönsterlav
Hypogymnia sp	Blåslavar
Peltigera sp	Filtlavar
Platismatia sp	Näverlavar
Rhizocarpon sp	Kartlavar
Fungi	**Svampar**
Cordyceps ophioglossioides	Smal svampklubba
Geastrum sp	Jordstjärna
Cantharellus aurora	Rödgul trumpetsvamp
Phellodon niger	Svart taggsvamp
Hydnellum suavolens	Dofttaggsvamp
Hydnellum ferrugineum	Dropptaggsvamp/ Skarp droptaggsvamp
Hygrocybe sp	Hagvaxskivling
Sarcodon imbricatus	Fjällig taggsvamp
Lactarius deterrimus	
Suillus granulatus	
Lactarius scrobiculatus	
Boletus edulis	
Cortinarius odorifer	
Sarcodon imbricatus	
Cantharellus tubaeformis	
Lactarius trivialis	
Cortinarius armeniacus	
Hypholoma capnoides	
Tricholoma equestre	
Collybia peronata	

Appendix 7

Species list Laxemar-Simpevarp

The mammals, birds, amphibians and reptiles are well-described for the sites (see references in table). However, the plant lists should not be regarded as complete and is put together using mainly the report /Andersson 2004a/. This list covers primarily the common and typical species for the area.

Latin	Swedish
Mammals	**Däggdjur**
See Table 4-24 and 4-29	
See Appendix 4	
Amphibians and reptiles	**Grod- och kräldjur**
See Table 4-44	
Vascular plants	**Kärlväxter**
Acer platanoides	Lönn
Achillea millefolium	Rölleka
Achillea ptarmica	Nysört
Agrostis canina	Brunven
Agrostis capillaris	Rödven
Agrostis gigantea	Storven
Allium oleraceum	Backlök
Alnus glutinosa	Klibbal
Andromeda polifolia	Rosling
Anemone nemorosa	Vitsippa
Anthoxanthum odoratum	Vårbrodd
Athyrium filix-femina	Majbräken
Betula pendula	Vårtbjörk
Betula pubescens	Glasbjörk
Calamagrostis arundinacea	Piprör
Calamagrostis epigejos	Bergrör
Calluna vulgaris	Ljung
Campanula persicifolia	Stor Blåklocka
Campanula rotundifolia	Ängsklocka
Carex acuta	Vasstarr
Carex diandra	Trindstarr
Carex echinata	Stjärnstarr
Carex lasiocarpa	Trådstarr
Carex nigra	Hundstarr
Carex ovalis	Harstarr
Carex rostrata	Flaskstarr
Cirsium arvense	Åkertistel
Cirsium palustre	Kärrtistel
Convallaria majalis	Liljekonvalj
Convolvulus arvensis	Åkervinda
Corylus avellana	Hassel
Crataegus laevigata	Rundhagtorn
Cystopteris fragilis	Stenbräken
Dactylis glomerata	Hundäxing
Danthonia decumbens	Knägräs
Daucus carota	Vildmorot
Deschampsia cespitosa	Tuvtåtel
Deschampsia flexuosa	Kruståtel
Dryopteris carthusiana	Skogsbräken
Dryopteris filix-mas	Träjon
Elytrigia repens	Kvickrot

Latin	Swedish
Empetrum nigrum	Kråkbär
Epilobium adenocaulon	Amerikansk dunört
Epilobium angustifolium	Mjölkört
Eriophorum vaginatum	Tuvull
Festuca ovina	Fårsvingel
Festuca rubra	Rödsvingel
Fragaria vesca	Smultron
Fraxinus excelsior	Ask
Juniperus communis	En
Lamium purpureum	Rödplister
Lathyrus pratensis	Gulvial
Ledum palustre	Skvattram
Linaria vulgaris	Gulsporre
Linnaea borealis	Linnea
Luzula pilosa	Vårfryle
Lycopodium annotinum	Revlummer
Lysimachia vulgaris	Videört
Maianthemum bifolium	Ekorrbär
Malus sylvestris	Vildapel
Matricaria perforata	Baldersbrå
Melampyrum pratense	Ängskovall
Melampyrum sylvaticum	Skogskovall
Melica nutans	Bergsslok
Mentha arvensis	Åkermynta
Milium effusum	Hässlebrodd
Moehringia trinervia	Skogsnarv
Molinia caerulea	Blåtåtel
Monotropa hypopitys	Tallört
Nardus stricta	Stagg
Oxalis acetosella	Harsyra
Phleum pratense	Timotej
Phragmites australis	Vass
Picea abies	Gran
Picea abies	Gran
Pinus sylvestris	Tall
Poa annua	Vitgröe
Poa compressa	Berggröe
Poa nemoralis	Lundgröe
Polypodium vulgare	Stensöta
Populus tremula	Asp
Potentilla erecta	Blodrot
Potentilla palustris	Kråkklöver
Primula veris	Gullviva
Prunus spinosa	Slån
Pteridium aquilinum	Örnbräken
Quercus robur	Ek
Ranunculus acris	Vanlig Smörblomma
Ribes alpinum	Måbär
Roegneria canina	Lundelm
Rosa canina	Nyponros
Rubus idaeus	Hallon
Rubus nessensis	Skogsbjörnbär
Rubus saxatilis	Stenbär
Rumex acetosella	Bergssyra
Salix caprea	Sälg
Salix cinerea	Gråvide

Latin	Swedish
Salix cinerea	Gråvide
Salix myrsinifolia	Svartvide
Sedum telephium	Kärleksört
Senecio viscosus	Klibbkorsört
Silene dioica	Rödblära
Solidago virgaurea	Gullris
Sorbus aucuparia	Rönn
Sorbus intermedia	Oxel
Stachys sylvatica	Stinksyska
Stellaria graminea	Grässtjärnblomma
Stellaria longifolia	Skogsstj.blomma
Taraxacum sp	Maskros
Thalictrum sp	Thalictrum sp
Trientalis europaea	Skogsstjärna
Trifolium medium	Skogsklöver
Trifolium pratense	Rödklöver
Trifolium repens	Vitklöver
Tussilago farfara	Tussilago
Urtica dioica	Brännässla
Vaccinium myrtillus	Blåbär
Vaccinium vitis-idaea	Lingon
Verbascum thapsus	Kungsört
Veronica chamaedrys	Teveronika
Veronica officinalis	Ärenpris
Vicia cracca	Kråkvicker
Vicia sepium	Häckvicker
Vicia sylvatica	Skogsvicker
Vincetoxicum hirundinaria	Tulkört
Viola palustris	Kärrviol
Viola riviniana	Skogsviol
Viola tricolor	Styvmorsviol
Bryophytes	**Mossor**
Calliergion sp	Skedmossor
Calliergionella sp	Spjutmossor
Climacium dendroides	Palmmossa
Dicranum sp	Kvastmossor
Drepanocladus sp	Krokmossor
Drepanocladus uncinatus	Krokmossa
Grimmia trichophylla	Kuddmossa
Hylocomium splendens	Husmossa
Hypnum cupressiforme	Cypressfläta
Mnium sp	Stjärnmossor
Pleurozium schreberi	Väggmossa
Polytrichum sp	Björnmossor
Ptilium crista-castrensis	Kammossa
Rhytidiadelphus triquetrus	Kranshakmossa
Sphagnum sp	Vitmossor
Lichens	**Lavar**
Cetraria ericetorum	Smal inlandslav
Cetraria islandica	Islandslav
Cladina arbuscula	Gulvit renlav
Cladina rangiferina	Grå renlav
Cladina sp	Renlavar
Cladonia sp	Bägarlavar
Cladonia stellaria	Fönsterlav
Peltigera sp	Filtlavar

Latin	Swedish
Fungi	**Svampar**
Antrodia pulvinascens	Veckticka
Bankera fuligineoalba	Talltaggsvamp
Bankera violascens	Grantaggsvamp
Clavulina cristata	Kamfingersvamp
Craterellus cornucopioides	Svart trumpetsvamp
Gyromitra infula	Biskopsmössa
Heterobasidion annosum	Rotticka
Hydnellum aurantiacum	Orange taggsvamp
Inonotus tomentosus	Luddticka
Lactarius zonarioides	Granriska
Laetiporus sulphureus	Svavelticka
Macrolepicata procera	Stolt fjällskivling
Mycena galericulata	Rynkhätta
Phellinus pini	Tallticka
Phellodon tomentosus.	Trattaggsvamp
Sarcodon imbricatus	Fjällig taggsvamp (tallvar.)
Sarcodon scabrosus	Skrovlig taggsvamp
Sarcodon squamosus	Fjällig taggsvamp (granvar.)
Sarcodon versipellis	Brödtaggsvamp
Scleroderma citrinum	Vitgul rottryffel
Sparassis crispa	Blomkålssvamp

Appendix 8

Photographs of the ecosystems described in Chapter 6

Detailed investigations of carbon pools and fluxes were undertaken in six different ecosystems (see Chapter 6). Below are pictures from these six ecosystems.

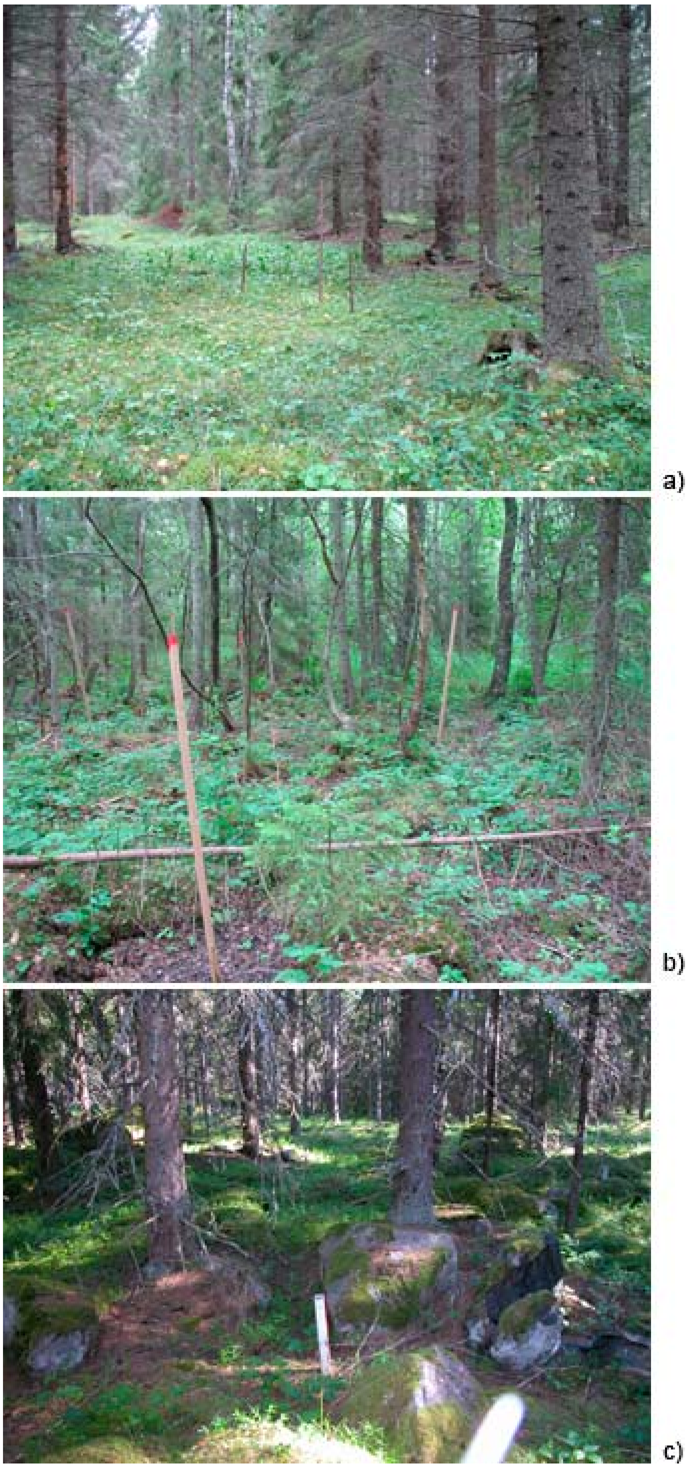


Figure A8-1. *Three investigated ecosystems in the Forsmark regional model area. a) Herb-rich Norway spruce (Picea abies) forest (FG1), b) Norway spruce – Alder (Alnus glutinosa) wetland forest (SS1), c) Norway spruce forest (B2a). Photo: Sara Nordén*

Figure A8-2. Three investigated ecosystems in the Laxemar-Simpevarp regional model area. a) Norway spruce forest on ditched peat land (G1), b) oak (Quercus robur) forest (L1), c) alder wetland (S1) close to the sea shore. Photo: Sara Nordén

Appendix 9

Atmospheric deposition

Below data are listed describing the expected atmospheric deposition for Forsmark (Table A6-1) and Laxemar-Simpevarp (A6-2) for a number of different elements.

Table A9-1. Expected atmospheric deposition for a number of different elements at Forsmark (dry deposition and/or precipitation). Precipitation in Forsmark is 559 mm year^{-1}. Data from 1) /Tröjbom and Söderbäck 2006a/, 2) /Pihl Karlsson et al. 2003/, 3) /Tyler and Olsson 2006/, 4) (Sicada October 2007).

Element	Deposition (g m^{-2} year^{-1})	Reference	Comment
C	1.26	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564).
N	0.36	2	Precipitation, site data only include data from 1 sampling occasion and therefore generic data is used. Station Jädraås.
P	0.012	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564).
U	0.000002	3	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden.
Th	0.000005	3	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden.
I	0.00028	1	Precipitation, based on two measurements at the site that were both below the detection limit of 1µg/l. Half the detection limit was assumed to be the deposition, which was in the lower range of the iodine deposition interval reported by /Sheppard et al. 2002/.
Al	1.76E–05	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564).
Br	0.0014	1	Precipitation, based on 12 measurements at the site that were all below the detection limit of 5µg/l. Half the detection limit was assumed to be the deposition.
Ca	0.17	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564).
Cl	0.51	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564).
Fe	0.018	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564).
Mg	0.046	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564).
K	0.098	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564).
Si	0.0084	1	Precipitation, based on one measurement at the site that was below the detection limit of 30µg/l. Half the detection limit was assumed to be the deposition.
Na	0.30	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564).
S	0.28	1	Precipitation, site data, mean from two stations (PFM002457 and PFM 002564).
Mn	0.013	4	Precipitation, based on site investigation in Laxemar-Simpevarp but with precipitation amounts for Forsmark.
Sr	0.0047	4	Precipitation, based on site investigation in Laxemar-Simpevarp but with precipitation amounts for Forsmark.

Table A9-2. Expected atmospheric deposition for a number of different elements at Laxemar-Simpevarp. Precipitation in Laxemar-Simpevarp is 600 mm year^{-1}. Data from 1) /Pihl Karlsson et al. 2008/, 2) /Knape 2001/, 3) /Tyler and Olsson 2006/, 4) /Tröjbom and Söderbäck 2006b/, 5) (Sicada October 2007).

Element	Deposition (g m^{-2} y^{-1})	Reference	Comment
C	1.88	1	Precipitation, generic data from station Rockneby in Kalmar län mean 2000–2007.
N	0.64	1	I Precipitation, generic data from station Rockneby in Kalmar län mean 2000–2007.
P	0.027	2	Generic data from Äspö.
U	0.000002	3	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden.
Th	0.000005	3	Estimate of atmospheric deposition during the winter period in a deciduous forest in southern Sweden.
I	0.0003	4	Precipitation, based on two measurements in Forsmark that were both below the detection limit of 1µg/l. Half the detection limit was assumed to be the deposition, which was in the lower range of the interval reported by /Sheppard et al. 2002/. Corrected for precipitation amount in Laxemar-Simpevarp.
Al	1.89E–05	4	Precipitation, based on site investigation in Forsmark but with precipitation amounts for Laxemar-Simpevarp.
Br	0.083	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=105, Sept 2002–Oct. 2007
Ca	0.42	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sept. 2002–Oct. 2007.
Cl	0.74	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=104, Sept. 2002–Oct. 2007. 1 outlier was removed from the original dataset.
Fe	0.038	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sept. 2002–Oct. 2007.
Mg	0.13	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007.
K	0.36	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sep 2002–Oct 2007.
Si	0.033	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sept. 2002–Oct. 2007.
Na	1.03	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sept. 2002–Oct. 2007.
S	0.345	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sept. 2002–Oct. 2007.
Mn	0.014	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=29, Sept. 2002–Oct. 2007.
Sr	0.0051	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sept. 2002–Oct. 2007.
Li	0.0015	5	Precipitation, based on 30 measurements at the site that were below the detection limit, half the detection limit was used in the estimate, Sept. 2002–Nov. 2017.
F	0.071	5	Precipitation, site data, mean from two stations (PSM002170 and PSM001516) n=30, Sept. 2002–Oct. 2007.

Appendix 10

Statistical descriptions of wetlands, agricultural land and forest stands

Data in GIS has been used to identify and describe wetlands, agricultural land and forests stands. The main source for identifying the terrestrial objects within the regional model area has been a vegetation map /Boresjö Bronge and Wester 2003/. See Appendix I in /Lindborg 2006/ for detailed information of methods and data for Laxemar-Simpevarp. The same procedure was also undertaken to characterize the Forsmark area. All work in GIS has been done using the ESRI Inc. software ArcView 3, ArcGIS 8.3 and 9.1 with extensions (ESRI 2005), and all statistics have been calculated using Statistica 6.0 (StatSoft Inc 2001).

Each property is described using number of observations, mean, median, min, max, lower and upper quartile, and standard deviation. Finally, a distribution curve is presented for the data for each parameter. No transformation of the data has been performed before calculating the descriptive statistics.

Table A10-1. Area and catchment area statistics for the wetlands in Forsmark and Laxemar-Simpevarp.

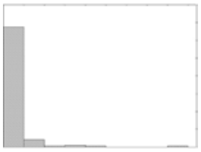
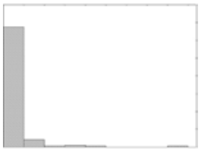
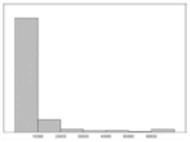
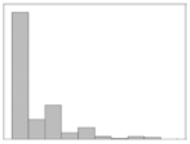
Property	N	Mean	Median	Minimum	Maximum	Lower Quartile	Upper Quartile	Std.Dev.	Distribution
Forsmark									
Wetland area (m^2)	148	37,367	10,766	996	815,763	4,604	32,216	87,727	
Catchment area (m^2)	148	737,400	102,900	500	12,975,400	28,300	401,100	1,822,351	
Laxemar-Simpevarp									
Wetland area (m^2)	536	9,600	3,400	20	391,700	2,100	6,800	28,800	
Catchment area (m^2)	534	1,326,000	30,100	0	81,210,300	10,300	127,500	7,987,500	

Table A10-2. Area and catchment area statistics for agricultural land in Forsmark and Laxemar-Simpevarp.

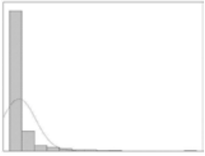
Property	N	Mean	Median	Minimum	Maximum	Lower Quartile	Upper Quartile	Std.Dev.	Distribution
Forsmark									
Agricultural area (m^2)	153	32,020	4,516	397	1,077,217	2,003	12,691	121,367	
Catchment area (m^2)	153	242,091	21,900	100	4.53·106	5,700	97,500	777,650	
Laxemar-Simpevarp									
Agricultural area (m^2)	1,175	12,200	4,900	50	242,000	2,300	12,500	21,600	
Catchment area (m^2)	1,175	1.52·106	56,000	0	92.45·106	11,000	0.32·106	6.38·106	

Table A10-3. Area and catchment area statistics for forest stands in Forsmark and Laxemar-Simpevarp.

Property	N	Mean	Median	Minimum	Maximum	Lower Quartile	Upper Quartile	Std.Dev.	Distribution
Forsmark									
Catchment area	1,000	15,805	200	0	5,884,500	0	600	229,880	
Laxemar-Simpevarp									
Catchment area	1,000	110,400	200	0	45,303,500	0	600	1,964,200