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## A comparison between mire-catchment interactions in the Sävar Rising Coastline Mire Chronosequence in Westrobothnia and the Forsmark area in Uppland

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*Keywords:* Catchment hydrology, Peat depth, Minerogenic mire, Landscape development, Biogeochemistry, Radionuclides.

This report concerns a study which was conducted for Svensk Kärnbränslehantering AB (SKB). The conclusions and viewpoints presented in the report are those of the authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

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# Abstract

Minerogenic mires (fens) are often found in depressions in the landscape and their surface vegetation is, unlike that of ombrogenic mires (bogs), in contact with groundwater either from the underlying mineral soil or from the upslope catchment area. The catchment area drains the surface and brings water with solutes to the mires. This, together with upwelling of groundwater into the peat column, feeds the mire vegetation. In this way the catchment area influences the productivity, peat accumulation and expansion rates of minerogenic mires. Substances harmful to humans may be transported to a mire either from groundwater upwelling, surface water from the catchment area, or deposited from the atmosphere. These substances could theoretically be diluted by water or other substances that are transported from the catchment area to the mire. This literature review compares long-term mire development and possible dilution effects in the mire recipients under different catchment settings for two areas representing different biomes: coastal areas of northern Uppland (Forsmark area; FM in the boreonemoral zone of central Sweden), and the coastal areas of Westrobothnia (Sävar Rising Coastline Mire Chronosequence; SMC in the boreal zone of northern Sweden). Both areas are found below the highest coastline and are characterized by relatively high isostatic rebound. Apart from differences in climatic settings, quaternary deposits differ between the areas, as Uppland is characterized by calcite rich till and clay sediments, while the SMC is dominated by till and post-glacial silt, clay and sand. It was found that mire lateral expansion after initiation was widespread in the SMC, while mires in the FM seem to be more restricted to the basin they were originally formed in. This likely reflects the mire initiation type (in the FM a higher proportion is believed to originate from terrestrialized lakes compared to primary mire formation), and climatic differences between the areas (which cause differences in the hydrologic balances), since topographically the lower-sloping FM should offer suitable conditions for lateral expansion. In both areas, the increment in peat depth, and in the SMC also the lateral expansion of peat, was rapid during the first ca 1 000–2 000 years, where after the expansion rates levelled off. In both mire areas, catchments are still influencing the elemental composition of surface peat, even though mires in the SMC are supported by somewhat larger catchment-to-mire areas compared to mires in the FM. The smaller catchment areas in the FM compared to the SMC may lead to a lower dilution of harmful substances, if the mire surfaces of the FM receive such substances through groundwater upwelling. Apart from the catchment-to-mire area ratio, catchment slope and wetness were found to be important for the transport of water and solutes to the mires, where a higher slope was found to co-vary with higher peat elemental concentrations. The slope of the catchment area, and especially the slope by the mire margins, will also control the possibilities of a mire to expand laterally, since a steep mire-surrounding catchment area will be unfavorable for lateral expansion.

# Sammanfattning

Minerogena myrar (kärr) återfinns ofta i sänkor i landskapet och deras vegetation är, till skillnad från ombrogena myrars (mossar), i kontakt med grundvatten och näring som antingen kan nå myrytan från myrens uppströms liggande tillrinningsområde eller genom grundvatten som sipprar upp under myren. Tillrinningsområdet kan genom näringstransport styra produktiviteten, torvackumulationen och expansionshastigheterna hos minerogena myrar. Om ämnen som är skadliga för mänskor transporteras till en myr antingen från grundvatten som stiger upp underifrån, transporteras från tillrinningsområdet eller deponeras från atmosfären, så kan dessa ämnen i teorin spädas ut av vatten från tillrinningsområdet. I den här litteraturöversikten diskuteras tillrinningsområdets roll för myrutveckling, samt för en möjlig utspädningseffekt i myrarna. Två områden som representerar olika biom jämfördes: Forsmark (FM) i norra Uppland, som ligger i den boreonemorala zonen, samt Sävar Rising Coastline Mire Chronosequence (SMC) i Västerbottens kustland som ligger i den boreala zonen. Båda områdena befinner sig under högsta kustlinjen och påverkas av relativt hög landhöjning. Förutom skillnader i klimatförhållanden skiljer sig kvartära avlagringar mellan områdena genom att Uppland kännetecknas morän och lersediment rika i kalcit, medan SMC domineras av morän, samt postglacial sand, silt och lera. Den här litteraturstudien visade att myrar bredde ut sig till omgivande fastmark i stor utsträckning i SMC, medan myrarna i FM verkar vara mer begränsade till den svacka där de ursprungligen bildades. Detta återspeglar troligtvis typen av myrbildning (i FM antas en högre andel myrar ha bildats genom igenväxning av sjöar jämfört med primär myrbildning), samt klimatförhållandena mellan områdena som orsakar skillnader i hydrologi. Skillnaderna i expansion mellan FM och SMC är troligtvis inte styrda av skillnader i topografi, eftersom den någon flackare FM borde erbjuda lämpliga förhållanden för lateral expansion. I båda områdena var ökningen av torvdjupet, och i SMC även den laterala expansionen av torv, snabb under de första ca 1 000–2 000 åren, varefter expansionshastigheterna planade ut. I båda myrområdena påverkar tillrinningsområdena yttorvens elementära sammansättning, även om myrarna i SMC stöds av något större tillrinningsområden jämfört med myrarna i FM. De generellt mindre tillrinningsområdena i FM jämfört med SMC skulle kunna leda till en lägre utspädning av eventuella skadliga ämnen som kan nå FM-myrarna genom grundvatten som stiger upp underifrån. Förutom arealförhållandet mellan tillrinningsområdet och myren visade sig lutningen och fuktigheten i tillrinningsområdet var viktiga för transporten av vatten och lösta ämnen till myrarna, där en högre lutning samvarierade med en högre elementkoncentration i torven. Utöver att kontrollera inflödet av vatten och näring till myren påverkar även tillrinningsområdets lutning, och särskilt lutningen vid myrkanten, myrens möjligheter att expandera lateralt, eftersom en brant kant och ett brant tillrinningsområde i stort kommer att vara ogynnsamt för lateral expansion.

# Contents

# 1 Introduction

## 1.1 Mire hydrology and mire-catchment interactions

Wetlands, and more specifically peat-forming mires, are multi-functional ecosystems (Hambäck et al. 2023) that support numerous ecosystem services, including mediation of hydrological and biogeochemical cycles within, upstream, and downstream of the mire area (Fergus et al. 2017; Helbig et al. 2020a, 2020b; Lane et al. 2018; Sponseller et al. 2018). One of the main ecosystem services that mires provide is the uptake and accumulation of atmospheric carbon, which may lead to long-term climate benefits (Loisel et al. 2014). While this is often considered a positive ecosystem feedback in terms of climate change mitigation, the accumulation of other elements in peat may represent also a long-term archive for more hazardous elements, including radionuclides that reflect past or present pollution (Li et al. 2023). Hazardous elements that have accumulated in peat may be released to more bio-available fractions and taken up by biota, especially if the peat is exposed, extracted, or if the redox conditions in peat changes. This constitutes a possible exposure pathway of contaminants also for human inhabitants (Saetre et al. 2013; Kautsky et al. 2016; Berglund et al. 2013).

Mires form and develop as a result of slow, long-term peat accumulation that operates over hundreds to thousands of years (e.g. Loisel et al. 2014; Clymo, 1984). A seasonally positive water balance is essential for the initiation and persistence of a mire. Saturated soil conditions (i.e. a water table level close to the soil surface) create anaerobic environments that cause mire net primary productivity rates (NPP) to exceed decomposition rates, which enables peat accumulation (Ivanov, 1981), and eventually the initiation of a mire ecosystem. Topography is the main factor controlling flow-paths, and hence, the water balance in boreal and boreonemoral landscapes, but also climate plays an important role in activating and de-activating smaller channels during wetter and drier periods (Treat et al. 2019; Graniero and Price, 1999). Depending on the local topography, pristine boreal and boreonemoral lowland landscapes are generally covered by mires, forests and lakes in a heterogeneous mosaic (Figure 1-1). Typically, mires are situated in groundwater discharge areas, i.e. low landscape positions where flow paths accumulate water and saturate the soil surface. Notably, mires can modify local hydrological conditions to suit the mire vegetation (van Breemen, 1995), which, if it happens, may lead to a blurring of the boundary between different landscape elements. In practice, human activity has heavily modified the extent of mires and other types of wetlands around the world. Despite this, it is still from an ecosystem development perspective useful to consider how mires originally expanded in the landscapes they occupy, since this can elevate our understanding of how different ecosystem services, that mires provide, are formed.

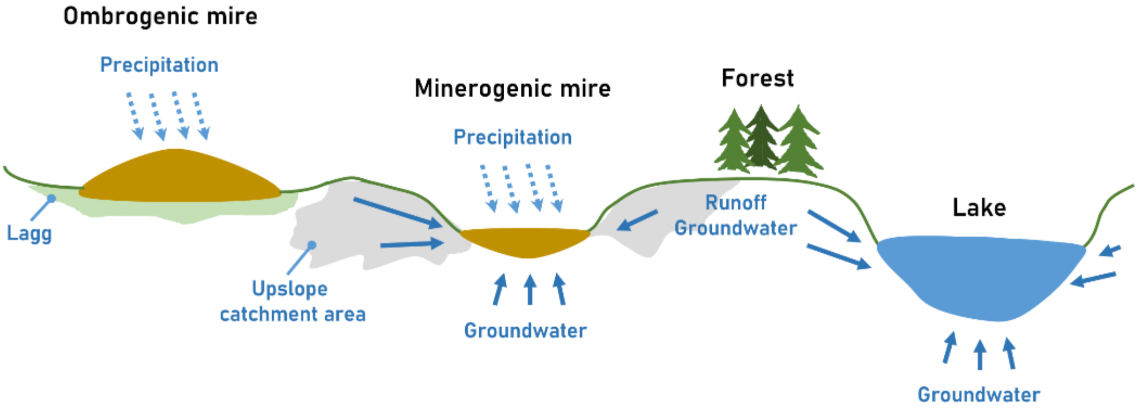

*Figure 1-1. The hydrological landscape mosaic covering ombrogenic mires (bogs), minerogenic mires (fens), lakes and upland forests. In: Ehnvall, 2023 (doctoral thesis).*

Hydrologically, mires are classified either as minerogenic (fens) or ombrogenic (bogs), depending on their water source. Minerogenic mires interact hydrologically with the surrounding upland area and other surface water bodies, if such are present (Lane et al. 2018). These mires primarily receive water and nutrients from the upslope catchment area, or from groundwater intrusions from below (Ivanov, 1981; Romanov, 1968). Water that has passed through a minerogenic mire may be discharged from one or several mire outlets (Sirin et al. 1998), diffused over wider outlet zones (Sallinen et al. 2019), or lost to aquifers through deep seepage (Hokanson et al. 2020; Marttila et al. 2021), as earlier described by Ehnvall et al. (2023a). Particulate or dissolved elements are transported downslope from the mire area by discharge water, to different degrees depending on the mire's nutrient and water regimes (Fergus et al. 2017; Sponseller et al. 2018). As a result, minerogenic mires can mediate fluxes of water and/or nutrients across the landscape, and also control the flow of water and nutrients to any downslope located mire. In contrast to minerogenic mires, which are hydrologically well-connected to the surrounding landscape, ombrogenic mires receive water and nutrients exclusively from precipitation (Sjörs and Gunnarsson, 2002), making them hydrologically isolated from the surrounding landscape, and typically nutrient-poor.

Although the hydrological division between minerogenic and ombrogenic mires is strict, minerogenic mires represent a wide spectrum of nutrient regimes, ranging from eutrophic (i.e. nutrient rich) to oligotrophic (i.e. nutrient poor), depending on external nutrient supply (Avetov et al. 2021), as well as on internal nutrient cycling within the mire area (Jonasson and Shaver, 1999). As a result, the plant species composition in nutrient-poor minerogenic mires may resemble that of ombrogenic mires (Laine et al. 2021). Yet, from a hydrological and mire ecosystem perspective, it is crucial to separate between ombrogenic and oligotrophic minerogenic mires when considering, for example, possible exposure of ground-water based contaminants, nutrients or other elements to the living vegetation, since minerogenic mires are likely to be more prone to such exposure due to the hydrologic connection by the groundwater.

## 1.2 Mires in boreal and boreonemoral Sweden

In Sweden, the northern limit for the formation of true ombrogenic conditions is generally considered to be in Bergslagen (Almquist-Jacobson & Foster, 1995), which is close to the border between the boreal and boreonemoral vegetation zones (Figure 1-2). Single ombrogenic mires may still occur north of this bog-limit, if favorable micro-climatic and topographic conditions prevail (e.g. Tavelsjömyran in Westrobothnia, first mentioned by Granlund, 1932). Generally, both minerogenic and ombrogenic mires can be found in the boreonemoral zone, while minerogenic mires are predominantly found in the boreal zone.

The mire coverage in the boreal Swedish landscape (Figure 1-2) varies heavily depending on local topography (Ehnvall et al. 2023a and 2024), but also on human activity that regionally has decreased the mire coverage through forest drainage and other management practices. Still, regionally in the boreal zone, the open and semi-open mire cover is up to ca 40 % of the land surface (SCB, 2024), generally with increasing mire cover from the coast towards the inland (Ehnvall et al. 2023). In the boreonemoral zone, which lays south of the boreal zone (Figure 1-2), temperatures are generally milder and mire catchments in this zone experience a shorter snow-covered period with less snow and warmer and drier summers. These climatic differences have implications on the overall plant phenology, the water balance of the landscape, as well as on the timing and magnitude of, for example, spring peak-flow. In the boreonemoral zone, forest vegetation is represented both by species typical of the northern boreal zone (coniferous forest) and the southern nemoral zone (deciduous forest). When compared to the boreal zone (up to 40 % mire coverage), the boreonemoral zone in Sweden has a considerably lower mire coverage (ca 10 %). This is both an effect of the denser human population and more widespread historical drainage of mires in the boreonemoral zone, but it also reflects underlying differences in the hydrological balance, which is the key control of any mire establishment and growth (Ivanov, 1981).

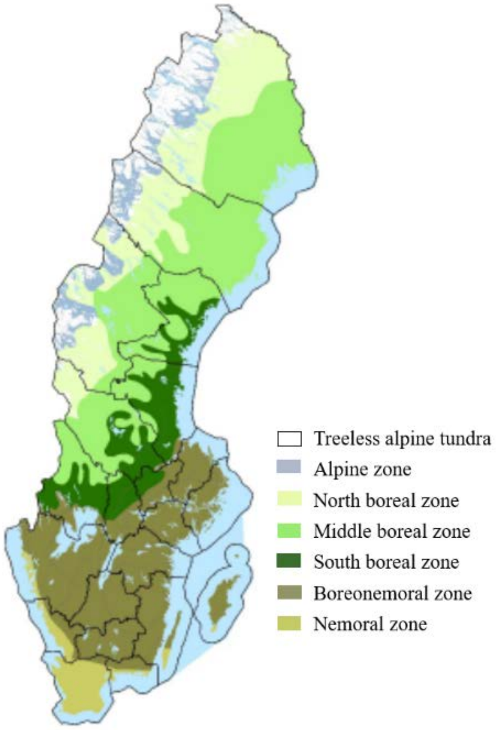

***Figure 1-2.** Swedish forest vegetation zones according to the Classification of the Nordic Council of Ministers (1984). County borders are depicted by black lines. Figure modified based on Skogsstyrelsen (2020).*

## 1.3 Isostatic rebound and the use of mire chronosequences in long-term ecosystem development studies

Vertical and lateral mire initiation and peat expansion rates are commonly investigated using peat chronologies (Quik et al. 2022) or bottom sediment analyses (Huikari, 1956). These methods offer high accuracy at the individual mire or sampling point level, but they are often expensive, time-consuming, and not feasible at larger spatial scales. Mire chronosequences offer a valuable alternative to peat chronologies for studying mire ecosystem processes over long time-scales, and at the landscape level (Johnson and Miyanishi, 2008).

Chronosequence studies can be carried out in landscapes with clear gradients that cover a large age difference within a limited geographical area (Figure 1-3), ensuring similar climate and topoedaphic properties in the study area. Such gradients are, for example, found in coastal areas with pronounced isostatic rebound rates, where ecosystem age correlates directly with elevation above sea level. Mires close to the present coastline are typically young, and mire age increases with altitude and distance from the present coastline, up to the highest historical coastline (Tuittila et al. 2013). Beyond the highest coastline, mires cannot be studied using the same chronosequence approach because, there, land surface age does not increase with altitude, since these areas have not been inundated by the sea during the Holocene.

Mire ecosystems can form, or initiate, following one of three main pathways: primary mire formation (formation of mires directly on mineral soil with no previous vegetation), terrestrialization (lake infilling) or paludification (forest 'swampification'). Large mire complexes in the boreal biome may comprise parts that initiated through primary mire formation or terrestrialization, but which over time has merged through lateral expansion and paludification of areas interlaying the original mires (Piilo et al. 2020).

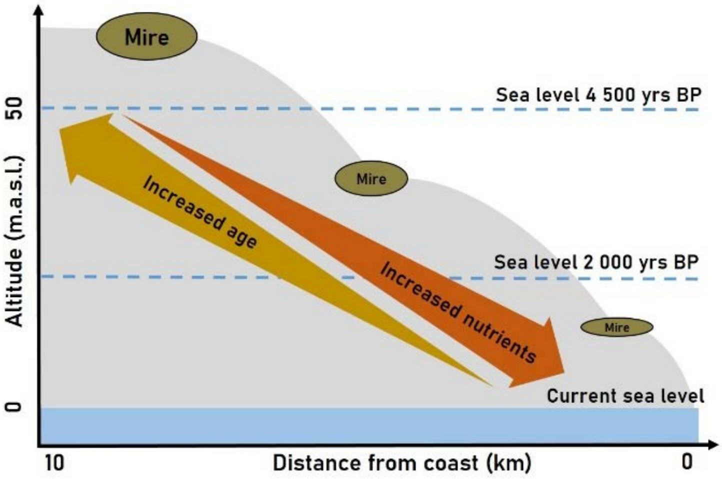

***Figure 1-3.*** *A schematic overview of the land uplift-based mire chronosequence approach applied in the Sävar Rising Coastline Mire Chronosequence in the county of Westrobothnia in the boreal part of Sweden. Mires located closer to the present coastline are typically younger and smaller in size, compared to those further inland at higher altitudes. Mires in younger parts of the chronosequence tend to be richer in nutrients due to shallower peat depths, and hence, shorter vertical distance to underlying mineral soil. In older parts of the chronosequence the peat column is deeper, and, hence, the mire surface is more disconnected from the underlying mineral soil. In younger parts of the chronosequence, more un-weathered upland catchment areas with mineral nutrients still remaining in them are present. In: Ehnvall, 2023 (doctoral thesis).*

The land uplift-based mire chronosequence approach assumes that mires in coastal areas initiated soon after land exposure from the sea (e.g. Tuittila et al. 2013). Consequently, mire ages cannot exceed the maximum age of the mineral soil surface, but mire age can in some cases be overestimated if mire initiation lags land availability. Examples of mire chronosequences that have frequently been used for various research purposes include the Sävar Rising Coastline Mire Chronosequence (SMC), which is used in this study, as well as the Nyby chronosequence (Laitinen et al. 2016) along the shores of the Bothnian Bay Lowlands (BBL) in northern Sweden and Finland, the mire chronosequences in the James and Hudson Bay Lowlands in Canada (Martini and Glooschenko, 1985), and chronosequences in the White sea area in Russia (Kutenkov et al. 2018).

Apart from describing ecosystem succession, land uplift-based chronosequence models can also describe the aging of mineral soils. Once mineral soil is exposed from the sea, it becomes susceptible to weathering. Easily weatherable minerals, such as phosphorus-releasing apatite, may disappear from the soil surface within just five hundred years (Giesler, 2010), while it takes up to 2 000 years for potassium- and calcium-releasing biotite and hornblende to be completely removed from the topsoil (Hoffland et al. 2002). As a result of such weathering gradients, and depending on a mire's position along the chronosequence and the mire surrounding areas (rock outcrops vs soils), the mire receives different amounts of mineral nutrients from corresponding upland catchment areas (Ehnvall et al. 2023b, Starr and Lindroos, 2006). The decrease in mineral nutrient transport to mires in older parts of the landscape may cause an oligotrophication (nutrient depletion) of the mire surface. Oligotrophication is likely to happen in the high-latitude boreal landscape, while "ombrotrophication" (i.e. the transition from minerogenic to ombrogenic conditions) rarely happens there due to unfavourable conditions for the establishment of true ombrogenic conditions. In contrast, in the boreonemoral zone, "ombrotrophication" is likely to happen (e.g. Sohlenius et al. 2013).

## 1.4 Knowledge gaps and report objectives

The theoretical understanding of how mires and their upslope catchment areas interact were early conceptualized for northern landscapes (e.g. Heinselman, 1970; Ivanov, 1981). Recent field and remote-sensing based studies have explored how the upslope catchment area and processes taking place by the mire margins (e.g. Sallinen et al. 2019) influence various mire properties, such as peat succession (Sallinen et al. 2023), lateral expansion (Ehnvall et al. 2023a) and mire productivity rates (Ehnvall et al. 2023b). The objectives of this literature review are 1) to review recent findings on mire-catchment interactions, 2) to discuss how the catchment area, through its support of water and elements to minerogenic mires, may affect the transport and accumulation of hazardous elements in the peat, and finally 3) to discuss how the catchment area affects the increase in peat depth over time, and hence, the build-up of biogeochemical archives through peat accumulation. Despite clear differences in climate settings between boreal and boreonemoral parts of Sweden, the effects of climate on mire development have been poorly studied in the past. The final objective of this literature review is 4) to cover differences in mire-catchment interactions between mires in the boreal and boreonemoral biomes.

# 2 Materials and Methods

## 2.1 Study approach

This literature review is focused on two geographical areas: the Sävar Rising Coastline Mire Chronosequence (SMC; Figure 2-1a) in the county of Westrobothnia in northern Sweden, representing the boreal biome, and the Forsmark area (FM; Figure 2-1d) in the county of Uppland in central Sweden, representing the boreonemoral biome. The results from the SMC are largely based on the doctoral thesis by Ehnvall (2023), and papers covered in the thesis. Results from the FM are based on various published reports from the Swedish Nuclear Fuel and Waste Management Company (SKB) and the Geological Survey of Sweden (SGU) based on coastal mires in the FM area.

The studied mires in FM are minerogenic with distinct upslope catchment areas, and they are, hence, comparable to the SMC mires, which are all minerogenic. The analyses focus primarily on the minerogenic stage of mires in the wider FM area, representing the period when the catchment area has the greatest influence for mire development, and the potential for transport of hazardous elements to the mire with discharging groundwater is the greatest. As many mires in the FM area are likely to undergo 'ombrotrophication', they will eventually lose most of their groundwater contact with the surrounding landscape, and groundwater discharge to the surface will be limited to marginal fens surrounding the bog plane. If pure ombrogenic conditions develop, advective transport of groundwater contaminants to surface peat will be limited, but contaminants may accumulate in deeper layers, including deeper layers of fen peat. As the mire surface rises, so does the groundwater table, and discharge to such areas is expected to eventually level off (Clymo, 1984). However, contaminants that have accumulated under minerogenic conditions may still be stored in underlying deposits, including layers of buried fen peat.

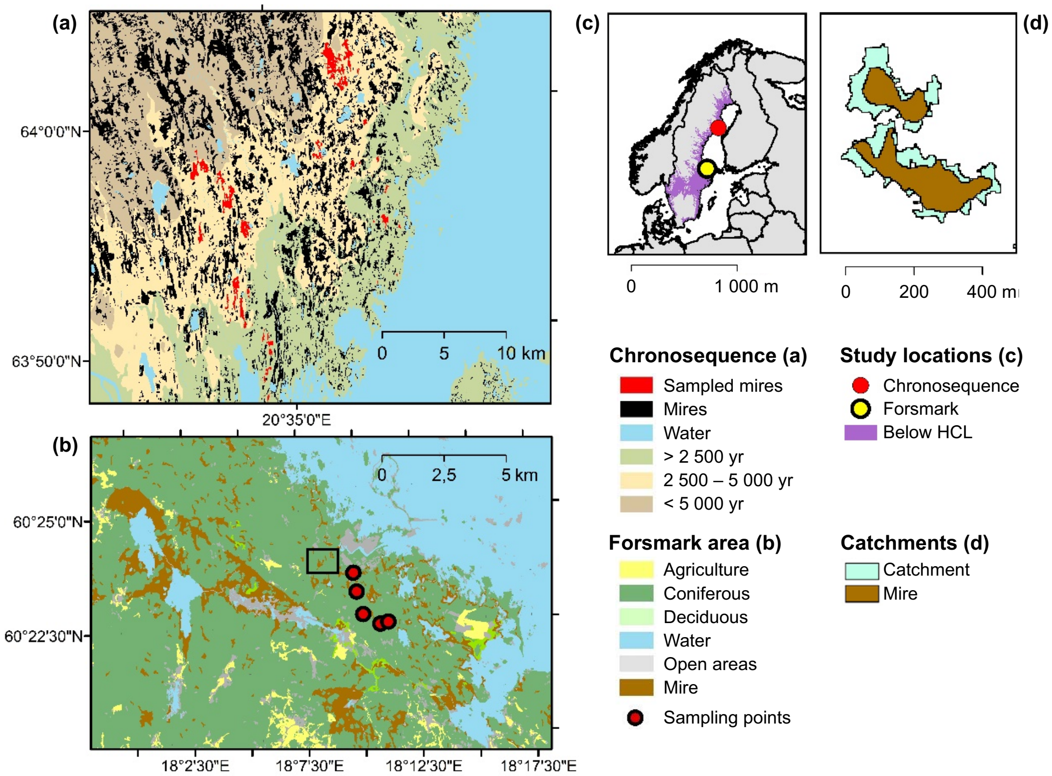

***Figure 2-1.*** *Sävar Rising Coastline Mire Chronosequence (SMC) (a) in the county of Westrobothnia, northern Sweden (b), examples of catchment areas (c), and the Forsmark area in the county of Uppland, central Sweden (d). SMC and FM are both located in post-glacial landscapes below the highest coastline marked in purple in (b). The high isostatic rebound rate (ca 9 mm yr*$^{-1}$*) in the SMC is a pronounced landscape characteristic, creating an age-gradient from the present coastline to the highest coastline. Also FM is shaped by isostatic rebound, although at a lower rate (6 mm yr*$^{-1}$*) compared to the SMC. Examples of upslope catchment areas of two mires in FM (c) in the area marked with a rectangle in panel (d).*

## 2.2 Study sites

The SMC covers an age gradient of 0–9 000 years, with 3 473 individual mire objects according to the aerial photo-based mire map in the Swedish property map produced by the Swedish Mapping, Cadastral and Land Registration Authority. A detailed description of the SMC is provided by Ehnvall et al. (2023b), and general site descriptors related to climate and geology are shown in Table 2-1. Landscape and vegetation photos from all field visited mires in the SMC can be viewed in the interactive mire map: https://slughg.github.io/MiresChrono/. Several digital elevation models (DEM) have been produced for the FM area, covering a land surface age range of 0–5 000 years (Petrone & Strömgren, 2020). For this work the 5 × 5 m DEM was selected, as it was considered to have a sufficient resolution to allow contrasting features of mires and catchments between the two study areas. When comparing mire processes in the FM area to the ones reported for SMC at the landscape level, we refer to all mire objects as defined by the Swedish Property Map, that are covered by the DEM. These are in total 671 mires and a total area of 310 km$^2$. It can be noted that the undisturbed landscape would have had more wetlands, as ditching for forestry and agricultural purposes has been practiced in the area. Photos from some of the field visited mires in the FM area are shown in Sheppard el al. (2011). For comparability between the areas, the SMC was also in this report restricted to land surfaces of 0–5 000 years of age, which covers in total 1 746 mires and a total area of 550 km$^2$.

**Table 2-1. Comparison between mires in the Sävar Rising Coastline Mire Chronosequence (SMC) and the Forsmark area (FM) in terms of climate and geology.**

| Descriptor | SMC | FM |
|---|---|---|
| Mire cover | Ca 25 % | Ca 10.8 % (5.9 % in forest, 4.9 % open) |
| Landscape slope (%) | Ca 6 % | Ca 3 % |
| Elevation | 0–60 m.a.s.l. | 0–34 m.a.s.l. |
| Isostatic rebound rate | Ca 9 mm yr$^{-1}$ | Ca 6 mm yr$^{-1}$ |
| $T_A$[1] | 3.5 (°C) | 6.1 (°C) |
| $T_{July}$ | 17.7 (°C) | 16.3 (°C) |
| $T_{Jan}$ | −6.8 (°C) | −2.0 (°C) |
| $P_A$ | 654 (mm) | 612 (mm) |
| $P_{July}$[1] | 79 (mm) | 71 (mm) |
| $P_{Jan}$ | 48 (mm) | 45 (mm) |
| Bedrock | paragneiss (quartz, feldspar and mica), with felsic (granodiorite, granite) and mafic (basaltic andesite, gabbrodiorite) rock intrusions | granite (to granodiorite) and pegmatitic granite, pegmatite, with intriusions of granodiorite to tonalite, amphibolite and other mafic rocks, and, felsic to intermediate volcanic rock |
| Quaternary deposits[2] | wave-exposed till covered ridges interlaid by valleys of finer minerogenic deposits (mainly of postglacial silt, clay and sand), Lacustrine and glacio-lacustrine sediments found along river Sävar | dominated by calcite-rich till and glacial clay, with variable occurrence of postglacial clay, sand and gravel, as well as glaciofluvial sediments |
| Land use[3] | lake 2.7 %, upland areas (mainly forest) 75 %, arable land 3.6 %, open areas 18.7 % (including some mires) | lake 2.6 %, forest 80.7 %, open areas 9.3 % (including some mires), arable land 7.4 % |

[1] Climate data from FM from the period 1986–2005 from SKB, 2023c.

[2] Bedrock and quaternary deposits data for SMC from the Geological survey of Sweden, and for FM from Hedenström & Sohlenius, 2008.

[3] Land use data for SMC from The Swedish Mapping, Cadastral and Land Registration Authority, and data for FM from Löfgren, 2010.

The main differences in environmental conditions between the SMC and the FM areas are the milder climate (Table 2-1), especially during winter and shoulder seasons (spring and autumn) and drier summer, as well as the more calcite in till and clay sediments in the upslope catchment areas in the FM (Hall et al. 2019), which at the national Swedish level creates unique conditions of shallow lakes with calcite rich sediments (Hederström & Sohlenius, 2008; Table 2-1). This is further reflected in the mire vegetation, as FM mires, at the mire population level, have higher proportions of *Bryales* mosses and other brown mosses compared to the SMC mires.

## 2.3 Isostatic rebound rates of the study areas

In both study areas, isostatic rebound has exposed new areas suitable for mire initiation and development from the sea since the deglaciation of the Scandinavian Ice Sheet around 8 000 BC (Nordman et al. 2020) in the SMC area and around 8 500–9 000 years BC in the FM area (Persson, 1992). The two major differences between the SMC and FM sites are the rates at which the land is exposed from the sea (Figure 2-2), and the landscape slope, which together will determine how large land areas are exposed with a specific isostatic rebound rate under a specific period of time. The SMC area is located close to the centre of the rebound maximum of the Scandinavian ice sheet, with a landscape slope is around 6 %. In contrast to SMC, the present rebound rate in the FM area is around 6 mm $yr^{-1}$ (Hedenström & Sohlenius)[1]. The landscape slope in FM is around 3 %. Taken together, this results in similar age-gradient with distance from the sea in the FM area compared to the SMC area.

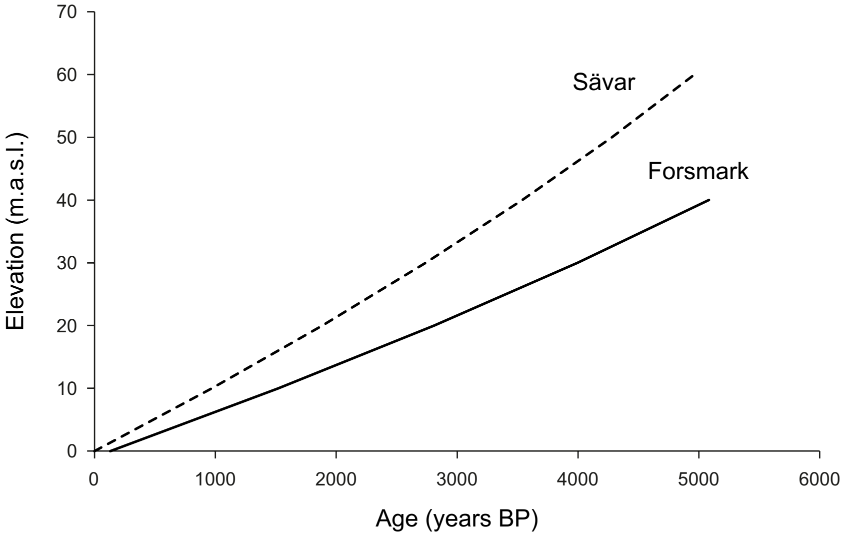

***Figure 2-2.*** *Isostatic rebound curves in the Sävar Rising Coastline Mire Chronosequence (dotted line) and the Forsmark area (solid line).*

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[1] The rate of isostatic rebound is also compensated by a sea-level rise of about 2.6 mm $yr^{-1}$, resulting in a present decrease of the relative sea-level, of about 4.1 mm $yr^{-1}$ in FM (SKB, 2023a).

## 2.4 Catchment areas and descriptors

A wide range of catchment characteristics covering topographically based indices, as well as coverages of different land use, soil and bedrock classes have been extracted for each mire object in the SMC, as described by Ehnvall et al. (2023b) and Ehnvall et al. (2024). Catchment delineation in the SMC was based on a 2 × 2 m DEM produced by the Swedish Mapping, Cadastral and Land Registration Authority. To enable a comparison between upslope catchment areas in the SMC and FM areas, we extracted simple catchment properties also for the FM mires. Catchment delineation in the FM area was performed in ArcGIS pro using the FM-specific DEM (5 × 5 m; Petrone & Strömgren, 2020). Based on the extent of the catchment areas and the mire polygons, we extracted the catchment-to-mire area ratios, as well as the catchment slopes (%), which are two basic properties controlling the inflow of water to minerogenic mires.

## 2.5 Peat chemical properties

Reported surface peat concentrations ($\mu g\ kg^{-1}$) of barium (Ba), calcium (Ca), chromium (Cr), cesium (Cs), iodine (I), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se), thorium (Th), and uranium (U) were used as indicators of the chemical status of the peat in mires in both areas, and for detecting any possible natural or human-caused contaminations of the peat. In the SMC, peat samples represent a 10 cm column just below the living vegetation. Samples were collected from edges (10 m from the mire edge) and the centre for the mire at 40 mires covering a 0–5 000 year land-surface age-range (N=80). The sampling was carried out in July and August 2018. Peat samples from five FM sites were collected from 20–25 cm depth in August 2010. The FM sites represent different mire types dominated by *Sphagnum*, sedges or reed, and with variable tree cover. Detailed descriptions of the sampling and sample preparation are provided by Ehnvall et al. (2023b) for the SMC and Sheppard et al. (2011) for FM.

# 3 Results and discussion

The role of the upslope catchment area is crucial for the overall ecosystem functioning of minerogenic mires. In the coming discussion, results from previous studies of mire-catchment interactions from the boreal SMC will be compared and discussed to the boreonemoral FM area with a warmer climate and more calcite rich till and clay sediments FM. The discussion covers differences in mire initiation and lateral peat expansion rates (3.1), catchment hydrological settings in the two areas (3.2), catchment controls on surface peat elemental concentrations (3.3), and finally, catchment controls of the vertical accumulation of peat (3.4).

## 3.1 Mire initiation, succession and peat lateral expansion rates in the boreal SMC and boreonemoral FM areas

The chronosequence approach applied in the SMC area (Ehnvall, 2023) assumes that mire initiation is dominated by primary mire formation on land areas exposed from the sea. Although no bottom sediment samples have been collected and analysed based on the wider mire population, mire initiation in the youngest part (< 2 000 years) of the SMC is understood to be dominated by primary mire formation (e.g. Ehnvall et al. 2023a), while the older parts (> 5 000 years) of the chronosequnce likely comprise a mixture of laterally expanded mire complexes and smaller mires formed through paludification and terrestrialization. This assumption is based on studies from the Finnish Bothnian Bay coast in the county of Ostrobothnia (Huikari, 1956), which is similar to the SMC in terms of climate and uplift rate.

The slower land uplift in the FM area (ca 6 mm yr$^{-1}$; Hedenströn & Sohlenius, 2008; SKB, 2023b) compared to the SMC area (9 mm yr$^{-1}$; Nordman et al. 2020), and the small topographic variations should create suitable conditions for extensive primary mire formation also in the FM area, since recently uplifted coastal areas, at least in theory, would stay wetter, and thus, create conditions more favourable for the establishment of peat-forming plants over a longer period of time, before the land surfaces are elevated further above the sea level. In practice, however, the milder climate of the FM area compared to the SMC may cause a more pronounced drop in the groundwater table across peat and non-peat covered parts of the landscape during dry periods. Under current climatic conditions, this drop in the groundwater level (and possible drought conditions resulting from it) often occurs earlier during the vegetation period in the FM area compared to the SMC area, and it will disfavour peat accumulation. This is because the decomposition of fresh plant litter, but also oxidation of already accumulated, exposed peat may be enhanced. Primary mire formation requires a continuous oversaturation of the upper soil horizon to be able to proceed (Ivanov, 1981; Kulczynski, 1949; Malmström, 1923; Rydin et al. 2013), and might, hence, have been disfavoured in the FM. In general, peat-forming wetlands (mires) are found above 5 meter above sea level in the FM, which seems to mark the uplift time (ca 800 years) required for establishing peat-accumulating ecosystems in the area. Areas below this elevation also comprise peat-forming mires, but, there, a thicker peat layer has not yet formed. The youngest parts on the FM are instead dominated by mineral-wetlands with gyttja and/or clay (SKB, 2008). This was also described by Schoning (2014), who suggested that peat formation was delayed by up to around 300 years in the FM area.

Terrestrialization, in general terms, relies less on water inputs from the surrounding landscape compared to primary mire formation. This is because the underlying water lens, that corresponds to the former lake threshold, will keep the mire surface wet also during periods when less water is transported from the upslope catchment area to the mire. Mire initiation through terrestrialization can, hence, proceed during drier periods when primary mire formation and paludification are restricted (Ruppel et al. 2013). Terrestrialization of lakes isolated from the Baltic sea is estimated to account for around half of all mire initiation in the wider region surrounding the FM area, and primary mire formation the other half (Sohlenius et al. 2013). How well these numbers apply to the specific FM area studied in the present report is not known. It has also been estimated that up to 10 % of the young mires in the FM area initiated through paludification several thousands of years after land exposure from the sea (Sohlenius et al. 2013). Mires in the FM area that initiated through paludification often have an initial alder or birch fen stage (Franzén et al. 2012), while terrestrialization is typically characterized by vegetation dominated by *Carex* and *Sphagnum*, or *Carex* and *Bryales* (Löfgren, 2010), and also in some, often young, cases by the ingrowth of *Phragmites* (e.g. Bergström, 2001). Peat stratigraphies have revealed a highly variable plant composition over time, suggesting a heterogeneous mosaic of plant communities during different stages of a mire's development history in the FM area (Fredriksson, 2004, Figures 5-1 and 5-2).

The mire initiation pathway may matter for the surface plants' exposure to groundwater-based contaminants depending on the regolith type. At the early lake stages of terrestrialization, these contaminants can be discharged to the lake through the entire lake bottom, but as more organic sediments are accumulated at the bottom of the basin, the sediments become more impermeable to groundwater upwelling and contaminants may accumulate in the bottom sediments rather than transported to the surface vegetation (Brydsten, 2004). Many lakes in FM have, though, an impermeable layer of clay, which restricts contaminants from reaching the water column. However, in mires that initiate through terrestrialization, peat can simultaneously accumulate by the surface and the bottom of the lake basin (Rydin et al. 2013). If an open water lens is preserved under a relatively shallow floating mat of surface peat, the transport or diffusion of hazardous elements to the living surface vegetation in larger parts of the mires may potentially be enhanced, compared to completely peat filled basins in old successional stages of terrestrialized lakes, or in mires that initiated through either of the other two pathways (primary mire formation or paludification). The internal transport of elements across the mire surface depends largely on the porosity of the peat, which is closely linked, for example, to the degree of decomposition (Minkkinen & Laine, 1998).

When the margins between mires and their surrounding upland forests are wet, vegetation typical of both ecosystems may compete for the same locales (Ruppel et al. 2013; van der Velde et al. 2021). In the SMC, like in the wider Bothnian Bay region, mire lateral expansion to the most suitable locations is generally rapid. Within less than 2 000 years after land exposure the most suitable land surfaces are occupied by mire ecosystems (Ehnvall et al. 2023a). The FM landscape is flatter compared to the SMC landscape (Table 2-1), and should topographically offer conditions similar or even more favourable for lateral expansion of peat compared to the SMC, since the physical constraints to lateral expansion, such as local ridges, are lower (Ehnvall et al. 2024). Yet, under present climatic conditions and based on the youngest 0–5 000 year old landscape, lateral expansion of peat seems to be somewhat restricted in the FM area, since no larger mire complexes (unless drained and converted for other land use purposes) appear in corresponding areas where mire complexes have developed in the SMC area (Schoning, 2015). It is important to note that large mire complexes do occur in more inland parts of the county of Uppland. Based on visual map inspection (Figure 2-1), large mires in the studied FM area seem to mainly form along lakes that are in the process of terrestrialization, rather than forming through lateral expansion of smaller mires originally initiated through primary mire formation. This is may be an effect of the overall landscape hydrology and soil wetness (Ehnvall et al. 2023a), which does not favour extensive lateral expansion of peat to upland mineral soils in the FM area. However, similar to the timing of lateral expansion in the SMC, mires in the FM area reach highest carbon accumulation rates after 700–1 500 years (Schoning, 2014), which suggests that the timing of the development of peat-forming mire ecosystems seems to be somewhat similar in the two areas.

Under favorable climatic conditions, mire expansion can be episodic and temporarily very fast, with lateral expansion rates in flat terrain of up to 3–8 m $yr^{-1}$ (Loisel et al. 2013; Mäukiläu, 1997; Peregon et al. 2009; Pluchon et al. 2014), or lake in-growth rates of 3.9 m $yr^{-1}$, as reported from Northern Sweden (Sannel and Kuhry, 2011). Data from the Swedish national peat archive indicate that some mires indeed initiated in the FM area several thousands of years after the sites were uplifted (Sohlenius et al. 2013). With changed, and more unpredictable climatic conditions in the future (IPCC, 2023), primary mire formation and mire lateral expansion in the FM area could temporarily be enhanced. Estimations suggest that large parts of the FM landscape could become covered by peat under a wetter future climate (Franzén et al. 2012), and large areas that are not currently covered by mires are indeed wet (Mayotte & Strömgren, 2023), and possibly suitable for future mire lateral expansion. Such lateral expansion is facilitated by low-permeable glacial and subglacial clay soils, which underlay many areas in the FM.

## 3.2 Differences in mire catchment support between the Sävar Rising Coastline Mire Chronosequence and Forsmark

The upslope catchment area is crucial for the initiation and preservation of minerogenic mires (Ivanov, 1981). The areas of mires below 5 000 years of age in the SMC and FM areas are similar in size, but mires in the SMC have considerably larger catchments areas compared to mires in the FM, generating higher catchment-to-mire area ratios in the SMC (Figure 3-1). This indicates that mires in the SMC are supported hydrologically by larger areas compared to mires in the FM area. Hence, elements (including hazardous substances) in the upslope catchment area are likely transported to the FM mires from a smaller catchment area. Importantly, however, the individual mires with their unique catchment areas are often part of larger drainage basins within which contaminants may be spread. On the other hand, a smaller catchment support might imply that contaminants originating from groundwater upwelling (Berglund et al. 2013), or from the catchment area, become less diluted by water and stable isotopes[2] in the FM if the mires receive smaller amounts of water and solutes from the catchment area compared to mires in the SMC. This indicates that mires in the SMC, in general, are under stronger influence from the catchment area compared to minerogenic mires in the FM area, which can eventually develop to ombrogenic mires.

Aside from the smaller catchment-to-mire area ratios in the FM, which indicate a lower nutrient transport to the mires (Ehnvall et al. 2023b), catchment slopes are lower in the FM area (Figure 3-1). This can be a contributing factor to ombrotrophication of mires in the FM area, since mires in the FM can potentially accumulate peat above the low-sloping mire margins, rise the water table above that of the surrounding mineral soil, and develop ombrogenic conditions. Although most of the present mires in the coastal-most part of the FM area are still minerogenic, open and dominated by *Carex*, or in addition also covered by birch and alder, and only a limited number of mires have lost their hydrological catchment support and reached ombrotrophic stages (Sohlenius et al. 2013), the FM mires do in general tend to develop towards more nutrient poor conditions. In this context, it is important to remember that the coastal landscapes in Westrobothnia and Uppland have different basic hydrological presumptions, and that hydrologically, strict ombrogenic conditions do not develop in Westrobothnia due to unfavourable present climatic conditions. This means that while a mire in the SMC over time undergoes nutrient-depletion though oligotrophication caused by the reduced inflow of nutrient in older parts of the chronosequence, where mineral soils have already released much of the easily-weatherable nutrients, it will (unlike mires in FM that undergo ombrotrophication) still receive water from the catchment area. This implies that the catchment area may also bring more recent contaminants to the mires, which do not originate from mineral weathering from the catchment area to the downslope-located mire (e.g. Bergknut et al. 2010). Despite the general trend in the FM towards more ombrogenic conditions, local factors will still control mire succession in the FM area, and it is likely that not all mires will eventually reach ombrotrophic stages (Sohlenius et al. 2013). Importantly, ombrogenic mires are often surrounded by a minerogenic part (´lagg´), which can likely receive contaminants from surrounding catchment areas.

At the landscape level, the proximity between mires and their catchment areas may influence the fluxes of water and elements between mires. In the SMC, mires are located close to each other, and catchment areas often overlap, making the mires to some degree ‘hierarchical’ in relation to each other, with upslope located mires likely influencing the flow of water and elements to downslope located mires (Lane et al. 2018). The lower absolute mire cover in the FM area, as well as the longer distance between mires compared to the SMC area makes the FM mires more isolated from each other, and the deficient hydrologic connectivity between mires probably makes catchment responses rather local. This could restrict the spread of contaminants, as they are likely to stay adsorbed to the peat in the mires.

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[2] A radioisotope is considered to be diluted with the corresponding stable isotope, as the uptake into plants of radioisotopes that have a natural analogue in abundance is approximately proportional to the ratio of the two isotopes in the environment, i.e. to the specific activity of the radioisotope (IAEA, 2010).

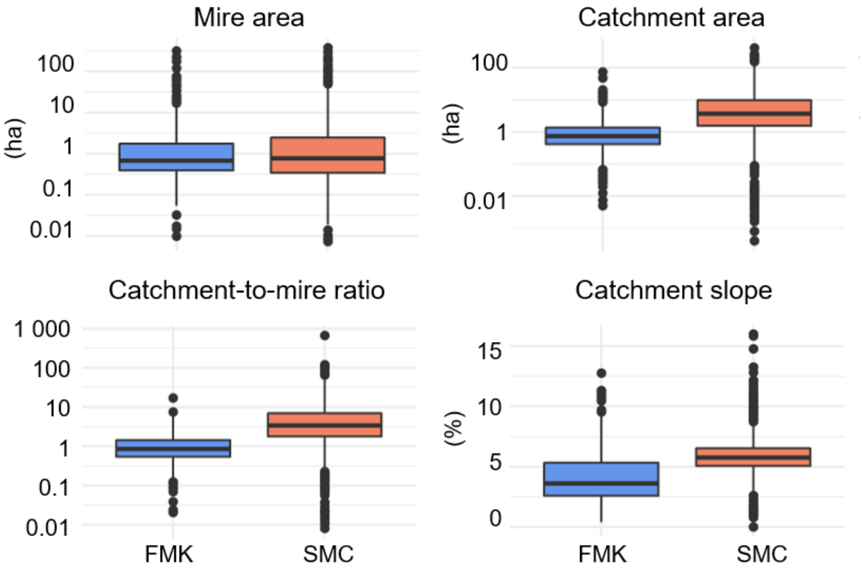

***Figure 3-1.*** *Comparison between catchment properties in the Forsmark area (FM shown in blue) and the Sävar rising coastline mire chronosequece (SMC shown in red). Whiskers correspond to 1.5 × (Q75–Q25).*

## 3.3 Catchment controls on surface peat elemental concentrations

In the SMC, the inflow of nutrients from the upslope catchment area is clearly influencing the productivity of the mire vegetation at the site (Ehnvall et al. 2023b). The positive co-variation between peat elemental concentrations and plant productivity described using the satellite-based Normalized Difference Vegetation Index was particularly strong considering phosphorus and potassium concentrations (Ehnvall et al. 2023b). This demonstrates that not only are catchment areas important for the pure fluxes of elements between landscape parts, but they also influence the actual ecosystem functioning through vegetation productivity, and hence, the possibilities for peat accumulation in the mire recipients. It is, however, often the decomposition rate, rather than plant productivity rate, that determines the final peat accumulation rate (Clymo et al. 1998). Hence, the results by Ehnvall et al. (2023b) should not be over-interpreted as a direct catchment effect on peat accumulation rates, but they should be understood as a catchment effects on plant productivity rates.

The mire plant productivity response to the catchment nutrient support in the SMC was further accentuated based on the horizontal (distance-to-edge) and vertical distance (peat-depth) to mineral soil, which were longer in mires with lower productivity. In other words, when the distance to mineral soil is longer, less nutrients reach the mire surface, and the mires tend to have a lower plant productivity rate (Ehnvall et al. 2023b). The distance to mineral soil, both vertical and horizontal, is largely a reflection of time and the lateral and/or vertical expansion of peat, which may eventually disconnect parts of mires from mineral soils. Depending on the initiation type and location where mires develop, the shape of the basin that the mire was formed in (especially considering mires formed from terrestrialized lakes) is of great importance for a mire's possibility to build up a deep peat layer. The topography underlying the peat, or the bathymetry, has been studied both in the SMC and FM area using single mires (e.g. Ehnvall, 2023; Sternbäck et al. 2006). Overall, in the SMC, a longer horizontal distance across the mire surface is indicative of a deeper mire basin (Figure 16 in Ehnvall, 2023), although the variation in peat depth is highly variable, and mires that have initiated and expanded through paludification may have much shallower peat layers. Similarly, shallower peat layers in mires formed through paludification compared to primary mire formation or terrestrialization have also been reported from the FM area (Sohlenius et al. 2013). Many present ponds and lakes in the FM area are shallow (< 1 m), and will relatively quickly develop to mires (Brydsten 2004), but their peat depth increment may be somewhat restricted by the original, shallow basin they develop in (Sternbäck et al. 2006). It is possible that some of these small and shallow mires may be converted to forests if a tree cover establishes there.

Apart from the catchment area as such, other catchment properties have also been found to co-vary with elemental concentrations in the peat of downslope located mires. In the SMC, among a wide range of properties covering topography, land use, soil and bedrock (Ehnvall et al. 2023b), it was found that catchment slope and soil wetness (based on hydrological modelling) were the most important variables driving mire productivity, at least during parts of the vegetation period. During several months of the vegetation period a high plant productivity (NDVI) co-varied with higher catchment slope. This is likely because catchment areas with low slopes ($< 5$ % slope) prevent water and nutrients from reaching downslope-located mires (Autio et al. 2020; Kortelainen et al. 2006), but instead trap nutrients higher up in the flat catchment areas. However, steep catchment ($> 5$ % slope) can result in more nutrient-poor minerogenic water reaching the mire due to shorter contact time between the soil water and mineral soil (Maher, 2010), or reflect a higher proportion of rock outcrops that contribute with very little nutrients. A medium steep catchment slope should, hence, result in the highest nutrient fluxes to a minerogenic mire. In addition, when only the transport of water is considered, a steep catchment slope should be most favorable for dilution of elements in surface peat of the downstream located recipient, since surface runoff often increases with slope (Everett and Dutt, 1985; Naslas et al. 1984). It is important to note, that the catchment responses in the SMC describe a landscape dominated by forests. While forests in SMC are heavily drained, and far from pristine, they still represent landscapes that are hydrologically and biogeochemically less disturbed by human compared to areas dominated by agriculture. In agricultural areas with extensive ditching, catchment responses may be weaker. In the FM area, low transport of allochtonous sediments from the catchment area to lakes has been reported (Brydsten, 2004). This has been explained by the low topographic variation (i.e. low slopes) in the area and few sources of allochtonous material in the landscape, which is largely dominated by wave-washed till or wetlands, together accounting for 70–90 % of the area. These factors (slope and sediments), however, might restrict sediment transport, but should still allow water with dissolved nutrients to be transported from the upslope catchment area to the mire.

Apart from contributing with plant nutrients, catchment areas may also bring hazardous substances to their recipients, such as atmospherically deposited pollutants (Bergknut et al. 2010). Based on the observed catchment support of mire plant nutrients, and their nourishment of the mire vegetation, it is likely that also more toxic elements will reach the mire surface from the catchment area, influence the mire vegetation, and eventually be accumulated in the peat. For hazardous substances with similar mobility as the plant nutrients discussed above, similar catchment properties will likely be important for the transport of the elements to the mires, i.e. the catchment-to-mire area ratio, as well as the catchment slope and wetness (Ehnvall et al. 2023b). The main difference between the catchment transport of plant nutrients and hazardous elements is, however, that hazardous substances might not be taken up by plants through preferential pathways in the catchment area, but instead to a greater extent reach the downslope located mire surface.

The elemental concentrations of the peat in SMC and FM are, for most of the hazardous elements of interest in this report, similar (Figure 3-2). In FM, the surface peat concentration of U and Mo were higher compared to SMC, while concentrations of Cs were lower (p-values $< 10^{-5}$). Concentrations of Ca were also higher in the FM ($p < 10^{-10}$), which reflects the influence of calcium carbonate ($CaCO_3$) rich till and clay sediments in the FM, and illustrates an important difference in the quaternary geology between the SMC and FM areas. At the same time, the higher Ca concentrations in the FM constitutes a clear catchment signal, which confirms that mire surfaces in the FM are still influenced by water flows from the upslope catchment areas. Over time, as the easily weatherable calcite will be depleted from the soil, the weathering of silicate minerals will continue (SKB, 2023b). Given the overall similarities in peat elemental concentrations, the two areas should be comparable considering their biogeochemistry, although catchment characteristics (Figure 3-1) and soils (Table 2-1) differ somewhat between the sites. This suggests that the bedrock (paragneiss in SMC and granite/pergmatite in FM) is of less importance for the transport of elements to mires compared to soil properties, although in some cases (e.g. for till) the soil chemistry is tightly linked to bedrock properties. The predominant importance of soil characteristics for nutrient transport to mire is in line with results from the SMC, which have indicated that bedrock properties are poorly reflected in the plant productivity (Ehnvall et al. 2023b).

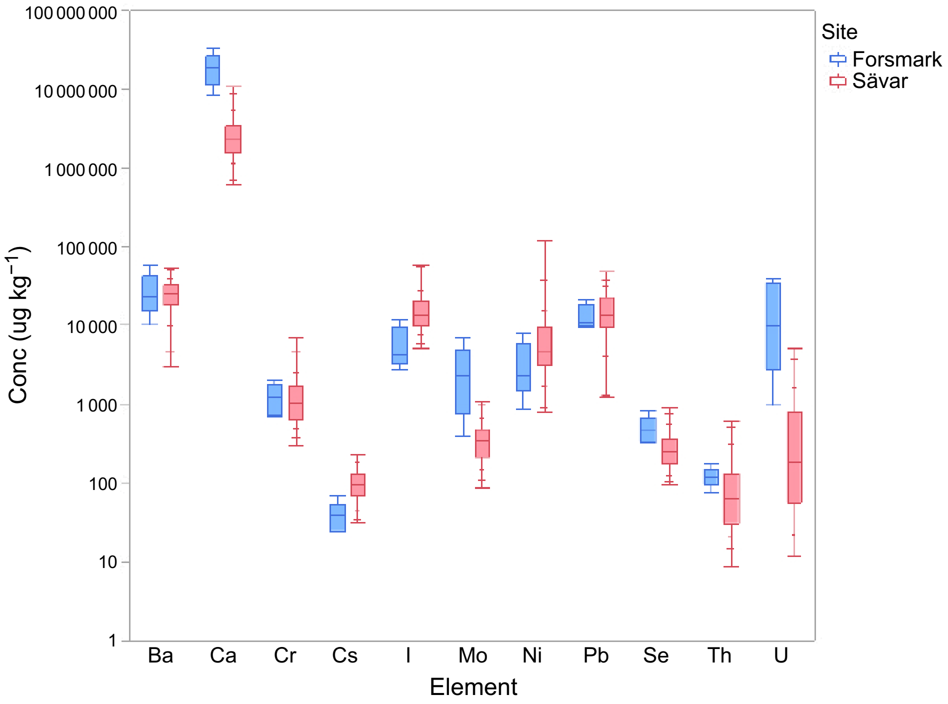

***Figure 3-2.** Comparison between elemental concentrations across the five Forsmark sites (blue boxes where each of the lines correspond to one of the five sampled mires) and the 40 Sävar chronosequence mires (red boxes). For the Sävar data a box corresponds to the 75th, the 50th and the 25th percentiles, the upper and lower whiskers represent the maximum and minimum values, with the 97.5th, 90th, 10th, 2,5th percentiles added in between.*

## 3.4 Catchment controls on the vertical accumulation of peat

In both, the SMC and FM area, peat depth increased rather quickly within the first thousands of years. For the FM area Sohlenius et al. (2013) reported a rate of 0.5–1.3 mm yr$^{-1}$, while Schoning (2014) suggested a considerably higher initial rate(up to 5 mm yr$^{-1}$) , which is more similar to the rate reported for the SMC (Ehnvall, 2023). After the initial increase, the peat depth increment slowed down in older mires to around 0.5 mm yr$^{-1}$ in the FM according to Sohlenius et al. (2013) or around 1 mm yr$^{-1}$ according to Schoning (2014). The latter rate is the same suggested for the SMC (Ehnvall, 2023). The difference in peat accumulation rates reported by Sohlenius et al. (2013) and Schoning (2014) likely reflect the selection of mire object, where Schoning et al. (2014) focused on small mires with distinct basins surrounded by higher upland areas, while in contrast, the peatlands studied by Sohlenius et al. (2013) cover a large variation in mire areas and ages. The changes in peat depths over time generated convex peat depth curves (Figure 3-3). The higher peat depth increment in younger mires is likely due to the formation of loose and poorly compacted peat in the young successional stages, and does not necessarily reflect a higher peat or carbon accumulation rate (Schoning, 2014). Over time, peat becomes more compacted, but it also generally forms at a slower rate compared to the younger successional stages, which together explain the leveling out of the peat depth curve over time. Peat depth increases in general at a higher rate in the SMC compared to the mires in the FM area studied by Schoning (2014), both in the young and old parts of the landscape. In the FM, *Sphagnum* dominated peat has been found to accumulate at an average rate of ca 1.0 mm yr$^{-1}$, while sedge-dominated peat accumulates at a slightly slower average rate (0.89 mm yr$^{-1}$; Schoning, 2014) because of the higher resistance towards decay in *Sphagnum* mosses compared to other peat-forming plants. However, during the first 500 years, the vertical accumulation rates of peat in the FM area is similar in *Sphagnum* and sedge dominated mires (Schoning, 2014).

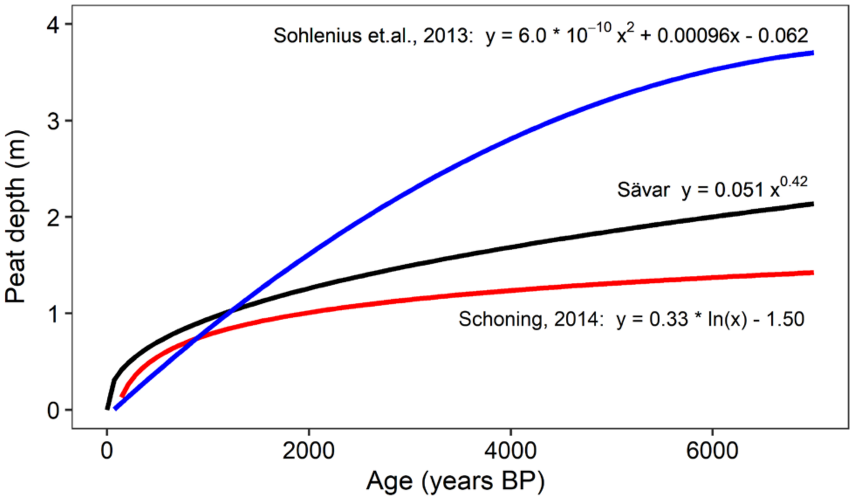

***Figure 3-3.*** *Peat depth across mires of different ages in the Sävar Rising Coastline Mire Chronosequence (black line; originally in Ehnvall, 2023) and the Forsmark area (red line represents fens only: originally in Schoning, 2014; blue line represents fens and bogs: Sohlenius et al. 2013).*

The higher accumulation rates in the SMC compared to the FM mires reported by Schoning (2014) is consistent with global estimates of carbon accumulation rates, which predict highest rates in areas with low evapotranspiration (Yu et al. 2009), such as in many parts of the boreal zone compared (SMC) to the boreonemoral zone (FM).

Vertical and lateral peat accumulation rates in individual mires are naturally linked to each other, but differences in their rates depend strongly on the compaction of the peat, and the slope of the surrounding terrain, which may restrict lateral expansion of peat even if the mire continues to grow vertically. As earlier discussed, the moisture conditions by the mire margins strongly restrict the lateral expansion of mires in the SMC (Ehnvall et al. 2023a). In the case of minerogenic mires, the moisture conditions by the margins is a result of water flow-paths from the catchment area, rather than wetting from the mire area (Malmström, 1923). A mire's position in the landscape in relation to its upslope catchment area is therefore absolutely crucial for the mire's possibilities to expand both vertically and laterally.

Unlike reports from the FM area on long-term peat accumulation rates (Schoning, 2014), unpublished data from SMC indicate that recent peat accumulation rates over the past 100 years measured using $^{210}$Pb are slightly higher in the older chronosequence mires in the SMC compared to the younger mires. This illustrates the complex nature of peat accumulation and mire development, since in these same SMC mires the total peat depth increased at a much slower rate in the older compared to the younger mires (Figure 3-3). The higher recent peat accumulation rates in older mires compared to younger mires may reflect the decreased inflow of nutrients from the catchment area (Ehnvall et al. 2023b), which over time can disfavor peat decomposition if the microbial activity is restricted due to nutrient depletion (Gorham, 1957; Damman, 1996; Almquist-Jacobson & Foster, 1995; Mäkilä et al. 2001). Such mechanisms could result in an increase in the peat accumulation over time. Recent peat accumulation rates describe mainly processes taking place in the aerobic acrothelm, and partly in the anaerobic catothelm and they should, hence, not be confused with long-term peat accumulation rates, which are typically much lower since peat may still be decomposed and lost in the acrothelm (Young et al. 2021, 2019).

In landscapes with weaker mineral nutrient gradients compared to the SMC, the peat accumulation rates typically decrease over time, and many boreal and boreonemoral mires are no longer actively accumulating peat. Today many of the minerogenic mires in the FM area have relatively dry surfaces, with unfavorable conditions for peat formation, but instead more suitable conditions for peat loss through decomposition (Schoning, 2014; 2015). In the FM area, minerogenic mires younger than 1 000 years are at present accumulating peat, while mires older than 1 500 years are unlikely to accumulate peat, unless the vegetation undergoes a major regime shift or the climate becomes more suitable for peat accumulation. The decreasing peat accumulation rate with mire age can, in the study areas, be a pure effect of isostatic rebound, which may result in drier conditions inland compared to by the coast. The importance of upslope catchment areas in maintaining a high water table and preventing the mire surface from drying out has been relatively poorly studied, but the extensive drainage of peatlands and forests over the past one-hundred years has undoubtedly altered the landscape hydrology across Sweden, and is likely contributing to the drying out of mire surfaces not only in drained mire areas that are directly affected by ditches, but also in mire areas that are disconnected from the catchment area through marginal drainage (Sallinen et al. 2019) or extensive drainage higher up in the catchment area.

# 4 Conclusions

Mires in coastal parts of the Swedish counties of Uppland (boreonemoral) and Westrobothnia (boreal) initiate and develop under different climatic and geologic conditions, which implies that peat accumulation rates and mire plant community composition may differ between the counties and biomes. Differences in environmental conditions are further reflected in basic mire hydrological properties, such that mires in Uppland may undergo true fen-to-bog transitions and develop ombrogenic conditions with no influence of groundwater on the mire vegetation. In contrast, in Westrobothnia, true ombrogenic conditions do not develop from a pure hydrological perspective, but instead, mires are minerogenic and cover a range from eutrophic to oligotrophic based on the nutrient content of the incoming water.

Despite differences in the environmental conditions between Uppland and Westrobothnia, the influence of the catchment area on the mire ecosystems is likely very similar when the initial minerogenic phase of young mires in Forsmark (FM, Uppland) is compared to mires in the Sävar rising coastline mire chronosequence (SMC) in Westrobothnia. A larger catchment area relative to the mire area and a steeper sloping catchment will bring more water and solutes (nutrients and other substances) to the mire surface. Mires in the coastal-most parts of the FM and SMC are comparable in size, but catchment areas are generally smaller in the FM compared to the SMC, which means water can be transported from a smaller area to the mire. This could lead to a lower dilution of harmful substances released by groundwater discharge into FM mires. The slope of the catchment areas will, hence, control fluxes of water and solutes to mires, but it will also control the possibilities of lateral expansion of the mires, since a steep mire-surrounding catchment area will be unfavorable for lateral expansion.

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