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Summary

Distribution of live and dead fine roots (g m^{-2}; varying diameter fractions) and live/dead ratios were analysed for trees and field-layer species at three different forest stands representing different vegetation types close to the Forsmark area in the central eastern parts of Sweden and in Oskarshamn area (Laxemar) in the south eastern parts of Sweden, close to the nuclear power plants at each site.

The mean fine root biomass (live tissue; < 1 mm in diameter) of tree species for the total profile was 267, 317 and 235 g m^{-2} for the Forsmark sites and 137, 371 and 50 g m^{-2} for the Laxemar sites, respectively. The related fine-root necromass (dead tissue) was 119, 226 and 184 g m^{-2} for the Forsmark and 87, 245 and 271 g m^{-2} for the Laxemar sites, respectively. The Laxemar *Alnus* shore forest site (ASM001434), differed from all other sites since the amount of fine roots was very low and uniformly distributed in the soil profile.

The bulk of living fine roots of trees (< 1 mm in diameter) was found in the top 2.5 cm of the humus layer *viz.* 94, 84 and 88% for the Forsmark sites and 77, 85 and 23% for the Laxemar sites. Accordingly, the live/dead ratios of fine roots (< 1 mm in diameter) decreased from the top 2.5 cm of the humus layer to the lower part from 14-1, 8-1 and 5-0 g g^{-1} for the Forsmark sites and 3-2, 5-1 and 0-0 g g^{-1} for the Laxemar sites, respectively. The related data of the live/dead ratio of the top 10 cm to the lower part of the of the mineral soil horizon were 1-1, 2-1 and 0-0 g g^{-1} for Forsmark and 1-0, 2-0 and 0-0 g g^{-1} for the Laxemar sites respectively.

The highest live/dead ratio was found in the upper 2.5 cm of the humus layer in all stands and for both tree and field-layer species. This distribution pattern was most evident for tree fine roots < 1 mm in diameter, but it was found also for field-layer species and for larger diameter fractions. The live/dead ratio seems to be the most powerful vitality criterion of fine roots. The dry weight of the field-layer species was quite substantial.

Sammanfattning

Fördelning av levande och döda finrötter i marken (g m^{-2}; torrvikt 65 °C; varierande diameterfraktioner), samt kvoten levande/döda finrötter (g g^{-1}) studerades för träd och fältskiktsarter i skogsbestånd med tre vanliga vegetationstyper nära Forsmark och tre i Laxemar i Oskarhamnsområdet.

Torrvikten av trädens levande finrötter (biomassa, < 1 mm i diameter) i hela markprofilen var 267, 317 och 235 g m^{-2} för bestånden i Forsmark och 137, 371 och 50 g m^{-2} för bestånden i Laxemar. Den motsvarande vikten för döda finrötter (nekromassa) var 119, 226 och 184 g m^{-2} för Forsmark och 87, 245 och 271 g m^{-2} för Laxemar. I Laxemar skiljde sig ett strandskogbestånd med klibbal från samtliga övriga bestånd genom att mängden finrötter av träd var låg och jämnt fördelade i hela markprofilen.

En större andel levande finrötter (< 1 mm i diameter) av träd återfanns i det övre 2,5 cm humusskiktet i så gott som samtliga bestånd, dvs. 94, 84 och 88 % i Forsmark och 77, 85 och 23 % i Laxemar. I enlighet med detta minskade kvoten levande/döda finrötter (< 1 mm i diameter) från det övre 2,5 cm humusskiktet till den lägre delen av detta skikt med 14-1, 8-1 och 5-0 g g^{-1} i Forsmark och 3-2, 5-1 och 0-0 g g^{-1} i Laxemar. Motsvarande data för det övre till det lägre mineraljordskiktet var 1-1, 2-1 och 0-0 g g^{-1} för Forsmark och 1-0, 2-0 och 0-0 g g^{-1} för Laxemar.

Den högsta kvoten levande/döda finrötter återfanns i det övre 2,5 cm av humusskiktet i alla horisonter för både träd och fältskiktsarter. Denna fördelning observerades främst för finrötter (< 1 mm i diameter), men återfanns delvis även i grövre fraktioner. Undersökningarna indikerar att kvoten levande/döda finrötter är ett kraftfullt kriterium på vitaliteten hos finrötter. Mängden av rötter i markprofilen från fältskiktsarterna uppgick, jämfört med trädrötterna, till relativt stora mängder.

Contents

1 Introduction

Fine-root characteristics such as the amount of fine roots in terms of dry weight in different soil horizons, rooting density and the live/dead ratios seem to be depending on a variety of abiotic and biotic factors specific for different forest stands /Persson 2000/.

The highest live/dead ratio is usually detected in the uppermost humus layer /cf. Persson et al. 1995, Persson and Ahlström 2002, Puhe et al. 1986/. There is a substantial flow of root litter to the forest soil from dead fine roots during the growth period. Root litter is normally decomposed quite fast. The rate of decomposition is influenced by soil temperature and soil water conditions /Santantonio and Hermann 1985/.

Tree roots can be separated 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 high degree of soil penetraton and high turnover rates /Vogt and Persson 1991/. High fluctuation rates in fine-root biomass and necromass are found in a great variety of European forest ecosystems /cf. e.g. Persson 1978, Helmisaari and Helmisaari 1992, Helmisaari and Hallbäcken 1999, Bakker et al. 2000, Persson and Ahlström 2002, Helmisaari et al. 2001, in press, Stober et al. 2000/.

On a global scale, a substantial fraction of the atmosphere CO_2 originates from dead decomposing root tissues /Norby and Jackson 2000/. At the ecosystem level, the input of root litter is an important contributor to the ecosystem processes (e.g. nutrient cycling). Together with litter from above-ground parts of the tree, the decaying root material forms the bases for the complex biological cycles in the soil that include bacteria, fungi and soil animals.

The distribution of fine roots in various soil horizons, is essential for mineral nutrient uptake, biomass production and plant health /Marschner 2002/. Since the most efficient fine roots are superficially distributed, they are easily influenced by different kinds of environmental stress, e.g. frost and drought /Raitio 1990/. Research into root senescence is complicated by the fact that cessation of root penetration is not synonymous with root death.

Root damage may be visualised by a decreased live/dead ratio of the fine roots /Persson and Ahlström 2002/. Few studies have so far examined patterns in live/dead ratios of fine roots in relation to soil water and mineral nutrient availability /cf. Persson 2000, 2002, Santantonio and Hermann 1985/. With regards to the sustainability of the forest ecosystems, decreased levels of cations and increased levels of nitrogen have increased the risk of damage symptoms /Daldoum and Ranger 1994, Persson et al. 1995/.

The aims of our project was to describe fine-root characteristics in six common forest types in the Forsmark and Laxemar regions. More specifically, the aim can be separated in:

- a description of fine-root depth distributions in a brief perspective using results from studies in similar environments,
- a description of dry weight figures (live and dead) of tree species and field-layer species in different diameter fractions,
- an evaluation of live/dead ratios as a vitality criterion of fine roots.

The investigation is part of the activities performed within the site investigations at Forsmark and Oskarshamn. The work was carried out in accordance with activity plans AP PF 400-04-109 and AP PS 400-05-010 (SKB internal controlling documents). The original results are stored in the primary database (SICADA) and are traceable by the activity plan numbers. Only data in SKB's databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major data revisions entail a revision of the P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

The areas investigated are forest areas within the range of about 10 km from the two different nuclear power plants. In both areas varying soil water conditions and mineral nutrient availability are found. At all the three Forsmark areas, and at one area in Oskarshamn (oak forest type), environmental values are high, and they are classified as being of national interest concerning nature conservation.

2 Material and methods

The field studies were carried out within three investigation sites close to Forsmark and Laxemar regions in the central eastern and south eastern parts of Sweden (see Table 2-1 and 2-2 for detail information of the sites and maps in Figure 2-1 and 2-2). The sites at Forsmark were representing three stands of coniferous *Empetrum* type, coniferous fern type and *Alnus* swamp herb-type /Nordiska Ministerrådet 1978/. The related forest stands at Laxemar were of herb rich oak forest type, coniferous *Vaccinium myrtillus* type and *Alnus* shore forest type. The climate is maritime in both Forsmark and Laxemar regions /SMHI 2004/. The soil type varied between leptosol/regosols/gleysols at Forsmark and histosols/gleysol at Laxemar (Table 2-2).

The average thickness of the humus layer was 15.3, 5.2 and 15.3 cm at the Forsmark sites and 11.5, 5.5 and 5.3 cm at the Laxemar sites. The soil pH (H_2O) for the humus (0–30 cm) was 6.7 at the coniferous fern type and 6.7 for the *Alnus* swamp herb-type at the Forsmark sites respectively. In Laxemar the soil pH (H_2O) for the humus (0–30 cm) was 3.9 for the coniferous *Vaccinium myrtillu*s type and 5.3 for the *Alnus* shore forest type respectively. The related soil pH (H_2O) was in the top 0–10 cm of the mineral soil 7.0, 7.2 and 7.1 at the Forsmark and 5.3 for the herb rich oak forest at Laxemar. These data suggest a deeper raw-humus layer at the Forsmark sites /Lundin et al. 2004, 2005/.

The mean tree height of the trees was 16.3, 19.8 and 18.5 m at the Forsmark and 17.1, 21.0 and 11.6 m at the Laxmar sites, respectively. The tree density (number of trees/ha) was 1,340, 780 and 3,340 at the Forsmark and 200, 400 and 1,600 at the Laxemar sites respectively (Table 2-2). The field-layer was more extensively developed under the more sparsely developed tree layers at the Laxemar sites.

The sequential core method /Vogt and Persson 1991/ was used to describe root distribution with depth (LFH-horizon and the mineral soil as deep as possible) of both living (biomass) and dead (necromass) fine roots in terms of dry weight. The depth distribution of tree species and dwarf shrubs was described, using the depth intervals 0–2.5, 2.5–5, 5–10 cm of the top LFH horizon and in 10 cm segments for the mineral soil profile down to 40 cm.

Table 2-1. A general site characteristic of the forest stands at Forsmark and Laxemar.

Area	Forsmark	Laxemar
Latitude, longitude	E 60° 22’ N, 18° 11’ W	57° 25’ N, 16° 33’ E
Mean annual temp. 2004[1]	+6°C	+7°C
Mean annual temp	5.5[2]	6.4[3]
Min – max annual temp	3.4–7.4[2]	4.8–8.4[3]
Mean precipitation (mm)	758[4]	633[3]
Min – max precipitation (mm) 1961–90	411–1,252[4]	403–997[3]
Vegetation period	May–September	April–October
Vegetation period (no of days > 5°C)	180[5]	199[6]

1) /SMHI 2004/.

2) (From Örskär) /Larsson-Mcann et al. 2002a/.

3) (From Laxemar) /Larsson-Mcann et al. 2002b/.

4) (From Lövsta) /Larsson-Mcann et al. 2002a/.

5) Data for 1988 from the island of Örskär.

6) Data for 1981 from northern peak of the island of Öland.

Table 2-2. Site characteristics of the investigated forest stands at Forsmark (AFM-codes) and Laxemar (ASM-codes). ***Picea abies = P. a., Pinus sylvestris = P. s., Betula verrucosa = B. v., Alnus glutinosa = A. g., Quercus robur = Q. r.***

SKB id code	**AFM001247** (Coniferous *Calluna-Empetrum*-type)	**AFM001068** (Coniferous fern type)	**AFM001076** (*Alnus* swamp herb-type)	**ASM001426** (Herb rich oak forest)	**ASM001440** (Coniferous *V. myrtillus* type)	**ASM001434** (*Alnus* shore forest type)
Soil moisture class[1]	Fresh	Fresh/moist	Moist	Fresh	Fresh	Moist
Soil pH (H_2O)[1] H 0-30	–	6.7	6.7	–	3.9	5.3
Soil pH (H_2O)[1] M 0-10	7.0*	7.2	7.1	5.3	–	–
Soil pH (H_2O)[1] M 10-20	7.0*	7.4	7.4	4.9	–	–
Soil pH (H_2O)[1] M 55-65	7.6*	7.9	7.7	5.2	–	–
Lundin's id.[1]	B2a	FG1	SS1	Löv 1	Gran 1	Sump 1
Soil type[1]	Leptosol	Regosol/ Gleysol	Gleysol	Histosol/ Gleysol	Histosol	Histosol
Stone/boulder[1] volumetric content in M 0-30 (%)	52*	43	52	57	0	0
Topographic wetness index (TWI)	5.2	9.3	6.2	9.4	8.9	9.0
Number of trees /ha	1,340	780	3,340	200	400	1,600
Basal area (m^2/ha)	22.5 (*P. a.*)	20.5 (*P. a.*) 6.5 (*B. v.*)	5.3 (*B. v.*) 7.33 (*A. g.*) 2.3 (*P. s.*) 3.0 (*A. g.*)	15.0 (*Q. r.*)	15.5 (*P. a.*)	17.5 (*A. g.*)
Tree age	59–60	80–88	85–95	112	55	34
Tree height (m)	16.3	19.8	18.5	17.1	21.0	11.6
Dominant height at 100 years[2]	G 20	G 20	(G 18)	EK 18	G 28	–
Diameter at breast height (dbh in m)	0.21	0.26 (*P. a.*)	0.31 (*P. a.*, n=5)	0.36	0.32	0.14
Above field-layer biomass (g m^{-2})	–	24	5	89	27	9
Veg. types[3]	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	*Pteridium aguilinum, Calluna vulgaris, Maianthemum bifolium, Vaccinium myrtillus, V. vitis-ideae, Hepatica nobilis*	*Maianthemum bifolium, Anemone nemorosa, Hepatica nobilis, Listera ovata, Rubus saxatilis*	*Filipendula ulmaria, Rubus saxatilis, Pteridium aguilinum, Convallaria majalis, Epipactus helleborine, Viola riviniana*	*Vaccinium vitis-idaea, Deschampsia flexuosa*	*Carex sp., Vaccinium myrtillus*	*Calamagrostis canescens, Carex nigra*
Ground-layer species	*Hylocomium splendes, Rhytidiadelphus triquetrus, Dicranum scoparium*	*Hylocomium splendens, Ptilium crista-castrensis*	*Pleurozium Schreberi, Dicranum Majus, Sphagnum spp*	*Pleurozium schreberi*	*Dicranum polysetum*	–

[1] /Lundin et al. 2004, 2005/.

[2] /Hägglund 1973/.

[3] /Nordiska Ministerrådet 1978/.

* Measured approximately 100 m from the locality.

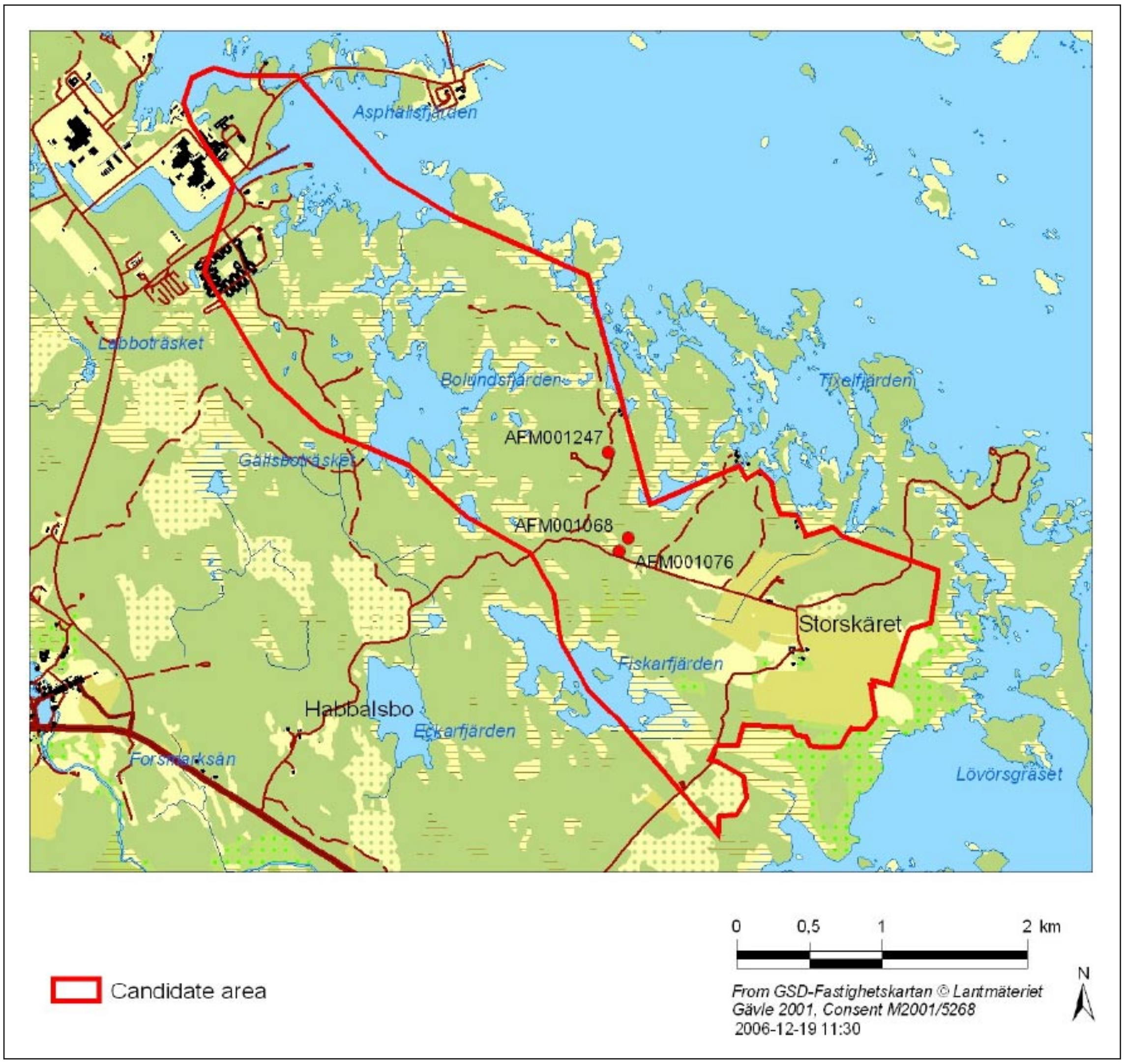

Figure 2-1. *Map of the Forsmark region with the investigated sites indicated.*

Figure 2-2. *Map of the Laxemar region with the investigated sites indicated.*

The soil sampling was carried out in the mid of October 2004. A steel corer, with an inner diameter of 4.5 cm, was used for the soil sampling. In total 32 soil cores were taken from the four corners of a quadrate covering 200 m^2, 8 in each corner (north, east, south and west). Each soil sample was taken as deep as possible, *viz.* to a depth where stones and larger blocks prevented further penetration by the soil corer.

The specific spot, within which the soil cores was taken, was chosen with the help of a sharp iron stick driven down into the soil profile. The aim of this procedure was to make sure that at least 10 cm of the soil profile was included in the soil samples from the mineral soil.

The three Forsmark stands and the "herb rich oak forest" at Laxemar, in particular, were rather stony in the mineral soil horizons (Table 2-2) and an increased concentration of roots along the surface area of the stones should be expected. These roots are extremely difficult to include by the soil corer in the soil samples. On the other hand, the method of deliberately sampling spots, where at least 10 cm of the mineral soil is included and then extrapolated to a square metre, suggests that the estimate of fine-root dry weight to some extent will be overestimated in the mineral soil. How this would affect the distribution pattern of roots in the soil areas between the stones is not known. Therefore any correction of the distribution pattern of the fine roots for the total soil profile was not carried out.

The soil corer was driven into the mineral soil as deep as possible. At those depths only limited live root fragments were sampled (with a low live/dead ratio). Thus, the live (biomass) and dead (necromass) fine roots were not underestimated in the deeper horizons, since only small root fragments were found in those horizons**.**

The thickness of humus horizon was measured in each soil core. The uppermost 0–2.5 cm layer consisted of humus in all sites. The thickness of humus layer was rather variable within the 6 different sites. The soil samples were transferred into plastic bags and transported as soon as possible to our laboratory and stored in a cold-storage at –4°C (a temperature that did not damage the live tissue and caused no change in ion concentrations; /cf. Clemensson-Lindell and Persson 1992/ until the final sorting took place.

The roots were sorted out from the soil cores immediately after thawing. To distinguish biomass (live roots) from necromass (dead roots) the fine roots were separated into live and dead categories based on morphological characteristics /Vogt and Persson 1991/. Roots were classified into the following root diameter fractions: < 1, 1–2, 2–3, 3–4, 4–5 and 5–10 mm and separated into tree and field-layer species. Separation was carried out for both tree roots and roots of other vascular species (dwarf shrubs, herbs and grasses). The diameter measurements were carried out in the mid of each fragment using a pair of vernier callipers.

It is essential to use distinct morphological criteria while sorting the root fragments into live and dead fine roots. Live fine roots were defined as roots that were white or to a varying degree brownish/suberized and often well branched, with the main part of the root tips light and turgid or changed to mycorrhizal ramifications /Agerer 1987–2002/.

In cases when there was difficult to judge if a root fragment was live or dead, it was cut lengthwise with a sharp dissection knife and the judgement was based on the colour between cortex and periderm. The stele of live roots was white to slightly brown and elastic. In roots considered as dead, the stele was brownish and easily broken, and the elasticity was reduced. Dead fragmented root pieces with a length < 1 cm were regarded as soil organic matter. The dry weight was estimated for all root fractions after drying in an oven at 65°C to constant weight (at least 24 hours).

The remaining soil from the soil cores /the rhizosphere and bulk soil) was stored in a cold-storage at –4°C until the chemical analyses were carried out. The rhizosphere soil was distinguished from the root fragments by shaking the root fragments with their attached soil gently in a glass jar. The rhizosphere soil was defined as the few millimetres of soil surrounding the plant roots and influenced by their activity /cf. Gobran et al. 2001/. Data for chemical analyses of the dried root samples and for the rhizosphere and bulk soil will be reported separately /Hannu and Karlsson 2006, Engdahl et al. 2006/.

3 Results

The amount of live tree fine 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; Table 3-5) of tree species for the total profile was 267, 317 and 235 g m^{-2} for the Forsmark sites, respectively and 137, 371 and 50 g m^{-2} for the Laxemar sites (Tables 3-1, 3-5).

The mean tree fine-root necromass (dead tissue) was 119, 226 and 184 g m^{-2} for the Forsmark and 87, 245 and 271 g m^{-2} for the Laxemar sites, respectively (Tables 3-1, 3-5). The proportion of live tree fine roots was surprisingly high especially in the uppermost parts of the humus layer and in the uppermost 0–10 cm of the mineral soil (Table 3-4). The depth of the humus layer was quite variable between the different sites.

At Forsmark the Norway spruce (*Picea abies*) fine roots (< 1 mm in diameter) amounted to 88, 94 and 80% respectively of the total dry weight (live + dead). Other tree species found on those sites were silver birch (*Betula verrucosa*), European alder (*Alnus glutinosa*) and Scots pine (*Pinus sylvestris*). At Laxemar Norway spruce (*Picea abies*) fine roots amounted to almost 100% of the total fine-root dry weight of tree species (< 1 mm in diameter) on the "coniferous *Vaccinium* forest site". Otherwise European alder (*Alnus glutinosa*) fine roots were completely dominating in the "Alnus shore forest site" and common oak (*Quercus robur*) in the "herb rich oak forest" (100% of the total fine-root dry weight).

Proportionally more live fine roots (< 1 mm or < 2 mm in diameter) of the trees were observed in the humus horizon compared to mineral soil (Tables 3-1 to 3-2 and 3-4 to 3-6), except for the "coniferous fern forest site" at Forsmark and the "*Alnus* shore forest site" at Laxemar. Tree fine roots < l mm in diameter consist of fine ramifications with mycorrhizal root tips which are morphologically very different from the rest of the root system.

However with increasing root diameter (< 10 mm in diameter; Table 3-5 and Table 3-6 compared with Table 3-7) more living tree roots were found in the mineral soil. Most coarse roots of the field-layer species were concentrated to the humus layer (Table 3-5 and Table 3-6 compared with Table 3-7). This distribution pattern seems to be independent of the diameter size of the fine roots.

Substantial amounts of fine roots of the field-layer species (Table 3-7) were found at all sites except for the "*Picea abies*-*Vaccinium myrtillus* forest" at Laxemar, where the field layer was scarcely developed. The amount of live fine roots of the field-layer species even exceeded that of live tree roots, at the "herb rich oak forest" at Laxemar. The highest amount of fine roots of field-layer species were found in the humus layer in Forsmark and Laxemar areas (Table 3-7).

There was a considerable variation in the amount of live and dead tree fine roots between different soil horizons. The dry weight of fine roots decreased with depth. In both moist sites (the "*Alnus* swamp" at Forsmark and the "*Alnus* shore forest" at Laxemar) a high proportion of dead fine roots was found in the top 0–10 cm of the mineral soil (biomass < necromass); Table 3-8). In all other sites and horizons the fine-root biomass was > necromass.

Root sampling took place to a depth where few roots occurred; only small dead root fragments were observed in the deepest part of the soil horizon. Therefore we concluded that almost all fine roots were sampled and that only insignificant amounts remained deeper down in the soil profile (Table 3-8).

It is important to know to what extent the distribution pattern of the tree roots is influenced by the competition from the roots of the field layer species. Our data suggest that tree roots are generally distributed deeper than roots from the field-layer species (Table 3-3). The highest amount of roots from the field-layer species was found in the sites with a low number of trees/ha; *viz.* in the "coniferous fern type forest" at Forsmark (780 trees/ha) and at the "herb rich oak forest" at Laxemar (200 trees/ha). The forest trees on those sites were among the oldest (the age of the trees was 80–112 years).

The Laxemar "*Alnus* shore forest site", differed from all other sites since the amount of fine roots was generally very low and uniformly distributed in the whole soil profile. At that site a substantial amount of dead fine roots of trees and field-layer species were found in the uppermost 0–10 cm part of the mineral soil compared to deeper horizons.

Our data clarify that it is necessary to sort the fine roots in both live and dead categories, to get a general picture of the spatial distribution of fine roots. The soil profile and distribution pattern of fine roots vary considerably between sites. It is necessary to relate to the natural soil-horizons since the distribution pattern of the fine roots seems to depend on how the soil profile is developed.

The highest live/dead ratio is to be found in the upper part of the humus layer in all horizons for both tree and field-layer species. A high live/dead ratio is furthermore found in the upper part of the mineral soil horizon. This distribution pattern is especially evident for the fine roots < 1 mm in diameter, but also occurs to some extent for other diameter fractions.

The below-ground distribution of the field-layer species (degree of root proliferation) was low in stands with a low tree stem density such as the "*Picea abies* site of *Vaccinium myrtillus* type" and the "herb rich oak forest" at Laxemar. The above-ground part of the field layer was dominated by ericaceous dwarf shrubs in those stands. In the Forsmark area the low stem density "coniferous fern forest" showed the highest above-ground biomass in the field layer.

Table 3-1. The distribution of fine roots (< 1 mm in diameter) at different depths (H = humus; M = mineral soil) at the forest sites: AFM001247 (*Picea abies, Pinus sylvestris* – fresh), AFM001068 (*Picea abies* – fresh/moist) and AFM001076 (*Alnus glutinosa* – moist) at Forsmark and ASM001426 (*Quercus robur* – fresh), ASM001440 (*Picea abies* – fresh) and ASM001434 (*Alnus glutinosa* – moist) forest sites at Laxemar. Estimates are given as mean values ± SD (n=31–32).

Site	Horizon	Soil depth (cm)	Tree roots (g m⁻²) Live	Dead	Total	Roots field-layer species (g m⁻²) Live	Dead	Total
Forsmark								
AFM001247	H 0-2.5		48±42	3±9	51±44	17±34	0	17±34
	H 2.5-5		64±29	15±22	79±37	10±13	0	10±13
	H 5-10		60±63	21±25	80±79	5±8	0	5±8
	H 10-15		9±20	9±21	18±40	0	0	1±2
	H 15-20		2±9	2±12	4±19	0	0	0
	M 0-10		71±96	58±63	129±138	9±18	3±5	12±20
	M 10-20		13±59	10±21	24±59	2±5	0	2±5
AFM001068	H 0-2.5		30±35	4±5	34±38	15±23	1±2	16±23
	H 2.5-5		4±12	4±11	8±22	1±6	8±22	8±28
	H 5-10		2±6	3±10	5±16	4±21	0	4±21
	M 0-10		228±138	136±70	364±165	74±55	36±122	109±129
	M 10-20		51±67	73±60	124±82	14±15	3±6	17±18
	M 20-30		2±8	5±15	7±16	1±4	0	1±4
AFM001076	H 0-2.5		56±58	11±11	67±62	6±9	1±4	7±12
	H 2.5-5		46±36	23±21	69±49	4±10	1±2	5±10
	H 5-10		55±52	51±40	106±74	3±5	4±7	7±10
	H 10-15		28±35	25±33	53±64	3±9	1±3	4±11
	H 15-20		13±30	9±16	22±41	0	0	1±2
	H 20-25		3±9	6±22	9±30	0	0	0
	H 25-30		0	0	0	0	0	0
	M 0-10		29±73	45±55	74±120	3±6	3±11	6±13
	M 10-20		6±11	14±21	20±29	0	1±2	1±2
	M 20-30		0	0	1±2	0	0	0
Laxemar								
ASM001426	H 0-2.5	2.5±0	24±28	7±10	31±33	84±88	32±45	116±120
	H 2.5-5	2.0±1.0	34±37	15±16	48±44	49±47	16±24	65±63
	H 5-10	1.5±1.9	21±28	8±12	28±37	30±52	7±17	38±64
	M 0-10	9.5±1.3	57±42	48±34	105±56	59±45	26±72	85±98
	M 10-20	1.7±2.6	3±7	9±23	13±29	3±6	1±2	4±7
ASM001440	H 0-2.5	2.5±0	102±61	18±23	120±69	2±8	0	2±8
	H 2.5-5	1.4±1.2	48±52	17±21	64±66	0	0	0
	H 5-10	0.5±1.2	10±29	11±30	21±54	0	0	0
	M 0-10	10.0±0.0	132±69	71±48	203±93	3±8	0	3±8
	M 10-20	10.0±0.0	51±49	71±37	122±60	0	0	0
	M 20-30	10.0±0.0	25±49	31±32	55±60	0	0	0
	M 30-40	10.0±0.0	4±10	26±34	30±36	0	0	0
ASM001434	H 0-2.5	2.5±0	14±17	47±79	61±84	23±33	7±13	30±43
	H 2.5-5	1.6±1.2	5±9	38±57	43±62	6±9	3±11	9±20
	H 5-10	0.3±0.8	1±4	7±19	8±22	0	0	0
	M 0-10	10.0±0	17±25	115±104	132±112	17±60	11±20	27±66
	M 10-20	10.0±0	7±16	35±40	41±51	3±5	7±14	9±17
	M 20-30	10.0±0	3±8	21±33	25±39	1±4	4±5	5±7
	M 30-40	8.9±3.0	2±8	10±14	12±18	1±1	3±5	4±6

Table 3-2. The distribution of fine roots (< 2 mm in diameter) at different depths (H = humus; M = mineral soil) at the following forest sites AFM001247 (*Picea abies, Pinus sylvestris* – fresh), AFM001068 (*Picea abies* – fresh/moist) and AFM001076 (*Alnus glutinosa* – moist) at Forsmark and ASM001426 (*Quercus robur* – fresh), ASM001440 (*Picea abies* – fresh) and ASM001434 (*Alnus glutinosa* – moist) at Laxemar. Estimates are given as mean values ± SD (n=32–34).

Site	Horizon	Tree roots (g m^{-2})			Roots of field-layer species (g m^{-2})		
		Live	Dead	Total	Live	Dead	Total
Forsmark							
AFM001247	H 0-2.5	56±46	4±11	60±50	19±39	0	19±39
	H 2.5-5	82±38	21±30	102±49	10±13	0	11±13
	H 5-10	82±84	30±39	112±106	6±12	0	7±12
	H 10-15	12±28	12±24	23±51	0	0	1±2
	H 15-20	2±9	4±23	7±30	0	0	0
	M 0-10	108±122	80±84	188±170	9±18	3±5	12±20
	M 10-20	22±68	16±31	38±94	2±5	0	2±5
AFM001068	H 0-2.5	36±41	5±10	42±45	17±25	2±7	19±28
	H 2.5-5	6±18	7±19	13±34	9±26	1±6	10±31
	H 5-10	5±20	3±11	8±30	2±25	0	5±25
	M 0-10	281±149	160±78	441±179	84±60	36±122	120±130
	M 10-20	79±84	110±78	189±95	15±17	3±6	18±20
	M 20-30	3±11	8±21	10±25	1±4	0	1±4
AFM001076	H 0-2.5	66±71	12±11	77±75	7±12	1±4	8±14
	H 2.5-5	58±39	36±35	94±58	5±17	1±2	6±17
	H 5-10	79±68	72±44	151±95	7±18	4±10	11±20
	H 10-15	40±49	39±45	79±92	3±9	1±3	4±11
	H 15-20	22±43	15±24	36±63	1±4	0	1±4
	H 20-25	5±17	11±34	16±49	0	0	0
	H 25-30	0	0	0	0	0	0
	M 0-10	50±107	74±86	124±165	5±12	3±11	8±16
	M 10-20	12±21	25±41	37±53	1±1	1±2	1±2
	M 20-30	0	0	1±3	0	0	0
Laxemar							
ASM001426	H 0-2.5	26±32	10±20	36±46	102±113	32±45	134±140
	H 2.5-5	40±43	17±24	51±48	51±48	17±24	68±64
	H 5-10	26±36	10±14	36±46	33±56	8±19	41±69
	M 0-10	86±64	75±52	162±87	62±47	30±81	93±107
	M 10-20	5±13	15±36	20±48	3±6	1±2	4±7
ASM001440	H 0-2.5	117±66	21±27	138±77	3±9	0	3±9
	H 2.5-5	65±69	23±34	88±91	±	0	±
	H 5-10	15±43	12±31	27±72	0	0	0
	M 0-10	185±99	98±64	283±130	4±13	0	4±13
	M 10-20	73±70	102±53	175±91	0	0	0
	M 20-30	35±61	49±54	84±86	0	0	0
	M 30-40	8±16	40±47	49±55	0	0	0
ASM001434	H 0-2.5	22±26	58±99	80±109	32±41	8±14	40±50
	H 2.5-5	10±18	50±76	60±86	8±14	5±15	13±29
	H 5-10	1±7	11±29	12±33	0	0	0
	M 0-10	29±40	162±136	191±145	17±60	15±26	32±67
	M 10-20	11±21	50±55	61±70	3±5	15±26	18±27
	M 20-30	7±18	33±56	39±68	2±4	5±6	6±8
	M 30-40	3±12	17±27	19±32	1±3	4±6	5±8

Table 3-3. The distribution of roots (g m⁻², < 10 mm in diameter) at different depths (H = humus; M = mineral soil) at the forest sites: AFM001247 (*Picea abies, Pinus sylvestris* – fresh), AFM001068 (*Picea abies* – fresh/moist) and AFM001076 (*Alnus glutinosa* – moist) at Forsmark and ASM001426 (*Quercus robur* – fresh), ASM001440 (*Picea abies* – fresh) and ASM001434 (*Alnus glutinosa* – moist) forest sites at Laxemar. Estimates are given as mean values ± SD. (n=31–32).

Site	Horizon	Tree roots ($g\ m^{-2}$)			Roots of field-layer species ($g\ m^{-2}$)		
		Live	Dead	Total	Live	Dead	Total
Forsmark							
AFM001247	H 0-2.5	69±77	13±46	81±89	20±39	0	21±39
	H 2.5-5	190±298	25±34	214±298	13±19	0	13±20
	H 5-10	145±179	39±53	183±195	13±39	0	13±39
	H 10-15	19±42	33±96	51±124	0	0	1±2
	H 15-20	4±15	4±23	8±37	0	0	0
	M 0-10	285±385	207±289	482±478	9±18	3±5	12±20
	M 10-20	64±198	23±41	87±287	2±5	0	2±5
AFM001068	H 0-2.5	41±54	6±11	47±59	35±74	2±7	36±74
	H 2.5-5	22±79	7±19	28±95	34±133	1±6	35±139
	H 5-10	8±36	4±13	12±48	8±43	0	8±43
	M 0-10	549±342	222±126	772±373	103±88	36±122	139±140
	M 10-20	262±448	232±307	494±544	15±17	3±6	18±20
	M 20-30	6±24	10±29	16±39	1±4	0	1±4
AFM001076	H 0-2.5	81±76	23±34	104±83	9±18	1±4	10±20
	H 2.5-5	92±87	49±47	95±70	10±38	1±2	11±38
	H 5-10	198±238	122±80	320±250	10±27	7±19	17±32
	H 10-15	99±184	88±110	184±267	3±9	1±3	4±11
	H 15-20	34±67	40±76	73±112	0	0	1±4
	H 20-25	6±18	17±52	23±57	0	0	0
	H 25-30	0	2±11	2±11	0	0	0
	M 0-10	147±227	127±148	273±279	9±32	3±11	12±34
	M 10-20	29±62	59±116	88±138	2±7	1±2	2±7
	M 20-30	4±16	8±26	12±39	0	0	0
Laxemar							
ASM001426	H 0-2.5	45±64	11±21	56±71	102±113	32±48	135±142
	H 2.5-5	49±52	23±27	72±62	67±82	17±24	84±95
	H 5-10	53±117	23±63	76±138	39±78	8±19	47±90
	M 0-10	308±375	232±338	540±464	62±47	31±80	93±107
	M 10-20	38±177	21±53	59±185	3±6	2±4	4±9
ASM001440	H 0-2.5	157±97	54±137	211±167	9±33	0	9±33
	H 2.5-5	129±170	33±49	162±188	4±22	0	4±22
	H 5-10	21±62	12±31	33±89	0	0	0
	M 0-10	403±301	226±279	630±437	4±13	0	4±13
	M 10-20	140±151	179±140	319±201	0	0	0
	M 20-30	88±198	119±162	206±281	0	0	0
	M 30-40	42±148	71±73	113±162	0	0	0
ASM001434	H 0-2.5	43±83	89±132	132±158	43±57	9±18	53±66
	H 2.5-5	53±117	79±116	132±206	9±18	5±15	14±33
	H 5-10	17±66	17±47	33±111	0	0	0
	M 0-10	76±103	320±334	396±388	17±60	32±85	49±103
	M 10-20	70±183	88±108	159±246	3±6	46±116	49±116
	M 20-30	70±177	51±77	121±217	2±4	11±28	13±28
	M 30-40	51±206	38±82	89±226	1±3	10±22	11±23

Table 3-4. The amount of fine roots (< 1 mm in diameter) per soil volume (g l^{-1}) at different depths (H = humus; M = mineral soil) at the following sites AFM 001247 (*Picea abies, Pinus sylvestris* – fresh), AFM 001068 (*Picea abies* – fresh/moist) and AFM 001076 (*Alnus glutinosa* – moist) forest sites at Forsmark and ASM 001426 (*Quercus robur* – fresh), ASM 001440 (*Picea abies* – fresh) and ASM 001434 (*Alnus glutinosa* – moist) forest sites at Laxemar. Estimates are given as mean values ± SD (n=32).

Site	Horizon	Tree roots (g m^{-2})			Roots of field-layer species (g m^{-2})		
		Live	Dead	Total	Live	Dead	Total
Forsmark							
AFM001247	H 0-2.5	2.0±1.7	0.2±0.5	2.2±2.0	0.7±1.4	0.01±0.05	0.7±1.4
	H 2.5-5	3.2±1.5	0.7±0.9	3.9±2.1	0.4±0.5	0.01±0.04	0.4±0.5
	H 5-10	1.9±1.7	0.5±0.6	2.4±2.3	0.1±0.2	0.02±0.08	0.1±0.2
	H 10-15	0.4±1.2	0.1±0.4	0.7±1.7	0	0	0
	H 15-20	0.1±0.4	0.1±0.3	0.1±0.6	0	0	0
	M 0-10	1.3±1.4	0.7±0.7	2.0±2.0	0.1±0.2	0.04±0.05	0.1±0.2
	M 10-20	0.6±1.2	0.3±0.5	0.8±1.5	0.04±0.10	0	0.04±0.10
AFM001068	H 0-2.5	1.4±1.5	0.3±0.6	1.7±1.9	0.6±0.9	0.03±0.08	0.6±0.9
	H 2.5-5	0.4±0.9	0.2±0.5	0.6±1.4	0.3±1.0	0.06±0.25	0.4±1.2
	H 5-10	0.3±0.8	0.2±0.5	0.4±1.3	0.04±2.11	0	0.04±2.11
	M 0-10	3.6±1.6	1.8±1.3	5.3±2.7	0.7±0.5	0.4±1.2	1.1±1.3
	M 10-20	1.7±1.2	1.1±0.7	2.7±1.6	0.2±0.2	0.04±0.10	0.2±0.3
	M 20-30	0.2±0.4	0.1±0.3	0.3±0.7	0.01±0.04	0	0.01±0.04
AFM001076	H 0-2.5	2.6±2.5	0.7±0.9	3.3±3.0	0.2±0.4	0.05±0.15	0.3±0.5
	H 2.5-5	2.7±1.9	1.1±1.1	3.8±2.8	0.2±0.4	0.04±0.09	0.2±0.4
	H 5-10	2.1±1.5	1.2±1.0	3.3±2.2	0.1±0.1	0.1±0.1	0.2±0.2
	H 10-15	1.2±1.3	0.7±0.8	1.9±2.1	0.1±0.2	0.02±0.07	0.1±0.2
	H 15-20	0.5±0.9	0.2±0.4	0.7±1.2	0	0	0
	H 20-25	0.2±0.6	0.2±0.6	0.4±1.2	0	0	0
	H 25-30	0	0	0	0	0	0
	M 0-10	0.7±1.2	0.5±0.6	1.2±1.8	0.03±0.06	0.03±0.01	0.1±0.1
	M 10-20	0.3±0.5	0.2±0.4	0.5±0.9	0	0	0
	M 20-30	0	0	0	0	0	0
Laxemar							
ASM001426	H 0-2.5	0.9±1.1	0.3±0.4	1.2 ±1.3	3.4±3.5	1.3±1.8	4.6±4.8
	H 2.5-5	1.4±1.5	0.6±0.7	1.0±1.2	1.1±1.9	0.2±0.5	1.3±2.2
	H 5-7.5	0.7±1.2	0.3±0.5	1.0±1.6	1.0±1.7	0.3±0.8	1.3±2.4
	M 0-10	0.6±0.4	0.5±0.3	1.1±0.6	0.6±0.5	0.3±0.7	0.9±1.0
	M 10-20	0.1±0.2	0.2±0.4	0.3±0.5	0.1±0.1	0.02±0.04	0.1±0.1
ASM001440	H 0-2.5	4.0±2.4	0.7±0.9	4.8±2.8	0.1±0.3	0	0.1±0.3
	H 2.5-5	2.0±2.1	0.7±0.9	2.7±2.7	0	0	0
	H 5-7.5	0.3±0.9	0.3±0.9	0.7±1.5	0	0	0
	M 0-10	1.3±0.7	0.7±0.5	2.0±0.9	0	0	0
	M 10-20	0.5±0.5	0.7±0.4	1.2±0.6	0	0	0
	M 20-30	0.3±0.5	0.3±0.3	0.6±0.6	0	0	0
	M 30-40	0.04±0.10	0.3±0.3	0.3±0.4	0	0	0
ASM001434	H 0-2.5	0.6±0.7	1.9±3.2	2.4±3.3	0.9±1.3	0.3±0.5	1.2±1.7
	H 2.5-5	0.2±0.4	1.5±2.3	1.7±2.5	0.2±0.4	0.1±0.4	0.4±0.8
	H 5-7.5	0.04±0.19	0.4±0.9	0.4±1.1	0	0	0
	M 0-10	0.2±0.3	1.1±0.2	1.3±1.1	0.2±0.6	0.1±0.2	0.3±0.7
	M 10-20	0.1±0.2	0.4±0.4	0.4±0.1	0.03±0.05	0.07±0.14	0.1±0.2
	M 20-30	0.03±0.8	0.21±0.33	0.2±0.4	0.01±0.04	0.04±0.25	0.05±0.07
	M 30-40	0.02±0.08	0.1±0.1	0.1±0.2	0	0	0

Table 3-5. The amount of live and dead fine roots (< 1 mm in diameter) in different soil layers (H = humus; M = mineral soil) at the following sites AFM 001247 (*Picea abies, Pinus sylvestris* – fresh), AFM 001068 (*Picea abies* – fresh/moist) and AFM 001076 (*Alnus glutinosa* – moist) forest sites at Forsmark and ASM 001426 (*Quercus robur* – fresh), ASM 001440 (*Picea abies* – fresh) and ASM 001434 (*Alnus glutinosa* – moist) forest sites at Laxemar. Estimates are given as mean values ± SD (n=32).

Site/root fraction	Horizon	Tree roots (g m^{-2}) Live	Dead	Total	Roots of field-layer species (g m^{-2}) Live	Dead	Total
Forsmark							
AFM001247							
Fine roots	H	182±91	51±47	233±120	32±46	1±3	33±46
Fine roots	M	84±116	68±71	152±170	11±20	3±5	15±23
Totals	H+M	267±118	119±74	385±148	43±53	5±6	48±53
AFM001068							
Fine roots	H	36±44	11±23	48±62	27±49	2±6	29±54
Fine roots	M	281±187	215±84	495±198	88±58	39±122	126±130
Totals	H+M	317±196	226±88	543±205	115±87	41±122	155±145
AFM001076	H	201±136	125±97	325±197	16±21	7±10	24±28
Fine roots	M	35±80	59±72	94±144	3±7	4±11	7±13
Totals	H+M	235±162	184±95	419±229	20±26	11±15	30±33
Laxemar							
ASM001426							
Fine roots	H	77±61	29±25	106±72	163±153	55±58	218±194
Fine roots	M	60±42	58±45	118±65	62±47	26±72	88±100
Totals	H+M	137±72	87±50	224±80	224±168	82±91	306±220
ASM001440							
Fine roots	H	159±97	45±49	205±133	2±9	0	2±9
Fine roots	M	211±116	199±103	411±172	3±9	0	4±9
Totals	H+M	371±151	245±103	616±211	5±17	0	6±17
ASM001434							
Fine roots	H	21±20	90±123	110±134	29±34	12±18	40±47
Fine roots	M	29±39	181±174	210±200	21±69	24±34	45±88
Totals	H+M	50±52	271±245	321±278	50±84	35±41	85±107

Table 3-6. The amount of live and dead fine roots (< 2 mm in diameter) in different soil layers (H = humus; M = mineral soil) at the following sites AFM 001247 (*Picea abies, Pinus sylvestris* – fresh), AFM 001068 (*Picea abies* – fresh/moist) and AFM 001076 (*Alnus glutinosa* – moist) forest sites at Forsmark and ASM 001426 (*Quercus robur* – fresh), ASM 001440 (*Picea abies* – fresh) and ASM 001434 (*Alnus glutinosa* – moist) forest sites at Laxemar. Estimates are given as mean values ± SD (n=32).

Site/root fraction	Horizon	Tree roots (g m^{-2})			Roots of field-layer species (g m^{-2})		
		Live	Dead	Total	Live	Dead	Total
Forsmark							
AFM001247							
Fine roots	H	234±112	71±70	305±157	36±51	1±3	37±51
Fine roots	M	131±162	96±98	227±230	11±20	3±5	14±23
Totals	H+M	365±151	167±108	532±190	47±57	5±6	52±57
AFM001068							
Fine roots	H	47±62	16±33	63±89	31±53	3±9	34±59
Fine roots	M	363±201	278±98	641±206	101±64	39±122	140±130
Totals	H+M	410±207	294±107	704±211	132±97	42±122	174±149
AFM001076	H	269±176	185±119	454±267	23±33	8±13	31±39
Fine roots	M	63±114	99±1,190	162±211	6±14	4±11	10±18
Totals	H+M	332±215	284±146	616±320	29±43	11±17	41±48
Laxemar							
ASM001426							
Fine roots	H	92±73	36±31	128±89	185±185	56±59	242±223
Fine roots	M	87±67	87±72	173±113	62±48	32±81	92±108
Totals	H+M	179±97	123±75	301±126	247±201	88±96	336±251
ASM001440							
Fine roots	H	197±118	56±59	253±166	4±11	0	4±11
Fine roots	M	302±157	289±158	591±255	4±13	0	5±13
Totals	H+M	499±176	344±155	844±279	8±22	0	9±23
ASM001434							
Fine roots	H	33±35	119±159	152±182	40±44	13±20	53±57
Fine roots	M	49±60	262±241	311±278	22±69	39±55	61±96
Totals	H+M	82±84	381±340	463±393	63±88	52±57	114±113

Table 3-7. The amount of live and dead tree roots (< 10 mm in diameter) in different soil layers (H = humus; M = mineral soil and H+M) at the following sites AFM 001247 (*Picea abies, Pinus sylvestris* – fresh), AFM 001068 (*Picea abies* – fresh/moist) and AFM 001076 (*Alnus glutinosa* – moist) forest sites at Forsmark and ASM 001426 (*Quercus robur* – fresh), ASM 001440 (*Picea abies* – fresh) and ASM 001434 (*Alnus glutinosa* – moist) forest sites at Laxemar. Estimates are given as mean values ± SD (n=32).

Site/root fraction	Horizon	Tree roots (g m^{-2})			Roots of field-layer species (g m^{-2})		
		Live	Dead	Total	Live	Dead	Total
Forsmark							
AFM001247	H	425±390	113±136	538±421	46±61	1±3	48±61
	M	349±437	230±248	579±545	11±20	3±5	14±23
	H+M	774±545	343±271	1,117±664	57±69	5±6	62±70
AFM001068	H	73±141	16±35	88±172	77±208	3±9	80±214
	M	818±590	464±305	1,282±674	118±90	39±122	157±141
	H+M	890±581	480±309	1,370±675	195±230	42±122	237±245
AFM001076	H	509±409	338±210	847±559	32±61	11±21	43±66
	M	178±242	194±192	371±360	11±39	4±11	14±40
	H+M	687±444	532±244	1,218±594	43±94	14±24	58±99
Laxemar							
ASM001426	H	147±141	58±69	206±176	209±227	58±61	267±266
	M	347±396	252±340	599±496	65±50	32±81	98±108
	H+M	494±441	310±355	805±579	274±242	90±100	264±291
ASM001440	H	307±216	99±147	406±267	12±41	0	13±41
	M	674±436	594±354	1,268±678	4±13	0	5±13
	H+M	981±387	693±404	1,674±652	17±51	0	17±51
ASM001434	H	113±178	184±223	297±357	52±60	14±23	67±73
	M	267±499	497±462	764±871	22±69	99±188	121±200
	H+M	380±594	681±565	1,062±1,051	75±105	113±190	188±213

Table 3-8. The live/dead ratio of fine roots at various root diameters (< 1, < 2, < 5 and < 10 mm in diameter) at different depths (H = humus; M = mineral soil) in the following sites AFM 001247 (*Picea abies, Pinus sylvestris* – fresh), AFM 001068 (*Picea abies* – fresh/moist) and AFM 001076 (*Alnus glutinosa* – moist) forest sites at Forsmark and ASM 001426 (*Quercus robur* – fresh), ASM 001440 (*Picea abies* – fresh) and ASM 001434 (*Alnus glutinosa* – moist) forest sites at Laxemar. Estimates are given as mean values ± SD (n=32).

Site	Horizon	Tree roots (g g^{-1})				Roots of field-layer species (g g^{-1})			
		< 1	< 2	< 5	< 10	< 1	< 2	< 5	< 10
Forsmark									
AFM001247	H 0-2.5	14.07	13.31	4.59	5.40	58.68	65.22	70.09	70.09
	H 2.5-5	4.17	3.96	5.20	7.65	27.66	39.62	48.60	48.60
	H 5-10	2.90	2.75	2.69	3.74	10.14	13.72	13.72	28.21
	H 10-15	0.94	0.99	0.80	0.56	1.99	1.99	1.99	1.99
	H 15-20	1.03	0.52	0.52	0.81	1.41	1.41	1.41	1.41
	M 0-10	1.23	1.36	1.29	1.38	3.84	2.84	2.84	2.84
	M 10-20	1.38	1.38	1.41	2.79	17.40	17.40	17.40	17.40
	H	3.59	3.30	2.96	3.75	25.20	28.40	31.35	36.62
	M	1.24	1.36	1.31	1.52	3.32	3.32	3.32	3.32
	H+M	2.24	2.19	1.94	2.25	9.39	10.28	11.10	12.57
AFM001068	H 0-2.5	8.04	6.69	8.05	6.83	23.88	9.95	19.00	19.75
	H 2.5-5	1.01	0.95	1.64	3.19	5.73	6.79	25.50	25.48
	H 5-10	0.64	1.41	2.24	2.24	–	–	–	–
	M 0-10	1.67	1.75	2.12	2.47	2.07	4.67	2.84	4.67
	M 10-20	0.70	0.72	0.96	1.13	4.58	4.67	4.67	4.67
	M 20-30	0.34	0.37	0.62	0.62	31.18	34.30	34.30	34.30
	H	3.38	3.05	3.87	4.29	14.59	10.15	24.42	24.84
	M	1.31	1.31	1.57	1.76	2.28	2.57	3.01	3.01
	H+M	1.41	1.40	1.67	1.85	2.82	3.13	4.56	4.59
AFM001076	H 0-2.5	5.09	5.61	3.85	3.50	4.81	5.66	6.17	6.17
	H 2.5-5	2.02	1.60	1.97	1.87	2.77	5.16	9.63	9.63
	H 5-10	1.09	1.10	1.19	1.62	0.96	1.75	1.42	1.42
	H 10-15	1.09	1.01	1.13	1.16	2.79	2.57	2.57	2.57
	H 15-20	1.51	1.49	1.12	0.85	1.68	3.94	3.94	3.94
	H 20-25	0.47	0.42	0.42	0.34	1.45	1.45	1.45	1.45
	H 25-30	–	–	–	–	–	–	–	–
	M 0-10	0.64	0.68	1.02	1.16	0.94	1.81	3.23	3.23
	M 10-20	0.43	0.51	0.45	0.49	0.75	0.95	0.45	2.43
	M 20-30	0.41	0.98	0.40	0.53	–	–	–	–
	M H	1.81	1.45	1.33	1.51	2.30	2.98	3.07	2.96
	H M	0.58	0.64	0.83	0.93	0.92	1.66	3.09	3.08
	M H+M	1.28	1.17	1.18	1.30	1.84	2.57	3.07	2.99

Site	Horizon	Tree roots (g g^{-1})				Roots of field-layer species (g g^{-1})			
		< 1	< 2	< 5	< 10	< 1	< 2	< 5	< 10
Laxemar									
ASM001426	H 0-2.5	3.36	2.71	3.93	3.93	2.67	3.21	0.11	3.15
	H 2.5-5	2.31	2.30	2.08	2.08	2.98	3.04	0.35	4.02
	H 5-10	2.76	2.68	1.63	2.31	4.10	4.10	0.81	4.80
	M 0-10	1.18	1.15	1.34	1.33	2.30	2.08	1.96	2.03
	M 10-20	0.35	0.37	0.50	1.88	3.20	2.74	7.87	1.80
	H	2.68	2.51	2.27	2.54	2.95	3.29	3.61	3.63
	M	1.04	1.02	1.22	1.37	2.33	1.10	2.02	2.01
	H+M	1.59	1.45	1.53	1.59	2.75	2.87	3.04	3.05
ASM001440	H 0-2.5	5.64	5.63	5.77	2.89	5.64	52.63	3.11	136.41
	H 2.5-5	2.89	2.79	3.28	3.93	8.67	20.33	7.47	109.44
	H 5-10	0.91	1.31	1.76	1.76	–	–	–	–
	M 0-10	1.84	1.90	1.67	1.78	36.78	52.22	41.70	52.22
	M 10-20	0.72	0.72	0.77	0.79	–	–	266.28	–
	M 20-30	0.80	0.72	0.64	0.74	–	–	–	–
	M 30-40	0.16	0.21	0.63	0.60	0.27	0.27	877.95	0.27
	H	3.51	3.54	3.97	3.10	23.04	41.00	126.70	126.70
	M	1.06	1.05	1.04	1.13	8.92	12.09	12.98	12.09
	H+M	1.51	1.45	1.43	1.41	11.99	18.38	39.23	37.01
ASM001434	H 0-2.5	0.29	0.38	0.39	0.49	3.30	4.15	1.73	4.65
	H 2.5-5	0.14	0.20	0.40	0.67	1.74	1.63	8.30	1.81
	H 5-10	0.11	0.11	0.57	1.01	1.25	1.25	110.57	1.25
	M 0-10	0.15	0.18	0.24	0.24	1.56	1.14	15.67	0.53
	M 10-20	0.20	0.21	0.56	0.79	0.39	0.17	26.29	0.06
	M 20-30	0.15	0.20	0.73	1.37	0.38	0.35	29.52	0.14
	M 30-40	0.19	0.16	0.52	1.36	0.23	0.30	18.26	0.12
	H	0.22	0.28	0.41	0.61	2.78	3.16	3.65	3.65
	M	0.16	0.19	0.37	0.54	0.89	0.58	0.41	0.23
	H+M	0.18	0.22	0.38	0.56	1.46	1.22	1.09	0.66

4 Discussion

Tree fine roots

Roots comprise a substantial portion of the total dry weight in forest ecosystems. Generally, tree roots account for up to a fourth of the total biomass /Persson 2002/. Data for structural coniferous and deciduous root systems under different environmental conditions show a remarkable consistent relationship between root system dry weight of structural roots and diameter at breast height /Santantonio et al. 1977/. The fact that the ratio between structural root dry weight/above-ground dry weight of woody tissues varied from 4% up to 40% was confirmed using literature data from 50 different forest ecosystems /Persson 2002/. Generally, roots account for 15–30% of the total tree biomass.

The woody root biomass of forest trees represents a varying proportion of the total forest biomass during the stand development /Persson 2002/. Root growth investment varies during the stand development and may at certain moments be even higher than in above-ground structures. Biomass accumulation in woody roots does not necessarily occur at the same time as accumulation in above-ground tree structures. Many woody roots remain alive as long as the trees stay alive. In temperate regions they may remain alive up to > 100 years.

The long-lived woody framework of structural roots supports a mass of short-lived nonwoody fine roots associated with mycorrhizal fungi. Fine-root biomass and necromass, in stands of different age, vary in response to water and nutrient availability, which makes the comparisons of age-series difficult /Persson 2000/. Quantification of fine roots is highly required in forest ecosystems due to their important role as carbon sinks and sources input of soil organic matter /Jackson et al. 1966/. However, it is not advisable, due to the high variability of the fine roots, to estimate the fine-root biomass as a proportion of total root biomass or to use other structural parts of the tree for such estimations /Vogt and Persson 1991/.

The data of the amount of fine-root biomass and necromass at the Forsmark and Laxemar sites 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.

All investigated coniferous forest sites, two at Forsmark and one at Laxemar, indicated high live/dead ratios. The live/dead ratio for the two coniferous sites at Forsmark was 2.2 (range = 14.1–1.4) and 1.4 (range = 8.0–0.3) respectively. The highest live/dead ratio is always found in the humus layer. The live/dead ratio for the Laxemar site was 1.5 (range = 5.6–0.2). Those live/dead ratios do not differ very much from literature data on live/dead ratios from about 10 European coniferous forest stands (*Picea abies*) ranging between 2.8–0.4 g/g /Persson 2000/.

The fine roots (< 1 mm in diameter) at the *Alnus glutinosa* sites at both Forsmark and Laxemar were fairly deep-rooted and consisted to a great extent of necromass (Tables 3-5, 3-8). The live/dead ratio in the total soil profile was 1.8 g/g (range = 5.1–0.4) and 0.2 g/g (range = 0.3–0.1 g/g) respectively (Table 3-8) in those sites. The older more densely developed "*Alnus glutinosa* site" at Forsmark differed considerably from the related Laxemar site with regards to both tree age and the number of trees/ha (Table 2-2).

The amount of fine roots in the "herb rich fairly open oak-forest" site at Laxemar was low, and the fine root of the field layer species was dominating in the soil profile. The live/dead ratio in the total soil profile was 1.5 g/g (range 3.4–0.4).

Comparable sites for deciduous trees in literature are few, however, the live/dead ratio of fine roots < 1 mm in diameter in a 161 year old European beech (*Fagus sylvatica*) stand in the northern part of France /Stober et al. 2000/ varied significantly during the season between 0.6–2.1 g/g. The live/dead ratio of fine roots < 1 mm in diameter in a 120 year old European beech forest in the Belgian Ardennes /van Praag et al. 1988/ was estimated to 0.6 g/g.

Field-layer species

Most studies on fine roots in forest ecosystems have concentrated on tree fine roots, while roots of the field-layer species, although most important in terms of dry weight, have been neglected /cf. Palviainen et al. 2005, Persson 1978/. Forest-trees are usually evolved in mixed ecosystems, in which survival in a competitive environment, not necessarily high production, is important. Our investigation confirms the quantitative importance of the fine roots of field-layer species (Table 3-8).

The field layer species were more substantially developed in the open forests stands, with a low stem density of the trees. Roots of tree and field-layer species were generally occupying different soil horizons and therefore to a limited extent they are competing with each other for water and nutrients. The superficial distribution pattern of field-layer species compared with tree species is confirmed with 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 sites consisted of fine roots of field layer species (Table 3-5).

In both of the "moist" sites (the "*Alnus* swamp" at Forsmark and the "*Alnus* shore forest" at Laxemar) a high amount of dead fine roots (necromass) was found in the total soil profile. In both those areas, in terms of dry weight, the field-layer species were proportionally more developed below-ground than above-ground (Table 2-2, Table 3-7). The above-ground biomass (living tissue) was only 9 and 11% of the total field-layer biomass in those areas.

Low above to below- ground biomass of the field-layer species (11%) was also found in the "coniferous fern type forest" (soil moisture class: fresh/moist) at Forsmark. These observations agree with data from an aspen (*Populus tremula*) site (fresh/moist) in a deciduous woodland in the province of Uppland /Persson 1975/, where the above-ground field-layer (herbaceous and graminaceous species) occupied about 16% of the total field-layer biomass.

In the two remaining areas, besides the "*Alnus* shore forest" at Laxemar, considerable higher above-ground in relation to below-ground biomass was recorded for the field layer. High above-ground biomass, 61% of the below-ground biomass, was recorded in the "coniferous forest of *Vaccinium myrtillus* type" and 25% in the "herb rich oak forest" (Table 2-2, Table 3-7). Both those areas were fairly dry (soil moisture class: fresh) and open (400 and 200 stems/ha, respectively) compared to other areas.

Comparable data to the Laxemar areas are some Scots pine stands in Jädraås district in the province of Gästrikland /Persson 1979/. The above-ground field layer (dwarf shrubs, mainly *Calluna vulgaris*) occupied 62% of the total field layer in a young stand and 38% in a mature stand /Persson 1980, 1983/. Both stands were fairly open (453 and 393 stems/ha, respectively) and dry. The field layer also consisted of dwarf shrubs of the family *Ericaceae*.

Live and dead roots

Distinguishing live and dead roots is a fundamental but difficult part of root investigations /Persson 1978/. Subsequent changes in the live-to-dead ration of the fine-root tissue is connected with its ageing /Persson 2000/. The low live/dead ratio at the "*Alnus* swamp" at Forsmark and the "*Alnus* shore forest" at Laxemar, in the total soil profile, should probably be related to a decreased decomposition in the water saturated soil environment. Furthermore, dry soil conditions have been demonstrated to decrease the live/dead ratio /Santantonio and Hermann 1985/.

Fine roots are sensitive to drought and their live/dead ratios are decreasing with less water availability in the soil /cf. Persson et al. 1995, Santantonio et al. 1977, Santantonio and Hermann 1985/. During the summer months temporary rain showers affect mainly the upper humus layers. Fine roots respond quickly to environmental changes and are rapidly penetrating those wet horizons.

Subsequent changes in the live/dead ratios of fine-roots are connected with drought stress. It has been demonstrated that fine roots are sensitive to drought and that their live-to-dead-ratios are decreasing with less water availability in the soil /Olsthorn 1991, Persson et al. 1995, Santantonio and Hermann 1985/. It is reasonable to expect a high death rate in the finest < 1 mm diameter root fraction, during summer drought. The live/dead ratio seems to be the most powerful vitality criterion of fine roots.

Fine roots are constantly penetrating the soil horizons for the uptake of soil water and nutrients /Person 2000/. The efficiency of the uptake processes is determined, to a great extent, by the growth of recently formed root tips. The live/death ratio, in this context, is an indicator of the growth activity of the fine roots, both temporarily and spatially in the soil profile. Processes influencing the live/dead ratio, at any moment, are growth, death and decomposition of the fine roots. A high live/death ratio, in any forest stand, indicates a healthy root system with a high rate of soil penetration (e.g. an efficient uptake function).

Substantial variations in fine-root biomass, necromass and live/dead ratios usually occur in tree stands depending on site quality /Clemensson-Lindell and Persson 1995, Ostonen et al. 1999, Persson 2002, Persson and Ahlström 2002, Raich and Nadelhoffer 1989/. In boreal forest ecosystems, the well-developed organic-rich podzol profiles with a thick humus layer most effectively buffer the soil system against drought and nutrient deficiencies.

Most dead fine roots (necromass) are generally found in the mineral soil. The high necromass concentration in this soil horizon is probably due to harsher environmental conditions, causing a high rate of death, counterbalanced to some extent by the invasion of new fine roots from the upper organic soil horizons.

Tree roots are developed in a mixed and competitive environment, in which a long-term strategy for their function is essential. Tree fine roots exposed to a relatively low nutrient availability are highly dependent on the mycorrhizae for their nutrient uptake /cf. e.g. Marschner 2002/. Fine-root "vitality" in terms of live/dead ratios of the fine roots should be expected to be high in the humus layers, since the extensive mycorrhizal infection in that layer makes the fine roots functional over a prolonged period of time /Persson and Ahlström 1999/.

Root diameter distribution

The contribution of different diameter classes to fine-root pattern in the soil profile may vary considerable, but few investigators seem to be aware of this problem while interpreting their data. Our data suggest that the distribution pattern of fine roots and coarser root fractions of both tree and field layer species may vary depending on the investigated diameter class. Our data suggest that the often-reported discrepancy in the data on fine-root distribution in literature is partly due to imprecise definition of size classes of the fine roots.

As a result of better moisture and nutrient conditions, there is generally a much greater proliferation of the fine roots including the mycorrhiza (< 1 mm in diameter) in the humus layer /cf. Persson 1978, 2000, Marschner 2002/. The importance of the humus horizon for the amount of tree fine-root biomass (< 1 mm in diameter) is obvious in all investigated vegetation types (Tables 3-1, 3-5 and 3-8). The root biomass of the field-layer species is furthermore superficially distributed in all diameter fractions.

Concluding remarks

Our investigations stress the importance, while studying fine-root distribution, to relate to the natural soil-horizons. The most commonly used methods of estimating fine-root production and mortality involves periodic measurements of live and dead (or live + dead) dry weights of fine roots in soil cores. The often-reported discrepancy in the data on root litter formation may partly be due to imprecise definition of size classes (diameter), vitality of the root fragments (biomass and necromass) and species (tree or field-layer species) of the fine roots.

Methods, which do not account for live and dead categories of fine roots, should be avoided and are of limited value. For tree species, subdividing and separating roots into < 1 mm in diameter has a sound morphological basis /Vogt and Persson 1991/. Most of the total length and surface area of the tree roots is to be found in the fine root fraction.

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