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Spatial Distribution of Fine Roots at Ploughed Norway Spruce Forest Sites

Niina Tanskanen and Hannu Ilvesniemi

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We examined the spatial distribution of fine roots at two forest sites that were ploughed 20 (site K1) and 33 years (site K2) before sampling and planted with Norway spruce (*Picea abies* (L.) Karst.) seedlings. Soil core samples were taken from the tilt and beneath the tilt, the furrow and the intermediate undisturbed soil to a depth of 0.4 m for fine root biomass, length and necromass determinations. Norway spruce fine roots were found throughout the ploughed forest sites. The fine roots were, however, unevenly distributed: the fine root biomass was highest in the tilt (624 and 452 $g\,m^{-2}$ at sites K1 and K2, respectively) and lowest in the undisturbed soil at site K1 (79 $g\,m^{-2}$) and in the furrow at site K2 (145 $g\,m^{-2}$). The estimated average fine root biomass at the ploughed forest sites (268 and 248 $g\,m^{-2}$ at sites K1 and K2, respectively) was, however, similar to those presented in other studies concerning sites that had not been ploughed. In the tilt, a substantial proportion of the fine roots was in the inverted mineral soil horizons and in the new organic horizon above the tilt. Consistent with the fine root biomass findings, the Norway spruce necromass was highest in the tilt but the vertical distribution of the dead roots was different: the necromass was highest in the buried O_{BT} horizon. The results of this study suggest that at the ploughed forest sites, a substantial part of Norway spruce nutrient and water uptake occured in the tilt during the first 20 or 33 years after plantation.

Keywords fine roots, forest soil, *Picea abies*, ploughing, spatial distribution, specific root length, understorey roots
Authors' addresses *Tanskanen*, Department of Forest Ecology, P.O. Box 27, FI-00014 University of Helsinki, Finland; *Ilvesniemi*, Finnish Forest Research Institute, P.O. Box 18, FI-01301 Vantaa, Finland **E-mail** niina.tanskanen@helsinki.fi
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1 Introduction

Mechanical site preparation has been used to ensure efficient reforestation at clear-felled areas in Finland since the late 1960s. Ploughing was one of the most widely used preparation methods, especially, during the 1970s and 1980s. It has been estimated that about 18% (3.94 million ha) of the total forest land area in Finland has been site-prepared (Finnish Forest Research Institute 2001), of which one-third has been ploughed or mounded.

Ploughing has been shown to promote the rapid establishment, early growth and good survival of seedlings by suppressing competing vegetation and improving soil temperature and moisture conditions (e.g. Mälkönen 1972, Leikola 1974, Pohtila 1977, Ritari and Lähde 1978, Saksa et al. 1990, Kubin and Kemppainen 1994). In ploughing, the stratified structure of the podzolic soil is substantially altered: the soil profile down to and including the upper B horizon is inverted on the soil surface as a tilt while the eluvial (E) and organic (O) horizons are buried within the tilt above the original soil surface. Accelerated decomposition and mineralisation has been found in site-prepared soils a few years after preparation (Palmgren 1984, Johansson 1994, Lundmark-Thelin and Johansson 1997) and attributed mainly to increased soil temperature (Salonius 1983). Thus, it may be assumed that in the first stage, the fine root system of the planted seedlings utilise the restricted space of the tilt. The spatial distribution of the fine roots at ploughed forest sites in the long term is not, however, known. It has been assumed that the growth of the seedlings might be reduced if roots are not extended out of the tilt to the undisturbed soil (Mälkönen 2003).

The root system of Norway spruce (*Picea abies* (L.) Karst.) is characterised by shallow lateral roots with sinkers. Most of the root biomass is located in the upper 30 cm of the mineral soil and in the humus layer (Köstler et al. 1968). The extent of the root system may vary as a function of tree species, stand structure and site type (Stone and Kalisz 1991). Ammer and Wagner (2002) estimated that the roots of Norway spruce extend about 8 to 15 m from the stem depending on the density of the stand. Taskinen et al. (2003) found that the Norway spruce root system was concentrated in the zone approximately 5 m around the tree in the mature Norway spruce stand. As the mean stem to stem distance in the forest stand was 4.5 m, the results suggest that the effective root system of an individual tree did not extend much further than to the adjacent neighboring trees (Taskinen et al. 2003).

Fine roots are an essential part of the root system of forest trees since fine roots with associated mycorrhizas are mainly responsible for nutrient and water uptake from soil. Although the proportion of fine roots and mycorrhizas of the total tree biomass is not large, their growth and maintenance may use a major part of total net primary production. Helmisaari et al. (2001) estimated that 43–60% of the total stand biomass produced annually was allocated to fine root biomass production in Scots pine (*Pinus sylvestris* L.) stands. Consequently, substantial amounts of organic matter are transferred to soil when the roots die. Compared to coarse roots, fine roots contribute more to soil organic matter accumulation because the fine roots stay alive only for a short period of time, and thus produce high amounts of fast-decaying organic matter (Vogt et al. 1991). Fine roots also contribute to soil organic pools while they are alive: nutrient uptake by plant roots is accompanied by other processes, such as release of protons, CO_2, enzymes and organic exudates. Increased carbon availibility due to root exudation and sloughing results in higher bacterial and fungal populations and higher microbial activity in the vicinity of plant roots (e.g. Stark 1994). Consequently, the chemical and physical properties of the rhizosphere soil differ from the bulk soil (Gobran and Clegg 1996).

Formation of soil heterogeneity is a result of continuous interaction between soil, plant roots and soil fauna (Stark 1994). Tanskanen and Ilvesniemi (2004) recently found that in ploughed soil profiles some solid phase aluminium was mobilised. The concurrent increase in soil organic C suggested that Al mobilisation was mainly due to organic matter produced by the roots. The spatial distribution of fine roots may be a key to understanding soil properties and potential changes in these properties at ploughed forest sites. The spatial distribution of fine roots at ploughed forest sites is also of major interest when plant nutrient and water uptake in the long term are considered. The aim of this study was to determine the spatial distribution of fine roots at two forest sites that were ploughed 20 and 33 years before sampling and planted with Norway spruce seedlings.

2 Material and Methods

2.1 Site Description

Soil samples were collected from two ploughed forest sites located in Karkkila (K1, 60°32´N, 24°16´E) and Kuorevesi (K2, 61°53´N, 24°35´E), in southern Finland. The mean temperatures in southern Finland are about –8 °C in January and 16 °C in July and annual precipitation averages 600–700 mm (Finnish Meteorological Institute 1993).

The K1 site was established by Finnish Forest Research Institute. The plot of 40 m × 40 m was clear-cut and ploughed in 1979 and planted with Norway spruce seedlings in 1980. The K2 site was established by Finnish Forest and Park Service. The plot of 30 m × 30 m was clear-cut and ploughed and planted with Norway spruce seedlings in 1966. As a result of ploughing, the forest sites consisted of a series of tilts and furrows with strips of undisturbed soil between. After ploughing, the depth of the furrows had been on average over 30 cm and the height of the tilts about 40 cm as compared to mineral soil surfaces at both sites. Seedlings were planted on the tilts.

Site K1 was a fertile *Oxalis-Myrtillus* (OMT) type according to Finnish classification of forest types (Cajander 1925) whereas site K2 was a less fertile *Myrtillus* (MT) type. At the time of sampling, the field layer was dominated by *Calamagrostis arundinacea* (L.) Roth in the undisturbed soil at site K1. The field layer was also comprised of species of *Vaccinium myrtillus* L., *Maianthemum bifolium* (L.) F.W. Schmidt, *Trientalis europaea* L. and *Rubus saxatilis* L. In the tilt and furrow, the ground layer was covered by mosses *Pleurozium schreberi* (Brid.) Mitt. and *Dicranum polysetum* Sw. The field layer at site K2 was characterised by *Deschampsia flexuosa* (L.) Trin. and *Vaccinium myrtillus* L., and the ground layer by *Pleurozium schreberi. Sphagnum girkensohnii* Russ. was variously abundant in the furrow at site K2. Seedlings of *Sorbus aucuparia* L. and *Betula pendula* Roth. were also occasionally observed at both study sites.

Table 1. Average thickness of the soil horizons (cm) in the tilt (T), beneath the tilt (BT), furrow (F) and undisturbed soil (U) at sites K1 and K2. Note that in the tilt the mineral horizons were reversed as a result of ploughing.

	O	Ah/E	Bs	BC
Site K1				
T	0.75	8	12	-
BT	5	8	30	20
F	2	-	15	20
U	4	8	30	20
Site K2				
T	1.8	5	8	-
BT	7	7	22	20
F	4	-	10	20
U	5.5	7	22	20

At the time of sampling, percentage of living Norway spruce seedlings was 101% of those planted at the more detailed studied K1 site. The stand had 2836 stems ha^{-1} and stem volume was 42 $m^3\,ha^{-1}$ while stem volume of birch trees was 2 $m^3\,ha^{-1}$. The mean height of Norway spruce seedlings was 6.2 m.

Site K1 was classified as a Cambic Podzol (FAO-Unesco 1990) with an Ah horizon; the parent material was glacial till of a silt-loam texture. Site K2 was classified as a Haplic Podzol (FAO-Unesco 1990) with an E horizon; the parent material was glacial till with a texture of sandy loam. A new O horizon was formed on top of the tilt (O_T) and in the furrow (O_F) (Table 1). The O_T layer consisted mainly of undecomposed litter residues of needles and hay, especially at site K1. The mineral soil beneath the tilt was similar to that of the undisturbed soil, and the buried O horizon (O_{BT}) was located on top of it (Table 1).

2.2 Root Sampling and Analysis

For fine root determinations, ten core samples from each sampling position – the tilt (T), beneath the tilt (BT), the furrow (F) and the intermediate undisturbed soil (U) – were taken with a soil auger (diameter 0.046 m) to a depth of 0.4 m in June 1999. The soil cores were divided into podzolic soil horizons. The Bs horizon was further divided into subhorizons consisting of the upper part (0–5, 5–10 cm) and lower part (10–20 cm, 20–30 cm) of the horizon. In the tilt and furrow, the first three cm (0–3 cm) of the exposed Bs horizon beneath the O_T and O_F horizons were sampled separately at both study sites, since a darker soil colour in comparison with the soil beneath indicated the occurrence of changes in the soil. Samples were stored frozen (–18 °C) until analysis.

In the laboratory, the roots were washed free of soil and classified into three groups: 1) Norway spruce roots, 2) dwarf shrub roots, and 3) grass roots. Dwarf shrub roots consisted also of roots of deciduous trees that were occasionally found at both study sites. Dead roots were distinguished from living roots on the basis of their colour and consistency. Length of living roots and diameter distribution were measured using the image analysis system WinRHIZO™ V 3.0.2 (Regent Instruments Inc., Quebec, Canada). The separated roots were dried at 70 °C for two days and weighed to determine the oven-dry biomass of Norway spruce fine (< 2 mm) roots and coarse (> 2 mm) roots. For understorey roots and dead roots, total biomass and necromass were determined. It must be noted that the necromass determined in the present study included all the dead roots sampled by the soil core method. Thus, necromass of fine and small roots may be more accurate description of the sampled necromass than total necromass.

2.3 Calculation

Total fine root density at ploughed forest sites was estimated by assuming that on average, 60% of the soil surface is disturbed during ploughing and half of the disturbed area is tilt and half is furrow (Kellomäki 1972, Ferm and Pohtila 1977, Saksa et al. 1990). A One-way analysis of variance and a Kruskal-Wallis test were used to compare the root biomass and length in different soil profiles (T, F, U), the Norway spruce biomass/necromass ratio and the specific root length (SRL = fine root length/fine root biomass, $m\,g^{-1}$) in the O horizons in different soil profiles. The nonparametric test, Kruskal-Wallis test was often preferred because the data distribution in many cases was not normal. Differences with a P value ≤ 0.05 were considered to be significant.

3 Results

3.1 Distribution of Norway Spruce Fine Roots

Norway spruce fine root biomass and length were highest in the tilt at both study sites (Table 2). The biomass and the length were lowest in the undisturbed soil at site K1 and in the furrow at site K2 (Table 2). Of all the fine roots at site K1, 70%

Table 2. The mean and standard error of biomass ($g\,m^{-2}$) and length (< 2 mm, $m\,m^{-2}$) of Norway spruce fine roots (< 2 mm) and roots of dwarf shrubs and grasses in the tilt and beneath the tilt (T), furrow (F) and undisturbed soil (U) at sites K1 and K2. Values with different letters differ significantly (P < 0.05) from each other for each site.

	Norway spruce		Dwarf shrubs		Grasses	
	Biomass <2 mm	Length <2 mm	Biomass Total	Length <2 mm	Biomass Total	Length <2 mm
Site K1						
T	624 ± 70 a	8939 ± 1716 a	200 ± 65 a	9761 ± 1355 a	12 ± 12 a	117 ± 113 a
F	189 ± 55 b	2642 ± 845 b	51 ± 16 b	2894 ± 1170 b	1 ± 1 ab	361 ± 127 ab
U	79 ± 24 b	1656 ± 517 b	99 ± 33 ab	955 ± 257 b	5 ± 2 b	967 ± 256 b
Site K2						
T	452 ± 95 a	5080 ± 1065 a	194 ± 56 a	1898 ± 518 a	22 ± 7 a	1750 ± 700 ab
F	145 ± 16 b	1752 ± 191 b	100 ± 31 a	1999 ± 665 a	0.5 ± 0.3 b	72 ± 41 a
U	231 ± 53 ab	4258 ± 912 ab	232 ± 58 a	1428 ± 331 a	9 ± 3 a	1236 ± 414 b

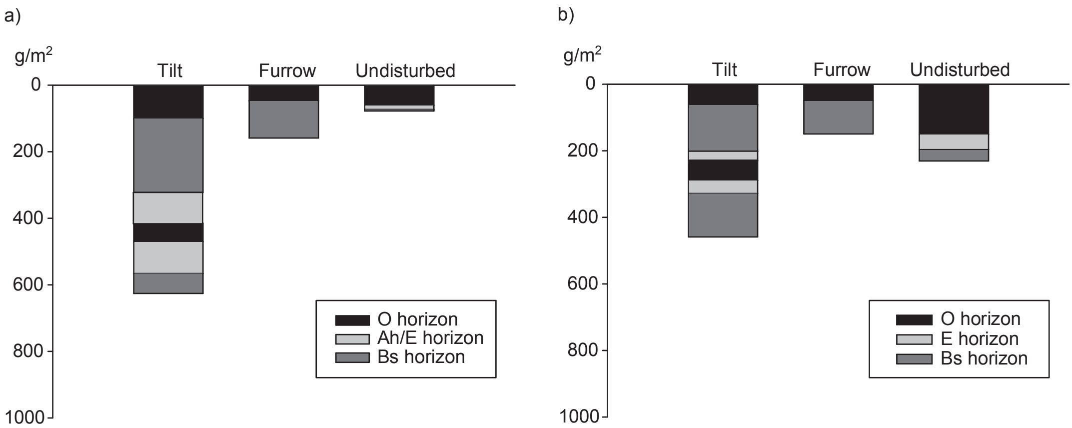

Fig. 1. Norway spruce fine root biomass in soil horizons of the tilt, furrow and undisturbed soil at site K1 (a) and site K2 (b).

were in the tilt, 20% in the furrow and 10% in the undisturbed soil, when it was estimated that 60% of the soil surface is disturbed during ploughing (Ferm and Pohtila 1977, Saksa et al. 1990). At site K2, the fine roots were more evenly distributed: 50% were in the tilt, 17% in the furrow and 33% in the undisturbed soil.

A major part of the Norway spruce fine root biomass and length was in the uppermost podzolic horizons: in the undisturbed soil, over 80% of all the fine roots were in the O_U and in the Ah_U/E_U horizons at both study sites (Fig. 1). Correspondingly, a majority of the fine roots in the furrow were in the new O_F horizon and in the 3-cm-thick Bs_F subhorizon beneath. In the tilt, a substantial proportion of all the fine roots was in the new O_T horizon and in the inverted mineral horizons of the tilt (68% at site K1 and 54% at site K2; Fig. 1). The proportion of fine roots in the buried O_{BT} horizon was on average 9% of all the fine roots in the tilt at both study sites (Fig. 1). In the mineral horizons beneath the tilt, the proportion of all the fine roots was higher at site K2 (37%) than at site K1 (23%).

The mean root diameter of the spruce increased with soil depth: the diameter was 0.5 mm in the Bs_T horizons in the tilt and 1.2 mm in the Bs_{BT} horizons beneath the tilt. Concurrently, the specific root length was higher in the mineral horizons of the tilt (17 ± 1 m g^{-1}, mean ± S.E.) than in the mineral horizons beneath the tilt (11 ± 1 m g^{-1}). At site K1, the SRL was also lower in the O_{BT} horizon than in the O_F and O_U horizons (Table 3). At site K2, no significant differences between the SRL in the O horizons were observed.

Table 3. Specific root length (SRL = fine root length/fine root biomass, m g^{-1}) of Norway spruce in the O horizon of the tilt (T), and beneath the tilt (BT), furrow (F) and undisturbed soil (U). Mean ± S.E. Values with different letters differ significantly ($P < 0.05$) from each other for each site.

	T	BT	F	U
Site K1	15 ± 1 ab	10 ± 1 a	26 ± 3 b	26 ± 3 b
Site K2	20 ± 2 a	14 ± 4 a	18 ± 2 a	21 ± 1 a

3.2 Distribution of Norway Spruce Necromass

Norway spruce necromass (including all the dead roots sampled by the soil core method) was highest in the tilt and lowest in the furrow at both study sites (Fig. 2). At both study sites, a substantial proportion of the necromass in the tilt was in the buried O_{BT} horizon and in the adjacent Ah_T and

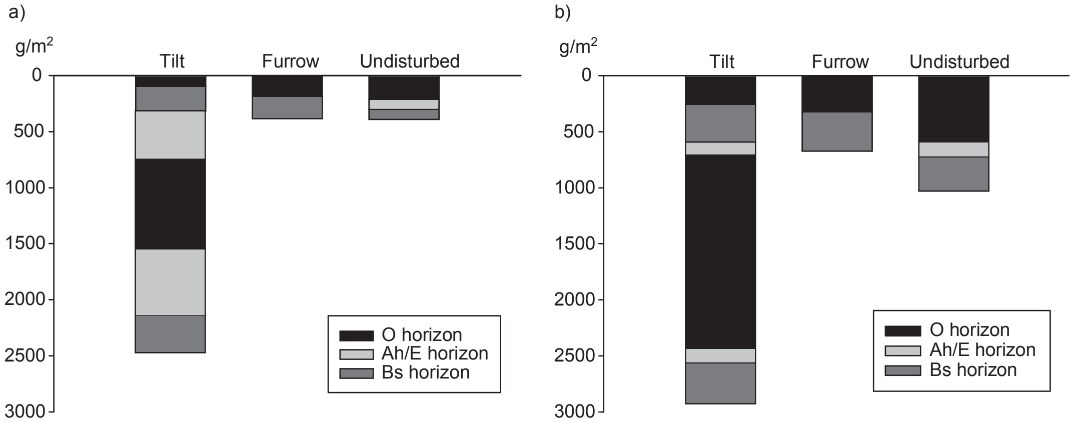

Fig. 2. Norway spruce necromass in soil horizons of the tilt, furrow and undisturbed soil at site K1 (a) and site K2 (b).

Table 4. Ratio of Norway spruce fine root biomass to total necromass in the O horizon of the tilt (T), and beneath the tilt (BT), furrow (F) and undisturbed soil (U). Mean ± S.E. Values with different letters differ significantly ($P < 0.05$) from each other for each site.

	T	BT	F	U
Site K1	1.11 ± 0.25 a	0.08 ± 0.01 b	0.50 ± 0.28 a	0.28 ± 0.09 a
Site K2	0.46 ± 0.15 a	0.13 ± 0.05 a	0.16 ± 0.03 a	0.28 ± 0.06 a

Ah_{BT} horizons at site K1 (Fig. 2).

The ratio of fine root biomass to total necromass was highest in the O_T horizon and lowest in the buried O_{BT} horizon at site K1 (Table 4). At site K2, no significant differences were observed (Table 4). The biomass/necromass ratio in the Bs_T horizons (1.22 ± 0.23) was also higher than in the corresponding Bs_{BT} horizons beneath the tilt (0.20 ± 0.06) at site K1.

3.3 Distribution of Understorey Roots

The length of dwarf shrub fine roots was highest in the tilt at site K1 and lowest in the undisturbed soil at both study sites (Table 2). However, when the total dwarf shrub root biomass was considered, the biomass was lowest in the furrow at both study sites (Table 2, Fig. 3). The total biomass of understorey roots can be regarded as relatively close to that of fine roots since roots less than 2 mm in diameter comprised 96% of the dwarf shrub roots and correspondingly, 98% of grass roots.

In the tilt, a relatively large proportion of shrub fine root length was in the inverted mineral horizons of the tilt whereas the proportion in the O_T horizon was small (6% at site K1 and 1% at site K2). In contrast, a substantial proportion of all the dwarf shrub roots in the undisturbed soil was in the O_U horizon (47% at site K1 and 65% at site K2).

Spatial variation in the grass roots was large, especially in the tilt and furrow at both study sites (see S.E. in Table 2). The grass fine root length was greatest in the undisturbed soil at site K1 and in the tilt at site K2. In the undisturbed soil, a relatively large proportion of the fine root length – over 60% of all the grass fine roots – was in the Bs_U horizons at both study sites. At site K2, the

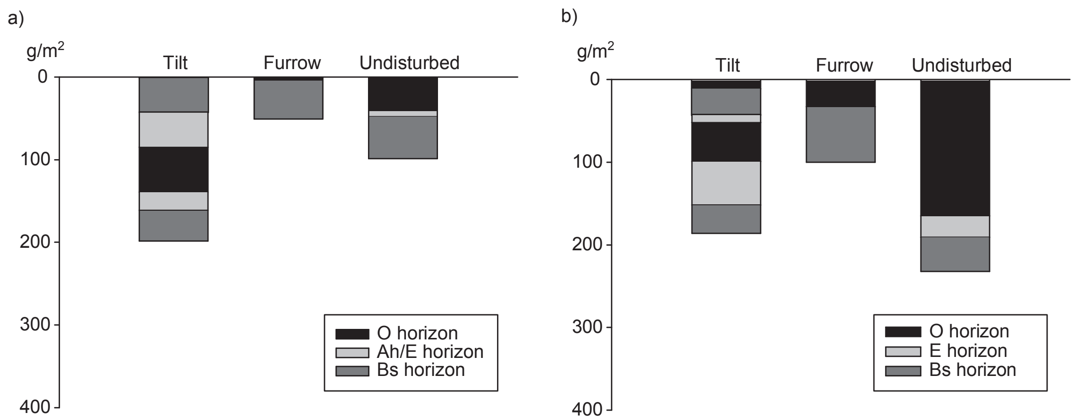

Fig. 3. Dwarf shrub root biomass (including roots of deciduous trees) in soil horizons of the tilt, furrow and undisturbed soil at site K1 (a) and site K2 (b).

grass rooting depth in the tilt was consistent with that of the undisturbed soil.

4 Discussion

Norway spruce fine roots were found throughout the ploughed forest sites. The fine roots were, however, unevenly distributed: the fine root biomass was clearly the highest in the tilt, indicating that a substantial proportion of Norway spruce nutrient and water uptake occured in the tilt although the time elapsed since ploughing was 20 and 33 years. The Norway spruce fine root biomass at the ploughed forest sites was 268 $g\,m^{-2}$ at site K1 and 248 $g\,m^{-2}$ at site K2 when it was assumed that on average 60% of the soil surface is disturbed during ploughing (Ferm and Pohtila 1977, Saksa et al. 1990). The estimates were at the same level as those reported by Helmisaari and Hallbäcken (1999), 210–528 $g\,m^{-2}$ for roots <2 mm; Lôhmus et al. (1991), 126 $g\,m^{-2}$ for roots <1 mm; Vogt et al. (1996), 57–202 $g\,m^{-2}$; and Taskinen et al. (2003), 182 $g\,m^{-2}$ for a boreal zone Norway spruce forest. This suggests that no major differences in fine root biomass were caused by ploughing at the studied forest sites. The fine root lengths, 3970 $m\,m^{-2}$ at site K1 and 3330 $m\,m^{-2}$ at site K2, were slightly higher than those (1504–3207 $m\,m^{-2}$) reported by Taskinen et al. (2003) and Persson and Ahlström (2002) for mature, 80–100-year-old Norway spruce stands. The higher root length in the present study may, however, be related to stand age since greater fine root biomass has been found in a Scots pine stand at canopy closure than in a mature stand (Helmisaari et al. 2001).

At site K2, the Norway spruce fine roots were more evenly distributed in the undisturbed soil than at site K1. The tilts at site K2 were lower and the undisturbed soil between the tilts was narrower, which may partly explain the differences observed. Site K2 was also a less fertile site and the time elapsed since the site preparation was longer, which may also explain the more even distribution of fine roots within the site. The extent of the root system may vary as a function of tree species, stand structure and site type (Stone and Kalisz 1991), the extent being greater in poor soils.

The root system of Norway spruce is characterised by shallow lateral roots with sinkers. This was also observed in the present study since most of the fine roots were located in the uppermost soil horizons. The rooting depth was deeper in the tilt than in the undisturbed soil. This may be due to intensive nutrient and water uptake in the tilt that leads occasionally to low soil water potentials and thereby forces the root system to penetreate into the deeper soil horizons to seek potential water sources.

Norway spruce necromass was highest in the tilt, consistent with the biomass findings. The estimated total necromass was 966 g m^{-2} at site K1 and 1307 g m^{-2} at site K2. The results were higher than those (112–900 g m^{-2}) presented by Persson and Ahlström (2002) and Helmisaari and Hallbäcken (1999) for fine root necromass in Norway spruce stands. The necromass determined in the present study included, however, all the dead roots of Norway spruce sampled by the soil core method and, subsequently, overestimated the fine root necromass. Within the tilt, the necromass was substantial in the buried O_{BT} horizon. Moreover, the ratios used to consider the vitality of the tree root system, the fine root biomass/necromass ratio and SRL (Clemensson-Lindell and Persson 1995, Persson and Ahlström 2002) were lower in the buried O_{BT} horizon than in the surface O horizons at site K1. The results indicated that this horizon has formerly played a significant role in nutrient supply but was nowadays less important for nutrient uptake.

The high fine root length of understorey vegetation in the tilt was an unexpected result since visually, most of the understorey vegetation grew in the undisturbed soil whereas the ground layer in the tilt was comprised mainly of mosses and a dense cover of dead needles. The high density of understorey roots in the tilt suggests that favourable conditions prevailed in the tilts and subsequently, dwarf shrub and grass roots exploited relatively large areas in order to occupy these nutrient reserves. The estimated total understorey root biomass (111 g m^{-2} at site K1 and 167 g m^{-2} at site K2; including roots of deciduous trees) was at the same level as those reported by Nilsson and Örlander (1999), 132 and 92 g m^{-2}; Makkonen and Helmisaari (2001), 79–646 g m^{-2}; and Taskinen et al. (2003), 99 g m^{-2} for understorey vegetation. Some root segregation was observed in the tilt – the low dwarf shrub root length in the O_T horizon (as compared to inverted mineral horizons beneath or to the corresponding O_U horizon) may be due to the decomposition stage of organic matter: the new O_T horizon consisted mainly of decaying spruce litter. It also seemed that a relatively larger proportion of the grass roots grew in the Bs_U and Bs_{BT} horizons than in the surface soil horizons above. This may suggest that grass roots were able to occupy soil horizons where the competition between the species was not so intense at the ploughed forest sites. However, in other studies, rooting profiles of the understorey vegetation has been shallow (Makkonen and Helmisaari 2001) and the roots of understorey vegetation occupied the same soil layers as Norway spruce fine roots (Taskinen et al. 2003).

It may be assumed that in the early stages of seedling development at the ploughed forest sites, the improved soil moisture, temperature and nutrient supply in the tilt (Mälkönen 1972, Leikola 1974, Pohtila 1977, Ritari and Lähde 1978) favour the fine root growth within the tilt. The results of this study – the high Norway spruce fine root biomass and necromass in the tilt – suggest that at the ploughed forest sites a substantial part of Norway spruce nutrient and water uptake occured in the tilt during the first 20 or 33 years after plantation. The distribution of fine roots at the ploughed forest sites also indicated that organic matter, produced primarily by root exudates and fine root turnover, may accumulate spatially unevenly in the tilts thereby modifying the properties of inverted podzolic soil profiles (Tanskanen and Ilvesniemi 2004) and, subsequently, the properties of the soil as a substrate for further fine root growth.

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