5.1.2 Tree biomass below-ground

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Fine-root biomass

In the Heinola (HEI) experiment in southern Finland, the Norway spruce fine-root biomass (< 2 mm diameter) was smallest in the PK-fertilized plot and greatest in the limed plot (Table 5.5). The differences between these two plots were significant ($p<0.05$). The biomass of finest roots (< 1 mm diameter) was small also in the N- and NCa-fertilized plots, especially in the upper soil layer (Fig. 5.16a). There were no significant differences in the necromass of fine roots (< 2 mm diameter). The fine-root biomass/necromass ratio was lowest in the PK-, NCa- and NPKCa-fertilized plots, and highest in the control plot (Table 5.5).

The fine-root biomass at Kemijärvi (KEM) in the PKCa-plot was smaller than in the control, N-, NP- and NPKCa-plots. There was also less fine-root biomass in the PK-, NCa- and limed plots than in the N-plot. The fine roots penetrated deeper soil layers in the N-fertilized plot than in the control (Fig. 5.17a). The fine-root necromass was greater in the NPKCa-fertilized plot than in all the other plots. The fine-root necromass was also greater in the NCa-plot than in the control, N-, PK, NP-, NPK- and limed plots. There was more necromass in the PKCa-plot than in the N-fertilized and limed plots. The biomass/necromass ratio was lowest in the PK-, NCa-, PKCa- and NPKCa-plots, and highest in the N-fertilized and limed plots (Table 5.5, Figs. 5.17a-b).

In the Sodankylä (SOD) experiment, the fine-root biomass (< 2 mm diameter) was larger in the NK- and NPK-plots than in the control and PK-plots. There was more necromass in the NP-fertilized plot than in the control plot. The biomass/necromass ratio was highest in the NPK-fertilized plot, and lowest in the N- and PK-fertilized plots (Table 5.5, Figs. 5.18a-b).

At Norråker (NOR), the NPKCa-plot had greater fine-root biomass than one of the control plots. There was more necromass in one of the N-plots and in NPK- and NPKCa-plots than in one of the control plots (Table 5.5, Fig. 5.19a).

Fine-root growth

The fine-root biomass in the ingrowth cores in the Kemijärvi (KEM) experiment was smallest in the limed plot and the PK- and PKCa-fertilized plots (Table 5.6). A greater part of fine roots grown into the ingrowth cores (biomass + necromass) had died (necromass) in the PK-, NCa- and PKCa-plots (Table 5.7). In these plots, the ingrowth of fine roots as percentage of fine-root biomass was also greatest (Table 5.8), varying between 22 and 70 % in the whole experiment. The fine-root ingrowth was greatest in all the plots receiving nitrogen alone or together with Ca or PK. The fine-root necromass was larger in the NCa- and N-plots than in all the other plots (Table 5.6).

At Sodankylä (SOD), the biomass of fine roots in the ingrowth cores was significantly larger in the NPK-, NP- and NK-plots than in the control (Table 5.6). The fine root ingrowth (biomass + necromass in the ingrowth cores) was largest in the same plots. A substantial part of fine roots in all plots had died after growing into the cores, especially in the PK- fertilized plot (Table 5.7). The percentage of fine root ingrowth (biomass+necromass) of the fine root biomass outside the cores during two years varied between 22 and 126 %, being highest in the PK- fertilized plot (Table 5.8). There was more fine-root necromass in the NPK-, PK- and NK-plots than in the control (Table 5.6).

Table 5.5. Fine-root mass (diameter <2 mm) in the humus layer and upper 30 cm mineral soil. At each plot 10 soil cores were collected at Sodankylä, Kemijärvi and Heinola. At Norråker 12 soil cores were collected. Values marked with the same letter do not differ significantly ($p<0.05$) between plots. The experiments are ordered according to increasing site index

Experiment	Treatment	Fine-root biomass $g\ m^{-2}$		Fine-root necromass $g\ m^{-2}$		Ratio Biomass/ necromass
		mean	s.e.	mean	s.e.	
Sodankylä	0	$_{a}$244.3	36.1	$_{a}$165.3	25.9	1.48
	N	$_{ab}$314.8	44.2	$_{ab}$474.0	77.6	0.66
	NP	$_{ab}$276.0	47.0	$_{b}$730.1	276	0.38
	NK	$_{b}$458.1	60.7	$_{ab}$237.6	35.7	1.92
	PK	$_{a}$119.1	27.2	$_{ab}$406.4	78.8	0.29
	NPK	$_{b}$458.8	68.3	$_{ab}$224.3	45.4	2.04
Kemijärvi	0	$_{bcd}$528.0	85.7	$_{ac}$226.3	35.5	2.34
	N	$_{d}$779.8	63.0	$_{a}$113.9	28.2	6.84
	PK	$_{ac}$225.1	43.2	$_{ac}$243.2	28.9	0.93
	Ca	$_{ab}$305.3	65.1	$_{a}$81.3	19.4	3.75
	NP	$_{bd}$581.9	90.8	$_{ac}$220.9	39.8	2.63
	NK	$_{abd}$487.3	103	$_{ab}$311.1	59.5	1.57
	NPK	$_{abd}$479.6	113	$_{ac}$283.6	46.8	1.69
	NCa	$_{abc}$302.0	47.1	$_{b}$506.8	70.1	0.60
	PKCa	$_{a}$158.7	26.9	$_{bc}$447.2	80.4	0.36
	NPKCa	$_{bcd}$520.3	98.3	$_{d}$788.6	96.2	0.66
Norråker	0	$_{a}$391.5	70.0	$_{b}$201.1	63.0	1.95
	0	$_{ab}$418.2	63.0	$_{ab}$513.8	74.0	0.81
	N	$_{ab}$567.8	45.0	$_{a}$797.8	97.0	0.71
	N	$_{ab}$544.0	118	$_{ab}$557.2	116	0.98
	NPK	$_{ab}$537.2	64.0	$_{a}$881.5	176	0.61
	NPKCa	$_{b}$726.2	89.0	$_{a}$812.1	131	0.89
Heinola	0	$_{ab}$209.7	32.9	$_{a}$236.4	26.4	0.89
	N	$_{ab}$151.1	27.7	$_{a}$289.1	23.0	0.52
	PK	$_{a}$116.3	24.0	$_{a}$372.9	31.2	0.31
	Ca	$_{b}$291.9	70.0	$_{a}$287.4	39.8	0.98
	NP	$_{ab}$256.9	38.7	$_{a}$332.9	42.4	0.77
	NK	$_{ab}$229.8	23.3	$_{a}$360.1	44.5	0.64
	NPK	$_{ab}$196.4	24.2	$_{a}$304.9	27.0	0.64
	NCa	$_{ab}$153.6	36.0	$_{a}$365.4	31.0	0.42
	PKCa	$_{ab}$173.7	28.9	$_{a}$223.6	38.6	0.78
	NPKCa	$_{ab}$169.1	19.1	$_{a}$351.5	33.2	0.48

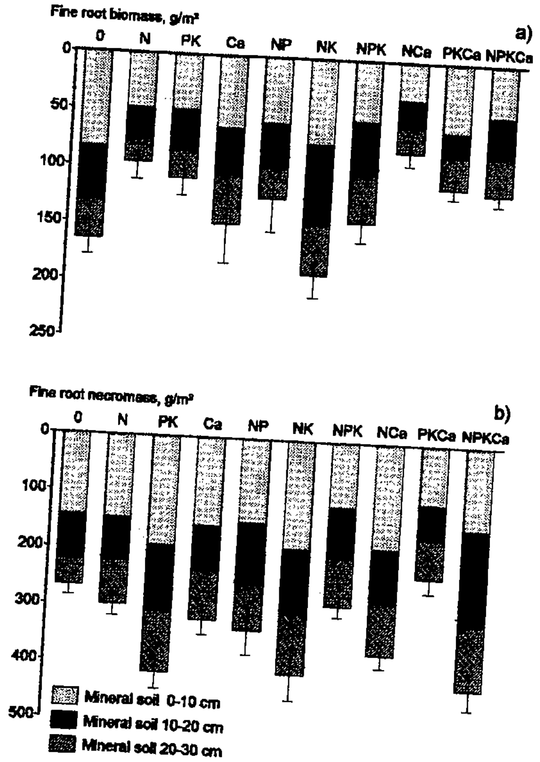

Figure 5.16 a-b. Biomass (diameter < 1 mm) (a) and necromass (<2 mm diameter) (b) of Norway spruce fine roots in May 1994 in the Heinola experiment 113 in southern Finland.

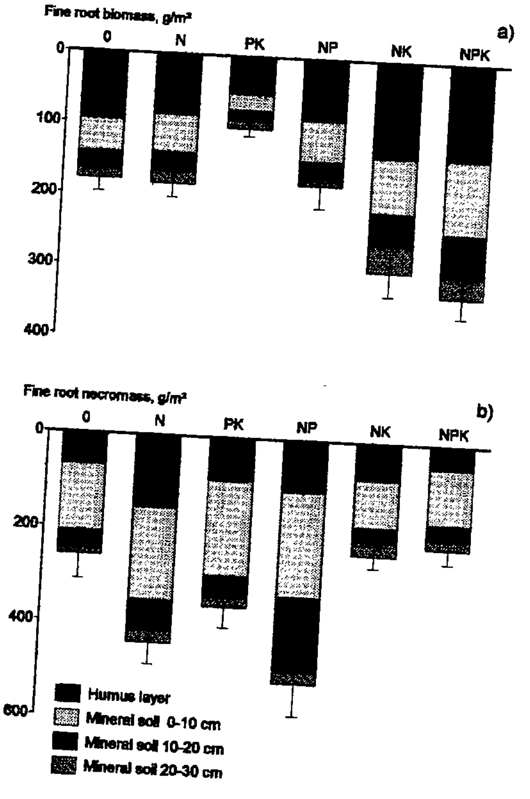

Figure 5.18 a-b. Biomass (diameter < 1 mm) (a) and necromass (diameter < 2 mm) (b) of Norway spruce fine roots in June 1994 in the Sodankylä experiment 197 in northern Finland.

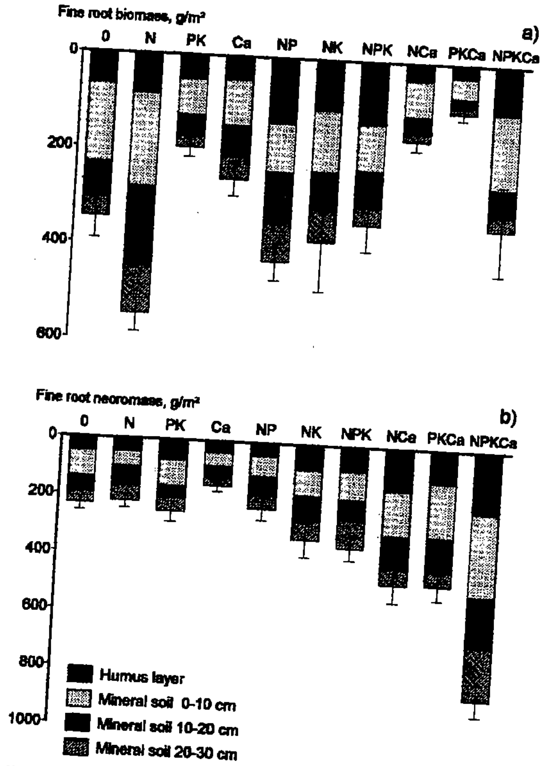

Figure 5.17 a-b. Biomass (diameter < 1 mm) (a) and necromass (diameter < 2 mm) (b) of Norway spruce fine roots in September 1993 in the Kemijärvi experiment 194 in northern Finland.

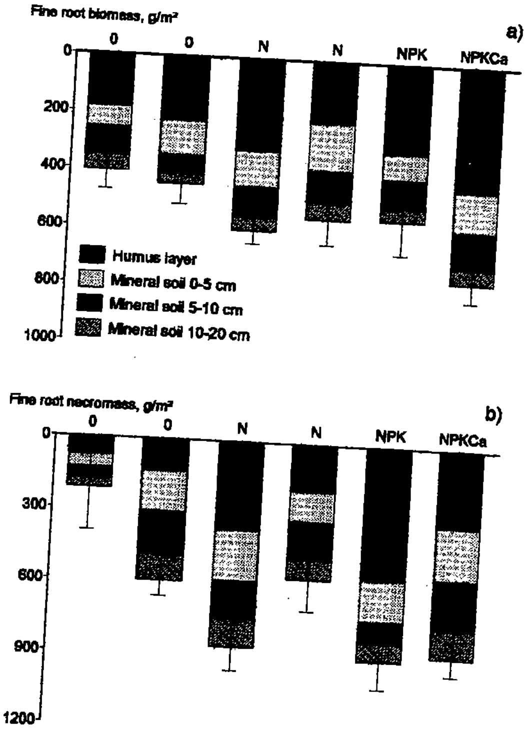

Figure 5.19. Biomass of Norway spruce living fine roots (a) and necromass (b) (diameter < 2 mm) of in August 1994 in the Norråker experiment in northern Sweden.

There was a positive correlation between the fine root biomass in the soil cores and in the ingrowth cores (Fig. 5.20). The fine root biomass in the ingrowth cores was positively correlated with the stem volume growth, stem volume and basal area in the two northern Finnish experiments Sodankylä (SOD) and Kemijärvi (KEM) (Fig. 5.21). In these experiments, the control plots, and PK-fertilized and limed (without N-addition) plots had smaller fine-root ingrowth and stem volume growth. In the southern Finnish experiment Heinola (HEI), however, the corresponding relationships were poor (R^2= 0.1-0.2).

Table 5.6. Spruce fine-root (diameter < 2 mm) growth in the upper 30 cm soil layer during two seasons in the Finnish experiments. The calculated growth is based on data from 15 ingrowth cores per plot. Values marked with the same letter do not differ significantly ($p<0.05$) between plots. The experiments are ordered according to increasing site index

Experiment	Treatment	Fine root biomass $g\ m^{-2}$		Fine root necromass $g\ m^{-2}$	
		mean	s.e.	mean	s.e.
Sodankylä	0	$_{a}$ 36	5	$_{a}$ 31	3
	N	$_{ab}$ 84	11	$_{ab}$ 43	5
	NP	$_{b}$ 111	15	$_{ac}$ 51	7
	NK	$_{b}$ 93	10	$_{bcd}$ 60	6
	PK	$_{ab}$ 76	9	$_{cd}$ 74	6
	NPK	$_{b}$ 117	19	$_{d}$ 80	12
Kemijärvi	0	$_{ab}$ 105	27	$_{a}$ 9	2
	N	$_{ab}$ 190	30	$_{b}$ 82	12
	PK	$_{ac}$ 69	12	$_{a}$ 44	5
	Ca	$_{a}$ 56	7	$_{a}$ 14	2
	NP	$_{b}$ 232	35	$_{a}$ 40	4
	NK	$_{bc}$ 201	60	$_{a}$ 39	11
	NPK	$_{ab}$ 151	33	$_{a}$ 25	4
	NCa	$_{ab}$ 160	25	$_{c}$ 124	12
	PKCa	$_{ac}$ 75	14	$_{a}$ 36	6
	NPKCa	$_{ab}$ 181	23	$_{a}$ 25	6

Table 5.7. Living spruce fine-roots (diameter < 2 mm) in percentage of total fine-root mass in the ingrowth cores after two growing seasons in different experiments and treatments (- sign indicates the absence of the treatment in the experiment)

Experiment	0	N	PK	Ca	NP	NK	NPK	NCa	PKCa	NPKCa
Sodankylä	54	64	50	-	69	61	59	-	-	-
Kemijärvi	92	70	61	80	85	84	86	56	67	88

Table 5.8. Ingrowth of spruce fine roots (root diameter <2 mm) during two growing seasons, % of fine root biomass (layer and 30 cm mineral soil) in different experiments and treatments (- sign indicates the absence of the treatment in the experiment)

Experiment	0	N	PK	Ca	NP	NK	NPK	NCa	PKCa	NPKCa
Sodankylä	27	40	126	-	58	33	43	-	-	-
Kemijärvi	22	35	50	23	47	49	37	94	70	40

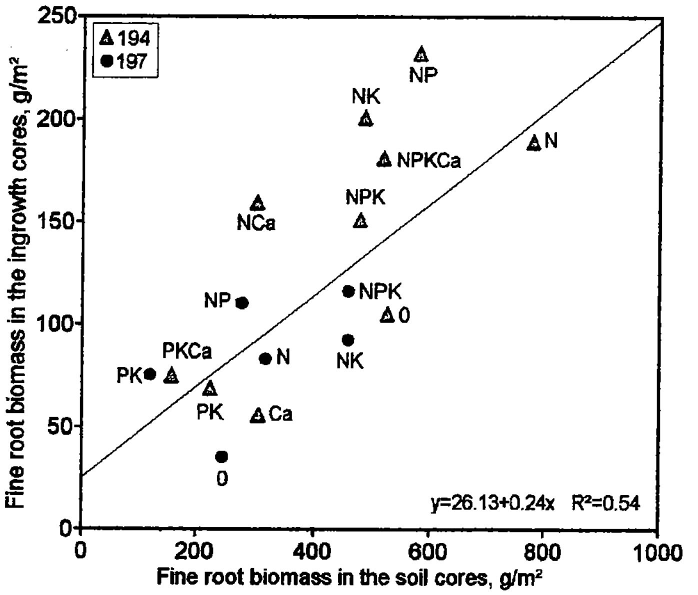

Figure 5.20. Relationship between fine root biomass (diameter < 2 mm) in the soil cores (humus layer and upper 30 cm of mineral soil) in September 1993 (Kemijärvi 194) and June 1994 (Sodankyl‰ 197), and in the ingrowth cores in September 1995.

Nutrient concentrations

The fine-root carbon and nutrient concentrations of living fine-roots were generally higher at Heinola (HEI) in southern Finland than in the two northern experiments (Table 5.9). The treatments had clear effects on the fine root concentrations of added nutrients. In all experiments, nitrogen concentrations were lowest in the control, PK-fertilized and limed plots. Phosphorus concentration of fine roots was lower in the NK- and NCa-plots than in the control. Phosphorus concentration was especially low in the NK-plot at Heinola (HEI). Ca-concentrations were lowest in the control, N-, NK and NP-plots. Potassium concentrations were lowest in the control, N- and NP- plots; and Mg-concentrations in the control, PK- and N- (HEI) plots.

Fine root dynamics

Biomass and growth relations

The fine-root biomass (to the depth of 30 cm mineral soil) in the control plots varied from 210 to 530 g/m^2. This is in the same range as reported for Scots pine stands in eastern Finland after canopy closure (Helmisaari 1995). The fine-root growth into the ingrowth cores during two years varied between 65 and 114 g/m^2 in the control plots and between 70 and 284 g/m^2 in the fertilized and limed plots. Persson et al. (1996) reported that the fine-root (< 1 mm diameter) ingrowth during the first two years after installing the cores into soil varied between 50 and 200 g/m^2 in a *Picea abies* fertilization experiment at the Stråsan experiment in central Sweden. These are relatively low estimates, obviously caused by a short soil incubation time.

Makkonen and Helmisaari (1998a) compared soil cores and root ingrowth cores in estimating Scots pine fine root production, and concluded that during the third year, the Scots pine biomass production calculated by the ingrowth core method was similar to that calculated by the soil core method. Thus, ingrowth of fine roots during the two first years after placing the ingrowth cores actually represents the "current growth potential" rather than the absolute fine-root production. The ingrowth core-method has the advantage that it is an ideal method to compare different experimental treatments or gradients (Vogt and Persson 1991). The "current growth potential" measured by the ingrowth cores gives a measure on the productivity of the fine-root system and the ability to penetrate the soil profile (Persson 1990). The results from the ingrowth cores concerning the cumulative production and mortality of fine roots may be especially useful in explaining the biomass results from the soil cores. The observed positive correlation between fine root biomass in the soil cores and in the ingrowth cores is partly autocorrelative: the ingrowth cores were placed in the holes made by soil cores, thus they had similar spatial variation e.g. in relation to trees on the individual plot.

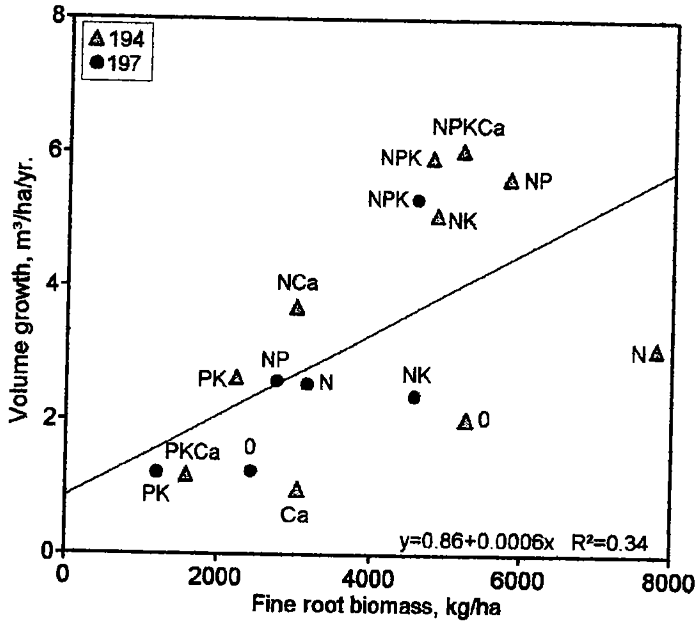

Figure 5.21. Relationship between fine root biomass (diameter < 2 mm) and annual stem volume growth in the experiments Kemijärvi 194 (period 1990-93) and Sodankylä 197 (period 1991-94).

Decomposition of fine roots was not studied in these experiments. It may have affected the necromass values from the ingrowth cores. According to Berg (1984) 1-2 mm diameter Scots pine fine roots lost about 30 % of their mass in two years.

The biomass/necromass ratios of fine roots in the control plots were similar to those reported by Persson (1980) and Finér (1991) for Scots pine roots. The fine-root biomass/necromass ratio in the control plots was lowest in those experiments where roots were sampled after winter in June 1994 (HEI and SOD) and highest in the one that was sampled in autumn 1993 (KEM). These differences may have been related to the annual growth pattern of fine roots. In boreal forests, root growth is fastest in the late summer and autumn after shoot and needle elongation, when soil moisture and temperature are favorable (Lyr and Hoffman 1967, Makkonen and Helmisaari 1998b).

Treatment effects

The fine-root biomass was smaller in those plots that had received lime (Ca, NCa, PKCa) or PK alone than in the control plots, though not always significantly. These plots that had a large fine-root necromass. The exception was the southern Heinola (HEI) experiment, where the limed plot had a large biomass of fine roots. Liming may be less harmful to fine roots on more fertile sites. For instance, Persson et al. (1996) reported that liming did not cause any negative effects on fine roots in experiments in southern Sweden. However, in Stråsan in central Sweden, limed plots fertilized with nitrogen had a much smaller fine-root biomass than the control plots. In our experiments, the mortality of fine roots was also greatest in the NCa-fertilized plots.

Table 5.9. Nutrient concentrations of spruce fine-roots (diameter < 1 mm) in the humus layer and upper 30 cm mineral soil. The chemical analyses are made on one pooled sample of 10 cores per plot

Experiment	Treatment	C*	N	P	Ca	K	Mg
				mg g^{-1}			
Sodankylä	0	489	7.2	0.71	2.44	0.54	0.93
	N	489	8.3	0.63	2.13	0.42	1.10
	NP	485	7.9	0.85	2.17	0.40	0.88
	NK	469	9.3	0.65	2.94	0.46	1.05
	PK	489	6.9	1.00	2.46	0.72	0.92
	NPK	468	9.0	0.85	2.71	0.47	1.13
Kemijärvi	0	318	5.8	0.79	1.76	0.37	0.52
	N	284	6.1	0.88	1.71	0.40	0.94
	PK	389	5.6	0.85	2.41	0.45	0.49
	Ca	338	6.5	0.82	4.43	0.46	1.65
	PKCa	421	5.8	0.84	3.37	0.57	0.93
	NP	367	7.9	0.84	2.55	0.38	0.79
	NK	363	6.5	0.73	1.65	0.45	0.74
	NPK	391	7.4	0.80	2.10	0.52	0.52
	NCa	400	7.5	0.76	2.87	0.41	1.21
	NPKCa	324	6.2	0.80	2.94	0.45	1.18
Heinola	0	420	7.4	0.97	2.59	0.47	0.81
	N	451	11.2	1.20	2.78	0.51	0.73
	PK	454	7.3	1.43	2.97	0.85	0.66
	Ca	338	6.7	0.84	3.64	0.79	1.12
	PKCa	465	10.1	1.28	7.32	0.59	0.97
	NP	444	10.1	1.16	3.09	0.64	0.92
	NK	432	8.7	0.69	2.47	0.58	0.82
	NPK	399	9.6	1.18	2.77	0.50	0.84
	NCa	431	8.6	0.85	4.44	0.51	1.03
	NPKCa	435	10.1	1.15	4.40	0.61	0.85

* Low values for carbon concentrations are probably due to contamination by mineral soil particles, which not were removed from the mycorrhizal fine-root tips during the preparation of the samples.

Also Lehto (1994b) reported that liming increased the proportion of dead short roots. This may be due to increased mortality, or decreased decomposition rates. Results from the Heinola experiment showed that liming increased both microbial biomass and carbon mineralization (e.g. Smolander et al. 1994). This means that the reason for the increased proportion of dead fine roots may not be a decreased decomposition rate. The lower fine-root biomass values in the PK-, Ca-, PKCa- and NCa-plots may rather have been caused by smaller fine-root production and greater mortality since in these plots the ingrowth of fine roots was also the smallest, and the proportion of dead fine roots in the soil cores and in the ingrowth cores highest. Also Majdi (1994) and Clemensson-Lindell and Persson (1995) reported that nitrogen-free fertilizers decreased fine-root production and biomass.

Lehto (1994a) reported lime-induced boron deficiency (due to increased pH in soil) in Norway spruce at mineral soil sites. However, B deficiency was not the only reason for the increased mortality of root tips on the limed Norway spruce plots (Lehto 1994a). According to Lehto (1994b), increased ionic strength and increased pH may be reasons for the increase in dead short root tips in lime and K treatments. However, Clemensson-Lindell and Persson (1993) did not find any relation between soil pH and root biomass. In their study, liming did not seem to affect the amount of fine or small roots significantly in the long run.

These plots having received nitrogen alone or in combination with PK, except at Heinola (HEI), had similar or greater fine-root biomass than control (especially N and NP in Kemijärvi, NK and NPK in Sodankyl‰, NPKCa in Norråker). The greater biomass values were caused by higher fine-root production, since the ingrowth of fine roots was also greatest in these plots. It has been well-established that nitrogen fertilization often increases fine root growth, but may be harmful to mycorrhizal development independently of soil conditions (Wallander and Nylund 1991).

The positive effects of nitrogen fertilization on fine root growth and biomass in the northern experiments in comparison to the southern one may largely be due to the fact that the sites in northern Finland are extremely nitrogen-deficient. The positive effects of nitrogen fertilization on fine root growth in the northern experiments may, however, partly be due to boron fertilization, since this has been reported to increase the number of root tips remarkably where there is boron deficiency (Lehto 1994a).

Above- and below-ground biomass relations

There are many possible reasons why liming decreases tree production (Derome et al. 1986), e.g. decreased nitrogen availability through immobilization (Popovic and Andersson 1984) and lime-induced boron deficiency (Lehto 1994a). The negative effect of fertilizers with lime or PK alone and PKCa on needle biomass and further, stem volume growth, may also be related to the smaller fine-root biomass and, especially, fine root growth. In limed plots nutrient and especially nitrogen uptake may have decreased with decreased fine-root biomass and growth. According to Lehto (1994b) increased mortality of mycorrhizas may result in decreased nutrient uptake in limed soils. The key factors in nutrient uptake are the root abundance and penetration of the soil profile, absorption ability of different parts of the roots, where the mycorrhizal fungi enlarge the active absorptive area considerably, the availability of nutrients in the soil and the transport of nutrients to the roots (Bowen 1984).

In the Kemijärvi (KEM) NCa-fertilized plot, needle biomass and stem volume growth was greater than in the control even if the fine-root biomass was as small as in the other limed plots. However, fine root ingrowth (and also turnover) was high in the NCa-plot. Thus, the increased fine root growth, and nitrogen fertilizer in the NCa-plot could have promoted nitrogen uptake, and biomass production.

Stem volume growth as well as fine-root biomass and ingrowth rate was much greater in the Sodankylä (SOD) NPK-plot compared to the N-plot. It is possible that in the N-fertilized plot there was an increased need for other nutrients than nitrogen. It is also possible that even if fine-root growth increased after nitrogen fertilization in relation to the control plots, there was a negative effect on mycorrhiza, and also on P-uptake. Wallander and Nylund (1991) found that carbohydrate pools in roots increased in response to elevated N levels but mycorrhizal development was reduced. Mycorrhizal results from this study are under preparation. The number of Norway spruce fine root mycorrhizas are located close to the soil surface than the biomass of fine roots (Helmisaari et al. 1995). According to Tryon and Chapin (1983), a sharp temperature decline through the soil profile, more loosely packed soil in superficial soil horizons, and dependence on litterfall for nutrients, are factors partially responsible for the concentration of roots in the uppermost soil horizons in boreal forests. A great part of the soil nutrient pool actually originates from fine-root litter, especially in mineral soil. The depthwise distribution of fine root biomass was towards deeper soil layers in the N-fertilized plots in some experiments. According to Abrazhko (1986) nitrogen fertilization has a decreasing effect on fine roots in forest top soil.

In the experiment of highest site index (HEI), fine-root biomass was especially small in the N- plot that also had a decreased stem volume growth compared with the control plots. Stem volume growth was greater or the same as in the control plots in all other fertilized plots. In this experiment, Ca- or PK-fertilizers caused a positive aboveground growth response, but also the fine-root biomass was high, especially in the limed plot. It is possible that in this southern site other nutrients than nitrogen, for instance phosphorus, are growth-limiting, and nitrogen fertilizers alone do not induce a positive growth response.

Compared to the lower productive stands in the north, the fine-root biomass at Norråker (NOR) and Heinola (HEI) was in the same range (control plots) or much lower (fertilized plots). However, the volume growth in the southern experiments was 3-20 times higher than in the northern experiments. In fact, climate and site fertility are the principle factors affecting above-ground biomass production. Below-ground production seems to be less dependent on climate. The above-ground carbohydrate supply does not normally (under nitrogen limitation) limit root growth (Persson 1983). Indeed, many authors have come to the conclusion that fine-root growth occurs relatively independent of shoot growth, and that the temporal variation is largely determined by changes in environmental conditions (e.g. soil moisture and nutrients). Furthermore, the rate at which water and nutrients become available in the root medium has a decisive effect on plant nutrition and growth rate (Vogt and Bloomfield 1991). These results suggest that the differences in the above-ground growth between stands of varying nutritional treatment on the same site may be related to the correspondent differences in the fine-root biomass, and especially, fine-root growth.

5.1.3 Conclusions

- There is a close relationship ($R^2>0.9$) between tree size expressed as D^2H and total biomass (DM) as well as for stemwood, stembark, living branches and needles for control plots at all the experiments.. Thus, the empirical equations for control plots may be applied to forest stand data to estimate the biomass pools at the time of the start of the experiments. This is required to calculate the long-term change of nutrients pools in tree biomass as well as changes of the tree nutrient utilization expressed as nutrient productivity or relative nutrient accumulation.

- There is a close relationship between total needle mass and tree size at control plots as for total biomass. However, the relative proportion between current and older needles differs between experiments. This may be connected with site index (i.e. the proportion of current needles decreases from south to northern sites) or tree size (the proportion of current needles increases by tree size). However, the influence of nitrogen deposition on the proportion of current needle mass can not be ruled out even if there is a intercorrelation with site index as shown by the gradient: Heinola (FIN;

8%), Åseda (SWE; 13%), Löten (NOR; 17%), Farabol (SWE; 20%) and Klosterheden (DEN; 30%).

- There may be significant differences in the fertilization response among different variables measuring forest growth i.e. basal area, stem volume and above ground biomass. At Farabol nitrogen addition led to increased stem volume as well as total biomass. However, nitrogen addition in combination with acidification (sulfur powder) increased the stem volume growth but not total biomass i.e. the production of needles and branches decreased. Acidification caused decreased production of all biomass components. The negative treatment response on above-ground biomass production is correlated with corresponding effects on exchangeable K in mineral soil and total P in humus.

- There is a positive interaction between PK- (or S) and N-effects, which has led to higher stem volume production at complete fertilization regimes (NPKS) compared to single treatments at a young SW Swedish experiment (Åseda). The nitrogen and sulfur interaction is opposite to the response at Farabol. The main difference between these systems is that the potassium pools where less affected by acidification compared to Farabol.

- Comparing the treatment effects at Åseda, it is revealed that the positive PK-effects on stem biomass and total biomass is not as clear as on stem volume. However, there is a positive interaction-effect of N and PK, which is more evident concerning stem biomass than stem volume. For total biomass accumulation this was most significant when PK was given together with N. The growth of living branches was increased to the highest extent of all biomass components after PK-fertilization only.

- In general, the Ca concentration in total tree biomass at control plots decreased with increased tree size, due to an incresed stemwood proportion which is poor in calcium. At Klosterheden and Farabol the Ca concentration was the lowest of all experiments. Also, the amount exchangeable Ca in the mineral soil was the lowest at these sites except for Sodankylä. This indicate a relationship between biomass accumulation in the trees and soil chemistry, especially the amount of bark which holds a substantial part of the calcium taken up. After N or NS-treatment in the Farabol stand (70 years old) in southern Sweden, the bark accumulation for corresponding tree sizes was unchanged or reduced compared to control. At Norråker in north Sweden, which has rather high Ca content in the soil, nitrogen fertilization led to increased bark mass accumulation compared to control despite its high stand age (181 years). Thus, the results suggest that older stands located in areas low in soil Ca content, caused by natural soil forming processes or enhanced leaching due to acid deposition, may be less capable to meet increased nitrogen availability by increased bark accumulation than stands at sites with better soil conditions. Thinner bark might lead to a decrease of its tree protection potential.

- At stand level, there is a more evident gradient from low to high stand index in nitrogen pools of above-ground biomass than for carbon pools. This indicates that the southern sites are more influenced by N than the northern sites.

- In plots receiving lime (Ca, NCa, PKCa) or PK alone the fine-root biomass was smaller than in the control plots, though not always significantly. These plots also had a large fine-root necromass. The lower fine-root biomass values in the PK-, Ca-, PKCa- and NCa-plots may have been caused by smaller fine-root production and greater mortality, since in the ingrowth of fine roots was also the smallest and the proportion of dead fine roots in the soil cores and in the ingrowth cores highest. The negative effect of fertilizers with lime or PK alone and PKCa on stem volume growth may be related to the smaller fine-root biomass and, especially, fine root growth.

- The plots receiving nitrogen alone or together with PK had similar or greater fine-root biomass than the control plots, except in the Heinola experiment which was situated at a fertile site type. The greater biomass values were caused by higher fine-root production, since the ingrowth of fine roots was also greatest in these plots.

- These results suggest that the differences in the above-ground growth between stands of varying nutritional treatment on the same site may be related to the correspondent differences in the fine-root biomass, and especially, fine-root growth.

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