Fine-root response to nitrogen manipulation in three Norway spruce catchment areas

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Abstract:

Investigations on the experimental impact of nitrogen manipulation on the distribution and standing crop of Norway spruce fine roots were carried out using data obtained from core sampling. The experimental areas were three catchment areas subjected to decreased nitrogen and sulphur deposition (G1 ROOF), increased nitrogen deposition (G2 NITREX) and ambient levels of nitrogen and sulphur deposition (F1 CONTROL), respectively, within the Lake Gårdsjön basin, SW Sweden. The excavated fine roots (< 1 mm in diameter) were separated with regards to vitality into live and dead fractions.

Signs of an increased percentage of living fine roots in the G1 ROOF catchment suggest that growth conditions for fine roots were improved by reduced N and S deposition. Related results from the G2 NITREX catchment, suggest a related trend towards health improvement of the fine roots. However, in this case the improvement probably is related to a temporarily change in the nutritional conditions, viz. an increased ion exchange after the N-addition. These results suggest that fine-root growth dynamics are affected by changes in nitrogen deposition, but that the growth response requires several years to be detectable. Similar pattern in the year-to-year changes in live and dead fine roots occurred in all catchment areas, which must be related to variations in climatic conditions, masking the changes due to different treatments.

Key words: acidification, fine-root biomass, fine-root necromass, fine-root chemistry, forest decline, nitrogen, *Picea abies*, tree vitality, soil cores

Introduction

Anthropogenic input has increased during the last century as a contributing factor to forest damage in middle Europe (MARSCHNER 1991, SCHULZE 1989, ULRICH, 1989). The air pollutants are characterised by a combination of both acidifying and fertilizing substances (ABER et al. 1989, MARSCHNER et al. 1991). Atmospheric pollutants may influence the growth and anatomy of forest trees directly by changing soil chemistry and indirectly by injuring needles (MCQUATTIE & SCHIER 1992). Consequences for forest soil can include changes in soil pH, loss of soil cations and changes in plant and microbial communities. With regards to the nutritional processes in the soil, root-soil interactions are most important. One question which is necessary to investigate is to what extent the roots actively takes part in the weathering processes?

Nitrogen eutrofication of the soil may arise either from:
- atmospheric deposition of both ammonium-N and oxidised N-forms, antropogenic fertilisation or a high abundance of N_2-fixing organisms (GIJSMAN 1991, OLSTHORN et al. 1991). As a consequence of elevated inputs of atmospheric N during past decades the N cycle has become disrupted in many forest ecosystems changing from a closed to an open cycle. Nitrogen leaching generally occur in damaged forests; but this is not a universal pattern (BERGHOLM et al. 1993).

Fine-root studies in damaged forests have exhibited a number of changes in fine-root development, which have been related to nutrient deficiencies and/or metal toxicity's (e.g. MURACH 1984, MEYER 1985, PERSSON et al. 1995). Different approaches have been applied in order to describe and quantify changes in the „vitality" of fine-roots (PERRSON et al. 1995). Root damage often seems related to low avalibility of most nutrients except for nitrogen (PERSSON et al. 1995). Damage to fine roots and mycorrhiza has been reported throughout a wide geographic range of forest decline (GLENN et al. 1991, PUHE et al. 1986, SCHLEGEL et al. 1992).

Several studies have examined the status of fine roots and mycorrhiza as a correlate of tree health, but there are no generally acceptable characteristics of damage signs (cf. PERRSON et al., 1995). PUHE et al. (1986) found a clo-

se relationship between needle loss and fine-root loss in damaged Norway spruce (*Picea abies* (L.) KARST.) stands, of different site quality and ages. In forest stands, fine-root production (and respiration) may (or may not) increase with increased N availability (PERSSON et al. 1995). Some field experiments have demonstrated lower absolute and relative below-ground production following fertilisation (PERSSON et al. 1995, LINDER & AXELSSON 1982). Frequently, a decreased standing biomass of tree fine roots is to be found on N rich sites indicating a higher turnover and shorter longevity of fine roots (NADELHOFFER et al. 1985, PERSSON 1980, PERSSON & MAJDI 1995). The decrease in fine root biomass along decreasing nitrogen status in forest stands is generally accompanied by a decrease in the depth of the forest floor (GUNDERSEN et al. 1997, in press).

Large scale fine-root investigations have been carried out in order to assess the influence of increased nitrogen levels (see literature in PERSSON et al. 1997, in press), different kind of liming (PERSSON & AHLSTRÖM 1991, CLEMENSON-LINDELL & PERSSON 1993, 1995) and the effect of soil acidification and aluminium toxicity (see PERSSON et al. 1995). So far, only limited fine root data are available from investigations in areas subjected to reduced nitrogen and/or sulphur deposition (BOXMAN et al. 1997, in press, PERSSON et al. 1997, in press).

Here we report results of the distribution and development of fine roots from 1990 to 1994 at three catchments in the Lake Gårdsjön basin, SW Sweden. Catchment G1 ROOF received experimentally decreased nitrogen deposition, catchment G2 NITREX increased nitrogen deposition and catchment F1 CONTROL ambient nitrogen and sulphur deposition (HULTBERG et al. 1993, WRIGHT & VAN BREMEN 1995). Root sampling was carried out using the soil core sampling technique (VOGT & PERSSON 1991). Five years' of sequential root data are presented describing changes in fine root development and chemistry in the different catchment areas. The investigations on the catchment G2 NITREX was a part of a nitrogen manipulation programme (NITRogen saturation EXperiments) at seven forest sites across Europe (WRIGHT & VAN BREMEN 1995).

Materials and methods

Site description

The experimental site Gårdsjön is located close to the Swedish west coast (58 04'N, 12 01'E), 50 km north of Gothenburg and about 10 km from the coast (cf. ANDERSON & OLSSON 1985). The Gårdsjön region has a humid climate, with 1100 mm mean annual precipitation and a mean temperature of 6.4°C (DISE & WRIGHT 1992). The deposition in the region is moderately high, with sulphur deposition of 25 kg S ha^{-1} yr^{-1} and nitrogen deposition of 13 kg N ha^{-1} yr^{-1} was measured (DISE & WRIGHT 1992). The area is characterised by an acid lake, surrounding terrestrial parts dominated by shallow podzolic soils with inclusions of barren rock and peat soils. The bedrock consists mainly of granites and old and young granodiorites (MELKERUD 1983). The forest area is dominated by Norway spruce (*Picea abies* (L.) KARST.) up to 80 year of age with inclusions of Scots pine (*Pinus sylvestris* L.) in dry parts and a mixture of deciduous trees. The field and bottom-layer consist mainly of dwarf shrubs (*Vaccinium myrtillus* L. and *V. vitis-idaea* L.), mosses and lichens. The composition of the tree stand was the same in all investigated catchments. Two vegetation types, *Vaccinium*-dominated and moss-dominated, respectively, were distinguished for the sampling programme within each catchment.

Three subcatchments within the Lake Gårdsjön basin were investigated. At the G2 NITREX site (G2) 35 kg N ha^{-1} yr^{-1} was added as ammonium nitrate to augment the natural N throughfall load (DISE & WRIGHT 1992). The total nitrogen deposition was then within the range received by many forest ecosystems in central Europe. The nitrogen was distributed at weekly doses by means of a sprinkler system in proportion to the amount of natural precipitation during the previous 7 days. The volume of additional water was about 5% of the natural precipitation. Treatment began in April 1991.

A catchment G1 ROOF, was covered by a transparent roof beneath the canopy to exclude sulphur and nitrogen in the throughfall. Water from lake Gårdsjön with added seasalts was sprinkled beneath (HULTBERG et al. 1993). Incoming throughfall was intercepted and channelled

from the catchment. Treatment began in April 1991. Litter was collected from the roof and adjusted to the soil underneath it. A third catchment, F1 CONTROL, received ambient levels of deposition.

Root sampling

Root sampling was performed by the use of soil cores taken with a 4,5 cm cylindrical steel corer (cf. VOGT & PERSSON 1991). Sets of seven to ten soil cores (depth about 30 cm) were taken in the beginning of October 1990 - 1994 in each of two vegetation types (*Vaccinium*- and moss-dominated) within each catchment. Investigation of the distribution pattern of fine roots, however, indicated no significant dependency of vegetation type or distance to the nearest tree. Therefore root data, in the present context are used for the total stand, disregarding the importance of those small scale distribution patterns. The total length of the soil core was 30 cm. The soil cores were divided into humus layer and mineral soil, both layers in turn divided into 5 cm segments, starting from the upper level of the mineral soil. The samples were stored in a deep freeze at -4° C until sorting could take place.

Immediately after thawing, roots were picked out from each soil layer and sorted. The fine roots less than 1 mm were separated into live and dead categories, based on morphological characteristics (VOGT & PERSSON 1991). Live fine roots were more or less brownish/suberized and often well-branched, with the main part of the root tips light and turgid. Stele white to slightly brown and elastic. In the dead roots, stele was brownish and easily broken, no elasticity remained. The roots were dried at 70° C for 48 hours and weighed to the nearest mg.

Statistics

Owing to the lack of replicated treatment areas and since the sampling was carried out only once a year, changes were difficult to evaluate statistically. Only significant differences between different years within each catchment and vegetation area are discussed. The SAS analysis of variance (SAS GLM) and Student's t-test were used (RAY 1982).

Results and discussion

Estimated root variables displayed a large variability between samples from the same area and year (Table 1). This reveals the high degree of heterogeneity within the catchments, and also within distances of a few metres. In spite of the large variations in live and dead fine roots to be found in the core samples, significant changes were frequently recorded between different years (Table 1). The most substantial amount of living fine roots was generally found in the LFH-layer (50-60%), which is important to know when evaluating year-to-year changes taking place. The high proportion of living fine roots in the LFH layer suggests that they were in a more vital growth stage. The amount of dead fine roots was generally very low in the LFH layer.

In G1 ROOF a significant increase in the amount of living fine roots in the LFH layer took place at the same time as a parallel decrease in the amount of dead fine roots. In the LFH layer of the G2 NITREX catchment there were no change in the amount of living fine roots, but a decrease in dead fine roots was found as well. In the LFH layer of F1 CONTROL, the amount of fine roots varied greatly between different years, and a decrease in dead fine roots was also found. The increase in the amount of living fine roots, in the LFH layer in G1 ROOF, subjected to reduced nitrogen and sulphur deposition, suggests a stabilisation and a gradual recovery of the fine roots. Similar changes were found in fine root growth data from the same catchment areas using ingrowth cores (PERSSON et al., in press). In this context, the amount of fine roots in the ingrowth cores provides a direct estimate of fine-root reproduction and therefore offers a measure of fine-root vitality (VOGT & PERSSON 1991, PERSSON 1993). This recover process was also proved by better nutritional conditions in the fine roots from the ingrowth cores, viz. increased potassium, phosphorous and calcium levels in relation to nitrogen (PERSSON et al., in press).

The highest percentage of living fine roots was recorded in the LFH horizon during the first year of study. From 1990 to 1994, there was a gradual decrease in the percentage of living fine roots in the LFH soil horizon in all catchment areas from high estimates of about 70% to low

estimates of about 40%. A consecutive decrease in living fine roots was not found in the mineral soil layer, where an increasing percentage of living fine roots was recorded generally. The observed difference with time, in the growth pattern of the fine roots, suggest that an increased depth penetration took place in all catchment areas induced by alterations in climatic conditions. Earlier Swedish investigations (PERSSON et al. 1995a) indicate an increased depth penetration and negative effects on the fine root development in the upper part of the soil profile caused by experimental drought.

If fine -root data for the whole soil profile down to 20 cm in the mineral soil is added together (live + dead fine roots) no significant changes were recorded during the period of study (Table 2). However, a closer look at data for live and dead categories (Table 2) reveals that the amount of living fine roots generally increased in G1 ROOF and G2 NITREX, and that the amount of dead fine roots decreased in all catchment areas. The percentage living fine roots in F1, G1 and G2, respectively increased from 45, 38 and 34% to 70, 68 and 67%, which is nearly twice the original amount. The general trends in the changes in all catchment areas should be expected to be induced by alterations in climatic conditions. The trends towards improvement in the vitality of the fine roots (more living fine roots) in G1 ROOF and G2 NITREX, however, should be expected to be induced by the experimental treatments. The increased percentage of living fine roots in the G1 ROOF must be related to improved growth conditions by reduced N and S deposition. The related changes in G2 NITREX, in is probably related to a temporarily change in the nutritional conditions, viz. an increased ion exchange after the N-addition.

The increased amount of fine roots in terms of dry weight in G1 ROOF and G2 NITREX during the period of study, were not followed by a related increase in fine-root length (Table 3). No significant changed were recorded in fine-root length, whereas the length to weight ratio decreased substantially in all catchment areas. This suggest that the fine-roots length penetration of the total soil profile remained the same during the period of study, whereas the dry weight decreased significantly. The decrease in dry weight may either be related less starch reserves or decreased diameter growth.

Our results from Gårdsjön cover so far only five years. This is a limited period of time to distinguish treatment effects from year-to-year changes induced by alterations in climatic conditions.

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References

ABER J., NADELHOFFER K.J., STEUDLER P. & J.M. MELILLO (1989): Nitrogen saturation in northern forest ecosystems. — Bioscience **39**: 378-386.

AHLSTRÖM K., PERSSON H. & I. BÖRJESSON (1988): Fertilization in a mature Scots pine (*Pinus sylvestris* L.) stand - effects on fine roots. — Plant and Soil **106**: 179-190.

ANDERSON F. & B. OLSSON (Eds.) (1985): Lake Gårdsjön. An acid forest lake and its catchment. — Ecol Bull. (Stockholm) **37**: 336 pp.

BERGHOLM J., JANSSON P.-E., JOHANSSON U., MAJDI H., NILSSON L.O., PERSSON H., ROSENGREN-BRINK U. & K. WIKLUND (1995): Air pollution, tree vitality and forest production - the Skogaby project. General description of a field experiment with Norway spruce in South Sweden. — Ecosystem Research Report **21**: 69-87.

BOXMAN A.W., BLANCK K., BRANDRUT T.-E., EMMET B., GUNDERSEN P., HOGERVORST R.F. KJOENAAS O.J., PERSSON H. & V. TIMMERMANN (1997, in press): Vegetation and soil biota response to experimentally-changed nitrogen inputs in coniferous forest ecosystems of the NITREX project. — Forest Ecology and Management.

CLEMENSSON-LINDELL A. & H. PERSSON (1993): Long-term effects of liming on the fine-root standing crop of *Picea abies* and *Pinus sylvestris* in relation to chemical changes in the soil. — Scand. J. For. Res. **8**: 384-394.

CLEMENSSON-LINDELL A. & H. PERSSON (1995): Fine-root vitality in Norway spruce stand subjected to various nutrient supplies. — Plant and Soil **168/169**: 167-172.

DISE N.B. & R.F WRIGHT (1992): The NITREX project (Nitrogen Saturation Experiments). — Ecosystems Research Rep. **2** (Commission of the European Communities) : 101 pp.

GIJSMAN A. (1991): Soil water content as a key factor determining the source of nitrogen (NH_4+ or NO_3-) absorbed by Douglas-fir (*Pseudotsuga menziesii*) and the pattern of rhizosphere pH along its roots. — Can. J. For. Res. **21**: 616-625.

GLENN M.G., WAGNER W.S. & S.L. WEBB (1991): Mycorrhizal status of mature and red spruce (*Picea rubens*) in mesic and wetland sites of northwestern New Jersey. — Can. J. For. Res. **21**: 741-747.

GUNDERSEN P., EMMET B.A., KJOENAAS O.J. & C. KOOPMANS (1997, in press): Impact of nitrogen deposition on nitrogen cycling in forests: a synthesis of NITREX data. — Forest Ecology and Management.

HULTBERG H., ANDERSSON B. & F. MOLDAN (1993): The the covered catchment - an experimental approach to reversal of acidification in forest ecosystem. In: RASMUSSEN L., BRIDGES T. & P. MATHY (Eds.), Experimental Manipulation of Biota and Biogeochemical cycling in Ecosystems. — Ecosystems Research Report 4 (Commision of the European Communities), Brussels, pp. 46-54.

LINDER S. & B. AXELSSON (1982): Changes in carbon uptake and allocation patterns as a result of irrigation and fertilization in a young *Pinus sylvestris* stand. - In: WARING R.H. (ed.), "Carbon Uptake and Allocation in Subalpine Ecosystems as a Key to Management", pp. 38-44. — For. Res. Lab., Oregon State University, Corvallis, U.S.A.

MAJDI H. & H. PERSSON (1993): Spatial distribution of fine roots, rhizosphere and bulk-soil chemistry in an acidified *Picea abies* stand. — Scand. J. For. Res. **8**: 147-155.

MARSCHNER H. (1991): Mechanisms of adaption of plants to acid soils. — Plant and Soil **134**: 1-20.

MARSCHNER H., HÄUSSLING M. & G. ECKHARD (1991): Ammonium and nitrate uptake rates and rhizosphere pH in non-mycorrhizal roots of Norway spruce (*Picea abies* (L.)KARST.). — Trees **5**: 14-21.

MC QUATTIE C.J. & G. A. SCHIER (1992): Effects of ozone and aluminium on pich pine (*Pinus rigida*) seedlings: anatomy of mycorrhiza. — Can. J. For. Res. **22**: 1901-1916.

MELKERUD P.A. (1983): Quatery deposits and bedrock outcrops in an area around Lake Gårdsjön, south-western Sweden, with physical, mineralogical and geochemical investigations. — Rep. Forest Ecology and Forest Soil **44**, Dept. Forest Soils, SLU, Uppsala, 87 pp.

MEYER F.H. (1985): Einfluß des Stickstoff-Faktors auf den Mykorrhizabesatz von Fichten-sämingen im Humus einer Waldschädenfläche. — Allg. Forst. Z. **40**: 208-219.

MURACH D. (1984): Die Reaktion der Feinwurzeln von Fichten (*Picea abies* (L.) KARST.) auf zunehmende Bodenversäurung. — Göttinger Bodenkd. Ber. **77**, 126 pp.

NADELHOFFER K.J., ABER J.D. & J.M. MELILLO (1985): Fine roots, net primary production and soil nitrogen availability: a new hypothesis. — Ecology **66**: 1377-1390.

OLSTHOORN A.F.M., KELTJENS W.G., VAN BAREN B. & M.C.G. HOPMAN (1991): Influence of ammonium on fine root development and rhizosphere pH of Douglas-fir seedlings in sand. — Plant and Soil **133**: 75-81.

PERSSON. H. (1980): Fine root dynamics in a Scots pine stand with and without near optimum nutrient and water regimes. — Acta Phytogeogr. Suec. **68**: 101-110.

PERSSON H. & K. AHLSTRÖM (1991): The effects of liming and fertilization on fine root growth. — Water, Air and Soil Pollution **54**: 365-379.

PERSSON H., SUN Y., MAJDI H. & L.O. NILSSON (1995a): Root distribution in a Norway spruce (*Picea abies* (L.) KARST.) stand subjected to drought and ammonium-sulphate application. — Plant and Soil **168/169**: 161-175.

PERSSON H. & H. MAJDI (1995): A study on fine-root dynamics in response to nutrient applications in a Norway spruce stand using the minirhizotrone technique. — Z. Pflanzenernähr. Bodenk. **158**: 429-433.

PERSSON H., MAJDI H. & A. CLEMENSSON-LINDELL (1995b): Effects of acid deposition on tree roots. — Ecol. Bull. (Copenhagen) **44**: 158-167.

PERSSON H., AHLSTRÖM K. & A. CLEMENSSON-LINDELL (1997, in press): Nitrogen addition and renewal at Gårdsjön - effects on fine-root growth and fine-root chemistry. — Forest Ecology and Management.

PUHE J., PERSSON H. & I. BÖRJESSON (1986): Wurzelwachstum und Wurzelschäden in skandinavischen Nadelwäldern. — AFZ **20**: 488-492.

RAY A.A. (1982): SAS User's guide: Statistics, Vers. 5 Ed. Cary, N.C., SAS Institute Inc. Cary, NC, 956 pp.

SCHLEGEL H., AMUNDSON R.G. & A. HÜTTERMANN (1992): Element distribution in red spruce (*Picea rubens*) fine roots; evidence for aluminium toxicity at Whiteface Mountain. — Can. J. For. Res. **22**: 1132-1138.

SCHULZE E.D. (1989): Air pollution and forest decline in a spruce (*Picea abies*) forest. — Science **244**: 776-783.

ULRICH B. (1989): Effects of acid precipitation on forest ecosystems in Europe. In: ADRIANO D.C. & H.H. JOHANSSON (Eds.), Advances in Environmental Sciences, Acidic Precipitation Vol. 2. Springer, New York, pp. 189-272.

VOGT K.A. & H. PERSSON (1991): Measuring growth and development of roots. In: LASSOIE J.P. & T.M. HINCLEY (Eds), Techniques and Approaches in Forest Tree Ecophysiology. pp 477-501, CRS press, Boca Raton.

Catchment/horizon	Year	n	Live (g m^{-2})	Live (%) of core totals	Dead (g m^{-2})
F1/LFH	1990	15	107±59ab	62±25ab	54±43ab
	1991	18	78±46b	74±19a	81±50a
	1992	18	109±71ab	66±17ab	39±24b
	1993	20	73±53b	41±27c	28±38b
	1994	20	123±58b	57±21b	28±51b
F1/humus	1990	14	31±24b	18±11bc	75±56a
	1991	18	29±63b	14±16c	96±61a
	1992	15	35±29b	19±11bc	37±28b
	1993	17	69±43a	38±21a	40±30b
	1994	14	59±32ab	27±14ab	34±47b
F1/mineral-soil	1990	15	38±34abc	22±19ab	110±77
	1991	18	13±11c	12±12b	73±52
	1992	18	29±30bc	18±17ab	65±41
	1993	20	62±66a	27±21a	124±173
	1994	20	55±38ab	24±16a	55±49
G1/LFH	1990	15	94±58ab	64±18a	55±44a
	1991	17	81±52b	70±18a	69±45a
	1992	19	108±65ab	60±24a	33±15b
	1993	20	80±53b	45±22b	29±26b
	1994	25	127±66a	46±19b	24±22b
G1/humus	1990	15	23±21b	20±20	84±89a
	1991	15	24±30b	16±11	80±59ab
	1992	14	50±35b	21±12	48±28abc
	1993	17	41±25b	27±17	35±28c
	1994	21	90±92a	26±15	42±38bc
G1/mineral-soil	1990	15	26±42bc	16±19b	113±96abc
	1991	17	18±16c	17±14b	167±109a
	1992	19	51±68bc	25±27ab	119±91ab
	1993	20	56±35ab	32±16a	106±75bc
	1994	25	91±72a	32±23a	59±37c
G2/LFH	1990	16	116±74	65±31a	79±59a
	1991	16	109±70	74±21a	71±43a
	1992	20	122±59	76±16a	45±34b
	1993	20	109±62	50±20b	30±26b
	1994	20	126±93	46±22b	32±28b
G2/humus	1990	14	28±24bc	21±25ab	88±51a
	1991	15	23±22bc	17±16ab	100±54a
	1992	20	19±16c	12±8b	36±21bc
	1993	19	52±32a	25±16a	50±30b
	1994	15	41±32ab	13±9b	17±15c
G2/mineral-soil	1990	17	26±33c	17±25bc	135±63a
	1991	16	12±16c	10±14c	127±89a
	1992	20	22±24c	12±13c	84±44b
	1993	20	55±44b	26±17b	101±53ab
	1994	20	112±72a	45±21a	68±39b

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Table 1. The distribution of fine roots (< 1 mm in diameter) in different soil horizons at catchments F1 CONTROL, G1 ROOF and G2 NITREX. Estimates are given as mean values ± SD. Values with different letters differs significantly (Student's t-test, $p<0.05$) between the years for each area. The depth of the LFH-horizon was 3.2 - 3.9 cm, the humus layer 5.0 - 7.7 cm and the mineral soil 18.4 - 22.9 cm; the total depth of the soil core being 30 cm.

Catchment	Year	n	Live ($g\ m^2$)	Dead ($g\ m^2$)	Totals ($g\ m^2$)	Live (%)
F1	1990	15	173±66ab	234±117a	407±123	45±17b
	1991	18	119±94b	250±112a	370±141	32±19c
	1992	18	167±102ab	135±56b	302±121	53±17b
	1993	20	194±102a	186±177ab	380±232	54±17b
	1994	20	220±73a	106±81b	326±100	70±18a
G1	1990	15	143±76b	252±139a	395±166	38±18cd
	1991	17	120±79b	306±129a	426±150	29±17d
	1992	19	196±140b	188±90b	384±161	48±19bc
	1993	20	171±58b	165±87bc	336±109	53±14b
	1994	25	294±151a	118±47c	411±162	68±15a
G2	1990	17	158±90bc	282±116a	440±149	34±19c
	1991	16	143±79c	292±134a	435±184	33±13c
	1992	20	163±72bc	165±76bc	328±110	50±16b
	1993	20	214±71ab	178±73b	392±102	54±14b
	1994	20	269±150a	112±54 c	381±163	67±17a

Table 2. Fine-root live (biomass), dead (necromass), totals (biomass + necromass) and live (%) of totals in the soil core down to 30 cm at catchments F1 CONTROL, G1 ROOF and G2 NITREX (g DW m2). Values with different letters differ significantly (Student's t-test, $p<0.05$) between the years for each catchment area. Mean values±SD, n = number of samples.

Catchment	Year	n	Length ($m\ m^2$)	Length/Weigth (m/g)
F1	1990	11	2987±987	16±2a
	1991	16	1504±1190	14±4ab
	1992	8	2440±949	12±2bc
	1993	20	2119±1254	11±2c
	1994	20	2282±812	10±2c
G1	1990	15	2374±1360	17±3a
	1991	14	1813±1236	15±3a
	1992	11	2835±1980	13±2b
	1993	20	2009±989	11±3bc
	1994	25	3127±2052	10±3c
G2	1990	11	2569±904	16±4a
	1991	14	2025±958	15±2ab
	1992	3	2311±382	12±0bc
	1993	20	2265±983	10±2c
	1994	20	3090±1535	12±5bc

Table 3. Live fine-rootlength and length/weight ratios in in the total soil core down to 30 cm at catchments F1 CONTROL, G1 ROOF and G2 NITREX. Values with different letters differ significantly (Student's t-test, $p<0.05$) between the years for each catchment area. Mean values±SD. n = number of samples.

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