EFFECTS OF ACID DEPOSITION ON TREE ROOTS IN SWEDISH FOREST STANDS

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Abstract. In nitrogen-loaded areas, many forest stands show a positive growth response to the increased nitrogen input. However, with extensive soil acidification and cation leakage, damage in forest stands is frequently observed, in particular in mature forest stands. The most important soil-mediated factors which cause a reduction in fine-root growth and mycorrhizal development are: (i) high nitrogen/cation ratios and (ii) aluminium (Al) toxicity, viz. elevated Al/cation ratios, leading to an increased sensitivity of the root systems to environmental stress. Extensive data on fine-root growth in response to experimental manipulation of plant nutrients in the forest soil are available from many large-scale field experiments in Sweden. It is concluded from the data that Al toxicity should be considered as a predisposing factor for forest decline on SW Swedish sites, reducing root function and inhibiting nutrient uptake. A chronically high nitrogen deposition is furthermore likely to produce longer-lasting damage symptoms on fine roots and their function. Aluminium-induced deficiencies of important cations in the forest trees may contribute to forest decline. In SW Swedish forest stands, potassium deficiency is likely to be another important predisposing factor.

Key words: Aluminium toxicity, forest decline, fine roots, nitrogen deposition, nutrient imbalances, potassium deficiency

1. Introduction

The influence of air pollution on forest trees includes direct effects on foliage as well as indirect soil-mediated effects (Aber *et al.*, 1989; Marschner, 1991a and b; Schulze, 1989; Ulrich, 1990). Historically, SO_4 has been the major acidification agent, but lately nitrogen compounds increasingly have become important. Many forest stands show a positive growth response to increased nitrogen input, even in heavily N-loaded areas (Nilsson and Wiklund, 1992). Nitrogen fertilization experiments suggest that part of the increased forest production is caused by a translocation of biomass production from below-ground to above-ground parts (Ågren *et al.*, 1980; Persson, 1993). At the same time fine-root growth dynamics are strongly affected by N supply (Hendricks *et al.*, 1993; Majdi, 1994; Persson, 1990).

The importance of understanding and quantifying the processes influencing fine-root dynamics (production, longevity, and mortality) is obvious. Extensive data on fine-root growth in response to experimental manipulation of plant nutrients in forest soils are available from own investigations (cf. Ahlström *et al.*, 1988; Clemensson-Lindell and Persson, 1993; Idem, 1995a and b, Majdi and Persson, 1993; Idem, 1995a and b; Persson, 1978; Persson, 1979; Persson, 1980; Persson and Ahlström, 1991; Idem, 1994).

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In this article root data from own investigations have been compiled in order to evaluate the general pattern. The primary objectives of the present paper were i) to analyse available data on the effects of high nitrogen and sulphur deposition on mineral nutrient balance in tree fine roots and ii) to evaluate the risk of Al interference with cation uptake by roots.

2. Chemical composition of fine roots

The concentrations of N, P, K, Ca, Mg, Fe, Al, and Ca/Al ratios of fine roots from mineral soil layers in different experimental forest sites are given in Table 1. The concentration of most nutrients in roots decrease with increasing root diameter. Although deficiency symptoms in forest trees may be reflected in nitrogen/cation ratios in fine roots, few attempts have been made to explain forest damage symptoms from fine-root chemistry.

Table 1. Chemical composition (mg g^{-1}), Ca/Al ratios (mol/mol) in living fine roots in soil cores of various tree stands in the upper 0-30 cm of the mineral soil horizon or in 30 cm ingrowth cores (Öringe). Estimates were obtained on untreated sites (0), control plots (C), plots subjected to irrigation and liquid fertilization (IL), dolomite lime application (D), carbonate lime application in two doses (Cal-2), application of peat/ wood ashes (P-W), application of complete solid fertilizers (FA or FB) and application of ammonium sulphate (NS).

Tree species/ site diameter/treatment	N	K	P	Ca	Mg	Al	Ca/Al
Picea abies - Skogaby							
< 2 mm, 0	7.4- 9.3	0.4-1.3	0.7-0.8	1.5-2.0	0.6-0.7	6.4-11.0	0.10-0.20
< 2 mm, C	5.8-9.1	0.2-0.4	0.6-0.8	1.5-1.6	0.5	5.5-10.1	0.05-0.22
< 2 mm, NS	7.8-9.3	0.2-0.4	0.7-0.9	1.3-1.7	0.5	4.7-11.7	0.06-0.30
< 2 mm, IL	7.1-9.2	0.5-0.6	0.7-0.8	2.0-2.3	0.6-0.7	4.0-13.3	0.11-0.34
Picea abies - Öringe							
< 1 mm, C	13.1-13.5	0.2-0.6	1.5-1.9	1.5-5.0	0.4-0.9	6.6-9.3	0.15-0.38
< 1 mm, D	11.4-14.3	0.3-0.8	1.2-1.9	1.4-5.7	0.6-1.2	6.2-8.8	0.15-0.45
< 1 mm, Cal-2	11.7-14.6	0.2-0.8	1.3-1.7	2.1-6.2	0.4-1.0	5.6-8.4	0.22-0.56
< 1 mm, P-W	11.8-15.2	0.3-1.0	1.4-2.4	2.5-6.1	0.6-1.1	4.8-8.7	0.22-0.57
Picea abies - Fäxboda							
< 1 mm, C	-	0.4-1.2	-	2.7-2.8	0.6-0.9	7.2-7.4	0.24-0.26
< 6.4 mm, 0	13.3-22.2	2.9-5.4	1.9-3.2	2.4-5.8	0.9-1.4	4.8-18.6	0.09-0.81
Pinus sylvestris - Jädraås,							
- mature stand							
< 2 mm, C	9.8	1.4	1.5	1.5	1.2	7.9	0.13
< 2 mm, IL	15.0	1.3	2.2	1.7	1.2	7.2	0.16
< 2 mm, FA	16.0	1.6	1.6	1.6	0.7	4.8	0.22
< 2 mm, FB	11.2	1.8	1.3	0.9	0.7	5.3	0.11
- young stand							
< 2 mm, C	6 .1	1.9	0.9	2.0	0.7	-	-

The investigations at Öringe clearly demonstrate that element concentrations (Ca, P, Mg and K) in fine roots are affected by changes in soil nutrient status after liming, ash-application, etc. (see Table 1). Furthermore, it was demonstrated from the same data that alkalizing substances increased the Ca/Al ratio of the fine roots and the pH in the soil solution. Thus, the nutritional status was generally improved, although increased pH and salt concentrations caused a negative growth response the first four years after application in the peat ash and high doses of calcium carbonate treatments.

The Ca/Al ratios are very low in most sites (Table 1). The concentration of Al in itself should not be expected to be critical for damage symptoms, but rather the Ca/Al molar ratio (Meiwes *et al.* 1986). The concentrations of Fe and Al were high in fine roots compared with large diameter roots and decreased with stand age (see Table 1; data on *Pinus sylvestris*). A low Ca/Al ratio (< 0.1 mol/mol) in the fine roots should be regarded as a possible indication of root damage (cf. Meiwes *et al.*, 1986). Available data from many of the investigated forest stands indicate a low Ca/Al ratio in fine roots (often < 0.1 mol/mol) and it may be concluded that Al toxicity may be a predisposing factor to forest decline (Table 1).

Nitrogen is the most important macro-nutrient affecting plant growth. The proportions of nitrogen to other macro-nutrients have been used to describe the plant requirements of different macro-nutrients (cf. Ingestad, 1979). In trees, elemental concentrations in fine roots may be regarded as better phytoindicators of the nutritional conditions in the forest soil than foliar concentrations and give a more direct indication of experimental impacts from fertilization, liming etc. (cf. Joslin *et al.*, 1988; Persson and Ahlström, 1991; Idem 1994). The proportions of nitrogen in relation to other macro-nutrients from mineral soil layers in different experimental forest sites have been compiled in Table 2. Some variation around the optimal proportion values should be expected without plant growth is effected. According to Ingestad (1979), the optimum

Table 2. Nitrogen: cation ratios in living fine roots in the mineral soil for important elements in various Swedish forest stands. For treatments see Table 1.

Tree species/ Site diameter/ treatment	N	K	P	Ca	Mg
Picea abies - Skogaby					
< 2 mm, C	100	3-4	8-11	20-21	7
< 2 mm, NS	100	2-5	8-11	15-20	6
< 2 mm, IL	100	6-7	9-10	25-28	7-8
Picea abies - Öringe					
< 2 mm, C	100	2-5	11-14	11-38	3-7
< 2 mm, D	100	2-6	9-15	11-44	5-9
< 2 mm, Ca1-2	100	2-6	10-13	16-47	3-8
< 2 mm, P-W	100	2-7	10-18	19-45	4-8
Pinus sylvestris - Jädraås,					
- mature stand					
< 2 mm, C	100	14	15	15	12
< 2 mm, IL	100	9	15	11	8
< 2 mm, FA	100	10	10	10	4
< 2 mm, FB	100	16	12	8	6
- young stand					
< 2 mm, C	100	31	15	33	11

weightproportions are 100 N: 45 K: 15 P: 6 Ca: 6 Mg for Picea abies. In field experiments where a close relationship between the tree growth rate and net uptake rate of nutrients is desired, complete sets of nutrients should be applied at these levels (see Majdi and Persson, 1993 for Skogaby; Persson, 1980 for Jädraås).

It is evident from the data in Table 2 that the potassium to nitrogen ratio is low in forest stands in SW Sweden (Skogaby and Öringe), when compared with other Swedish sites (Jädraås). Significantly lower potassium concentrations from needle analyses were also found in the Skogaby NS treatment in 1992 compared with the IL-treatment (Nilsson and Wiklund, 1995). The data suggest that K shortage may be a reality in Southern Swedish forest stands and that accelerated acidification in combination with increased nitrogen deposition (the NS-treatment at Skogaby) increase the risk of K deficiency. K deficiency is known to depress the allocation pattern to roots in Betula pendula seedlings (Ericsson and Kähr, 1993).

3. Effects on fine-root development

Part of the increased above-ground tree production subsequent to nitrogen deposition seems to be related to a shift in the carbon allocation pattern from below- to above-ground, caused by changes in fine-root turnover (Santantonio and Herman, 1985; Persson, 1993). Root investigations in the field indicate so far that:

- Liquid fertilization (with a complete fertilizer) caused an increased fine-root production (cf. e.g. Persson, 1980; Ahlström et al., 1988).
- Solid fertilization in combination with liming generally caused a decrease in fine-root production, whilst solid fertilization alone (ammonium nitrate and urea) in some field experiments caused a decrease in fine-root production. However, in some experiments an increase in fine-root growth was observed (Persson, 1980; Persson *et al.*, 1995; Persson and Ahlström, 1991).
- Ammonium sulphate application, viz. increased nitrogen and sulphur deposition (the NS-treatment at Skogaby), caused a decreased fine-root vitality (Clemensson-Lindell and Persson, 1995a/based on morphological characteristics), an increased concentration of fine roots to the LFH-layer and an increased amount of dead fine roots in the soil profile (Majdi and Persson 1995a, Persson *et al.*, 1995). Experimentally decreased nitrogen and sulphur deposition in a catchment area in SW Sweden (roof experiment) tend to increase fine-root vitality (Clemensson-Lindell and Persson, 1995b).

Estimates of change in the amount of fine roots and nutrient concentrations were until the last decades very rare in literature (Persson, 1990). The development of a new technique, e.g. the minirhizotron technique (Majdi et al., 1992; Hendrick and Pregitzer, 1993), makes it possible to follow the growth dynamics of the fine roots in the field with high resolution. Since the same roots are followed at the same part of the tube, the observed rate of changes in production or mortality of fine roots are directly related to fluctuations in soil chemistry and nutrient availability or environmental changes (soil temperature or moisture).

Results from the minirhizotron investigations on fine-root production and mortality in the control (C) and ammonium sulphate treatment areas (NS) in Skogaby are shown in

Figure 1. Total net fine-root production in the NS treatment areas were lower than in the control during the whole study period. Since the amount of fine roots at any given time is governed by the balance between the production and mortality of fine roots, the NS treatment may in the longer run result in fewer fine roots.

Reduced vitality of fine roots in the NS treatment at Skogaby was indicated in 1992 from data obtained from direct soil coring, and sorting the fine roots into 3 vitality classes based on morphological characteristics (Clemensson-Lindell and Persson, 1995a). The amount of living fine roots of class 2 decreased significantly in treatment areas subjected to increased nitrogen and sulphur deposition (NS), while the amount of dead roots increased. Although a 30% increase in above-ground production was shown on NS-treated areas in response to the NS-application, the vitality of the fine-root system appeared to be in a state of deterioration.

Recent findings on fine-root carbon and nutrient cycling stress the importance of a more holistic approach to the ecosystem structure and function, for the assessment and prediction of disturbances to terrestrial systems (Hendricks *et al.*, 1993). The main question to answer is to what extent fine-root and foliar carbon allocation and utilisation patterns are similar across nitrogen availability gradients. The ability of the forest ecosystems to accumulate nitrogen from atmospheric depositions is limited before an imbalance between demand for and supply of cations is obtained. Chronically high nitrogen deposition is likely to produce longer-lasting effects on fine-root systems and their function.

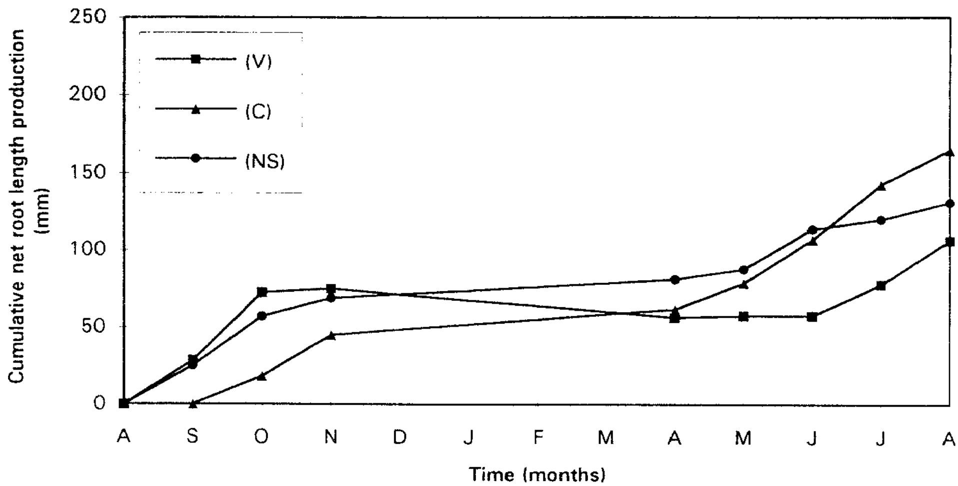

Fig. 1. Cumulative net fine-root production (production - mortality) in the control and ammonium sulphate and nitrogen free fertilizer treatments at Skogaby from August 1991 to August 1992 at a depth less than 30 cm. The data were obtained in 10 minirhizotron tubes in each of three plots in the different treatment areas. Area of observation = 1.80 * 1.35 cm at each 1.35 cm depth. For more information see Majdi and Persson (1995b).

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