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Fertilization to Increase and Sustain Tree Growth in Coniferous Stands in Sweden

Staffan Jacobson

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES



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Abstract

Intensified forest management practices, together with the deposition of air pollutants, have considerable potential implications for silviculture. These factors influence N availability in soil and also cause soil acidification, involving reductions in the levels of plant-available base cations. The aim of the work described in this thesis was to evaluate the need for compensatory additions of other nutrients apart from N, from a forest yield perspective, after whole-tree harvesting and N fertilization, focusing on Swedish conditions but including also some studies from Finland and Norway. All studies were undertaken in field experiments on mineral soils, representing a wide range of site conditions. Stem growth and nutrient concentrations in needles were assessed in closed-canopy Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) stands.

Whole-tree harvesting in thinnings reduced stem growth (by 5–10% on average) for at least 10 years. These growth reductions were counteracted fully by adding inorganic N-fertilizer and, thus, there was no need for additions of other nutrients. The stem growth responses to additions of wood ash without N were small and variable, and not statistically significant at any of the studied experimental sites. Experiments at a large set of experimental sites previously subjected to repeated N fertilizations showed that the addition of nutrients other than N generally had negligible effects on the short-term (4–15 years) growth response. Furthermore, it was concluded that N fertilization, with the addition of B, generally did not cause any serious long-term (20–30 years) nutrient deficiencies in trees, even after substantial N additions.

Key words: ammonium nitrate, cations, needle nutrient composition, nitrogen, Norway spruce, *Picea abies*, *Pinus sylvestris*, phosphorus, potassium, Scots pine, whole-tree harvesting, wood ash.

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Staffan Jacobson
Department of Silviculture
Umeå

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Author's address: Staffan Jacobson, SkogForsk (The Forestry Research Institute of Sweden), Uppsala Science Park, SE-751 83 Uppsala, Sweden.

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Appendix

Papers I-IV

The present thesis is based on the following papers, which will be referred to in the text by the corresponding Roman numerals.

- I. Jacobson, S., Kukkola, M., Mälkönen, E. and Tveite, B. 2000. Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. *Forest Ecology and Management* 129: 41–51.
- II. Jacobson, S., Sikström, U. and Nohrstedt, H-Ö. 2000. Effects of previous high N addition on nutrient conditions in above ground biomass of a *Picea abies* stand in Sweden. *Scandinavian Journal of Forest Research* 15: 30–38.
- III. Jacobson, S and Pettersson, F. 2001. Growth responses following nitrogen and N-P-K-Mg additions to previously N-fertilized Scots pine and Norway spruce stands on mineral soils in Sweden. *Canadian Journal of Forest Research* 31: 899–909.
- IV. Jacobson, S. 2001. Addition of stabilized wood ashes to Swedish coniferous stands on mineral soils – effects on stem growth and needle nutrient composition. (Manuscript)

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Introduction

Nitrogen limitation common

Biomass production of forest stands is determined, above all, by the amount of light intercepted by the canopy during the growing period (Kellomäki et al., 1979; Cannell, 1989; Linder & Flower-Ellis, 1992), and hence by the amount of foliage in the stand and its distribution (Wang & Jarvis, 1990; Albaugh et al., 1998). However, most forest stands produce levels of leaf area well below their optimum potential. Numerous field experiments, for a range of species growing in contrasting environments, have shown that manipulation of the availability of nutrients, water, or both, can have dramatic effects on forest biomass production (cf. Tamm, 1985; Linder, 1990). In the temperate and boreal zones, nutrient availability is the major factor regulating forest growth (Tamm, 1991).

It was recognized at an early stage that low nitrogen (N) availability could limit production in temperate forests (e.g. Hesselman, 1937; Mitchell & Chandler, 1939), and from the results of several fertilization experiments it became evident that N is the primary limiting nutrient for tree growth on mineral soils in most boreal and temperate forests (cf. Tamm, 1991; Vitousek et al., 1997).

N is unique among plant nutrients in that it initially originates from the atmosphere, from where it is transferred to the biosphere by biological N₂-fixation or by lightning. Human activities such as industrial fixation of N₂ for use as fertilizer, cultivation of N₂-fixing crops and mobilization of N during high-temperature fossil fuel and biomass combustion, have doubled the rate of N input into the terrestrial global N cycle (Vitousek et al., 1997). Due to the human input of N to the biosphere there has been a substantial rise in N deposition since the 1950s in Sweden (Lövblad, 2000) and N deposition can significantly affect nutrient cycling and soil biogeochemistry (Gundersen, 1991). Excess N may accelerate the removal of base cations through increased plant uptake or leaching (Aber et al., 1989), so increased attention has been paid to the possibility that N deposition may create conditions in which N is no longer the limiting nutrient for forest growth.

Reasons for low N availability

Nitrogen is the most abundant nutrient in plant tissues. Soils contain the largest N pool in forest ecosystems, usually exceeding 80% of the total ecosystem capital (Nohrstedt, 1993; Fenn et al., 1998). Most soil N occurs in an organic form and at any instant it is to a large extent unavailable for either plant uptake or leaching. Hence, available soil N pools must turn over several times per year to meet the N demand of plants (e.g. Johnson, 1992). However, it has been demonstrated that plants can also take up organic N (Näsholm et al., 1998; Nordin et al., 2001), although the quantitative significance of utilizing organic N as an N source is not yet clear. Unlike N, other major nutrients (P, S, K, Ca, Mg, Mn), which originate

primarily from soil minerals, can accumulate to a substantial degree at soil exchange complexes (Fenn et al., 1998). Reasons for the low availability of N involve various factors, such as the slow turnover rates of dead plant material, and the effects of natural disturbances (e.g. fire and insect defoliation) which mobilize N that is easily lost from the ecosystem (Vitousek & Howarth, 1991).

Besides N, phosphorus (P) is considered to be the main growth-limiting nutrient for plants in natural environments (Aerts & Chapin, 2000). The major proportion of total P in the surface soil (0–5 cm) is in organic form (Attiwell & Adams, 1993), and hence, as for N, the availability of P is inherently linked to the turnover of the organic material. Apart from differences in the biogeochemical cycles of N and P, there are also significant biochemical differences between the two elements. Most importantly, organic N is carbon-bonded and often occurs in complexed forms, whereas organic P is ester-bonded and often soluble (Vitousek & Howarth, 1991). Due to the production of extra cellular phosphatases this P may become available for plant uptake (McGill & Cole, 1981), and it has been shown that the production of these enzymes is increased in forest soils with low concentrations of soluble P. It has been proposed that N availability could be determined by the availability of P, due to P limitations of the N₂-fixing organisms (Cole & Heil, 1981; Vitousek & Howarth, 1991). However, energetic constraints on the colonization and activity of the N₂-fixing organisms provide more plausible explanations for the relatively minor contribution of N₂-fixation to N supplies in temperate terrestrial ecosystems (Vitousek & Howarth, 1991).

A number of studies have demonstrated positive correlations between forest productivity and N concentration in the humus layer on the one hand, and soil acidity (pH) and base saturation on the other (e.g. Dahl et al., 1967; Lahti & Väisänen, 1987; Giesler et al., 1998). These results have been cited as evidence showing that the supplies of base cations (K, Ca, Mg) are limiting factors for forest productivity, and that anthropogenic acidic deposition will have a direct negative impact on forest growth through its reduction of base cation availability in the soil (e.g. Sverdrup et al., 1992; Sverdrup & Rosén, 1998). However, extensive series of field experiments have shown that, in most parts of Sweden, additions of N increase forest growth (Pettersson, 1994a), despite the fact that they often also lower the pH of the soil (Binkley & Högberg, 1997). Giesler et al. (1998) suggested that soil pH, as well as the supply of base cation, may affect plant productivity indirectly via effects on N supply, for example by modifying factors that influence N₂ fixation and through its effects on microbial N turnover, and that this could explain the demonstrated correlation. However, another possible explanation is that N and base cation levels are correlated because they are solutes in the same water flows from recharge areas to discharge areas (Giesler et al., 1998; Högberg, 2001).

N fertilization

Commercial application of N fertilizers commenced in Swedish coniferous forests by the mid-1960s. The focus on N was a result of early experiments indicating that simultaneous supply of other nutrients (P, K, Ca, Mg) generally did not increase the growth response on mineral soils (cf. Nohrstedt, 1990). The addition of 150 kg N ha⁻¹, which is a normal commercial dose in Sweden for medium-aged and older stands (i.e. stands in which the canopy has closed, and after first thinning), normally results in an average relative growth increase of about 30–55% over a period of 7–11 years (Pettersson, 1994b). During the last 40 years about 1.6 – 1.7 million ha of productive forest has been subjected to N-fertilization, once or several times, representing 7–8% of the total area of productive forest in Sweden. Practical forest fertilization peaked by the end of the 1970's, when ca. 190 000 ha of forest on mineral soil was fertilized annually. By the end of the 1980's the annual area started to decrease, owing partly to concerns about the effects of N deposition (Pettersson, 1994a), and currently areas totalling ca. 20 000 ha are fertilized annually. Other reasons for this dramatic drop in fertilization activity included the extension of the period between fertilizations from 5–7 years to 10–15 years, in combination with more careful selection of appropriate stands.

In the 1960s, urea was the N-fertilizer generally used in practical forestry. However, at the beginning of the 1970s Malm & Möller (1974) showed that the growth increment was 30–40% higher when ammonium nitrate (AN) was used (at the same N-dosage) instead of urea. Urea fertilization induces a weaker growth response mainly because it is associated with a more pronounced immobilization of ammonium N in the litter and humus layers (Melin & Nömmik, 1988). Hence less N is available for tree growth. Furthermore, some of the N added as urea could be subject to ammonia volatilization because of the increase in pH it causes (e.g. Nömmik, 1973; Melin, 1986). From the middle of the 1970s AN, later supplemented with dolomite lime, has been the only N-fertilizer in practical use in Swedish forestry.

In many stands in northern Sweden that had been refertilized with N during the 1970's clear damage could be seen in the crowns in the form of needle death and dead tops. Needle analyses established that this damage was caused by boron (B) deficiency (Albrektsson et al., 1977; Huikari, 1977; Aronsson, 1980, 1983). Additional experiments showed that an addition of 1 kg B ha⁻¹ was sufficient to restore the B concentration in the needles (Möller, 1984). In Sweden today, use is made of B-enriched N fertilizer.

Results generated from experiments with repeated N fertilization indicated that the effect on growth following a refertilization was lower than that of the initial fertilization (Pettersson, 1987, 1990; Jacobsson & Nohrstedt, 1993). These observations were more pronounced at high N-dosages and at short fertilization intervals. The results from the optimum nutrition experiments (cf. Tamm, 1985,

1991; Tamm et al., 1999) prompted development of a hypothesis suggesting that the reduced growth increment following repeated N application was caused by deficiencies of other macronutrients, mainly P and K. Based on this hypothesis, a large number of Swedish N-fertilization experiments were refertilized with N and other macro-nutrients during the later part of the 1980s.

Whole-tree harvesting and wood ash addition

Interest in using logging residues for energy purposes has increased in Sweden in recent decades, and whole-tree harvesting (WTH) is now a common practice in many parts of the country. In southern Sweden, logging residues were harvested in 60% of the clearcuts in 1996 (Filipsson, 1998). In contrast to conventional stem harvesting (CH) where all needles, branches and non-merchantable stem-wood are retained on site, WTH involves the harvesting of most of the above-ground parts of the trees. WTH is predominantly practiced in clear-fellings, but residues from thinnings and pre-commercial thinnings are also sometimes collected, and their use is expected to increase, provided the increasing demand for bioenergy sources continues (Filipsson, 1998).

From a management perspective, removal of the residues from clear-cuts can facilitate restocking, since they may obstruct mechanical site preparation and planting (Hakkila, 1973). However, the primary concern associated with WTH has focussed on the increased export of nutrients it entails, potentially reducing long-term site productivity (Tamm, 1969; Weetman & Webber, 1972; Mälkönen, 1976; Kimmins, 1977). While WTH may increase biomass removal by 10–40%, it is associated with much larger relative increases in nutrient removal, because of the much higher nutrient concentrations in the canopy compared to the stem (Carey, 1980; Compton & Cole, 1990). Moreover, depletion of base cations in the forest soil is associated with soil acidification, and it has been shown that WTH can lead to increased soil acidity, and decreased base saturation, in the organic layer (Nykvist & Rosén, 1985; Staaf & Olsson, 1991; Olsson et al., 1996). However, the additional nutrient removal caused by WTH may to some extent be counteracted, since nutrient leaching losses appear to be higher when the logging residues are left on the site (Rosén & Lundmark-Thelin, 1987; Stevens & Hornung, 1990; Staaf & Olsson, 1994), probably because of enhanced mineralization of the soil organic layer and increased nitrification rates (Emmet et al., 1991).

A number of studies have demonstrated tree-growth reductions due to WTH, after both thinnings and clear-cuts, in Fennoscandia (Egnell et al., 1998) as well as in other parts of the world (e.g. Sterba, 1988; Compton & Cole, 1990; Proe et al., 1996). Reported growth losses typically range between 5 and 15% during study periods of 10–15 years, and even more dramatic growth losses (20–30%) may occur (Sterba, 1988; Proe et al., 1996). The vital issue of whether these reductions in forest growth after WTH are temporary, or not, is as yet an unanswered question.

Since the nutrient requirements of tree stands are highest at an age that approximately coincides with the time of first thinning (Ovington, 1959; Mälkönen 1974), i.e. at around 30–50 years depending on the fertility of the site, stands at this stage should be fairly sensitive to nutrient removal. Mälkönen (1976) considered nutrient compensation through fertilizer application to be necessary after WTH in thinnings.

The increased use of forest logging residues for bioenergy generates large quantities of ash. To prevent, or reduce, the negative effects of WTH, it has been suggested that it would be of value to recycle the nutrients contained in the wood ash (Vance, 1996; Olsson et al., 1996; Eriksson, 1998). Wood ash has a high acid-neutralizing capacity (ANC), and most of the macronutrients (except N) and micronutrients from the biomass are retained in the ash in an inorganic form. In its general guidelines concerning harvesting of logging residues, the Swedish National Board of Forestry recommends that the wood ash should be put back into WTH sites, in order to circulate nutrients and counteract soil acidification (Anon., 1998).

The effects on stem growth of adding wood ash to organic forest soils are well documented. On drained peatlands addition of loose ashes normally yields a high and persistent increase in stem growth (Silfverberg & Huikari, 1985; Silfverberg & Hotanen, 1989). The main object of adding wood-ash to mineral soil is to restore or counteract the long-term nutrient depletion in the soil, rather than to induce a short-term growth increase. Consequently, there are very few reports dealing with growth responses after applications of wood-ash to mineral forest soils.

Assessing the nutrient status of a forest stand

There are various ways to assess the nutritional status of a forest stand. The most common approaches include, (i) identification of visual symptoms, (ii) chemical foliar analysis, (iii) soil analysis, (iv) inference through site and stand characteristics, and (v) fertilizer trials (Carter, 1992). Deficiency symptoms are most likely to be detected in the leaves, as they are the site of many important metabolic activities (Walker, 1991), and chemical foliar analysis has been widely used for diagnosing the nutrient status in forest stands for many years. However, a large number of factors such as tree species, genotype, site, year, seasonality, position within the crown, age of trees and needles etc., affect the concentration of nutrients in needles and need to be taken into account when interpreting results (Raitio, 1995). Furthermore, as pointed out by Carter (1992), interpretations of foliar nutrient concentrations cannot stand alone, but should be related to stand growth performance and site characteristics.

When analysing the different nutrient concentrations in the foliage it is useful to distinguish between mobile and less mobile nutrients. Nutrients such as N, P, K and Mg are regarded as mobile elements, and can move readily in the phloem

(Walker, 1991). These nutrients can easily be retranslocated from older to younger tissues, and as a result, deficiency symptoms tend to be more pronounced in older foliage (Walker, 1991). Less mobile nutrients (Ca, Fe, B, Mn, Cu, Zn, Mo) tend to remain where they are initially incorporated into the plant, leading to more obvious deficiency symptoms in the younger tissues. Sulfur (S) and Cl are intermediate in their mobility and deficiencies of these elements tend to affect the whole shoot (Walker, 1991).

The results from chemical foliage analysis can be interpreted by comparing the observed nutrient concentrations with reported threshold values (as proposed, for instance, by Ingestad, 1962; Nihlgård, 1990 and Brække, 1994). The ranges of optimum and deficiency concentrations of each nutrient are most probably fairly wide, even within species (cf. Ingestad, 1962; Tamm, 1964). Hence, nutrient analyses can only give reliable indications of nutrient stress at very high or very low concentrations. Some authors have also questioned the diagnostic reliability of critical limit values since they are valid only for the conditions in which they were determined (van den Driessche, 1979; Timmer, 1991). Furthermore, the critical and optimum levels vary significantly with age and developmental stage of the trees (Miller et al., 1981). According to van den Driessche (1979), foliar analysis is valuable in diagnosing the likely cause of nutrient limitations only where there are clear nutrient deficiency symptoms.

Other methods for interpreting nutrient concentrations in foliage include graphical vector analysis (Timmer & Stone, 1978; Timmer & Morrow, 1984), DOP-index [Deviation from Optimum Percentage] assessment (Montañés et al., 1993), and DRIS [the Diagnosis and Recommendation Integrated System] of Beaufils (1973) (cf. Timmer, 1991).

It has been suggested that the proportions of the nutrients in relation to N are at least as important as the absolute concentrations of each nutrient for the 'vitality' and growth of a plant (cf. Linder, 1995). Monitoring ratios between nutrients decreases the variation between years, and the effect of growth dilution, i.e. the decrease in concentration due to increased needle size (van den Driessche, 1979). Furthermore, by calculating the ratio between nutrients, it is possible to detect 'nutrient imbalances' during the growing season without correcting for carbohydrate reserves (Linder, 1995). Optimum nutrient ratios have been suggested by several authors (Ingestad, 1979; Nihlgård, 1990; Brække, 1994; Linder, 1995), and interpretation of foliage analysis via nutrient ratios, and the concept of nutrient balance, has been frequently adopted in Sweden during the last decade.

Objectives

The high atmospheric deposition of S and N, together with intensified harvesting practices, have led to soil acidification, entailing a decline in base cation status, with possible implications for silviculture. The general aim of this thesis was to

examine the possible need for compensatory additions of other nutrients apart from N after intensified forestry practices such as whole-tree harvesting and N fertilization. The issue is formulated strictly from the viewpoint of forest yield and is restricted to consideration of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) stands on mineral soils, predominantly in Sweden.

The following specific questions were addressed in the four papers:

- (I) Is stem growth of first-thinning stands of Scots pine and Norway spruce affected by whole-tree harvesting and is there a need for nutrient compensation?
- (II) Do previous high N additions generate any residual effects on the nutritional status in the above-ground parts of a productive Norway spruce stand?
- (III) Does the addition of nutrients other than N in conjunction with N re-fertilizations increase stem growth response?
- (IV) Is stem growth of coniferous trees on mineral soils affected by the application of wood ash?

Materials and methods

Experimental sites

Most studies were undertaken in field experiments in coniferous stands in Sweden. In the study reported in Paper I, results from Finnish and Norwegian experimental sites are also included. With one exception (Paper II), the studies were performed on a series of experimental sites, representing a wide range of site conditions (Fig. 1, Table 1). The study in Paper II was performed in a productive Norway spruce stand in the central part of Sweden. Detailed information about the sites can be found in the respective papers (I–IV).

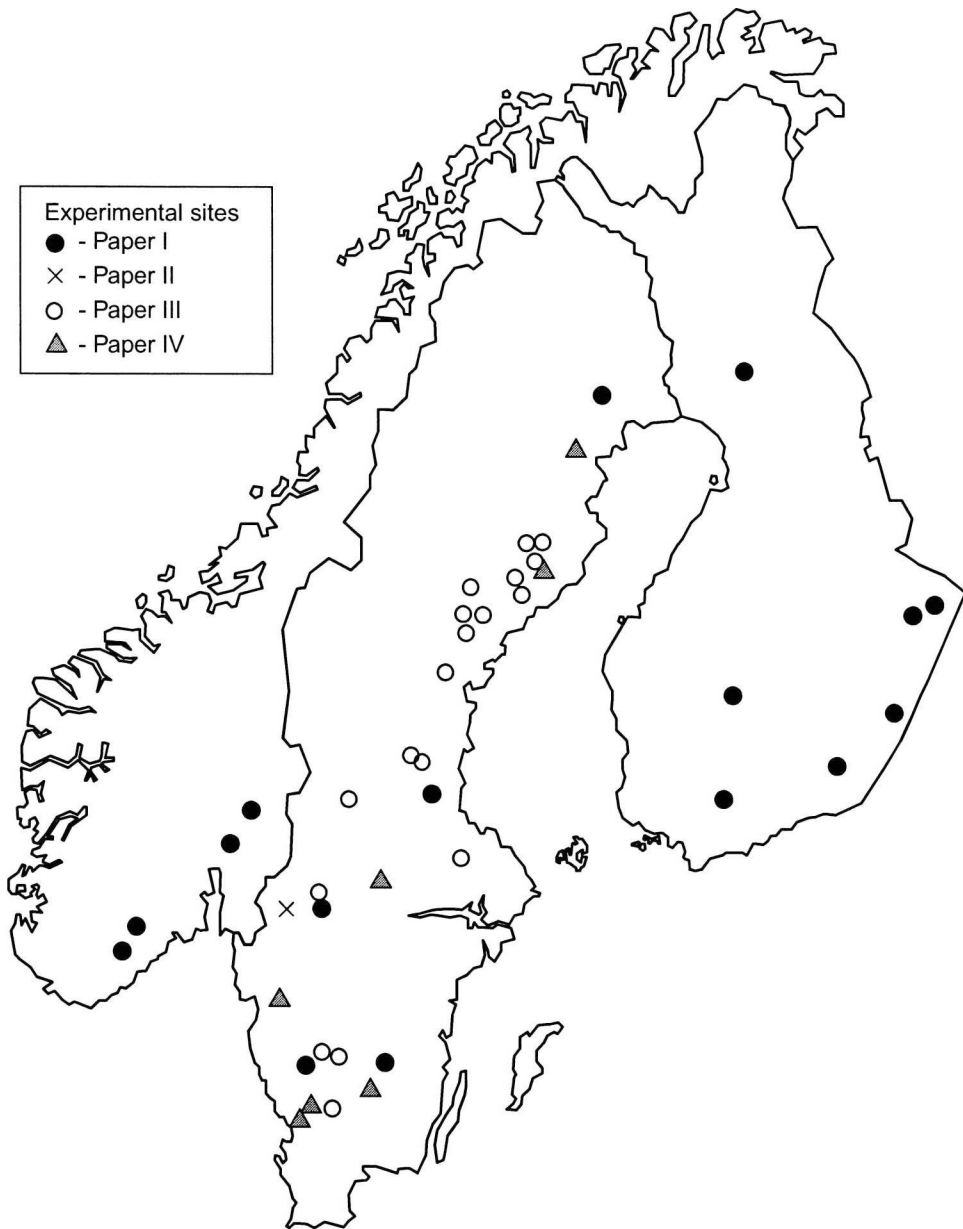


Fig. 1. Location of the experimental sites.

Table 1. Experimental sites

Site	Latitude	Tree species	Stand age (yrs) ^a	Site quality (m ³ ha ⁻¹ yr ⁻¹)
<u>Paper I</u>				
181 Örsås	57° 23'	<i>Picea abies</i>	30	13.9
732 Loppi	60° 39'	“	50	11.3
733 Eno	62° 49'	“	27	10.4
735 Ruokolahti	61° 30'	“	53	9.6
1057 Nannestad	60° 15'	“	40	9.0
1081 Nome	59° 17'	“	29	9.6
184 Vetlanda	57° 25'	<i>Pinus sylvestris</i>	36	6.8
193 Munkfors	59° 51'	“	32	6.8
204 Lakaträsk	66° 19'	“	71	3.4
219 Åmot	61° 02'	“	30	7.3
729 Rovaniemi	66° 27'	“	53	4.4
730 Keuruu	62° 05'	“	32	8.2
731 Ilomantsi	62° 52'	“	63	4.3
734 Savitaipale	61° 14'	“	34	7.7
1056 Løten	60° 44'	“	40	5.9
1082 Nissedal	58° 55'	“	41	5.1
<u>Paper II</u>				
D11 Mangskog	59° 50'	<i>Picea abies</i>	80	9.3
<u>Paper III</u>				
141 Transtrand	61° 08'	<i>Picea abies</i>	118	6.6
142 Dörarp	57° 00'	“	74	11.3
143 Voxna	61° 40'	“	20	6.1
170 Ramsele	63° 28'	“	73	5.5
191 Håcksvik	57° 18'	“	93	9.0
D100 Bjurholm	64° 05'	“	106	4.2
5 Graninge	63° 04'	<i>Pinus sylvestris</i>	79	5.6
43 Tärnsjö	60° 07'	“	97	4.3
59 Voxna	61° 27'	“	130	3.3
132 Nissafors	57° 24'	“	51	5.5
133 Hällnäs	64° 27'	“	107	3.1
165 Hagfors	60° 00'	“	70	5.9
171 Åsele	64° 07'	“	63	3.4
235 Östavall	62° 23'	“	102	5.2
D70 Beroniussådden	64° 19'	“	58	5.2
D73 Brännforsliden	64° 41'	“	90	3.1
D74 Norsk Hydro	64° 41'	“	58	3.1
G84 Västanbäcksmon	63° 37'	“	57	3.4
<u>Paper IV</u>				
182 Uddevalla	58° 27'	<i>Picea abies</i>	35–60	11.3
241 Torup	56° 55'	“	40	11.3
244 Åled	56° 46'	“	65	12.0
183 Asa	57° 10'	<i>Pinus sylvestris</i>	35	7.7
242 Vindeln	64° 12'	“	40	5.6
250 Riddarhyttan	59° 48'	“	50	5.9
251 Älvsbyn	64° 12'	“	60	3.7

^a Refers to total stand age at the start of the studied treatment

Treatments

The design of the 16 experimental sites, established to quantify the growth response of first-thinning stands to whole-tree harvesting (WTH), and to estimate the need for nutrient compensation (Paper I), included the following common treatments: (i) conventional harvesting of merchantable stem-wood with bark (CH), (ii) WTH, (iii) WTH and compensatory fertilization equivalent to the estimated amounts of N (21–126 kg ha⁻¹), P (3–20 kg ha⁻¹) and K (9–54 kg ha⁻¹) removed in logging residues, and (iv) CH and fertilization with 150 kg N ha⁻¹ in pine stands and with 150 kg N ha⁻¹ plus 30 kg P ha⁻¹ in spruce stands (in the experiments in northern Finland and northern Sweden, 1 kg B ha⁻¹ was also added in this treatment), (v) WTH and fertilization as in the previous treatment. Ammonium nitrate (AN; N 34.5%), dolomite ammonium nitrate (dAN; N 27.5%, Ca 4.0%, and Mg 2.0%), superphosphate and potassium chloride were the fertilizers used.

The study on nutrient conditions of different above-ground tree compartments (Paper II) was performed in a fertile Norway spruce stand, previously treated with different doses (120, 240, 360, 480 and 600 kg N ha⁻¹, respectively) of urea-N (N 46.0%) four times at intervals of five years. The total amount of N added varied accordingly from 480 to 2400 kg ha⁻¹.

To study the growth response of adding nutrients other than N in conjunction with N refertilizations (Paper III) a series of 18 long-term N fertilization experimental sites were refertilized with N (90–600 kg ha⁻¹), either alone or with various combinations and doses of P (20–60 kg ha⁻¹), K (40–150 kg ha⁻¹) and Mg (10–60 kg ha⁻¹). Many of the experimental plots had previously been subjected to heavy N fertilization regimes over a period of 20–30 years, with varying doses and intervals. The N fertilizers used were urea, AN or dAN. P, K, Mg and micronutrients were applied in readily soluble forms.

To determine whether the stem growth of coniferous trees on mineral soils is affected by adding stabilized wood ash (Paper IV), a series of seven field experiments was established in Sweden in 1988–1995. The studied treatments comprised addition of wood ash in doses of 1, 3, 6 and 9 Mg ha⁻¹ (d.w.), as well as combined ash + N treatments. The ashes used differed in origin and constitution. The N-dose was 150 kg ha⁻¹, except at one site where the N treatment consisted of annual additions of 20 kg ha⁻¹ yr⁻¹, split into two occasions. N was added in the form of AN or dAN.

Measurements and calculations

All experiments were set up according to a randomized block design, with permanent quadratic sample plots of 0.05–0.16 ha, and with varying numbers of replicates (2–6) at each experimental site. All tree-growth measurements (Papers I, III and IV) were performed on permanent sample trees (25–60 trees per plot) in a circular area centred in the middle of each plot. The measurements taken included diameter at breast height (dbh), obtained by cross-calipering at permanent marks on the stem, and height of the trees. At the end of the study period (4–15 years after treatment) the measurements were repeated and, at most experimental sites, increment cores were taken with a borer at breast height. The stem volume of individual trees was estimated using empirical functions of Näslund (1947).

With the aim of determining the effect of previous high N additions on the nutritional status of the above-ground parts of a Norway spruce stand, various biomass fractions (including stem wood, stem bark, branches and needles) were destructively sampled and chemically analysed (Paper II).

The nutrient composition of needles was examined, with varying intensities, in all studies. Current-year needles were sampled during the winter (December–March) from 10 trees from each plot. Twigs from the south side of the upper third of the crown were sampled. The needles from the ten trees were pooled into one sample representing each plot. Detailed information regarding chemical analyses can be found in the separate papers (I–IV).

Statistical analyses

Mean values for all sample trees per plot were used in the analyses. Treatment effects were evaluated by analysis of variance and linear regression, using SAS software (SAS, 1997). When analysing the results from the individual experimental sites, block and treatment factors were included in the model. In addition, to adjust for differences in pre-treatment conditions, several variables were tested as covariates, and included in the model if the p-value of the covariate was <0.20 . Moreover, since most of the studies that form the basis of this thesis were based on a series of experimental sites with similar treatments, the results from the individual sites were generally pooled and analysed together. In these pooled analyses we assumed that the individual experimental sites, as well as the interaction between site and treatment, could be regarded as random factors. This assumption is, of course, questionable, partly because the number of experimental sites was small, and partly because it is difficult (for many reasons) to achieve strictly random sampling in practice. Consequently, the average values obtained from these analyses must be interpreted with caution.

Major results and discussion

Effects of nutrient removal

During the first 10-year period, there were indications (although not statistically significant) that the removal of the logging residues after thinning had reduced the volume growth in both Scots pine and Norway spruce stands by, on average, 5–6% (Paper I). Yet, there was a large variation in growth response between the experimental sites. This analysis was mainly based on repeated measurements of the diameter and height of the trees. In a later analysis, including 12 of the 16 experimental sites, in which increment cores were also assessed, the between-site variation in growth response was much lower (Jacobson & Kukkola, 1999). On average, the later analysis reported a reduction in volume growth of 7% in Scots pine stands ($p < 0.07$) and 12% in Norway spruce stands ($p < 0.01$) after whole-tree harvesting (WTH) compared to conventional stem-only harvest (CH).

A cover of logging residues keeps the soil moisture higher and more constant (Jansson, 1987; Hendrickson et al., 1985), which stimulates microbial activity and thus increases the rates of mineralization and nitrification in the underlying soil organic layer (Emmet et al., 1991). Hence, apart from the fertilizing effects of the nutrients in the residues, growth on CH-treated plots may benefit from increases in the release of inorganic N. Needle analyses of the remaining trees, sampled 5–7 years after treatment, demonstrated a positive correlation ($R^2 = 0.88$) between relative growth effects and relative N-concentrations in the current year needles after WTH (Fig. 4 in Paper I). These results, together with the significant growth response of the stands to the addition of fertilizer N (or NP addition), irrespective of the biomass harvesting intensity (cf. Figs. 2–3 and Fig. 3 in Paper I), indicate that the growth reduction following WTH was related to the N supply. These results are in accordance with reports by Compton & Cole (1990) and Cole (1995), which clearly demonstrated that reductions in productivity associated with WTH could be completely counteracted by the addition of N fertilizer.

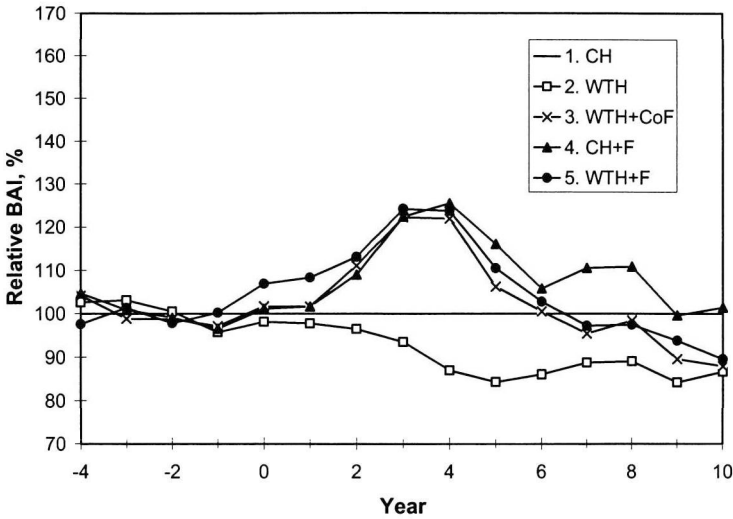


Fig. 2. Annual relative basal area increment (BAI) for the different treatments in the whole-tree harvested thinning stands in relation to conventional thinning with all logging residues left on the site (100%). Mean values for four Norway spruce sites. The treatments were: 1) stem-wood harvesting only (CH), 2) whole-tree harvesting (WTH), 3) WTH + compensatory fertilization (CoF) with 64–126 kg N ha⁻¹, 7–20 kg P ha⁻¹ and 23–54 kg K ha⁻¹, 4) CH + F with 150 kg N ha⁻¹ and 30 kg P ha⁻¹, 5) WTH + F with 150 kg N ha⁻¹ and 30 kg P ha⁻¹ (Jacobson & Kukkola, 1999).

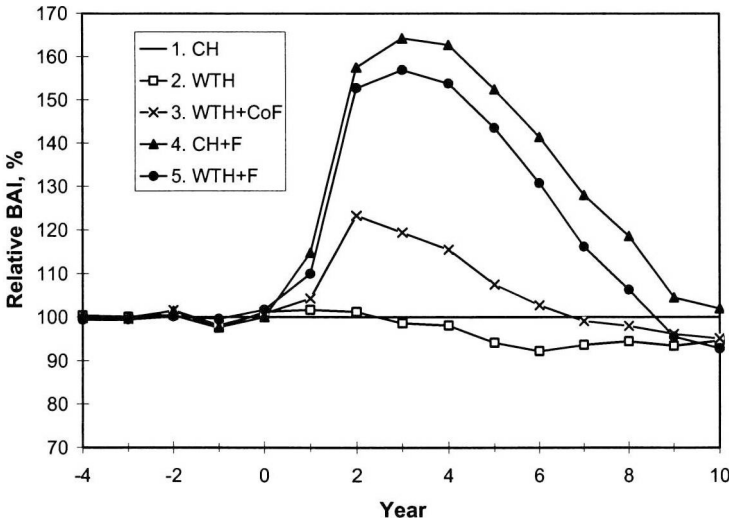


Fig. 3. Annual relative basal area increment (BAI) for the different treatments in the whole-tree harvested thinning stands in relation to conventional thinning with all logging residues left on the site (100%). Mean values for eight Scots pine sites. Treatment symbols as in Fig. 2. Amounts of nutrients added in treatment 3: 21–60 kg N ha⁻¹, 3–6 kg P ha⁻¹ and 9–21 kg K ha⁻¹. No P was added in treatments 4 and 5 (Jacobson & Kukkola, 1999).

The duration of the growth reductions after WTH, reported in Paper I, is a matter for speculation. According to the data in Figs. 2 and 3 (and Fig. 3 in Paper I), the growth on WTH plots did not show any signs of recovery within ten years. Hyvönen et al. (2000) presented data on decomposition and nutrient release from logging residues after clear-cuts in Norway spruce and Scots pine stands. After 6–8 years they found that the needles had lost 30–50% of their initial amount of N. After the same period twigs had lost only 0–20% of their initial N and there was no net release of N from branches. The authors concluded that, in the long run, the nutrients contained in the coarse litter fraction will also be an important nutrient source for the subsequent forest generation. These results indicate that there may be more prolonged growth reductions after WTH.

Effects of nutrient addition

Addition of inorganic N

The effect of adding inorganic N on tree growth was considered in Papers I, III and IV, totalling 41 experimental sites. With few exceptions, the added N resulted in enhanced stem growth. Although N fertilization usually results in increased stem growth throughout Sweden, there are sometimes no significant growth responses, and this is not a new phenomenon. Very poor or non-apparent growth responses are mostly found at relatively fertile Norway spruce sites (Mälkönen et al., 1990; Pettersson, 1994a; Eriksson & Karlsson, 1997). However, several studies have detected significant growth responses after N addition on more fertile sites (e.g. Nohrstedt et al., 1993; Pettersson, 1994a), even in highly productive Norway spruce sites located in areas with high N deposition (Nilsson & Wiklund, 1995). The site or stand factors that determine whether or not there will be increased growth following N fertilization at fertile sites are not yet understood. One possibly decisive factor is whether or not other nutrients are available in sufficient quantities. Furthermore, positive growth effects of irrigation have been observed in fertile Norway spruce stands in southern Sweden (Nilsson & Wiklund, 1992; Bergh et al., 1999), implying that a low availability of water during the growing season may be the primary limiting factor for growth in this region. However, water limitation is a complex issue, as it may affect soil microbial activity, in particular N mineralization (Giesler et al., 1998), as well as possibly implying direct water limitation of photosynthesis (Högberg, 2001).

In the study presented in Paper II, the nutritional status of all fractions of the above-ground parts of trees were analysed. Despite the previous very high N additions (480–2400 kg N ha⁻¹), no clear residual changes in nutrient concentrations were found.

Addition of NPKMg

An extensive number of experimental sites that had been previously subjected to heavy N fertilization regimes were used to study the effects on tree growth of adding P, K, Mg and micronutrients in conjunction with N refertilization (Paper III). The length of the observation period (i.e., after the NPKMg-treatment) differed between experimental sites, ranging from 4–15 years, averaging seven years. It was found that differences in growth response between fertilization with N alone and N in combination with PKMg were in most cases negligible for both Norway spruce and Scots pine sites. The repeated additions of N alone had no effect on the P, K and Mg concentrations in current-year needles, and it was concluded that the repeated N fertilizations had not caused any serious, growth-affecting nutrient deficiencies. However, it should be noted that the very fertile Norway spruce sites in south-west Sweden were poorly represented in this study and, hence, the generality of these results should be treated with a certain degree of caution. Furthermore, the study found little or no evidence to support previous indications that growth responses markedly decline following repeated N fertilization (cf. Jacobson and Nohrstedt, 1993).

The results from this study are in accordance with most earlier findings in Fennoscandia, i.e. that the supply of other nutrients (P, K, Ca, Mg), either alone or together with N, generally does not increase the growth response on mineral soils (e.g. Nohrstedt, 1990; Nohrstedt et al., 1993; Pettersson, 1994a; Tveite, 1994). However, Kukkola & Saramäki (1983) reported additional growth responses when adding P together with N in Norway spruce stands, and that the effect of P addition became proportionally more important as the fertility of the site increased.

Eriksson & Karlsson (1997) presented results from thinning and fertilization trials in southern Sweden that had been repeatedly fertilized with N and N+P. For Scots pine (eight stands) the authors reported significant growth responses after N addition ($5 \times 150 \text{ kg N ha}^{-1}$), but no additional effect of the P-addition ($2 \times 100 \text{ kg P ha}^{-1}$). For Norway spruce (eight stands), there was no significant growth response to either N ($5 \times 150 \text{ kg N ha}^{-1}$) or N+P ($1 \times 100 \text{ kg P ha}^{-1}$). The lack of growth responses in Norway spruce stands were perhaps not unexpected, considering that the sites were very fertile, with site indices averaging 34 m (i.e. sites where the dominating trees are expected to reach a height of 34 m at the age of 100 years).

The clearest example of an additive P effect on growth reported from Sweden is that of the optimum nutrition experiment in Stråsan (Norway spruce), where N was applied annually and the other elements at intervals of 2–3 years (Tamm, 1985). During the 18-year reported study period, the growth response after N addition was pronounced, and supplying P together with N resulted in a significant additional increase in stem-wood yield (Linder, 1990). Furthermore, there was also a positive interaction between NP and the addition of K+Mg and a

mixture of microelements (Tamm, 1985). In contrast, results from two optimum nutrition experiments in Scots pine stands, with similar designs, showed no additional growth responses when PK was added together with N (Tamm, 1985; Tamm, 1999). The additional growth responses to adding nutrients other than N found in the Stråsan experiment are most probably due to several interactive factors. The most important explanation is perhaps that, in contrast to most other reported studies, N at this site was added annually and at relatively high doses. Another aspect that must be taken into account is that the site had been subjected to a heavy prescribed burning before planting. Ten years later, at the start of the experiment, the growth of the seedlings was markedly retarded, which is often the case with Norway spruce on burned soils (Tamm, 1985). A substantial decrease in the soil organic material, due to the prescribed burning, may have contributed to the significant additive P effect on growth. Moreover, at an early stage, boron (B) deficiency was documented in the N and NP fertilized plots, but not on the NPKMg+micro plots (Aronsson, 1985), since the microelement mixture contained B. Hence, it is possible that the positive effect on growth of adding KMg+micro may simply be an effect of correcting B deficiencies in the trees.

Addition of wood ash

The results presented in Paper IV showed that the response of stem growth to the addition of wood ash was small, variable, and not statistically significant at any of the studied experimental sites. However, they also indicated that the addition of wood ash may increase stem growth on fertile sites and decrease growth on less fertile sites. The number of experiments was small, but the results agree well with experiences gathered from forest liming (cf. Andersson et al., 1996; Sikström, 2001). The alkaline wood ash probably influences the supply of inorganic N available for tree growth. The addition of wood ash on fertile sites, with N-rich moder/mull soils, probably resulted in an increased net mineralization of N, while in the more N-poor forest soils it probably led to an increase in N-immobilization. The C to N ratio in the humus layer has been proposed as an indicator that could be used to judge whether a pH increase in the soil leads to increased or decreased rates of net N mineralization. According to a rule of thumb, based on experience from forest liming experiments, net N mineralization increases after liming if the C to N ratio in the humus layer is less than 30 and falls when the C to N ratio is greater than 30 (Nömmik, 1979; Persson, 1988). Moreover, according to Persson and Wirén (1996), the addition of an alkaline compound to a N-rich soil (C:N <28) may result in increased rates of nitrification and NO₃⁻ leaching. The pool of total N in soil has been reported to decline after liming fertile sites (Kreutzer, 1995; Persson et al., 1995). Furthermore, 40 years after liming with large (9–10 Mg ha⁻¹) additions of CaCO₃ at four sites in southern Sweden, Persson et al. (1995) found that net N mineralization tended to be lower in the limed plots, implying reduced N availability in the long term at limed fertile sites. They also reported that potential nitrification was still higher in the limed plots after 40 years than in

controls. Hence, it has been suggested that increased pH and not increased availability of ammonium caused the long-lasting increased rates of potential nitrification at these sites (Rudebeck, 2000).

The addition of wood ash tended to increase the concentrations of many analysed nutrients in needles (Fig. 2 in Paper IV), most markedly (among the macronutrients) for K. However, results from an analysis of two sites where needles were sampled 11 years after treatment suggested that the elevated K concentrations were short-term effects (Fig. 4). Since the growth performance of the stands in this study implied that a shortage of N was limiting primary production, the somewhat elevated needle nutrient concentrations were regarded as evidence of “luxury” uptake. From this perspective, and from the forest stand growth point of view, the concept of recycling nutrients with wood ash must be regarded as a preventive action against possible nutrient imbalances in the future. The usefulness of such a preventive action presupposes a long-term capacity of the ecosystem to retain the nutrients added in available forms.

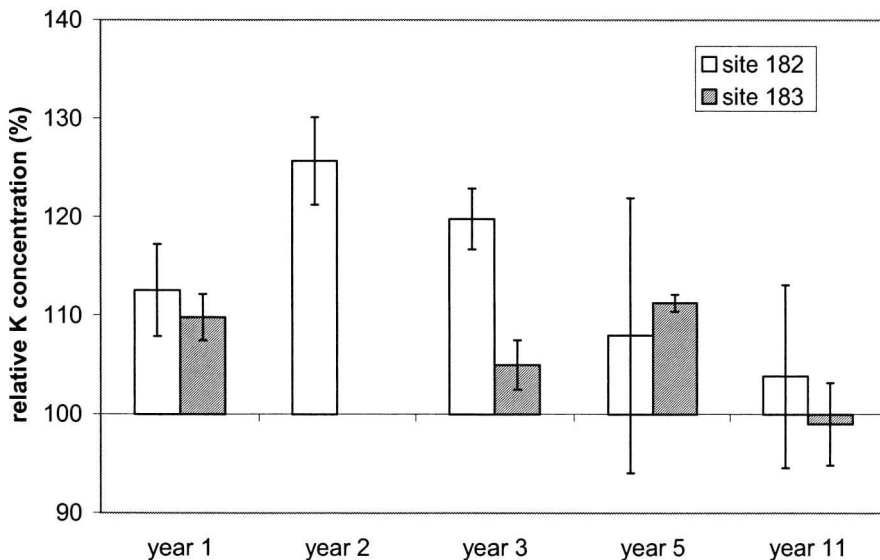


Fig. 4. The relative K concentration after wood ash addition (1 Mg ha^{-1}), in relation to untreated control plots (100%), during an 11-year observation period at experimental sites 182 (Norway spruce) and 183 (Scots pine). Vertical bars indicate $\pm \text{SE}$.

Recycling the nutrients in wood ash has been proposed as a method to compensate for the nutrients removed by WTH (Olsson et al., 1996; Eriksson, 1998), and hence to sustain future forest production (Clarholm, 1994; Sverdrup & Rosén, 1998). During the relatively short study period (5–11 years), the results described in Paper IV implied that the nutrients supplied with the ash did not promote growth. However, on fertile sites, the results indicated that an addition

of wood ash may, at least temporarily, compensate for the growth reductions that occur after WTH, presumably because of its effects on soil N turnover. On less fertile sites, addition of N is a prerequisite to counteract the decreased growth.

Interpretation of needle-nutrient composition

Of the several approaches widely employed in the evaluation of data on element levels in needles, the most common is the use of critical concentrations. As discussed earlier, the use of these threshold values involves some uncertainty, and they should be regarded merely as guidelines when evaluating the nutritional status of a stand. Furthermore, there are differing definitions of ‘critical’ or ‘deficiency’ levels, ranging from nutrient concentrations that are just deficient for maximum growth, down to levels where visible deficiency symptoms appear. Yet, several authors have also tried to sub-divide the wide span of nutrient concentrations that occur in needles using several different ‘threshold’ values (e.g. Brække, 1994; Table 2).

Table 2. Concentrations [mg (g DM)^{-1}] of N, P and K, and ratios (%) of P and K to N, in current-year needles of non-juvenile Norway spruce and Scots pine stands; suggested threshold values (according to Brække, 1994; revised in Brække et al., 1998), and values from repeatedly N-fertilized plots (cf. Paper III).

	N	P	K	P:N	K:N
<i>Threshold values</i>					
Optimum	>18	>1.8	>6	10	33
Pre-optimum	15–18	1.5–1.8	5.0–6.0		
Deficiency	12–15	1.2–1.5	3.5–5.0		
Strong deficiency	<12	<1.2	<3.5		
<i>Scots pine sites</i>					
132 Nissafors	15.4	1.54	5.50	10	36
165 Hagfors	18.3	1.60	5.40	9	30
171 Åsele	16.7	1.53	5.20	9	31
235 Östavall	14.7	1.29	5.00	9	34
43 Tämsjö	14.3	1.35	5.20	9	36
59 Voxna	16.3	1.52	4.70	9	29
D70 Beroniussådden	18.9	1.51	3.25	8	23
D74 Norsk Hydro	11.1	1.20	4.75	11	43
G84 Västanbäcksmön	15.2	1.44	4.72	9	31
<i>Norway spruce sites</i>					
142 Dörrarp	15.1	1.53	4.82	10	32
170 Ramsele	14.7	1.65	5.40	11	37
191 Håcksvik	15.3	1.40	4.65	9	30

Needles were sampled at twelve of the experimental sites reported in Paper III. The chemical analyses were performed on current-year needles that developed in the first and second years after the latest fertilization. At all experimental sites, in both untreated control plots (data not shown) and N-treated plots (Table 2), the P and K concentrations were below suggested optimum values (Table 2). Moreover, the P:N, and K:N ratios were also below suggested optimum levels in the N-treated plots at the majority of the sites, indicating P and/or K limitation. Nevertheless, with the exception of one of these sites, it was found that differences in growth responses between fertilization with N alone and N in combination with PK were negligible (Paper III). Obviously, despite heavy previous N additions, the studied sites were still N limited. This example illustrates the problems of rigorously interpreting needle-nutrient composition data, and stresses the importance of relating the results to stand growth performance and site characteristics.

According to Liebig's "law of the minimum", only one element at a time can act as a growth-limiting factor. However, non-elemental resources, such as water and light (i.e. factors that affect the rates of mass transport), can be limiting simultaneously with nutrient elements (Ingestad & Ågren, 1995). According to Ingestad (1979), balanced mineral nutrition implies that mineral nutrients are present in the correct proportions relative to N. However, nutrient ratios that Ingestad suggested to be optimal, in the same report, are derived from studies with non-mycorrhizal seedlings performed under conditions of optimal N uptake, optimal N concentrations, and optimal growth, and later modifications of these ratios (such as those reported by Brække, 1994 and Linder, 1995) are based on the same approach. Thus, as illustrated above, the diagnostic value of the nutrient to N ratios is limited as long as N is in short supply. It merely gives an indication of what elements may become limiting at the point where N ceases to limit primary production.

Support for statement on general N limitation

Nutrient imbalance is the normal situation in most forests, since available nutrients in the soil are seldom found in optimal proportions for growth. Trees have evolved to have substantial tolerance to imbalances in nutrient supply, and tree decline or mortality occurs only in extreme situations (Binkley & Högberg, 1997). With the exception of the induced B deficiency in the northern parts of Fennoscandia, it has not been shown that nutrient imbalances, caused by either N fertilization or N deposition, have led to reductions in tree growth in Sweden. The feared adverse effects of N deposition, such as N saturation and excessive N leaching, have been found to occur only at higher values than those currently occurring in Sweden (Näsholm & Persson, 2000).

The results from the studies included in this thesis suggest that N is still the growth-limiting nutrient for the vast majority of Swedish coniferous forests on mineral soils. This is in accordance with earlier reports (e.g. Pettersson, 1994a;

Binkley & Högberg, 1997). Fertile Norway spruce sites in the south-western parts of Sweden, where the N deposition levels are highest, were poorly represented in these studies. However, according to Nohrstedt et al. (1993), Pettersson (1994a), Nilsson & Wiklund (1995) and Sikström (2001), N limitation also seems to occur at many sites in this region.

Growth rates of Swedish forests have increased by c. 30% during the past 40 years (Elfving & Tegnhammar, 1996), and anthropogenic N deposition has frequently been cited as the main cause of the rise (e.g. Falkengren-Grerup & Eriksson, 1990; Eriksson & Johansson, 1993). However, Elfving & Tegnhammar (1996) showed that the increase in forest growth was just as large in areas with very low deposition of N as it was in areas with high N deposition. This indicates that factors other than N, like improved silvicultural practices and genetic selection, were of greater significance. Several studies have demonstrated that forest biomass is a minor sink for the input of different N sources (Melin, 1986; Kauppi et al., 1995; Nohrstedt et al., 2000), and it has been claimed that deposition of N results only in limited accumulation of carbon in temperate ecosystems (Nadelhoffer et al., 1999). Pettersson (1999) estimated that 15%, at most, of the reported growth increase in southern Sweden could be attributed to N deposition. A possible explanation for the small contribution of N deposition to tree growth is that the small N input is supplied throughout the year, and to a large extent during the non-growing season. Furthermore, forest ecosystems seem to have a greater long-term capacity to retain, and immobilize, deposited N in the soil than previously expected (Nohrstedt & Bertills, 2000). In addition, results from an experiment with annual N fertilization during a 20-year period showed that N was rapidly immobilized in soil organic matter when the N additions were discontinued (Quist et al., 1999). Thus, there was no build-up of a lasting pool of plant-available N in the soil. These results should help establish an understanding of why N continues to be the primary growth limiting nutrient in the vast majority of the Swedish coniferous forests on mineral soils, despite the high levels of N deposition or repeated N fertilizations.

Conclusions

- In order to sustain tree growth after whole-tree harvesting, there seems to be no need for additions of other nutrients than N (or N+B).
- Macro-nutrients other than N, added as wood ash or fertilizer, do not generally alter tree growth. N fertilizations, with B included in the fertilizer, do not cause any serious nutrient deficiencies in the trees, even after heavy N additions.

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