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An Assessment of Different Fertilization Regimes in Three Boreal Coniferous Stands

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In 1981–82 three field experiments were established with the aim of elucidating (i) the growth response of middle-aged coniferous stands at different fertilization intensities and, hence, the economic outcomes; and (ii) the need to add nutrients other than nitrogen (N). Nutrient additions were performed at intervals of two, four, six and eight years. The experiments were established on typical podzolized and N-limited mor-humus sites, two in Scots pine (*Pinus sylvestris* L.) stands and one in a Norway spruce (*Picea abies* (L.) Karst.) stand, at three different locations in Sweden. The ages of the stands were 65–70 years at the time of establishment. Growth responses were calculated after a 22-year study period. The growth responses were significant in all treatments. The addition of nutrients other than N did not affect stem growth at any of the sites. The growth response tended to increase with decreasing application interval. The results also revealed that the efficiency of fertilization is reduced as the interval between fertilizations is shortened. Accordingly, the growth effect per kg of added N was negatively correlated to fertilization intensity. The least intensive fertilization regime (an eight-year interval) resulted in an average net increase in C sequestration of 35 kg per kg N added. The profitability, in terms of internal rate of return, the present net value at different interest rates and the cost of production, i.e. the cost to produce one extra m^3 under the different N regimes, are presented and discussed.

Keywords biomass yield, boreal forests, carbon sequestration, fertilization regimes, foliar analysis, *Picea abies*, *Pinus sylvestris*
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1 Introduction

There is a general belief that the demand for raw materials from Swedish forests will increase. At the same time there is an expectation that the supply of forest products will decline as a result of increased environmental pressure on forest land, i.e. setting aside more areas for nature conservation purposes. Hence, the potential for the development of more intensive silvicultural systems in certain forest areas is much discussed in Swedish forestry today. Increases in forest production can be achieved in many ways, including prompt and appropriate regeneration treatments, the use of genetically improved stock, the optimal choice of species and stocking control, more efficient utilization, and fertilization.

It was recognized at an early stage that low nitrogen (N) availability could limit production in temperate forests (e.g. Hesselman 1937, Mitchell and Chandler 1939), and the results of several fertilization experiments made it clear 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).

Commercial application of N fertilizers had begun in Swedish coniferous forests by the mid-1960s. The application of 150 kg N ha^{-1}, which is a normal commercial dose in Sweden for middle-aged and older stands (i.e. stands in which the canopy has closed, and after the first thinning), normally results in an average relative growth increase of about 30–55% over a period of 7–11 years (Pettersson 1994a). During the last 40 years about 2 million ha of productive forest has been subjected to N-fertilization, one or more times, representing 10% of the total area of productive forest land in Sweden. Forest fertilization peaked around the end of the 1970s, when c. 190 000 ha of forest on mineral soil was fertilized annually. By the end of the 1980s the annual fertilized area started to decrease, in part because of better fertilization management (i.e. mainly the extension of the period between fertilizations in combination with a more careful selection of suitable stands) but later also because of the recession in the early 1990s. In addition, environmental groups and governmental bodies started to question forest N-fertilization from an environmental point of view, leading to more strict recommendations from the Swedish Forestry Agency. In the 1990s the fertilized area had dropped to c. 20 000 ha per year. During the last few years the general increased demand for wood has lead to more fertilization once again and, currently, a total of c. 60 000 ha are fertilized annually.

The reason for interest in forest fertilization was, of course, that it was a profitable investment, generally yielding real internal rates of return exceeding 10% (e.g. Laakkonen et al. 1983). Apart from the increment in wood volume, another important revenue factor associated with forest fertilization is the effect on tree dimensions. An increased stem diameter translates into increased timber proportions as well as an increased timber price. Furthermore, a greater stem diameter reduces logging costs (e.g. Brunberg 2007).

The cost of fertilizer is a major item of expenditure, normally accounting for up to two thirds of total fertilization costs. Composite fertilizers, containing for example phosphorus (P), potassium (K) and magnesium (Mg), are considerably more expensive than nitrogen-only fertilizers. Therefore, in order to keep the fertilization budget as low as possible it is vital to avoid standard nutrient addition regimes if they do not result in increased production in a particular forest stand.

Human input of N into the biosphere has resulted in a substantial increase in N deposition since the 1950s in Sweden (Lövblad 2000) and this 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). Increased attention has, therefore, been paid to the possibility that N deposition may create conditions in which N is no longer the limiting nutrient for forest growth. Furthermore, it has been hypothesized that the addition of a more "balanced" fertilizer, i.e. including many essential macro- and micronutrients, is necessary when making use of more intensive fertilization regimes (Bergh et al. 1999 and 2005; Andersson 2002).

In 1981–82 three experimental sites, with various fertilization regimes, were established. The most intensive treatments were fertilized every second year with N, N+P, and N+P+K+Mg+micronutrients. This experimental series also included treatments with more extensive fertilization: adding N at intervals of four, six and eight years. Using this experimental design it is possible to calculate the marginal cost of the extra tree volume produced and, hence, assess the profitability of an intensive fertilization strategy at these sites.

The main object of this study was to evaluate tree growth potential and economic outcome at different fertilization intensities in middle-aged coniferous stands; a subsidiary aim was to determine whether there was any need to add nutrients other than N. Hence, the results should provide valuable information for designing practical fertilization strategies, and for predicting possible future needs for compensatory additions of mineral elements other than N. In addition, the study illustrates the effects on tree carbon (C) sequestration of different N-fertilization strategies.

2 Material and Methods

2.1 Experimental Sites and Design

The three field experiments were established in middle-aged coniferous stands at three different locations in Sweden. The experiments were established at typical podzolized and N-limited mor-humus sites, two in Scots pine (*Pinus sylvestris* L.) stands and one in a Norway spruce (*Picea abies* (L.) Karst.) stand (Table 1). The ages of the stands were 65–70 years at time of the establishment (1981–82) of the trials.

The experiments were set up in a randomized block design involving three replicates. The experimental plots were 30 × 30 m^2. Plots were arranged in blocks based on stem basal area, number of stems per ha and site characteristics (e.g. field and ground vegetation, soil moisture, site index, slope, etc.). Plots within a block were not allowed to deviate more than 5 and 10% from the block mean basal area and mean number of stems, respectively. The defined classes of the common site characteristics were not allowed to differ within a block.

The treatments applied (Table 2) represent different N-fertilization regimes, i.e. N added at different intervals. The N-dose was 150 kg ha^{-1}, added in the form of ammonium-nitrate (NH_4NO_3), and from 1991 onwards in the form of ammonium-nitrate with dolomite lime (N 27.5%, Ca 4.0%, Mg 1.0%). Boron (B) was added (1 kg ha^{-1}) in all treatments from the start. In total, 1650 kg N ha^{-1} was added in treatments 1–3. In addition, in two of the most intensive treatments (treatment no. 2 and 3), P or P, K, Mg and micronutrients were added.

Table 1. Experimental site and stand characteristics at the time of establishment (1981–82).

	165 Hagfors	170 Ramsele	171 Åsele
Latitude (N) [a)]	60°00´	63°28´	64°07´
Longitude (E) [a)]	13°42´	16°10´	17°33´
Altitude (m a.s.l.)	190	350	330
Annual mean temperature (°C) [b)]	4.2	2.1	0.5
Precipitation (mm yr^{-1}) [b)]	720	600	560
Soil type	Podzol	Podzol	Podzol
Soil texture and genesis	Sandy-silty till	Silty till	Sandy sediment
Dominant tree species	Scots pine	Norway spruce	Scots pine
Site index (H100, m) [c)]	24	24	19
Site quality (m^3 ha^{-1} yr^{-1})	5.9	5.5	3.4
Current increment (m^3 ha^{-1} yr^{-1})	5.7	8.0	3.6
Stand age (yrs)	65	65	75
Standing stem volume (m^3 ha^{-1})	180	215	105
Stems (no. ha^{-1})	800	1700	1000

[a)] According to WGS 84
[b)] Alexandersson et al. (1991)
[c)] Height of dominant trees at age 100 yrs according to Hägglund (1973, 1974).

Table 2. Treatments and total amount of N added. (Doses in kg ha^{-1}).

Treatment		Fertilizer dose	Application interval (yrs)	Number of applications	Total amounts added N	Ca	Mg
0	Untreated control	-	-	-	0	0	0
1	2-1650N	150 N	2	11	1650	120	36
2	2-1650N-P	150 N, 20 P	2	11	1650	120	36
3	2-1650N-PKMg	150 N, 20 P, 46 K, 8 Mg, micro	2	11	1650	120	124
4	4-900N	150 N	4	6	900	60	18
5	6-600N	150 N	6	4	600	40	12
6	8-450N	150 N	8	3	450	40	12

2.2 Tree Growth Measurements and Calculations

All tree-growth measurements were performed on permanent sample trees in a circular area, with a radius of 10 m, centred in the middle of each plot. At the time of establishment, all trees with a diameter >5 cm at breast height (1.3 m above ground) were permanently numbered and measured. The measurements included diameter at breast height (dbh, mm), determined by cross-callipering at permanent marks on the stem, and height of the trees (dm). The number of permanent sample trees per plot varied from c. 25, 30 and 50 in 165 Hagfors, 170 Ramsele and 171 Åsele, respectively. There were no thinnings performed during the study period. At the end of the 22-year study period, the measurements were repeated and increment cores were taken with a borer at breast height. The increment cores were measured under a microscope registering tree ring widths (resolution of 0.01 mm). The volume of individual trees was estimated using empirical functions provided by Näslund (1947). The amounts of different biomass components (stemwood, stem-bark, living and dead branches, needles, stumps and coarse roots) were calculated using biomass functions by Marklund (1988). The amount of C was estimated as 0.5 times the dry weight of biomass. N-use efficiency (here defined as kg C sequestered per kg added N) was calculated as the estimated amount of additional C sequestered in the fertilized treatments divided by the cumulative amount of N added.

2.3 Needle Sampling and Analyses

Current-year needles were sampled five and ten years after establishment of the trials as well as at the end of the study period. Samples were collected during the winter (December–March) from 10 trees growing immediately outside each circular plot. Twigs from the upper third of the crown on the south side were brought down with a shotgun. The needles from the ten trees were pooled and treated as one bulk sample per plot, which were then dried overnight at 70 °C, ground and mixed thoroughly. The concentrations of P, K, Ca, Mg, Mn, S, Na, Fe, Zn, Al, B and Cu in the needles were determined by ICP-AES, after wet oxidation in a mixture of concentrated HNO_3 and $HClO_4$ (10:1 by volume). Nitrogen concentrations were determined by NA 1500 elemental analyser (Carlo-Erba).

2.4 Economic Analyses

The calculations were performed based on the assumption that the stands were harvested at the end of the observation period.

The yield of saw-timber (min. 14-cm diameter at the top) and pulp wood (min. 5-cm diameter at the top) of individual trees was estimated using yield functions provided by Ollas (1980). The gross value of the timber was calculated according to a real price-list for the region. The price was not adjusted for different log qualities. The logging costs were calculated according to productivity norms for heavy-duty single-grip harvesters at final felling (Brunberg 2007) and current machine costs (Brunberg, 2003). The tree stand variables, required in the economic calculations, were the corrected mean values from the experiments. Fertilization costs were set to 240 Euros (€) per hectare.

The tested profitability criteria of the different fertilization regimes were the internal rate of return, the present net value at different rates of interest (0–5%) and the cost of production, i.e. the cost to produce one extra m^3.

In addition, and in comparison to the studied treatments, calculations were performed on the isolated growth effects of the last eight year period of treatment no. 7 (eight-year interval), representing a single fertilizer application eight years before final felling.

2.5 Statistical Analyses

Treatment effects on total stem-volume increment (V_I), and nutrient concentrations of the needles (NC) in individual years were tested using analysis of variance. For V_I, several variables related to stand properties were tested as covariates to adjust for differences in pre-treatment conditions. The covariates basal area increment during the five years before treatment (BAI_{-5}), initial stand basal area (BA_0), initial stand volume (V_0) and number of stems per hectare (ST_{ha}) were tested and included in the model if the respective p-values were less than 0.20.

The following model was used for the individual experiments:

$$y_{jk} = \mu + u_j + t_k + b(g_{jk} - \bar{g}) + e_{jk} \quad (1)$$

where
y_{jk} = V_I or NC for plot jk
μ = total mean
u_j = random effect of block j (j=1,2,3)
t_k = fixed effect of treatment k (k=1,…, n; n=7)
b = coefficient for the regression of the covariate
g_{jk} = the covariate variable for plot jk
e_{jk} = residual effect for observation jk, N.I.D. (0, σ_e^2)

The need for transformation was determined on the basis of the Shapiro-Wilk test, kurtosis, skewness and visual interpretations of the residuals in normal-probability plots. The General Linear Model procedure in the SAS-package (SAS 1997) was used for the statistical analyses of the individual experimental sites. Differences between treatment means were tested according to the Tukey-Kramer test for multiple comparisons.

3 Results

3.1 Tree Growth Response

The growth responses were significant in all treatments (Table 3, Fig. 1). In the most intensive N-treatments, the average stem-volume growth during the study period was more than double that of the control at two of the experimental sites. At one of the Scots pine sites the corresponding figure

Table 3. Annual stem-volume increment (m^3 ha^{-1} yr^{-1}), associated with the different treatments at the three experimental sites. Values in the same column marked with different letters differ significantly ($p<0.05$, according to Tukey-Kramer's test for multiple comparisons).

Treatment	Application interval (yrs)	Experimental sites		
		165 Hagfors	170 Ramsele	171 Åsele
	p-value, treatment:	<0.01	<0.01	<0.01
0	-	5.6 a	7.1 a	3.3 a
1	2	8.3 b	14.6 c	7.9 bc
2	2	8.2 b	13.6 bc	8.0 bc
3	2	8.6 b	13.0 bc	8.2 c
4	4	8.1 b	13.0 bc	7.5 bc
5	6	6.8 b	12.0 bc	6.9 bc
6	8	7.3 b	10.3 b	6.1 b

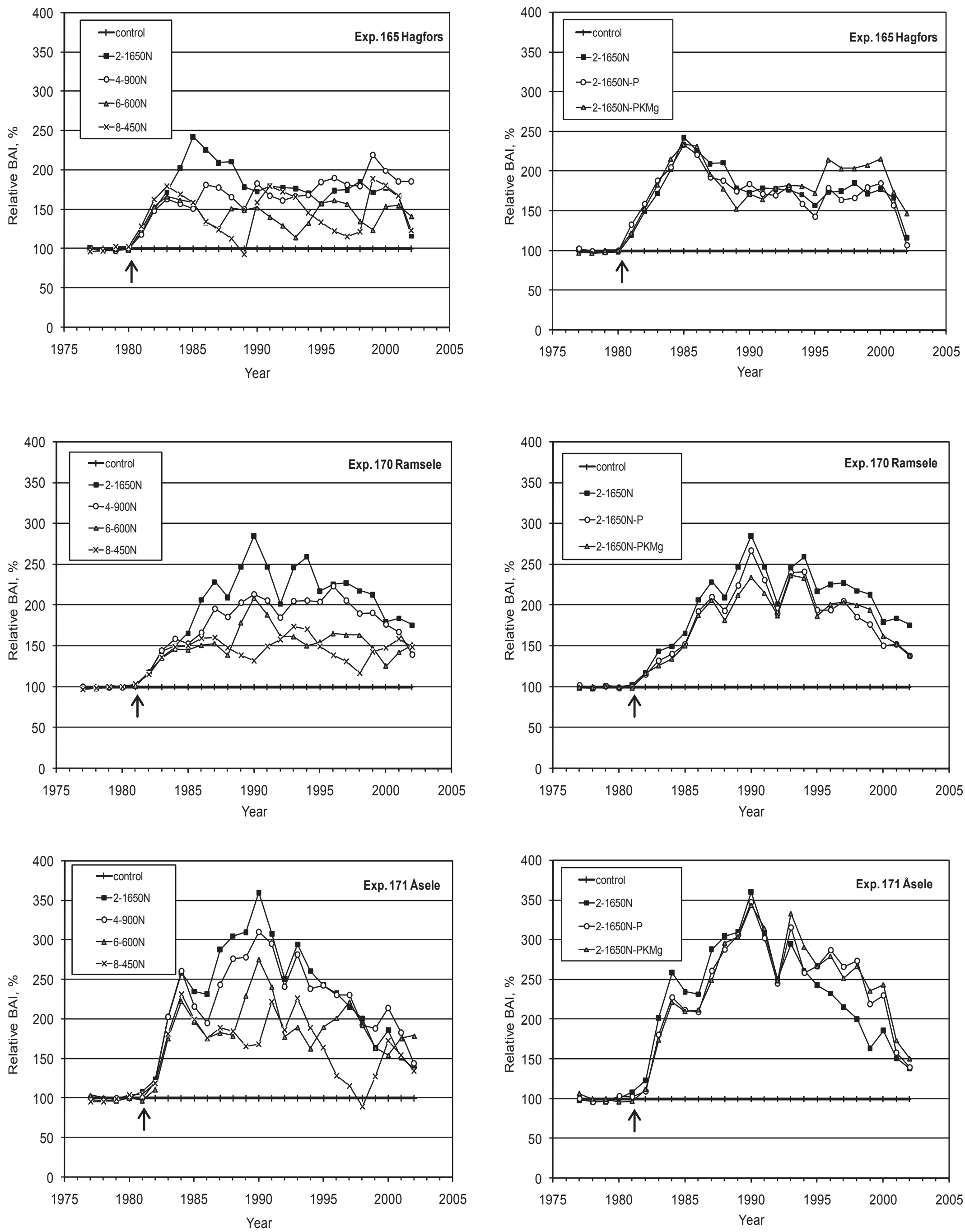

Fig. 1. Annual relative basal area increment (BAI) of the different treatments in relation to untreated control plots (100%). Adjusted for pre-treatment growth rates. Time of initial fertilization is indicated by arrow.

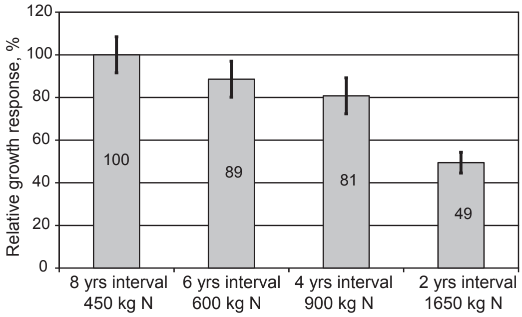

Fig. 2. Growth response per kg added N in relative terms, where the least intensive fertilization regime, 8-years interval, is set to 100%. Mean values of all experiments ± 1 S.E. of the mean.

was 50%. The addition of nutrients other than N did not affect stem growth at any of the sites. The growth response tended to increase with decreasing application interval. However, the differences in growth responses between the different N treatments were by no means dramatic and generally not significant (Table 3). Accordingly, the growth effect per kg added N was negatively correlated to fertilization intensity (Fig. 2). The treatments had no significant effect on tree stem form at any of the sites, expressed either as the relationship between dbh and height or as change in form factor.

In the untreated control plots, mean above-ground C sequestration during the study period did not vary much between the sites (4.2–4.7 Mg C ha^{-1} $year^{-1}$). The estimates of N-use efficiency at the individual sites varied from 17 to 35 kg C sequestered per kg N added, with the highest efficiencies recorded at the least intensive fertilization regimes. The corresponding mean figures of all sites was 17, 27, 32 and 35 kg C sequestered per kg N added in the treatments 1–3, 4, 5 and 6, respectively.

3.2 Nutrient Concentrations in Needles

The nutritional status of the current-year's needles varied somewhat between the experimental sites (Table 4). Repeated applications of N increased the N-concentrations in the current-year's needles at all three sampled sites; this increase was

Table 4. Nutrient concentrations in current-year needles at the studied sites at the end of the study period. Mean values of three replicates at each site. Values in the same row marked with different letters differ significantly ($p<0.05$, according to Tukey-Kramer's test for multiple comparisons). Critical concentrations for strong deficiency and optimum nutrition, according to figures suggested by Brække (1994, revised in Brække et al. 1998).

Element	Control	Treatments 2-1650 N	2-1650 NP	2-1650 NPKMg	4-900 N	6-600 N	8-450 N	Critical concentrations Strong deficiency	Optimum
	mg (g DM)$^{-1}$								
Exp. 165 Hagfors									
N	12.6 a	17.4 b	15.9 b	18.0 b	16.1 b	15.4 a	13.7 a	<12	>18
P	1.4 a	1.7 b	1.6 a	1.6 a	1.5 a	1.6 a	1.5 a	<1.2	>1.8
K	5.5	5.5	6.1	5.0	5.3	5.9	5.6	<3.5	>6.0
C a	1.9	1.5	1.4	1.7	1.9	2.0	1.7	<0.4	>0.7
Mg	0.8	0.9	0.8	0.9	0.8	1.0	0.7	<0.4	>0.8
Exp. 170 Ramsele									
N	12.2 a	15.4 b	14.0 a	15.8 b	14.1 a	12.8 a	12.5 a	<12	>18
P	1.5	1.4	1.5	1.5	1.4	1.6	1.6	<1.2	>1.8
K	5.4	4.1	5.7	4.8	5.4	5.8	5.9	<3.5	>6.0
C a	5.0	3.5	3.9	3.3	4.2	4.1	3.7	<0.4	>0.7
Mg	1.1	1.1	1.1	1.3	1.1	1.2	1.1	<0.4	>0.8
Exp. 171 Åsele									
N	13.3 a	16.7 b	17.1 b	17.9 b	15.5 b	13.7 a	12.5 a	<12	>18
P	1.5	1.6	1.7	1.6	1.4	1.5	1.4	<1.2	>1.8
K	4.7	4.7	4.8	5.5	5.0	5.1	5.0	<3.5	>6.0
Ca	1.8	1.1	1.5	1.3	1.7	1.8	1.6	<0.4	>0.7
Mg	0.9	1.1	1.1	1.0	1.1	1.0	1.0	<0.4	>0.8

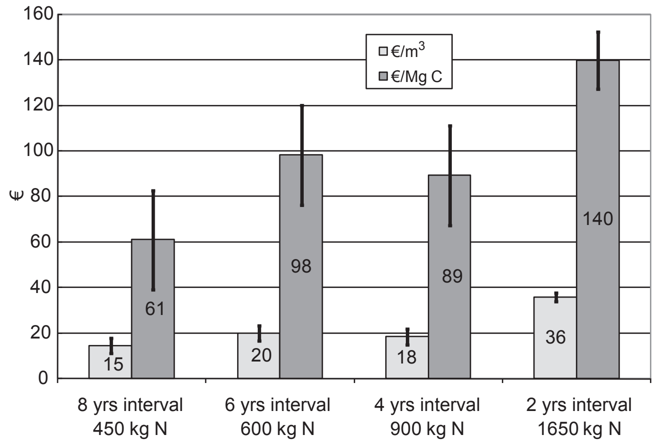

Fig. 3. The cost, in euros (€) to (i) produce one cubic meter of stemwood and (ii) to sequester one Mg of C by fertilization under the different fertilization regimes. Mean values of all experiments ± 1 S.E. of the mean.

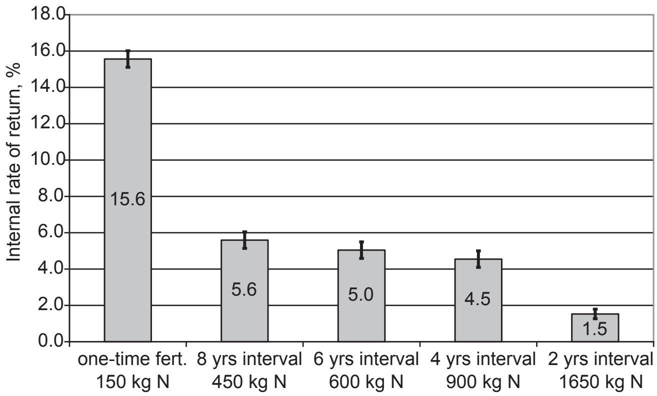

Fig. 4. The internal rate of return of the tested fertilization regimes and of the simulated treatment, representing a single fertilizer application, eight years before final cutting. Mean values of all experiments ± 1 S.E. of the mean.

statistically significant under the most intensive N-treatments (2–4-year application intervals), but had no general effect on the P, K, Ca and Mg concentrations (Table 4). At all three sampled sites, the concentrations of the analysed elements other than N were consistently higher than the threshold values deemed likely to cause deficiency (cf. Brække 1994). The Ca and Mg concentrations, as well as the concentrations of the analyzed micronutrients (data not shown), were all above the proposed optimum levels.

3.3 Economic Outcome

As a consequence of the negative correlation between the growth response per kg added N and fertilization intensity, the cost of producing one additional cubic meter as a result of fertilization, or similarly to sequester one Mg C, increased with increasing intensity of the fertilization regime (Fig. 3).

The internal rate of return increased with decreasing intensity of the fertilization regime

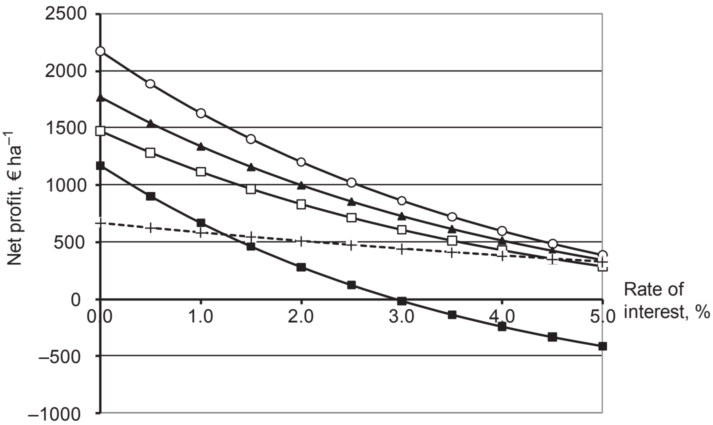

Fig. 5. Net profit under different fertilization regimes and at different rates of interest. Costs and profits are discounted to the year of initial fertilization (22 years and 8 years). Mean values for all experimental sites. ■ = 2-years interval (1650 kg N ha^{-1}), ○ = 4-years interval (900 kg N ha^{-1}), ▲ = 6-years interval (600 kg N ha^{-1}), □ = 8-years interval (450 kg N ha^{-1}), + = single fertilizer application (150 kg N ha^{-1}).

Table 5. The relative (%) distribution of different revenue factors after fertilization. Mean values of all tested fertilization regimes.

	165 Hagfors	170 Ramsele	171 Åsele
Higher proportions of timber	5.7	10.5	15.0
Higher timber price	16.1	13.1	15.5
Reduced logging costs	3.8	9.8	10.6
Σ Dimensional effects	25.6	33.4	41.1
Effect of increased volume	74.4	66.6	58.9
Σ Total	100	100	100

(Fig. 4). The treatment simulating a single fertilizer application eight years before final cutting differed significantly from the other treatments, producing a much higher internal rate of return.

When using repeated fertilization regimes the net value decreased rapidly when the rate of interest was increased (Fig. 5). At an interest rate of three percent, the profit was reduced to zero for the most intensive fertilization regime (2-year interval). The net value of the late single fertilizer application was not influenced by the rate of interest as much as the other treatments, due to shorter time of discounting.

The effects of the tree dimensions on the total revenue after fertilization were on average 33% (Table 5). This was most significant in the less fertile Scots pine stand, with its comparatively small stem diameters and volumes.

4 Discussion

The application of N resulted in significant increases in tree volume growth at all three study sites, confirming earlier findings that nutrient availability is a major limitation to production in boreal forests. The results from this study are also in accordance with most of the previous 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 tree growth response on mineral soils (e.g. Pettersson 1994b, Jacobson and Pettersson 2001, Nilsen 2001, Nohrstedt 2001, Nilsen and Abrahamsen 2003). However, there are studies indicating a somewhat different picture. Kukkola and 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. Nilsen (2001) reported data from some older studies where the addition of P had been shown to lead to additional stem growth when given together with N in young spruce stands. Another example of an additive P effect on growth was reported from an optimum nutrition experiment in Sweden, in a young Norway spruce stand, where N was added annually and at relatively high doses (Tamm 1985, Linder 1990). However, the fact that the site had been subjected to intense prescribed burning before planting, resulting in a substantial decrease in the soil organic material and markedly retarded growth of the seedlings, means that the general conclusions from that study may not be generally applicable.

The fertilization regime appeared to have an effect on needle N concentrations. However, the different levels presented in Table 4 also reflect, to a high degree, the time of sampling in relation to the latest fertilization. In the results presented here the sampling was made two, two, four and six years after the latest fertilization in the treatments with two, four, six and eight years fertilization interval, respectively.

At none of the studied sites did the different treatments lead to nutrient concentrations suggesting deficiency (cf. Brække 1994). This result is in accordance with several other fertilization studies (e.g Mälkönen and Kukkola 1991, Jacobson et al. 2000, Jacobson and Pettersson 2001). Obviously, despite the high N applications, the sites were still N limited. The admixture of dolomite to the fertilizer (c. 18% by weight) may complicate the conclusions regarding micronutrients because of uncertain and variable amounts of micronutrients in the added lime. However, the content of the nutrients of major concern, P and K, is in relative terms generally negligible in dolomite.

At all three sampled sites, the P and K concentrations were consistently below suggested optimum values (Table 4), as were the P:N, and K:N ratios, possibly indicating P and/or K limitation. According to Ingestad (1979), balanced mineral nutrition implies that mineral nutrients are present in the correct proportions relative to N. However, the nutrient ratios that Ingestad (1979) suggested as being optimal were derived from studies with non-mycorrhizal seedlings performed under conditions of optimal N uptake, optimal N concentrations, and optimal growth. Later modifications of these ratios (such as those reported by Brække 1994 and Linder 1995) are based on the same approach. Thus, in our boreal coniferous forests, the diagnostic value of the nutrient to N ratios, as well as suggested optimum values for nutrients other than N, is limited as long as N is in short supply. Such published figures merely give an indication of what elements may become limiting at the point where N itself ceases to limit primary production.

The results from this study emphasize the fact that the effects of fertilizer on tree dimension should not be overlooked. The results also reveal that the efficiency of fertilization, with the N-doses used in practice today, is reduced as the interval between fertilizations is shortened. This is in accordance with many earlier studies (e.g. Kukkola and Saramäki 1983). Accordingly, the growth effect per kg added N was negatively correlated to fertilization intensity. For example, the relative growth effect of adding 150 kg N ha^{-1} every second year was only 50% of that possible when adding fertilizer every eight years (Fig. 2), and when making the same comparisons on the internal rates of return (Fig. 4) the relation was c. 25%. Due to shorter time between fertilization and harvest, the late single fertilizer application showed the highest internal rate of return. However, in order to maximize production, for example in a stand with high stumpage values, a more intensive fertilization strategy may still be justified, even though the marginal costs to produce this extra volume are high. The marginal cost to produce the extra volume when fertilizing every second year in comparison to every eight years, i.e. setting the differences in total fertilization costs in relation to the differences of total gained stem volume, was on average 52 € per m^3, amounting to more than three times the cost of fertilizing very eight years (cf. Fig. 3).

The internal rates of return did not differ significantly between the treatments with four (900N), six (600N) and eight (450N) years fertilization interval (Fig. 4), with values between 4–6%. This result is also reflected in the figures of the net profits (Fig. 5), with similar net profits as long as the rate of interest is below 5%. However, the net profit of adopting a regime with fertilization every fourth year during the 22-year study period could also for example be compared with (i) the total net profits obtained from six single fertilizer applications in six different stands, or (ii) the added net profits when fertilizing every eight years in two different stands. Furthermore, fertilization involves increased risks of wind- and snow damages. Hence, the forest owner should reflect on spreading his fertilization investments on several stands instead of putting all eggs in one basket.

The last N applications were done six (treatment 450N), four (treatment 600N) or two (treatment 900N and 1650N) years before the end of the study period. Hence, the growth measurements were performed when there were still growth responses remaining. Assuming an extra growth response of 2 (450N), four (600N) and eight (1650N and 900N) m^3, the relative growth responses presented in Fig. 2 would be slightly changed to 100–91–85 and 52% in the treatments with 450N, 600N, 900N and 1650N, respectively. On the other hand, according to Fig. 1, the relative BAI levels did not seem to differ much between the different treatments, indicating small differences in remaining growth responses.

Larger landholders may evaluate their N-fertilization program without taking interest rates into account, by extracting the predicted growth increase the very same year by final-cutting in a different stand. Economically beneficial fertilization programs, involving re-fertilizations, may then be viable in middle-aged forest stands. A prerequisite for this is a suitable age class distribution within the forest holding and a long-term fertilization programme.

5 Conclusions

Repeated applications of ammonium-nitrate, with the addition of dolomite lime, did not cause any serious nutrient deficiencies, and the addition of P and K, often considered to be the next elements limiting growth after N, did not significantly alter the growth response during the 22-year study period. The results from this study do not support the hypothesis that N fertilization, the way it is performed today, depletes the supply of other nutrients in boreal forest ecosystems. Hence, according to this study, there are minor grounds for concerns that forest N fertilization may cause such problems, especially at the doses recommended for practical forestry in Sweden.

N fertilization on mineral soils in Sweden is a profitable investment. An addition of a standard N dose (150 kg N ha^{-1}) may produce a real internal rate of return amounting to 15%. An intensive fertilization regime, involving additions every two to four years, will produce a higher volume increment than treatment every eight to ten years, but the marginal timber volume will be expensive.

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References

Aber, J.D., Nadelhoffer, K.J., Steudler, P. & Melillo, J.M. 1989. Nitrogen saturation in northern forest ecosystems. BioScience 39: 378–386.

Alexandersson, H., Karlström, C. & Larsson-McCann, S. 1991. Temperature and precipitation in Sweden 1961–90, reference normals. Swedish Meteorological and Hydrological Institute, Meteorologi nr 81. Norrköping. 88 p. (In Swedish.)

Andersson, M. 2002. Spatial allocation of forest production – aspects on multiple-use forestry in Sweden. Acta Universitatis Agriculturae Sueciae, Silvestria 257. 40 p. Doctor's dissertation. ISBN 91-576-6341-6.

Bergh, J., Linder, S., Lundmark, T. & Elfving, B. 1999. The effect of water and nutrient availability on the productivity of Norway spruce in northern and southern Sweden. Forest Ecology and Management 119: 51–62.

— , Linder, S. & Bergström, J. 2005. Potential production of Norway spruce in Sweden. Forest Ecology and Management 204: 1–10.

Brække, F.H. 1994. Diagnostiske grenseverdier for næringselementer i gran- og furunåler. NLH, Aktuelt fra Skogforsk 15-94. Ås. 11 p. (In Norwegian.)
— , Salih, N. & Ingerslev, M. 1998. Nutrient status of stands – needle analyses. In: F. Andersson, F.H. Brække & L. Hallbäcken (Eds.), Nutrition and growth of Norway spruce forests in a Nordic climatic and deposition gradient. TemaNord 1998: 566. Nordic Council of Ministers, Copenhagen. p. 152–192.
Brunberg, T. 2003. Forestry costs and revenue in Sweden 2002. The Forestry Research Institute of Sweden, Resultat 11. 4 p. (In Swedish with English abstract.)
— 2007. Basic data for productivity norms for extra large single-grip harvesters in final felling. The Forestry Research Institute of Sweden, Redogörelse 2. 8 p. (In Swedish with English summary.)
Gundersen, P. 1991. Nitrogen deposition and the forest nitrogen cycle – role of denitrification. Forest Ecology and Management 44: 15–28.
Hägglund, B. 1973. Site index curves for Norway spruce in southern Sweden. Royal College of Forestry, Department of Forest Yield Research, Research Notes 24. (In Swedish with English summary.)
— 1974. Site index curves for Scots Pine in Sweden. Royal College of Forestry, Department of Forest Yield Research, Research Notes 31. (In Swedish with English summary.)
Hesselman, H. 1937. Om humustäckets beroende av beståndets ålder och sammansättning i den nordiska granskogen av blåbärsrik Vacciniumtyp och dess inverkan på skogens föryngring och tillväxt. Meddelanden från Statens Skogsförsöksanstalt 30: 529–716. (In Swedish with German summary.)
Ingestad, T. 1979. Mineral nutrient requirements of Pinus sylvestris and Picea abies seedlings. Physiologia Plantarum 45(4): 373–380.
Jacobson, S., Sikström, U. & 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.
— & 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.
Kukkola, M. & Saramäki, J. 1983. Growth response in repeatedly fertilized pine and spruce stands on mineral soils. Communicationes Instituti Forestalis Fenniae 114. 55 p.
Laakkonen, O., Keipi, K. & Lipas, E. 1983. Profitability of nitrogen fertilization in mature forests on mineral soils. Folia Forestalia 577: 1–20. (In Finnish with English summary.)
Linder, S. 1990. Nutritional control of forest yield. In: Nutrition of trees. The Marcus Wallenberg Foundation Symposia Proceedings 6. p. 180–202.
— 1995. Foliar analyses for detecting and correcting nutrient imbalances in Norway spruce. Ecological Bulletin 44: 178–190.
Lövblad, G. 2000. Nitrogen deposition now and in the future. In: U. Bertills & T. Näsholm (eds.). Effects of nitrogen deposition on forest ecosystems. Swedish Environmental Protection Agency, Report 5067. p. 21–28.
Mälkönen, E. & Kukkola, M. 1991. Effect of long-term fertilization on the biomass production and nutrient status of Scots pine stands. Fertilizer Research 27: 113–127.
Marklund, L.-G. 1988. Biomass functions for pine, spruce and birch in Sweden. Swedish University of Agricultural Sciences, Department of Forest Survey, Report 45. 73 p. (In Swedish with English summary.)
Mitchell, H.L. & Chandler, R.F. 1939. The nitrogen nutrition and growth of certain deciduous trees of northeastern United States. With a discussion of the principles and practice of leaf analysis as applied to forest trees. Black Rock Forest Bulletin 11: 1–94.
Näslund, M. 1947. Funktioner och tabeller för kubering av stående träd. Tall, gran och björk i södra Sverige samt i hela landet. Meddelanden från Statens skogsforskningsinstitut 36: 3–36. (In Swedish.)
Nilsen, P. 2001. Fertilization experiments on forest mineral soils: a review of the Norwegian results. Scandinavian Journal of Forest Research 16: 541–554.
— & Abrahamsen, G., 2003. Scots pine and Norway spruce stands responses to annual N, P and Mg fertilization. Forest Ecology and Management 174: 221–232.
Nohrstedt, H.-Ö. 2001. Response of coniferous forest ecosystems on mineral soils to nutrient additions: a review of Swedish experiences. Scandinavian Journal of Forest Research 16: 555–573.
Ollas, R. 1980. Nya utbytesfunktioner för träd och

bestånd. Forskningsstiftelsen Skogsarbeten, Resultat-Ekonomi 5. 4 p. (In Swedish.)

Pettersson, F. 1994a. Predictive functions for calculating the total response in growth to nitrogen fertilization, duration and distribution over time. The Forestry Research Institute of Sweden, Report 4. 34 p.

— 1994b. Predictive functions for impact of nitrogen fertilization on growth over five years. The Forestry Research Institute of Sweden, Report 3. 56 p.

SAS 1997. SAS/STAT® Software: changes and enhancements through release 6.12. SAS Institute Inc., Cary, NC. 1162 p.

Tamm, C.O. 1991. Nitrogen in terrestrial ecosystems. Ecological Studies 81. Springer-Verlag, Berlin–Heidelberg. 115 p.

— 1985. The Swedish optimum nutrition experiments in forest stands – aims, methods, yield results. Journal of the Royal Swedish Academy of Agriculture and Forestry, Supplement 17: 9–29. (In Swedish with English summary.)

Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H. & Tilman, D.G. 1997. Human alteration of the global nitrogen cycle: sources and consequences. Ecological Application 7: 737–750.

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