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Long-term responses of Scots pine and Norway spruce stands in Sweden to repeated fertilization and thinning

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ABSTRACT

Recent investigations have shown that annual wood production in Sweden can be increased by 30 million m^3 per year in a long-term perspective (>50 years) by using new forest management methods such as new tree species or seedling materials. However, to meet the increased demands during the next 20 years, Sweden will have to rely on silvicultural methods available today. Growth in boreal and cold temperate forest is with only few exceptions limited by nutrients availability, primarily nitrogen, and one way to satisfy the increased demands in a short-term perspective is nitrogen fertilization. A set of thinning and fertilization experiments were started in the 1960's in Scots pine and Norway spruce stands over the whole of Sweden representing different soil, moisture and vegetation types. We used data from these experiments to examine the long-term effects of repeated fertilization in thinned stands on growth, stand development, and yield. The 34 Scots pine sites and 13 Norway spruce sites included in our analyses had at least four treatment plots (no thinning, repeated light thinnings, repeated light thinnings with repeated N fertilization, and repeated light thinnings with repeated N + P fertilization). In northern Sweden, 100 kg N ha^{-1} and 150 kg N ha^{-1} were applied at each fertilization event for Scots pine and Norway spruce stands, respectively. In southern Sweden, 150 kg ha^{-1} N was applied in Scots pine stands and 200 kg ha^{-1} N in Norway spruce stands. Phosphorus was applied at the rate of 100 kg ha^{-1}. Several sites also included non-thinned fertilized plots. Pine stands but not spruce stands were responsive (up to 25% more growth depending of the attribute assessed) to repeated fertilization. Surprisingly, the non-thinned pine stands showed strong continuing response to fertilization throughout the 30+ year observation period resulting in higher cumulative volume response than the thinned stands. In thinned stands incremental volume response to fertilization continued but slowly diminished with time indicating that fertilization and thinning effects were less than additive. However, thinning and fertilization effects were additive for diameter growth. Fertilization accelerated stand development with significant shifts in diameter distributions to larger and potentially more valuable trees. Conclusively, repeated nitrogen fertilization is a silvicultural practice that will result in significant and sustained increases in Scots pine production.

1. Introduction

There are numerous indications of future shortages of raw wood and fiber material from forests in Sweden (Nilsson et al., 2011). There will be an increase in the requirement for raw material by the forest industry and increased demand for sustainable sources of energy in the future, both in Sweden and other parts of Europe. At the same time, there is an expectation that the supply of forest raw materials will decline as a result of certification of forestry and the requirement by the community for multiple use and protection of forest land. Forestry in Sweden must meet these demands and consider all environmental aspects, and at the same time maintain a high level of felling and cost-effective production.

In order to meet the demand from the forest industry and society, silvicultural actions can be taken to increase the production and harvest. Recent investigations in Sweden have shown that new silvicultural methods (intensive fertilization, clonal forestry, exotic tree species) can increase the annual production by 30 million m^3 per year in a long-term perspective (>50 years) (Nilsson

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et al., 2011). However, to meet the increased demands during the next 20 years we have to rely on silvicultural methods available today, which can increase the production and possibilities to harvest more in a shorter time perspective. One more controversial way of course is to harvest more than annual increment in Sweden.

Growth in boreal and cold temperate forests is with only few exceptions limited by nutrients, primarily nitrogen (N) (Tamm, 1991; Tamm et al., 1999) and one way to satisfy the increased demand in a short-term perspective is nitrogen fertilization. Fertilization has been conducted in Sweden since the 1960′s and reached a peak in the late 1970's, when 189.000 hectares were fertilized every year (Lindkvist et al., 2011). Fertilization decreased drastically in the 1980's and 1990's and reached a low level in 2002, when only 14.000 hectares were fertilized. Since then there has been a strong increase with about 90.000 ha fertilized in 2010. The present recommendations for fertilization are to use ammonium nitrate fertilizers in mature stands, with N-supplied at 150 kg ha^{-1}. The ammonium nitrate fertilizers contain usually ca 4% calcium (Ca) and 2% magnesium (Mg) to compensate for the acidification an increased growth due to fertilization can cause. Besides N (+Ca and Mg), boron (B) is also commonly added to avoid deficiencies, which might occur with repeated nitrogen fertilization on nutrient poor sites (Sundberg, 2010). The effects of fertilization generally last for 8–10 years and the additional volume increment is normally between 13 and 20 m^3 ha^{-1}, depending on location, tree species and site characteristics (Pettersson, 1994; Jacobson and Pettersson, 2001). For Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.), the recommendation for northern Sweden is for 450 kg N ha^{-1} to be applied during a whole rotation period, while in Central Sweden it is 300 kg N ha^{-1}. This means that the fertilization can be repeated 2 or 3 times during a rotation period which typically is between 60 and 100 years depending on site fertility. The rationale for these limits in the amount of fertilizers is the risk for nutrient leaching. In southern Sweden fertilization is not recommended except for Norway spruce stands in south-eastern Sweden, where forest residues are removed at final harvest. There is a general belief that the fertilization effect decreases the 2nd and 3rd time that a stand is fertilized (Jacobson and Nohrstedt, 1993).

Thinning has been used in Sweden during the last 100 years and the main purposes are (i) to remove trees to improve the remaining stand development and economy, (ii) to avoid self-thinning, (iii) to obtain an early income during the rotation period and (iv) to keep up the level of harvest in order to supply the forest industry with raw material (Wallentin, 2007). Different thinning regimes will change the structure, tree dimensions and might influence the quality and the areal production of the stand. Today coniferous stands in Sweden are normally thinned 2–4 times during the rotation period, depending on soil fertility. Thinning guidelines, often based on dominant height and basal area, are commonly used. Thinning is also combined with fertilization to further promote the development of individual trees (Valinger, 1990).

Stem wood production in a forest stand is determined by the amount of light absorbed during the growing season and the efficiency with which this absorbed light is converted to stemwood (Cannell, 1989). If stand leaf area levels are low to moderate, due to low fertility and/or thinning, additions of limiting nutrients will typically result in substantial increases in leaf area and light absorption (Linder and Axelsson, 1982; Linder, 1987; Albaugh et al., 1998; Sampson and Allen, 1999). In addition, fertilization results in enhanced light use efficiency including greater photosynthesis rates (Roberntz and Stockfors, 1998) and proportionately increased allocation of fixed carbon to stem wood production (Linder and Axelsson, 1982; Albaugh et al., 1998; Bergh et al., 1999). In contrast to fertilization, thinning typically reduces stand leaf area to levels that are lower than what is needed for maximum light interception, thereby reducing stand growth on a per hectare basis. However, individual tree growth is typically enhanced due to greater light absorption by individual trees and also greater light use efficiency (Mäkinen and Isomäki, 2004; Blevins et al., 2005).

In Sweden, a new series of thinning and fertilization experiments were started in the 1960's in Scots pine and Norway spruce stands (Nilsson et al., 2010). These experiments have a good climatic and geographical representation over the whole of Sweden for different soil, soil moisture and vegetation types. The experimental setup had 8 different thinning regimes and several thinning treatments were combined with fertilization.

The objectives of this paper were to (i) determine the long-term effects of repeated fertilization in repeatedly thinned Scots pine and Norway spruce stands, (ii) examine the effects of repeated thinning and repeated fertilization and their interactions in Scots pine and Norway spruce stands, (iii) provide guidelines for fertilization and thinning.

2. Materials and methods

The experiments were installed at the time of first thinning (dominant height 12–18 m) in uniform, even-aged, pure or almost pure, stands of Scots pine and Norway spruce. The experiments were installed over an 18-year period from 1966 to 1983. The Scots pine stands were located all over Sweden (lat. 56.4° to 66.7° N), whereas the Norway spruce stands were only located in the south and central parts of Sweden (lat. 56.1° to 61.7° N) (Fig. 1). In total 48 experiments in Scots pine and 24 experiments in Norway spruce were installed. In this study, 14 experiments in Scots pine and 11 experiments in Norway spruce were excluded because they did not include fertilization, an appropriate control for the fertilized treatment, or had not been through at least three cycles of thinning. The description of the experiments below relates to the 34 Scots pine sites and 13 Norway spruce sites included in this study. The experimental design of the larger study was recently summarized in Nilsson et al. (2010).

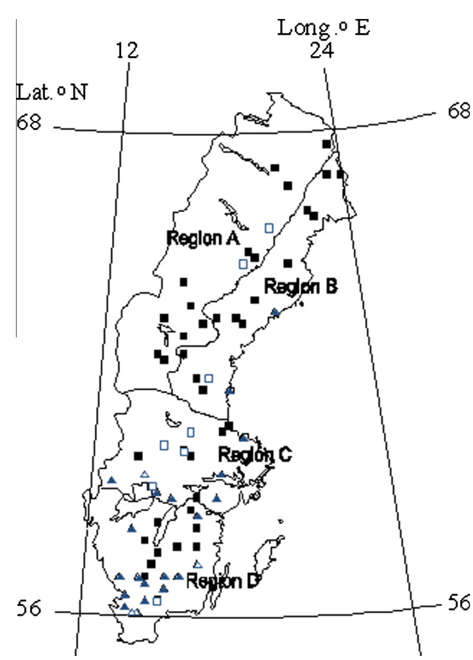

Fig. 1. Geographical location of blocks of the thinning and fertilization experiments in Scots pine (squares) and Norway spruce (triangles).

The experiments were established in successful regenerations with relatively high stem density, basal area and stem volume before thinning (Tables 1 and 2). Average height was about 12 m for both the Scots pine and Norway spruce stands, which is a typical height for first commercial thinning in Sweden. The Scots pine sites represented a large part of the fertility gradient found for Scots pine in Sweden whereas the Norway spruce sites represented fertile sites (Tables 1 and 2).

Most of Scots pine stands were established by direct seeding (24 stands), usually from local seed sources. Of the remaining stands, 5 were established by natural regeneration and 5 were planted. All Norway spruce stands had been regenerated by planting. Local, as well as central European provenances were used.

The experimental design consisted of treatment plots randomized within one block per site. The light-frequent thinning plots with and without fertilization were represented on every site included in this study whereas the non-thinned plots with and without fertilization were only present on 10 Scots pine sites and three Norway spruce sites. The size of each net-plot was typically 25×40 m (0.1 ha) with a surrounding buffer zone of 10 m but sometimes the plot-size varied. However, the size of an individual net-plot was never less than 0.09 ha. The maximum coefficient of variation for basal area before treatments within a block was not allowed to exceed 8%. After marking all plots, treatments were randomly assigned to plots. The same thinning and fertilization treatments were used in the buffer-zones as in the net plots, but the trees in the buffer zone were not individually numbered as they were in the net-plot, in which all trees >45 mm diameter at breast-height were permanently numbered.

The thinning treatment was frequent light thinnings from below. In Scots pine, 3 thinnings were done while Norway spruce stands were thinned four times. In the first thinning, 20–25% of the basal area was removed. In subsequent thinnings, the residual basal area after thinning increased by 0.2% per year, and consequently almost all growth between any two thinnings was removed during later thinnings or by natural mortality. Non-fertilized and fertilized plots were thinned to the same basal area within each site. The interval between thinnings was determined on the basis of dominant height growth. The predetermined increase of dominant height between thinnings varied between Scots pine and Norway spruce and between southern and northern Sweden. Thinning was done when the increase of dominant height reached 2.2–3.0 m for Scots pine and 2.5–3.0 m for Norway spruce. All thinnings were carried out in order to avoid damage from logging machines on remaining trees and soil. Mean stand basal area before and after thinning for the first, second, and third thinning for each treatment in Scots pine experiments are summarized in Table 3. For further description of the thinning treatment, see Nilsson et al. (2010).

The first fertilization was done in early summer before the second growing season after first thinning (Nilsson et al., 2010). The interval between the four first nitrogen fertilizations was 5 years; thereafter the interval between nitrogen additions was 7 years. The first phosphorus (P) fertilization was done at the same time as the first nitrogen fertilization. The interval between the first and second phosphorus applications was 21–22 years. Nitrogen was added as ammonium nitrate (NH_4NO_3) and phosphorus as superphosphate ($CaSO_4 + Ca(H_2PO_4)_3$). The amount of nitrogen varied between Scots pine and Norway spruce and between southern and northern Sweden. In northern Sweden, 100 kg N ha^{-1} and 150 kg N ha^{-1} were applied at each fertilization event for Scots pine and Norway spruce stands, respectively. In southern Sweden, 150 kg N ha^{-1} was applied in Scots pine stands and 200 kg N ha^{-1} in Norway spruce stands. Phosphorus was applied at the rate of 100 kg P ha^{-1} for both tree species in all regions. In order to achieve even distribution of the fertilizers, the plot was temporarily divided into strips (typically 5 m width) for fertilization. The same per-hectare amount of fertilizer was given to both the net-plot and the buffer-zone.

Because of the extended period of time over which blocks were established and the desire that all sites be thinned at least three times, the length of the observation period and consequently the number of fertilizer applications varied by site. The observation period averaged 32 years for both species and varied from 24 to 40 years for Scots pine and 23–41 years for Norway spruce. Given this schedule, the sites were fertilized from 5 to 7 times with 6 times being average. With six fertilization cycles, Norway spruce received 900 and 1200 kg N ha^{-1} in the north and south, respectively and Scots pine received 600 and 900 kg N ha^{-1}. A total of 200 kg P ha^{-1} was applied to all sites.

Diameter at breast height (130 cm above ground; DBH) was recorded for all trees at the start of the experiment, at the time of every thinning, and at irregular intervals between the thinnings. Diameters were measured, using calipers, in two perpendicular directions and recorded to the nearest mm. The caliper positions were permanently marked to ensure that it did not vary between measurements. At the same time, tree species, tree class (social position), status (retained, removed, missing, wind-felled), physical damage and vitality were recorded. Tree-height, height to the living crown and thickness of the bark (only Scots pine) were recorded for 20–40 systematically selected sample trees within the plot. Two separate groups of sample trees were selected, one among the retained trees and one among the removed trees. Among the retained trees, about five trees were selected from the 100 trees per hectare with the largest diameter. Among both the retained and the removed trees, sample trees were selected at a fixed quotient (Karlsson, 1998). This sampling procedure resulted in a higher proportion of large sample trees. Damage and the cause of damage were recorded for all trees on all measurement occasions. For further information of the measurement procedure see Nilsson et al. (2010) and Karlsson (1998).

Table 1
Initial stand characteristics before thinning and basal area after thinning for the 34 Scots pine stands.

Stand attribute	Units	Mean	Range	Coefficient of variation%
Age	years	40.1	32–54	15.0
Density	# ha^{-1}	2160	1238–3324	25.9
Average diameter	cm	12.2	10.1–14.7	9.32
Average height	m	12.1	10.5–14.1	9.66
Basal area before thinning	m^2 ha^{-1}	24.5	17.4–35.9	18.0
Basal area after thinning	m^2 ha^{-1}	17.4	12.5–26.5	18.5
Volume	m^3 ha^{-1}	150	100–232	22.1
Site index[a]	m	24.4	19.5–27.9	7.20

[a] Hägglund (1974).

Table 2
Initial stand characteristics before thinning and basal area after thinning for 13 Norway spruce stands.

Stand attribute	Units	Mean	Range	Coefficient of variation%
Age	years	32	23–50	17.1
Density	# ha^{-1}	3344	1300–4880	31.9
Average diameter	cm	11.9	9.4–15.1	16.0
Average height	m	12.6	10.8–17.8	15.1
Basal area before thinning	m^2 ha^{-1}	33.3	23–39.61	16.0
Basal area after thinning	m^2 ha^{-1}	25.1	18.1–30.2	15.5
Volume	m^3 ha^{-1}	216	133–300	22.4
Site index[a]	m	32.3	28.5–37.4	6.38

[a] Hägglund (1972, 1973).

Table 3
Treatments means for stand basal area before and after thinning for the three thinning events in Scots pine stands. Data are summarized for the 34 blocks used in the analysis of fertilizer effects in thinned stands (first 3 rows) and the 10 blocks used for the factorial analysis of thinning and fertilization (second 5 rows). The letter shown in ( ) is the treatment code used in the field and in previous reports about this study.

Treatment	First thinning		Second thinning		Third thinning	
	Before $m^2\ ha^{-1}$	After	Before	After	Before	After
Thinned control (A)	23.8	18.2	25.4	18.7	25.5	19.0
Thinned + N (G)	23.9	17.0	26.9	17.9	26.2	18.5
Thinned + NP (H)	23.5	17.1	27.0	17.9	26.1	18.5
Thinned control (A)	23.6	18.1	25.7	18.7	26.2	19.3
Thinned + N (G)	24.0	17.0	27.7	18.2	27.1	18.6
Thinned + NP (H)	23.7	17.1	28.2	17.6	26.4	19.1
Non-thinned control (I)	24.5	23.9	31.6	30.7	37.9	36.0
Non-thinned + N (K)	24.7	24.0	34.0	32.5	41.8	39.3

Stem-volume of sample trees was calculated with functions developed by Brandel (1990) using diameter at breast height (DBH), height (H) and height to the first living branch (HL) for Norway spruce and DBH, H, HL and thickness of the bark for Scots pine. Different functions were used for northern and southern Sweden. Thereafter, volume was assigned to all calipered trees in DBH-classes of 2 cm but weighted by the sum of squared diameter for sample and calipered trees in each diameter-class. Mean volume of diameter-class c was calculated as:

$$V_{c\_mean} = V_{c\_p}/N_{c\_p} * D_{c\_s}/D_{c\_p}$$

where V_{c_mean} is the mean volume of diameter-class c; V_{c_p} is sum of volumes of sample trees in diameter-class c; N_{c_p} is number of sample trees in diameter-class c; D_{c_s} is mean square diameter of all calipered trees in diameter-class c and D_{c_p} is the mean square diameter of sample trees in diameter-class c. If sample trees were missing from a class where one or more calipered trees were present, V_{c_mean} was calculated using V_{c_p}, N_{c_p} and D_{c_p} from the nearest diameter-class containing at least one sample tree. For further description of volume calculations see Nilsson et al. (2010).

Dominant height for each plot by measurement date was estimated by the height-curve developed by Näslund (1936):

$$H = DBH^x/(a + b * DBH)^x + 1.3$$

where H is the tree height (m); DBH is diameter at breast height (cm); a and b are coefficients and x has a value of 2 for Scots pine and 3 for Norway spruce (Petterson, 1955). Thereafter, the dominant height was estimated by use of the height function, as the height corresponding to the arithmetic mean diameter of the 100 trees per hectare with the greatest DBH. The number of trees per plot for estimating dominant height was about 5–10. Site index (SI) was determined from species-specific site index curves (Hägglund, 1972, 1973, 1974).

Dependent variables included assessments of both periodic annual increment and yield (final size) for several individual tree and stand level attributes. Individual tree yield attributes included average height and average diameter measured only on trees living at time of measurement. Periodic annual growth estimates for individual tree attributes were calculated as the net change in the average size of living trees from one measurement date to the next divided by the number of years in the period. Stand level attributes included final yield and periodic annual increment estimates for basal area and stem volume per hectare. Periodic annual growth estimates for stand and tree attributes were calculated as the gross change in the attribute from one measurement date to the next (net change in the attribute from one measurement date to the next plus the amount of the attribute removed in thinnings and natural mortality during the period) divided by the number of years in the period. Annualized measures of periodic growth were used because of the differing lengths of time between measurements and in the total measurement period. In addition, the total amount of stem volume removed during thinnings and SI determined at the final measurement date were calculated.

A randomized complete block analysis of variance was used to test for the long-term effects of repeated fertilization on growth and yield attributes in thinned plots using the dependent variables described above using the control, N alone, and N + P fertilized plots. Site (34 and 13 locations respectively, for Scots pine and Norway spruce) was included as a block effect and treatment effects were tested using two single degree of freedom contrasts to test

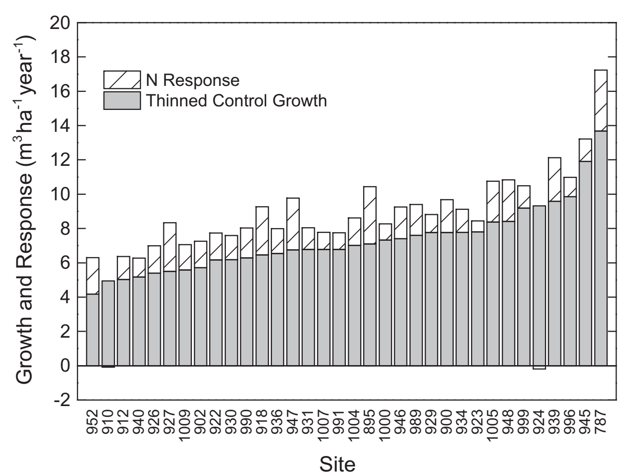

Fig. 2. Periodic annual growth and annual response to N fertilization for 34 thinned Scots pine stands.

Table 4
Statistical summary of site and treatment effects (probability > F) and coefficients of variation (CV) for growth and final stand attributes from the analyses of variance of 34 thinned Scots pine stands.

Stand attribute	Prob > F			CV
	Site	Control vs. fertilizer	N vs. N + P	%
PAI volume	<.001	<.001	0.615	7.2
PAI basal area	<.001	<.001	0.619	7.7
PAI diameter	<.001	<.001	0.961	7.8
PAI height	<.001	<.001	0.700	6.2
Volume	<.001	0.001	0.196	7.7
Basal area	<.001	0.822	0.176	6.7
Diameter	<.001	<.001	0.525	4.6
Height	<.001	<.001	0.565	3.3
Site index	<.001	<.001	0.636	2.9
Volume thinned	<.001	<.001	0.492	12.6

for an overall fertilizer effect (control vs. the average of N alone and N + P) and the effect of adding P in addition to N (N + P vs. N alone). Separate analyses were run for the two tree species. The effects of treatment on stand structure (number of trees and volume by diameter class) were presented graphically.

A randomized complete block analysis of variance was used to test for the long-term effects of repeated thinning, repeated fertilization, and their interaction on growth and yield attributes using the dependent variables described above. Treatments included in this analysis were: non-thinned control, non-thinned fertilized, thinned control, and thinned fertilized. Data were available for 10 sites for Scots pine and only 3 sites for Norway spruce. Site was included as a block effect and treatment effects were tested using a factorial design of thinning and fertilization that provided tests of thinning, fertilization, and their interaction. Separate analyses were run for the two tree species. The effects of treatment on stand structure (number of trees and volume by diameter class) were presented graphically.

Correlation and regression analyses were used to explore relationships among periodic stem volume growth on control plots, fertilizer response (average of the N alone and N + P treatments, expressed as an absolute $m^3\ ha^{-1}\ year^{-1}$ and as a percentage of control growth), initial stand characteristics including age, height, SI, density, diameter, basal area, and volume (Tables 1 and 2), number of measurement years, and location/site factors including longitude, latitude, altitude, temperature sum (cumulative degree days > 5 °C), soil moisture class, landscape position, soil texture, and vegetation type. The latter four were classification and not continuous variables.

Time trends in volume growth response to fertilization (for Scots pine only) with and without thinning were examined by grouping the data into three periods. The 1st period included on average an 11 year period from the 1st thinning to immediately before 2nd thinning (average age 42–53 years). The 2nd period included on average a 12 year period from the 2nd thinning to immediately before 3rd thinning (average age 53–65 years) and the 3rd period included on average a 10 year period from the 3rd thinning to final measurement (average age 65–75 years).

Changes in stand structure over time and treatment effects on stand structure were examined for the 10 Scots pine sites that had the thinning × fertilization factorial array of treatments. Graphical analyses were used to examine the distribution of total net stem-wood volume production (current standing volume + all volume removed in previous thinnings and natural mortality) across diameter classes at the end of each of the three time periods described above: (1) immediately before the 2nd thinning (average age 53 years), (2) immediately before the 3rd thinning (average age 65 years), and (3) at the final measurement (average age 75 years). Treatment effects were also graphically examined for volume growth that occurred within each of the three measurement periods. All statistical analyses were performed using SAS 9.2 and 9.3 (SAS Institute, Cary, NC).

3. Results

Scots pine growth varied across sites for all measured attributes (Fig. 2, Table 4). Periodic annual increment (PAI) in stem volume averaged 7.3 $m^3\ ha^{-1}\ year^{-1}$ and ranged from less than 5 to over

Table 5
Correlation coefficients (r) of stem-wood growth on control plots and fertilizer response with initial stand and site variables for 34 Scots pine and 13 Norway spruce stands.

Stand and site variable	Scots pine			Norway spruce		
	Control growth	Absolute response	Relative response	Control growth	Absolute response	Relative response
Control growth	–	0.24	−0.29	–	−0.54	−0.56
Age	−0.51	0.09	0.41	0.34	0.34	0.31
Density	0.67	0.46	0.10	0.12	−0.12	−0.14
Average diameter	−0.15	−0.07	0.02	−0.04	0.12	0.08
Average height	−0.08	0.15	0.23	−0.42	0.18	0.22
Basal area	0.75	0.58	0.19	0.27	−0.10	−0.16
Volume	0.63	0.58	0.27	−0.06	0.01	−0.01
Site index	0.53	0.01	−0.30	0.42	−0.46	−0.34
Years measured	−0.72	−0.22	0.12	−0.29	−0.09	−0.21
Longitude	−0.14	0.26	0.40	0.53	0.09	0.04
Latitude	0.04	0.38	0.41	0.22	0.03	−0.04
Altitude	−0.03	−0.02	0.01	−0.45	0.09	0.10
Temperature sum	−0.02	−0.30	−0.33	0.10	−0.08	−0.02
Moisture class	0.16	0.07	−0.04	–	–	–
Landscape position	−0.12	0.02	0.12	–	–	–
Texture	0.45	0.31	0.02	0.52	−0.16	−0.22
Vegetation type	0.37	−0.03	−0.21	−0.26	0.23	0.10

For pine: r of >0.35 has prob. < 0.05, r of >0.28 has prob. < 0.10; for spruce r of >0.55 has prob. < 0.05, r of >0.47 has prob. < 0.10.

Table 6
Treatment means and average (N and N + P) fertilizer response for growth and final stand attributes in 34 thinned Scots pine stands.

Variable	Units	Treatment means			Average response	Average % response
		Control	N	N + P		
PAI volume	$m^3\ ha^{-1}\ year^{-1}$	7.30	9.00	8.93	1.67	22.8
PAI basal area	$m^2\ ha^{-1}\ year^{-1}$	0.65	0.81	0.80	0.16	23.8
PAI diameter	$cm\ year^{-1}$	0.34	0.43	0.43	0.09	26.5
PAI height	$m\ year^{-1}$	0.26	0.30	0.30	0.04	15.4
Final volume	$m^3\ ha^{-1}$	213	227	222	12	5.4
Final basal area	$m^2\ ha^{-1}$	22.3	22.6	22.1	0.1	0.2
Final diameter	cm	24.3	27.4	27.2	3.0	12.3
Final height	m	20.6	21.9	21.8	1.2	6.1
Final site index	m	25.0	26.2	26.1	1.2	4.6
Volume thinned	$m^3\ ha^{-1}$	125	156	160	33	26.4

13 m^3 ha^{-1} $year^{-1}$ (Fig. 2). This variation was significantly correlated ($p < .10$) with initial age, initial stand density, initial basal area, initial volume, site index, number of years measured, soil texture and vegetation type (Table 5).

All Scots pine attributes showed positive and significant responses to fertilization except for final basal area (Table 4). The addition of P in conjunction with N (N + P treatment) resulted in no change in growth as compared to additions of N alone (Tables 4 and 6). As a result, we averaged the growth measures from the two fertilizer treatments to provide an estimate of fertilizer response for each attribute (Table 6).

Mean responses to fertilization ranged from about 5% for final height, volume and SI to about 25% for volume removed during thinning, periodic annual increments of diameter, basal area and volume (Table 6). The largest volume gains with fertilization (both absolute and relative) were realized in the volume removed during thinning rather than volume remaining at final harvest. Averaged across sites, the total gain in volume (final measurement gain plus gains removed in thinning) totaled 45 m^3 ha^{-1}, an amount that would have taken 6 more years to grow on control plots given their average volume growth rate of 7.3 m^3 ha^{-1} $year^{-1}$. Final diameter was on average increased by 3.0 cm, an amount that would have taken 9 more years to achieve on control plots given their average diameter growth rate of 0.34 cm $year^{-1}$.

Stand structure was substantially changed by fertilization, resulting in a shift in the diameter distribution to larger and potentially more valuable trees (Fig. 3). The majority of trees were greater than 24 cm on thinned + fertilized plots with just the opposite found on thinned control plots (Fig. 3). Similarly, more than one-half of the volume was found on trees greater than 27 cm on fertilized plots with the opposite found on control plots. Fertilizer responses also varied across sites. As noted previously, stem-wood volume periodic annual response averaged 1.7 m^3 ha^{-1} $year^{-1}$ (23%). However, on an individual site basis, it varied from 0 to 3.5 m^3 ha^{-1} $year^{-1}$ (0–50%) (Figs. 2 and 4). Absolute volume response was significantly correlated ($p < 0.10$) with initial basal area, initial volume, and latitude. Relative volume response was significantly correlated with age, longitude, and latitude (Table 5).

Spruce growth varied across sites for all accessed attributes (Table 7 and Fig. 5). Periodic annual increment (PAI) in stem volume growth averaged 16.4 m^3 ha^{-1} $year^{-1}$, more than double the growth rate of the Scots pine stands, and ranged from 10 to over 25 m^3 ha^{-1} $year^{-1}$ (Table 8 and Fig. 5). Control growth was significantly correlated ($p < .10$) with longitude and soil texture (Table 5). Unlike Scots pine, none of the Norway spruce stand attributes showed a significant response to additions of N alone or N + P (Tables 7 and 8; Figs. 5 and 6).

Thinning significantly affected most attributes for Scots pine (Table 9). Thinning significantly reduced PAI for volume, final volume, final basal area, and SI; had no effect on PAI for basal area, PAI for height and final height, and significantly increased PAI for diameter, final diameter, and thinned volume (Table 10). As with the larger 34 sites pine data set, all attributes showed significant positive responses to fertilization (Tables 9 and 10). The effects of thinning and fertilization were generally additive as indicated by the non-significant thinning × fertilizer interactions. However, periodic annual increment for volume and final volume both showed less response to fertilization on thinned plots than on non-thinned plots (2.82 vs. 1.72 m^3 ha^{-1} $year^{-1}$ and 69 vs. 20 m^3 ha^{-1} respectively; Table 10) which resulted in statistically

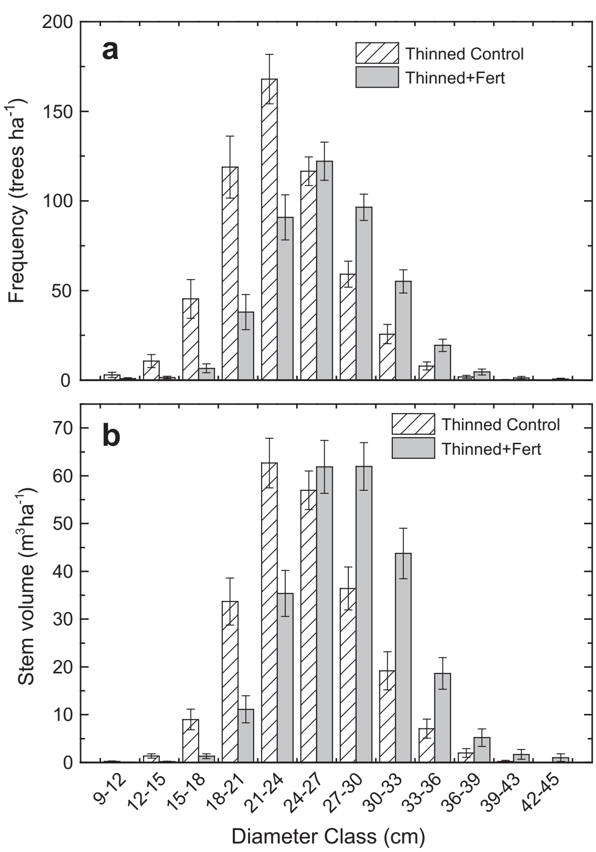

Fig. 3. Distribution of numbers of stems (a) and stem volume (b) by diameter class at the final measurement for thinned control and thinned + fertilized treatments for 34 thinned Scots pine stands.

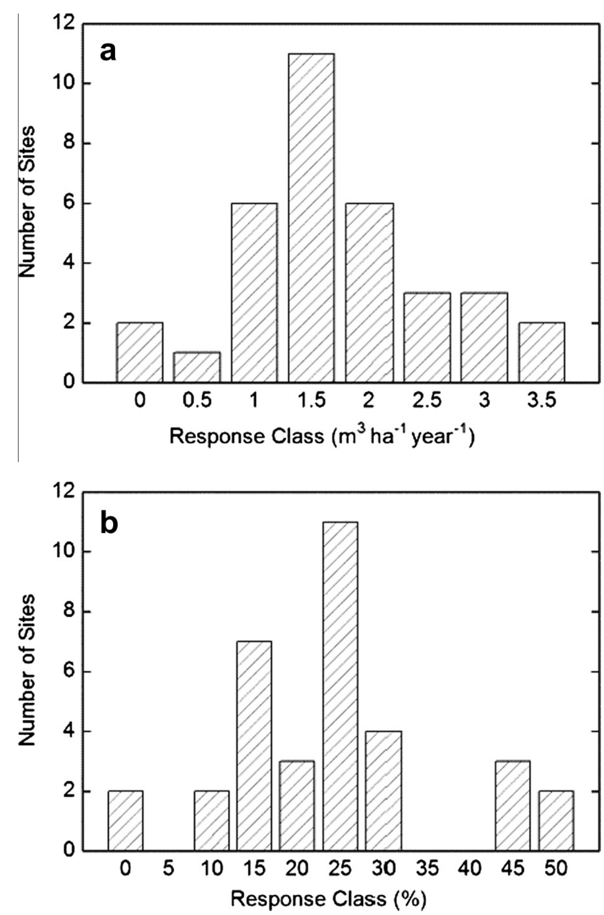

Fig. 4. Frequency distribution of Scots pine annual stem-wood volume growth responses to fertilization expressed on an absolute (a) and percentage basis (b).

Table 7
Statistical summary for site and fertilizer treatment effects and coefficients of variation (CV) for growth and final stand variables in 13 thinned Norway spruce stands for the entire response period.

Stand attribute	Prob > *F*			CV
	Site	Control vs. fertilizer	N vs. NP	%
PAI volume	<.001	0.365	0.905	10.7
PAI basal area	<.001	0.613	0.431	9.8
PAI diameter	<.001	0.504	0.355	12.9
PAI height	<.001	0.251	0.741	6.7
Final volume	<.001	0.578	0.215	21.3
Final basal area	<.001	0.813	0.340	21.1
Final diameter	<.003	0.374	0.727	10.0
Final height	<.001	0.375	0.517	5.9
Final site index	<.001	0.079	0.251	3.4
Volume thinned	<.001	0.740	0.418	26.7

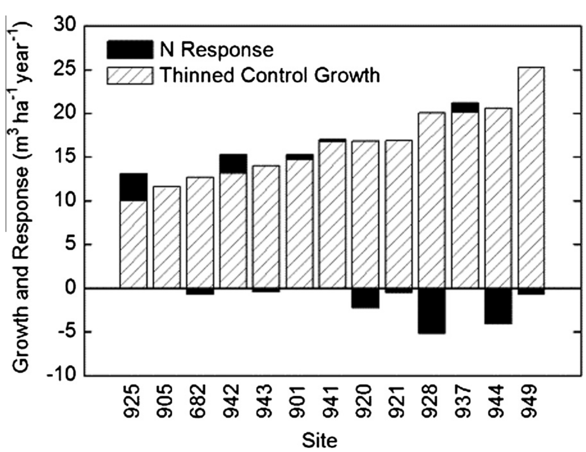

Fig. 5. Periodic annual growth and annual response to N fertilization for 13 thinned Norway spruce stands.

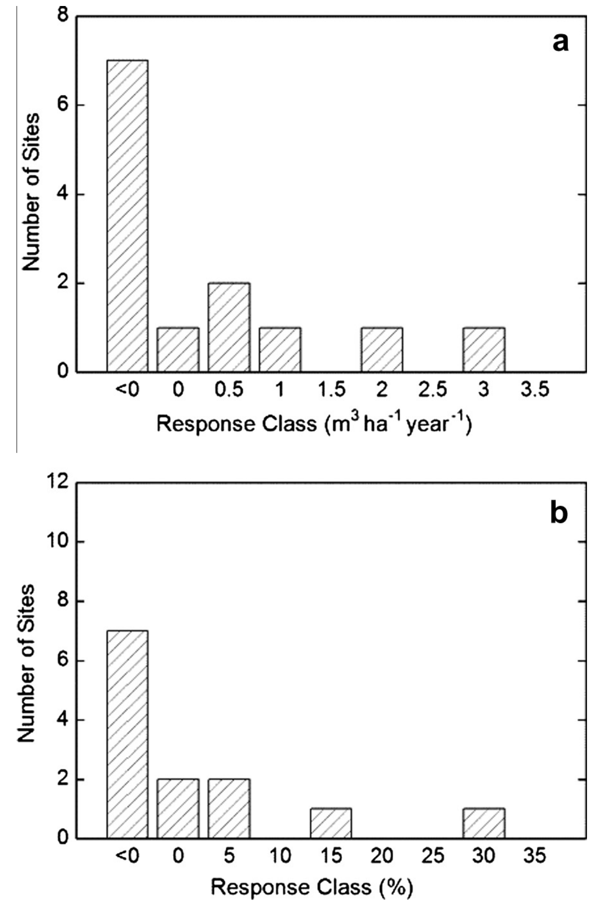

Fig. 6. Frequency distribution of Norway spruce annual stem-wood volume growth responses to fertilization expressed on an absolute (a) and percentage basis (b).

significant negative interactions for thinning and fertilization for these two variables (Table 9). Rankings for volume growth ($m^3\ ha^{-1}\ year^{-1}$) were: fertilized only (11.12) > thinned + fertilizer (8.81) > non-thinned control (8.30) > thinned only (7.09).

Periodic annual diameter growth of Scots pine was positively affected by thinning (Tables 9 and 10). Diameter growth was twice as responsive to thinning alone as compared to fertilization alone (0.11 vs. 0.05 cm $year^{-1}$) and the additive effects of thinning and fertilization on diameter growth resulted in a large average final diameter on thinned and fertilized plots, 27.5 cm as compared to the 20.3 cm average diameter found on non-thinned control plots, a 7.2 cm (35%) increase.

Fertilizer response varied across the three time periods and response across time also differed by thinning treatment (Fig. 7). As noted above, overall the three periods, fertilizer response was greatest on non-thinned plots; however, during the 1st period fertilizer responses were similar for non-thinned and thinned plots (≈2.5 $m^3\ ha^{-1}\ year^{-1}$). During the 2nd period, fertilizer response was significantly different between thinned and non-thinned plots ($p = 0.01$) since fertilizer response increased on non-thinned plots to over 3 $m^3\ ha^{-1}\ year^{-1}$ while it decreased on thinned plots to 1.5 $m^3\ ha^{-1}\ year^{-1}$. During the 3rd period fertilizer response was not significantly different between thinned and non-thinned plots ($p = 0.175$). Mean response dropped slightly on non-thinned plots back to levels observed during the first period and response on thinned plots continued to drop. Similar trends were found for

Table 8
Treatment means and fertilizer response for 13 thinned Norway spruce stands for the entire response period.

Variable	Units	Treatment means			Average response	Average % response
		Control	N	N + P		
PAI volume	$m^3\ ha^{-1}\ year^{-1}$	16.36	15.49	15.79	−0.72	−4.4
PAI basal area	$m^2\ ha^{-1}\ year^{-1}$	1.23	1.22	1.27	0.02	1.2
PAI diameter	cm $year^{-1}$	0.52	0.53	0.55	0.02	3.8
PAI height	m $year^{-1}$	0.40	0.39	0.39	−0.01	−2.5
Final volume	$m^3\ ha^{-1}$	362	346	329	−24	−6.8
Final basal area	$m^2\ ha^{-1}$	29.7	29.1	28.0	−1.2	−3.9
Final diameter	cm	29.3	29.9	30.5	0.9	3.1
Final height	m	25.6	25.1	25.0	−0.55	−2.1
Final site index	m	33.4	32.6	32.4	−0.9	−2.7
Volume thinned	$m^3\ ha^{-1}$	329	313	334	−5.5	−1.7

Table 9
Statistical summary of site, thinning and fertilizer effects and coefficients of variation (CV) for growth and final stand attributes in 10 Scots pine stands.

Variable	Prob > *F*				CV
	Site	Thin	Fert	Thin*Fert	%
PAI volume	<.001	<.001	<.001	<.029	8.6
PAI basal area	<.001	<.196	<.001	<.470	11
PAI diameter	<.001	<.001	<.001	<.213	11
PAI height	<.001	<.967	<.001	<.253	7.7
Final volume	<.001	<.001	<.001	<.035	11
Final basal area	<.003	<.001	<.055	<.229	13
Final diameter	<.001	<.001	<.001	<.254	5.8
Final height	<.013	<.563	<.001	<.392	4.1
Final site index	<.001	<.004	<.001	<.403	3.1
Volume thinned	<.304	<.001	<.015	<.836	31

fertilizer response in thinned stands for the 10 sites (thinned × fertilized subset) and for all 34 sites (Fig. 7).

The effects of thinning and/or fertilization on the tradeoffs between volume growth per hectare and individual tree diameter growth are illustrated in Fig. 9. After the first response period of 11 years (immediately prior to the 2nd thinning, average age = 53 years), both fertilized treatments (non-thinned and thinned) had greater volume than their non-fertilized plot counterparts and both thinned treatments had lower volume than their non-thinned counterparts; however, the distribution of volume across diameter classes had not been affected very much (Fig. 8a). By the end of the second response period (another 12 years and immediately prior to the 3rd thinning, average age = 65 years), volume had increased significantly on all plots but the treatment ranks for total volume remained the same as for the previous period (Fig. 8b). By the end of this 2nd period, the distribution of volume across diameter classes had differentiated by treatment with significantly more volume present in larger diameter classes on fertilized plots, both for thinned and non-thinned plots. By the end of the 3rd response period (another 10 years following the 3rd thinning, average age = 75 years), the treatments ranked: fertilized only > thinned + fertilized = non-thinned control > thinned only for total volume (Fig. 8c). However, the distribution of the volume differed with thinned + fertilized plots having much greater volume in larger trees than control plots. The thinned only plots had the lowest volume and had only slightly more volume in the larger diameter classes than the control plots. Although thinned + fertilized plots had more volume in the very largest diameter classes than any of the other treatments, the fertilized only plots and thinned + fertilized plots had the same total volume in trees above 24 cm.

The periodic annual volume growth rates show the shift in rank of the thinned + fertilized plots from being second ranked for volume growth during the 1st period to being 3rd ranked for the 3rd period (Fig. 9). As noted above, continued strong per hectare volume growth of the fertilized only plots was maintained throughout the three periods with strong growth exhibited in all diameter classes.

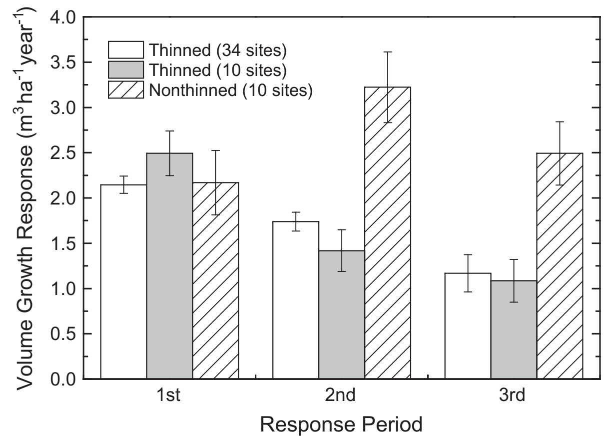

Fig. 7. Periodic annual volume growth response to fertilization (1st period – 1st thinning to immediately before 2nd thinning, ages 42–53 years; 2nd period – 2nd thinning to immediately before 3rd thinning, ages 53–65 years; and 3rd period – 3rd thinning to final measurement, ages 65–75 years) for the Scots pine stands.

There were no significant effects of fertilizer or the interaction of fertilizer and thinning on Norway spruce stands; however, significant site and thinning effects were found (data not shown). Readers are referred to Nilsson et al. (2010) for a detailed discussion of thinning effects on the larger spruce data set.

4. Discussion

The lack of fertilizer response in the Norway spruce stands was not surprising given their high growth rates and site indexes. The one spruce stand (site 925) that appeared to respond to fertilization (without replication within site it was not possible to determine whether a given stand was actually statistically responsive) had the lowest control growth (Fig. 5). These same Norway spruce stands showed little to no drop in periodic annual increment with light to moderate thinning (Nilsson et al., 2010), indicating that stand leaf area levels were still very high following thinning, a condition which suggested high nutrient availability and therefore little opportunity for response to fertilization. Results from earlier evaluations of the same fertilization experiments in Norway spruce in south-western Sweden also showed no growth response to nitrogen fertilization (Persson et al., 1995). Similar findings have been reported in Denmark, where nitrogen fertilization gave a very small growth response (Ingerslev et al., 2001). Apparently these sites are very fertile whether due to anthropogenic deposition of nitrogen (Ingerslev et al., 2001) and/or inherent fertility (Tamm, 1991; Tamm et al., 1999). In southern Sweden and Denmark mature Norway spruce stands might have reached maximum canopy closure and additional nitrogen/nutrients with increased foliar

Table 10
Treatment means for the thinning and fertilizer effects for 10 Scots pine sites.

Variable	Units	Treatment means			
		Non-thinned control	Non-thinned + Fert	Thinned control	Thinned + Fert
PAI volume	m^3 ha^{-1} $year^{-1}$	8.30	11.12	7.09	8.81
PAI basal area	m^2 ha^{-1} $year^{-1}$	0.64	0.84	0.63	0.79
PAI diameter	cm $year^{-1}$	0.23	0.28	0.34	0.42
PAI height	m $year^{-1}$	0.24	0.30	0.25	0.29
Final volume	m^3 ha^{-1}	362	431	209	229
Final basal area	m^2 ha^{-1}	37.7	41.6	21.7	22.6
Final diameter	cm	20.3	22.1	24.8	27.5
Final height	m	20.5	22.3	20.9	22.2
Final site index	m	25.6	27.0	25.0	26.0
Volume thinned	m^3 ha^{-1}	54	79	133	162

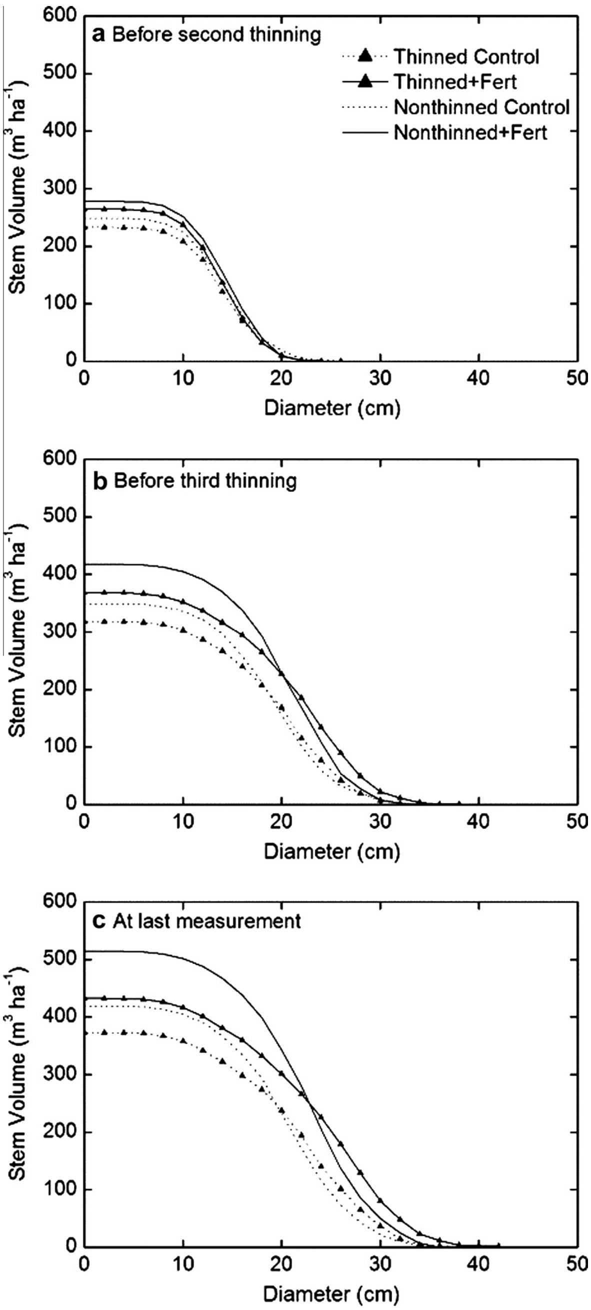

Fig. 8. Treatment effects on the distribution of cumulative standing volumes by diameter classes for three periods ((a) immediately before the 2nd thinning – average age = 53 years, (b) immediately before the 3rd thinning – average age = 65 years, (c) at the final measurement – average age = 75 years) for the 10 Scots pine stands with thinning and/or fertilization treatments.

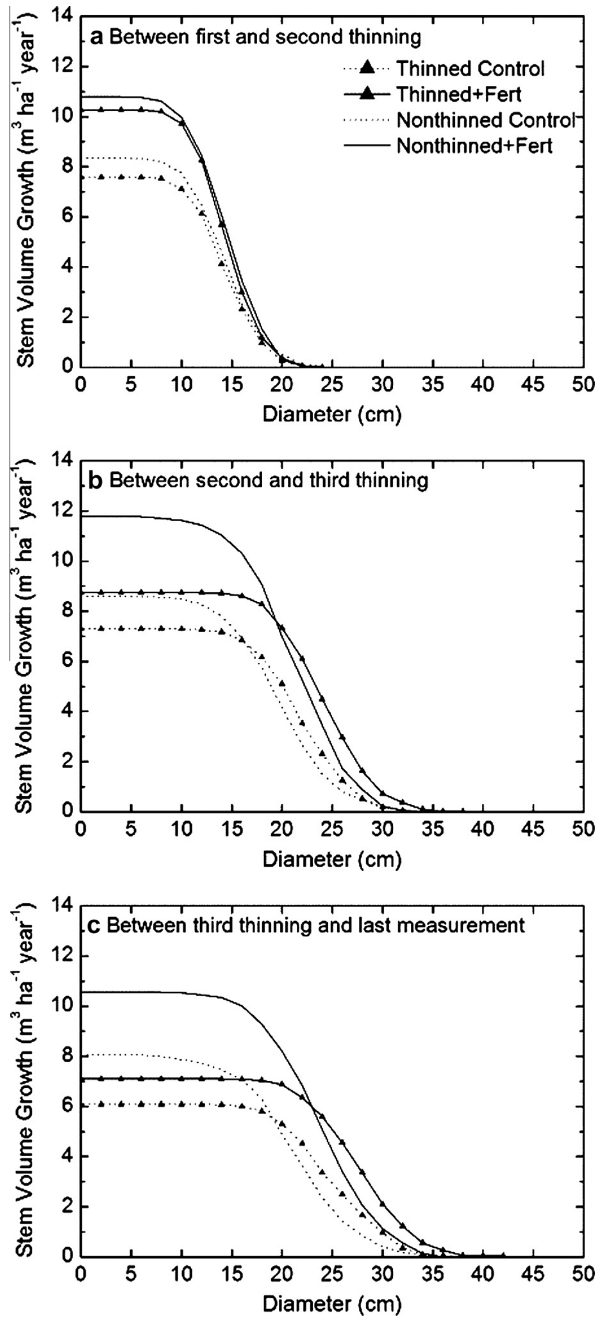

Fig. 9. Treatment effects on cumulative stand volume growth by diameter classes for three periods ((a) between the first and second thinning (11 years), (b) between the second and third thinning (12 years), (c) between the third thinning and final measurement (10 years) for the 10 Scots pine stands with thinning and/or fertilization treatments.

biomass will therefore not result in increased light interception and photosynthetic production.

The strong volume growth response (up to 3.5 $m^3 ha^{-1} year^{-1}$, 50%) of the Scots pine stands to fertilization and the observed variation in response (Figs. 2 and 4) was expected given that previous Swedish studies (Nohrstedt, 1990, 2001; Pettersson, 1994; Pettersson and Högbom, 2004) and other studies (e.g. Saarsalmi and Mälkönen, 2001) have reported that Scots pine stands respond well to nitrogen fertilization. Several of the factors that were correlated with fertilizer response for our sites (initial basal area (+), initial volume (+), latitude (+), growth on control plots (−), SI (−) and temperature sum (−)) have also been correlated with response in previous studies (Pettersson, 1994). Unfortunately, more ecophysiologically based variables such as leaf area, foliar nutrient concentrations, or water deficits that have been strong predictors of fertilizer response in other areas, were not available for these sites. Therefore, it is impossible to make any mechanistic explanations and we are limited to speculations of causal effects instead.

This study provides over 30 years of response data to repeated fertilization with and without thinning, allowing an examination of long-term responses to repeated fertilization under two stocking conditions. On thinned Scots pine plots, significant fertilizer responses were found throughout the response period although they diminished with time (Figs. 7 and 9). The drop off in fertilizer response with time was principally due to a decrease in periodic annual increments on the thinned + fertilized plots. In contrast, fertilizer responses on non-thinned plots were maintained at high levels over the 30 years. It appears that the repeated thinnings may have reduced density on thinned plots, resulting in that stand leaf area levels that were less than required to maintain maximum growth rates even with fertilization.

In addition, the decline in fertilizer response over time on the thinned plots as compared to non-thinned plots also diminished the potential positive effects that thinning and fertilization could have had on shifting the diameter distributions to larger and potentially more valuable trees. Although the thinned-fertilized plots had slightly more volume in the largest diameter classes than nonthinned-fertilized plots, the volume in trees $\geqslant$24 cm was the same at final measurement for both treatments (Fig. 8). These findings suggest that repeated fertilization without thinning may maximize both stand volume and value, which might have implications for the operational fertilization in Sweden and Finland. It is quite possible that thinning and fertilization regimes other than the two imposed in this study might lead to even better outcomes.

As noted above, one possibility for the lower response on thinned versus non-thinned plots was that repeated thinning kept the stands in such a low relative density that they were never able to redevelop the stand leaf area to achieve the growth levels observed on non-thinned plots. Another possibility is that the nutrients added (N and P) were not the only elements limiting leaf area development and growth. Since the supply of 200 kg P ha^{-1} gave no extra growth response for Scots pine and Norway spruce in conjunction with N. Similar findings have been seen in experiments in Finland (Saarsalmi and Mälkönen, 2001; Saarsalmi and Tamminen, 2005) and P supply in mature stands of Scots pine can therefore not be recommended for operational fertilization in terms of production and economy.

5. Conclusions

(1) Scots pine stands showed significant positive fertilization responses for most characteristics assessed. Responses varied by site and this variation was explained in part to differences in SI (−) and latitude (+), indicating that poorer sites responded better. No response to fertilization was observed in Norway spruce stands and was most likely due to the high fertility of these sites.
(2) Volume growth response to fertilization was greater in non-thinned stands than thinned Scots pine stands. The larger responses in non-thinned stands were associated with incremental response being maintained through time in contrast with thinned stands where incremental response diminished with time. The greater fertilizer response in non-thinned stands was likely due to the additional volume growth on trees that were not removed via thinning and the inability of the remaining trees in thinned stands to fully regain maximum leaf area again.
(3) Fertilization and thinning effects were less than additive for volume growth but additive for diameter growth.
(4) Fertilization changed the stand structure and resulted in significant shifts in the diameter distributions to larger and potential more valuable trees. Periodic volume growth gains indicated a 6 year shift and final diameter gains indicated a 9 year shift.

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References

Albaugh, T.J., Allen, H.L., Dougherty, P.M., Kress, L.W., King, J.S., 1998. Leaf area and above-and belowground growth responses of loblolly pine to nutrient and water additions. For. Sci. 44 (2), 317–328.
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. For. Ecol. Manage. 119, 51–62.
Blevins, D.P., Prescott, C.E., Allen, H.L., Newsome, T.A., 2005. The effects of nutrition and density on growth, foliage biomass, and growth efficiency of high-density fire-origin lodgepole pine in central British Columbia. Can. J. For. Res. 35 (12), 2851–2859.
Brandel, G., 1990. Volume functions for individual trees; Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula pendula* & *Betula pubescens*). In: Swedish University of Agricultural Sciences, Department of Forest Yield Research. Report 26. 183 p. ISSN 0348-7636. (In Swedish with English summary.).
Cannell, M.G.R., 1989. Physiological basis of wood production: a review. Scand. J. For. Res. 4, 459–490.
Hägglund, B., 1972. Site index curves for Norway spruce in northern Sweden. In: Royal College of Forestry, Department of Forest Yield Research. Report 21. 298 p. (In Swedish with English summary.).
Hägglund, B., 1973. Site index curves for Norway spruce in southern Sweden. In: Royal College of Forestry, Department of Forest Yield Research. Report 24. 49 p. (In Swedish with English summary.).
Hägglund, B., 1974. Site index curves for Scots pine in Sweden. In: Royal College of Forestry, Department of Forest Yield Research. Report 31. 54 p. (In Swedish with English summary.).
Ingerslev, M., Mälkönen, E., Nilsen, P., Nohrstedt, H.-Ö., Óskarsson, H., Raulund-Rasmussen, K., 2001. Main findings and future challenges in forest nutritional research and management in the Nordic countries. Scand. J. For. Res. 16 (6), 488–501.
Jacobson, S., Nohrstedt, H.-Ö., 1993. Effects of repeated nitrogen supply on stem growth and nutrients in needles and soil. In: SkogForsk. Report 1. 36 p. ISSN 1103–6648.
Jacobson, S., 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. Can. J. For. Res. 31 (5), 899–909.
Karlsson, K., 1998. A strategy for reducing the number of sample trees when estimating stand volume on sample plots. In: Swedish University of Agricultural Sciences, Department of Forest Yield Research. Report 43. 18 p. ISSN 0348-7636.
Linder, S., 1987. Responses to water and nutrition in coniferous ecosystems. In: Schultze, E.-D., Zwölfer, H. (Eds.), Potentials and Limitations of Ecosystem Analysis. Ecol. Stud. 61, Springer Verlag, Berlin, Heidelberg, pp. 180–202.
Linder, S., Axelsson, B., 1982. Changes in carbon uptake and allocation patterns as a result of irrigation and fertilization in a young *Pinus sylvestris* stand. In: Waring, R.H. (Ed.), Carbon Uptake and Allocation in Subalpine Ecosystems as a Key to Management. For. Res. Lab., Oregon State Univ., USA, pp. 38–44.
Lindkvist, A., Kardell, Ö., Nordlund, C., 2011. Intensive forestry as progress or decay? An analysis of the debate about forest fertilization in Sweden, 1960–2010. Forests 2, 112–146.
Mäkinen, H., Isomäki, A., 2004. Thinning intensity and growth of Scots pine stands in Finland. For. Ecol. Manage. 201 (2–3), 311–325.
Näslund, M., 1936. Skogsförsöksanstaltens gallringsförsök i tallskog. Meddelanden från Statens skogsförsöksanstalt 29 (1), 74 (In Swedish).
Nilsson, U., Agestam, E., Ekö, P.-M., Elfving, B., Fahlvik, N., Johansson, U., Karlsson, K., Lundmark, T., Wallentin, C., 2010. Thinning of Scots pine and Norway spruce monocultures in Sweden – Effects of different thinning programmes on stand level gross- and net stem volume production. Stud. For. Suec. 219, 46.
Nilsson, U., Fahlvik, N., Johansson, U., Lundström, A., Rosvall, O., 2011. Simulation of the effect of intensive forest management on forest production in Sweden. Forests 2, 373–393.
Nohrstedt, H.-Ö., 1990. Effects of repeated nitrogen fertilization with different doses on soil properties in a *Pinus sylvestris* stand. Scand. J. For. Res. 5 (1–4), 3–15.
Nohrstedt, H.-Ö., 2001. Response of coniferous forest ecosystems on mineral soils to nutrient additions: a review of Swedish experiences. Scand. J. For. Res. 16 (6), 555–573.
Persson, O.A., Eriksson, H., Johansson, U., 1995. An attempt to predict long-term effects of atmospheric nitrogen deposition on the yield of Norway spruce stands (*Picea abies* (L.) Karst.) in southwestern Sweden. Plant Soil 168–169, 249–254.
Petterson, H., 1955. Barrskogens volymproduktion. Meddelande från Statens Skogsforskningsinstitut 45, 391 (In Swedish).
Pettersson, F., 1994. Predictive functions for calculating the total response in growth to nitrogen fertilization, duration and distribution over time. SkogForsk, Report 4. 34 p. ISSN 1103-6648.
Pettersson, F., Högbom, L., 2004. Long-term growth effects following forest nitrogen fertilization in Pinus sylvestris and *Picea abies* stands in Sweden. Scand. J. For. Res. 19 (4), 339–347.
Roberntz, P., Stockfors, J., 1998. Effects of elevated CO_2 concentration and nutrition on net photosynthesis, stomatal conductance and needle respiration of field-grown Norway spruce trees. Tree Physiol. 18, 233–241.

Saarsalmi, A., Mälkönen, E., 2001. Forest fertilization research in Finland: a literature review. Scand. J. For. Res. 16 (6), 514–535.
Saarsalmi, A., Tamminen, P., 2005. Boron, phosporus and nitrogen fertilization in Norway spruce stands suffering from growth disturbances. Silva Fennica 39 (3), 351–364.
Sampson, D.A., Allen, H.L., 1999. Regional influences of soil available water-holding capacity and climate, and leaf area index on simulated loblolly pine productivity. For. Ecol. Manage. 124 (1), 1–12.
Sundberg, M., 2010. Is boron necessary in Swedish forest fertilization? Swedish University of Agricultural Sciences, Southern Swedish Forest Research Centre. Final thesis 154. (In Swedish with English abstract.).
Tamm, C.O., 1991. Nitrogen in terrestrial ecosystems. Ecological Studies, vol. 81. Springer-Verlag, p. 115.
Tamm, C.O., Aronsson, A., Popovic, B., Flower-Ellis, J., 1999. Optimum nutrition and nitrogen saturation in Scots pine stands. Stud. For. Suec. 206, 126.
Valinger, E., 1990. Influence of thinning, fertilization, wind and tree size on the development of Scots pine trees. In: Swedish University of Agricultural Sciences, Deparment of Silviculture. Doctoral Thesis. 27 p. ISBN 91-576-4223-0. (In Swedish with English summary.).
Wallentin, C., 2007. Thinning of Norway Spruce. Acta Universitatis Agriculturae Sueciae, Doctoral Thesis 2007:29. Faculty of Forest Science, Southern Swedish Forest Research Centre, Alnarp, Sweden. 116 p. ISSN 1652-6880.