JOURNAL OF FOREST SCIENCE, *61*, 2015 (2): 72–79

doi: 10.17221/110/2014-JFS

Effect of repeated fertilization on stem growth in old stands of *Pinus sylvestris* in South East Norway

O. Haveraaen, L.H. Frivold

Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway

ABSTRACT: We studied effects of repeated nitrogen applications on the stem growth of mature Scots pine at four sites with the yield potential of around 3–4.5 $m^3 \cdot ha^{-1} \cdot yr^{-1}$. Treatments included control (0) and fertilization with ammonium nitrate at 100 and 200 N $kg \cdot ha^{-1}$. Some plots were supplied with corresponding doses of urea. Each treatment was normally performed five times at six or seven year intervals. At all sites fertilization was omitted in one block once or twice to study the response to delayed application. The plot size was 22 × 22 m with buffer zones of 4 m. Measurements were made on an inner plot, 14 × 14 m. Tree ring widths usually reached a maximum two to four years after fertilization, returning to about the original level after seven to ten years. Responses to ammonium nitrate were significant, and larger to 200 than to 100 N $kg \cdot ha^{-1}$. Responses to urea were significant at 200 N $kg \cdot ha^{-1}$only. The annual volume increment over the experimental period was 1.5 to 2.0 $m^3 \cdot ha^{-1}$ larger in plots provided with 200 N $kg \cdot ha^{-1}$ than in control plots, or even more as the buffer zones of 4 m did not completely prevent tree roots from growing into neighbouring plots.

Keywords: nitrogen; Scots pine; tree ring widths; volume increment

Available nitrogen is a major limiting factor for growth in many boreal coniferous forests in areas far from sources of nitrogen pollution (Tamm 1991; Högberg et al. 2006). Potential benefits from the application of nitrogen fertilizers include higher increment of commercial timber, increased biomass for replacement of fossil fuels, and – depending on interactions between litter production and activity of soil microbes – increased carbon accumulation in soil (Jandl et al. 2007; Hyvönen et al. 2008; Saarsalmi et al. 2014). In Norwegian forestry, fertilization commenced in the 1960s, mainly to increase revenues of forest owners. Results from early experiments with agricultural fertilizers in conifer stands appeared very promising (Brantseg 1967a), and the chemical industry developed fertilizers specially designed for use in forestry. Forest fertilization was at its peak in 1966, when fertilizers were applied on about 0.1 per cent of the country's productive forest area. However, it soon turned out that the high expectations of growth increases were not always met. According to forestry statistics provided by Statistics Norway, the recorded annual fertilized area rapidly diminished and is now quite insignificant.

To provide a fast return on investment, it was recommended to boost the increment of mature forest stands before the final cut (Brantseg 1962). This was usually done by performing a single fertilization and keeping the stand until the width of growth rings had returned to a normal level, which usually takes seven to eight years in Scots pine (*Pinus sylvestris* L.) and nine to ten years in Norway spruce (*Picea abies* [L.] Karst.) (Brantseg et al. 1970; Pettersson, Högbom 2004). The effects of repeated fertilization in boreal coniferous forests in Fennoscandia have been widely studied in stands prior to full maturity (Nilsen 2001; Nohrstedt 2001; Saarsalmi, Mälkönen 2001; Bergh et al. 2014; Saarsalmi et al. 2014). These studies include fertilizer application both at intervals (Kukkola, Saramäki 1983; Mälkönen, Kukkola 1991; Jacobson, Pettersson 2001, 2010; Pettersson, Högbom 2004; Hyvönen et al. 2008) and annually (Tamm 1991; Nilsen, Abrahamsen 2003; Högberg et al. 2006).

Less is known about repeated applications of fertilizers in old, mature stands of Scots pine (aged 100+), where boosting the increment may still be an option in the context of carbon sequestration and for producing large trees. Scots pine is a long-lived species that is able to respond to improved growth conditions from thinning at ages far beyond normal commercial maturity (Martínez-Vilalta et al. 2007). This suggests that old pine stands might also be able to respond to fertilization. On the other hand, ample supplies of nitrogen may at least theoretically lead to deficiencies of other nutrient elements (Nilsen, Abrahamsen 2003; Högberg et al. 2006). The objective of our study was to investigate stem growth in old Scots pine stands treated with repeated fertilizations with nitrogen in various forms, doses and intervals.

MATERIAL AND METHODS

Sites, treatments and field work. In the 1960s, a number of forest fertilization experiments were established in two municipalities in South East Norway: Elverum and Stor-Elvdal (61°N, 11°E). Most of them were concluded after one or two fertilizations and published in local journals.

However, four experimental sites, established in old pine forests in 1964/65, were retained for a long-term experiment with several repeated fertilizations (Table 1).

Site 3 has sandy soil while the three others have glacial till. The soil is particularly shallow in parts of site 18. Data provided by the Norwegian Meteorological Institute for the normal period 1961–1990 show a mean temperature in June–September of 11.7°C at Koppang in Stor-Elvdal (61.62°N, 10.90°E; 303 m a.s.l.) and an estimated temperature of 12.7°C at Elverum (60.92°N, 11.60°E; 190 m a.s.l.). Mean annual precipitation was about 600 mm. Estimated background nitrogen deposition in 1978–2001 was around 6 $kg \cdot ha^{-1} \cdot yr^{-1}$ (Hole, Tørseth 2002).

The vegetation types (Fremstad 1997) of the four sites were *Cladonia* and *Vaccinium vitis-ideae* woodlands. Prior to the first fertilization, age/height site indices ranged from F10 to F13 by the Norwegian site class system (Tveite, Braastad 1981), indicating a mean yield potential of 3 to 4.5 $m^3 \cdot ha^{-1} \cdot yr^{-1}$. Total age ranged from 106 to 118 years, implying that the stands at all sites had reached usual commercial maturity. Stand density was around 500 stems per hectare.

All four experimental sites had randomized block designs. Each site comprised three or four blocks, all with the three treatments: control (0) and fertilization with ammonium nitrate (AN) at 100 N $kg \cdot ha^{-1}$ and 200 N $kg \cdot ha^{-1}$. Fertilizers included commercial calcium ammonium nitrate ("Kalkammonsalpeter", Norsk Hydro AS, 26% N) prior to 1977, and commercial ammonium nitrate ("Skog-An", Norsk Hydro AS, 34.5% N) from 1977 onwards when the former brand was withdrawn from the market. Some blocks also included plots that were fertilized with urea (UR), 46% N, at 100 and/or 200 N $kg \cdot ha^{-1}$. All fertilizers were spread manually and evenly. The same treatment was normally carried out five times at six or seven year intervals. However, the application of fertilizers was omitted once or twice in one block at all sites to study reactions to delayed fertilization (Table 2).

Each treatment plot measured 22 × 22 m divided by 4 m wide buffer zones and data were collected in an inner plot of 14 × 14 m. At the start of the experiment in 1964 (1965 at site 18), each tree was given a permanent number. For each plot, six permanent sample trees were randomly selected from the list of tree numbers. Diameter and bark thickness at breast height were measured on all trees; tree heights were measured with a hypsometer on the sample trees. Measurements were repeated in the autumns of 1969, 1976, 1983, and 2001.

All sites were located in private forests, and over the years some of the owners made interventions that were not a part of our experiment. Site 3 and 18 remained intact during the entire experimental period. In 1977, site 9 became subject to a slight intermediate cutting that reduced the basal area by about 10%. Shortly after the 1990 fertilizations, owners of site 9 and 11 removed about half of the standing crop (Table 3), making the two sites unsuitable for analyses of further development.

Lab work and calculations. Cores of minimally 25 annual rings were collected from all trees at all

Table 1. Site and stand characteristics of study plots

Site	Blocks	Lat. [°N]	Long. [°E]	Elevation	Vegetation type[1]	Age at breast hight 1.3 m	Site index	Site productivity ($m^3 \cdot ha^{-1} \cdot yr^{-1}$)	Standing volume ($m^3 \cdot ha^{-1}$)
3	3	60.96	11.49	200	A1a–A2a	105	F11	3.5	165
9	3	61.46	11.02	320	A2a	95	F13	4.5	185
11	4	61.45	11.03	320	A2a	105	F12	4.0	185
18	4	60.97	11.48	220	A1a	105	F10	3.0	175

[1]A1a – *Cladonia* woodland, subtype *Cladonia-Pinus sylvestris*; A2a – *Vaccinium* woodland, subtype *Vaccinium vitis-idaea*

Table 2. Treatment programme of the experiment

Site	Block	Fertilizers (N in kg·ha^{-1})					Fertilized (yr)				
		control	AN		UR						
3	I–II	0	100	200			1964	1970	1977	1984	1990
	III	0	100	200			1964		1977	1984	1990
9	I–II	0	100	200	100		1964	1970	1977	1984	1990
	III	0	100	200	100	200	1964			1984	1990
11	I–III	0	100	200	100	200	1964	1970	1977	1984	1990
	IV	0	100	200	100	200	1964		1977	1984	1990
18	I–III	0	100	200			1965	1971	1978	1985	1990
	IV	0	100	200			1965			1985	1990

N was applied to plots either as AN (commercial calcium ammonium nitrate before 1977 and commercial ammonium nitrate thereafter) or as UR (urea). Site 9 and 11 became subject to severe, unintended interventions shortly after the 1990 treatment

sites in 1976 and in 1983 from all trees at site 11 and from all remaining trees at site 9. In 2001, we collected cores of minimum 50 annual rings from each permanent sample tree at sites 3 and 18 and from each remaining tree at sites 9 and 11. Cores were analysed with a micrometre in the laboratory and we used the annual ring widths for calculating the development of diameter under bark, basal area, and basal area increment of each cored tree.

We assumed that the ratio between the basal areas of sample and non-sample trees remained constant if no thinning was performed. This was relevant through the entire experimental period at sites 3 and 18, for which we used this ratio for simulating the annual development of non-cored (non-sample) trees in the period 1984 to 2001. For site 9, where a few trees had been removed in 1977 presumably at random, we simulated the annual development of missing trees for the period 1977–2001 by use of the ratio between the basal areas of removed and remaining trees derived from the 1976 measurements. We could not assume that the trees removed from sites 9 and 11 in 1990/91 had been selected at random; the last coring of these trees had been made in 1983. To simulate their development from 1984 through 1989, we identified the trend of differences in the growth rate from 1976 to 1983 between trees removed in 1990/1991 and remaining trees, and prolonged the development trends of the basal area ratios up to and including 1989.

At the final measurement in 2001, all cored trees were felled in the control plots and in the plots fertilized with 200 kg·ha^{-1} of N as ammonium nitrate, and we collected a stem disk at every four meters from the lower part of the stem and at every two meters from the upper part of the stem. We estimated the height development of the sampled trees by analysing the disks, and made a separate height-diameter function for each plot to determine heights of non-sampled trees. We calculated the stem volume of each tree using the height-diameter based stem volume functions for Scots pine in Norway (Brantseg 1967b). Finally, we aggregated all empirical and simulated data to values per plot and per hectare at given times.

Calculations, simulations and statistical analyses were performed in MS Excel. Data are assumed to have a normal distribution; diameters of all callipered trees at the start of the experiment had the

Table 3. Number of trees per hectare at each site, and the range of the number of trees and cored trees per inner plot (196 m^2)

Year of treatment	Recorded specimen	Area unit	Site			
			3	9	11	18
1964/65	standing trees	hectare	534	536	477	468
1964/65	standing trees	plot	9–12	8–13	9–10	8–11
1976	cored trees	plot	9–12	8–13	9–10	8–11
1977	trees after thinning	plot		8–10		
1983	cored trees	plot		8–10	9–10	
1990/91	trees after thinning	plot		5–6	4–6	
2001	standing trees	hectare	534	268	260	468
2001	standing trees	plot	9–12	5–6	4–6	8–11
2001	cored trees	plot	6	5–6	4–6	6

sites 9 and 11 were thinned unintendedly and their development after 1990 is left out from the experiment skewness of –0.10 and excess kurtosis of –0.34 (n = 559). We used a simple F-test for differences in basal area increment between periods. Student's t-test was used for differences between fertilizers from the first fertilization to six years after the final fertilization; 1989 for sites 9 and 11 and 1995 for sites 3 and 18. The level of significance is 0.05.

All data regarding basal area and volume were under bark.

RESULTS

Tree ring widths increased strongly one year after the application of fertilizer, reaching a maximum after three or four years, after which they rapidly decreased and got close to the original level at the time of the next application (Fig. 1). In most cases this pattern repeated itself after each new application. Trees reacted positively to repeated fertilizations even if the time span between them was up to 20 years (Fig. 1b, 1d, 1f, and 1h).

It is noted that the graphs for control plots are typically undulating, with ups and downs that coincide fairly well in time with those of fertilized plots. We investigated if this effect was related to weather factors, using site 18, block I–III (Fig. 1g) as a sample. Mean monthly values of temperature and precipitation during the growing season were fairly equal for years of maximum and minimum annual tree ring widths; p-values did not indicate any significant differences between them (Table 4).

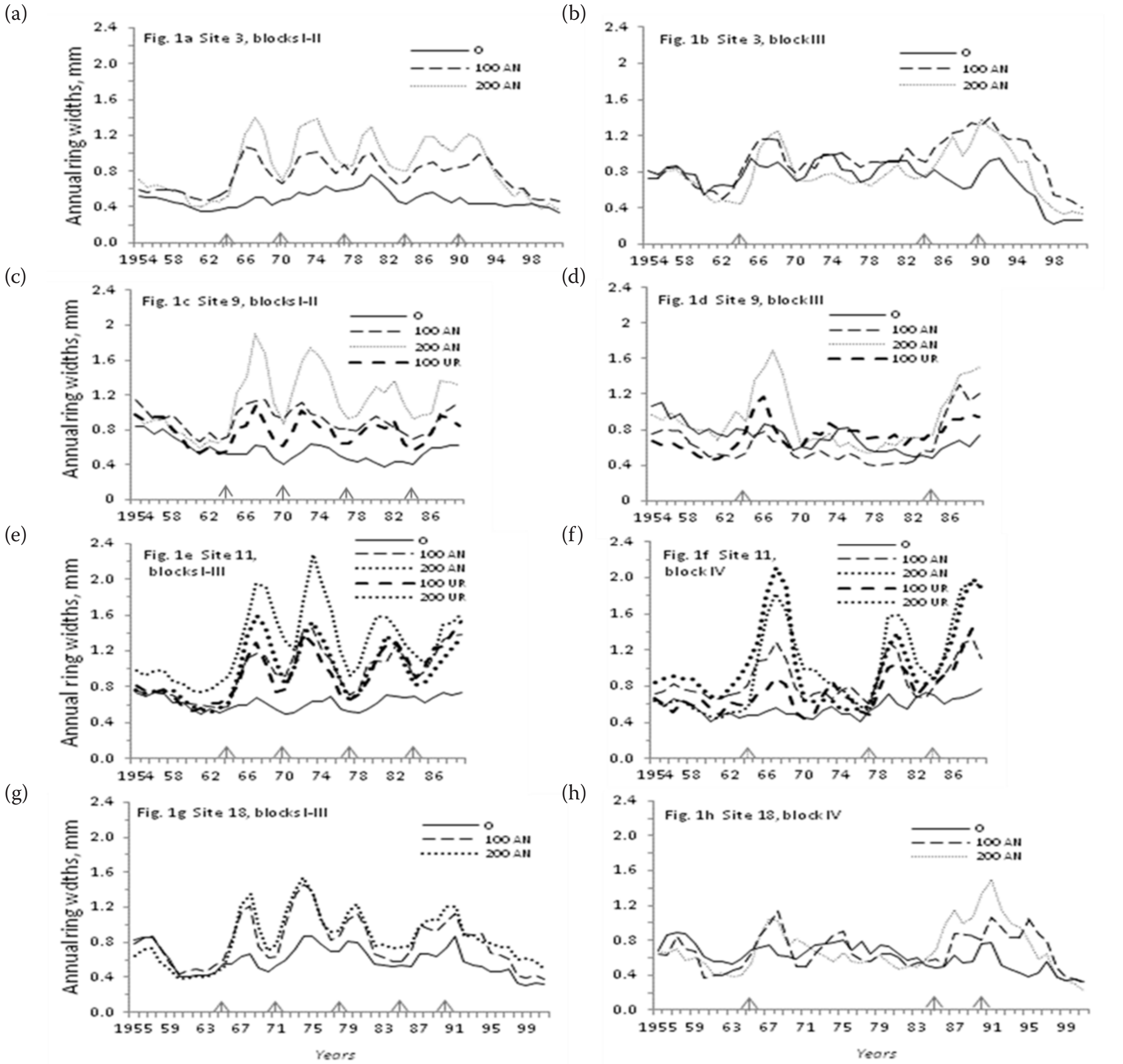

Fig. 1. Annual tree ring widths over years

arrow – years of fertilizer application, zero – control; 100, 200 AN – 100 kg·ha^{-1} and 200 kg·ha^{-1}of nitrogen applied as ammonium nitrate, respectively; and 100, 200 UR – 100 kg·ha^{-1} and 200 kg·ha^{-1} of nitrogen applied as urea, respectively

Table 4. Monthly summer temperature and precipitation during the experimental period for years when annual tree rings widths at blocks I–III of site 18 were at a maximum (1966–68, 1972–74, 1979–81, 1987–93) and at a minimum (1969–71, 1977–97, 1982–84, 1993–96), cf. Fig. 1g

		Annual tree ring width	Mean values			
			May	June	July	August
Temperature – daily mean (°C)		at a max	7.9	12.8	14.2	12.3
		at a min	8.0	12.3	14.5	12.7
Precipitation – sum (mm)		at a max	57	87	97	84
		at a min	65	79	89	77
P-value	temperature		0.701	0.308	0.561	0.444
	precipitation		0.494	0.664	0.638	0.716

weather data provided by the Norwegian Meteorological Institute, *P*-values based on monthly means for the years with maximum ring widths versus the years with minimum ring widths

The mean annual basal area increment of the last ten years prior to the initial application of fertilizer ranged from 0.14 to 0.23 $m^2 \cdot ha^{-1}$. Nitrogen applied as ammonium nitrate produced effects on basal area increment for more than six years after the final fertilization, ranging from 0.08 to 0.12 $m^2 \cdot ha^{-1} \cdot yr^{-1}$ for 100 $kg \cdot ha^{-1}$ of N, and from 0.12 to 0.18 $m^2 \cdot ha^{-1} \cdot yr^{-1}$ for 200 $kg \cdot ha^{-1}$ of N. Urea produced similar or slightly smaller effects with the same amount of N. There were no significant differences in fertilization effects between the particular time periods from 1964/65 through 1989/95.

For the period between initial fertilization and five or six years after final fertilization, differences in basal area increment between control plots and corresponding plots fertilized with 100 AN, 200 AN, and 200 UR were statistically significant (Table 5). *P*-values from tests of other relations showed that only the difference between 100 AN and 200 AN was significant.

The annual volume increment at given periods generally showed a higher yield with increasing amount of fertilizer (Fig. 2).

The increase from the application of 200 $kg \cdot ha^{-1}$ of N in the form of ammonium nitrate was between 1.5 and 2.0 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in relation to control plots.

DISCUSSION AND CONCLUSION

The experiment provides empirical data for a considerable span of time; up to 38 years after the first application of nitrogen. The data on annual tree ring widths (Fig. 1) confirm that Scots pine at poor and medium sites, with mean yield potentials of 3.0–4.5 $m^3 \cdot ha^{-1}$, can respond to improved nutrient conditions at fairly advanced ages, 100–150 years. Responses to the reapplication of fertilizers were sustained. This is in accordance with Jacobson and Pettersson (2001), who found but a few examples of declining responses to repeated N fertilizations and suggested damage to fine root development and mycorrhiza from high doses of N fertilization as a reason for such cases.

Fig. 1 also indicates that applying fertilizers at shorter intervals, like five years instead of seven, would produce timber with less variation in annual ring width.

The co-variation between ups and downs in the widths of annual rings in fertilized plots and control plots is apparent (Fig. 1). Further, Fig. 2a and 2d clearly show that the volume increment

Table 5. *P*-values from paired difference Student's *t*-test of mean annual basal area increments of the period from the first fertilizer application in 1964/65 through 1989/1995, five or six years after the last fertilizer application (cf. Table 2)

Treatment	No. of blocks			
	10	10	5	3
	100 AN	200 AN	100 UR	200 UR
0 vs 100 AN, 200 AN	0.001*	< 0.001*		
0 vs 100 UR, 200 UR			0.051	0.017*
100 AN vs 200 AN		0.005*		
100 UR vs 200 UR				0.452
100 AN vs 100 UR			0.397	
200 AN vs 200 UR				0.366

AN – fertilization with ammonium nitrate, UR – fertilization with urea; 0, 100 and 200 – rates of nitrogen per application in $kg \cdot ha^{-1}$; *significant *P*-values

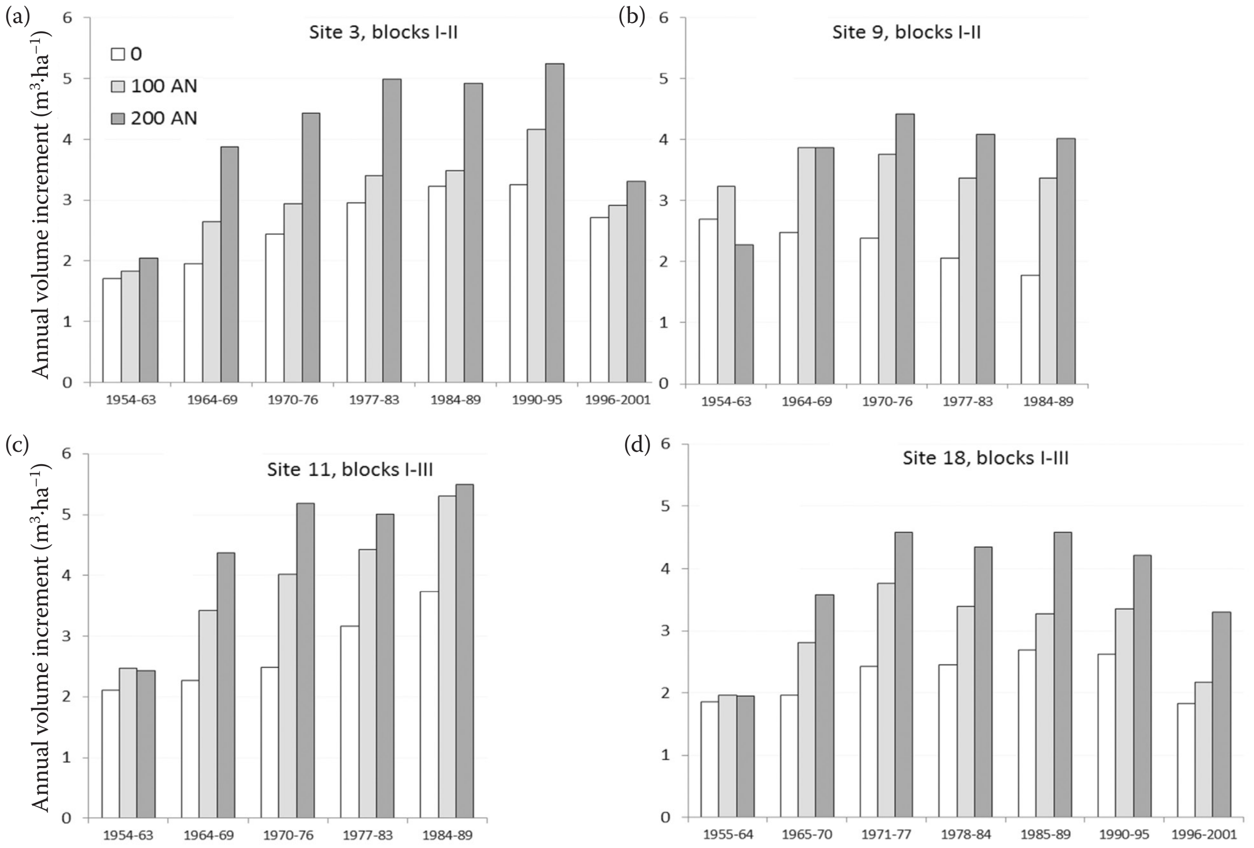

Fig. 2. Mean annual volume increment in $m^3 \cdot ha^{-1}$ at different periods, at control plots (0, white bars) and plots fertilized at regular intervals with 100 and 200 $kg \cdot ha^{-1}$ of N in the form of ammonium nitrate (100 AN, light grey bars; 200 AN, dark grey bars) (a–d); fertilizers were applied in 1964, 1970, 1977, 1984 and 1990 (at site 18 in 1965, 1971, 1978, 1985 and 1990); reactions to the 1990 applications at site 9 and 11 are left out because of subsequent non-experimental interventions

also decreased in the period 1996–2001 in the control plots, 6–12 years after the last fertilization. The non-significant differences in monthly mean rainfall and temperature between years with wide and narrow annual rings in the experimental period (Table 4) suggest that other factors were critical for producing the co-variation. Laitakari (1929) identified up to 17 m long roots in middle-aged Scots pine and roots were generally longer at poor sites than at rich sites. Apparently, our buffer zones of 4 m between all plots were not wide enough to prevent tree roots from growing into the neighbouring treatment zone. Further, needles from N-fertilized pines contain more nitrogen than needles from non-fertilized pines on corresponding sites (Miller, Miller 1976; Högberg et al. 2006; Jacobson, Pettersson 2010). In the long run, litterfall from trees on fertilized plots dispersed by the wind will also contribute to even out differences between treatments. Hence, fertilization in neighbouring plots is the most likely reason for the co-variation. Such even-out effects have probably influenced the 100 N plots as well. This indicates that the real fertilization effects in our experiment were even greater than shown by the data.

The significant effects of fertilization with ammonium nitrate on basal area increment, whether the dose per application was 100 or 200 N $kg \cdot ha^{-1}$, and the somewhat poorer responses to urea, are supported by numerous experiments in less aged stands of Scots pine in Fennoscandia (Nilsen 2001; Nohrstedt 2001; Saarsalmi, Mälkönen 2001). There is a risk of N volatilization after the application of urea under certain conditions of moisture, temperature and pH at the soil and vegetation surface (Derome 1979). This explains why the responses to urea vary more than with other N fertilizers (Gustavsen, Lipas 1975) and are significantly lower than with ammonium nitrate (Kukkola, Saramäki 1983). The application of ammonium nitrate may lead to leaching of NO_3 if fertilization is immediately followed by heavy rain, but such heavy rainfalls are not common in early summer in South East Norway.

Studies by Pettersson and Högbom (2004) indicate that nitrogen fertilization does not affect the taper of trees in mature stands to any degree of practical importance. The relative increases in volume increments, of approximately 20–50% (Fig. 2), can largely compare with responses to repeated nitrogen fertilizations in less aged stands of Scots pine (Kukkola, Saramäki 1983; Mälkönen, Kukkola 1991; Pettersson, Högbom 2004; Jacobsson, Petterson 2010; Saarsalmi et al. 2014). Bergh et al. (2014) found a declining response to repeated fertilizations in thinned stands compared with non-thinned stands. The intermediate cutting at our site 9 was probably too slight to demonstrate such an effect.

We did not adjust the results for differences between plots in the ten-year period prior to fertilization, nor for the unintended fertilization effects on adjacent control plots. For future experiments, we would recommend a layout with larger plots and wider buffer zones.

In conclusion, the experiment showed that more than 100-years-old boreal Scots pine stands of low and medium site quality can adequately respond in growth to applications of nitrogen fertilizers repeated at 5–20 year intervals. The responses were greater to 200 N kg· ha^{-1} than to 100 N kg·ha^{-1}. Ammonium nitrate was a more reliable fertilizer than urea.

References

Bergh J., Nilsson U., Allen H.L., Johansson U., Fahlvik N. (2014): Long-term responses of Scots pine and Norway spruce stands in Sweden to repeated fertilization and thinning. Forest Ecology and Management, 320: 118–128.

Braastad H. (1980): Tilvekstmodellprogram for furu. Summary: Growth model computer program for *Pinus sylvestris*. Meddelelser fra Norsk institutt for skogforskning, 35: 265–359.

Brantseg A. (1962): Gjødsling i skog. In: Børset O. (ed.): Skogbruksboka. Vol. 2: Skogskjøtsel. Oslo, Skogforlaget: 413–416.

Brantseg A. (1967a): Avdeling for skogbehandling og skogproduksjon. Summary: Division of Forest Management and Yield Studies. Meddelelser fra Det norske Skogforsøksvesen, 24: 151–212.

Brantseg A. (1967b): Furu sønnafjells. Kubering av stående skog. Funksjoner og tabeller. Summary: Volume functions and tables for Scots pine, South East Norway. Meddelelser fra Det norske Skogforsøksvesen, 22: 695–739.

Brantseg, A., Braastad, H., Brekka, A. (1970): Gjødslingsforsøk i gran- og furuskog. Summary: Fertilizer experiments in stands of *Picea abies* and *Pinus silvestris*. Meddelelser fra Det norske skogforsøksvesen, 27: 537–607.

Derome J.R.M. (1979): Urea hydrolysis and ammonia volatilization from urea pellets spread on top of the litter layer. Communicationes Instituti Forestalis Fenniae, 92: 1–22.

Fremstad E. (1997): Vegetasjonstyper i Norge. Summary: Vegetation types of Norway. NINA-Temahefte, 12: 1–279.

Gustavsen H.G., Lipas E. (1975): Lannoituksella saatavan kasvunlisaeyksen riippuvuus annetusta typpimaeaeraestae. Summary: Effect of nitrogen dosage on fertilizer response. Folia Forestalia, 246: 1–279.

Högberg P., Fan H., Quist M., Binkley D., Tamm C.O. (2006): Tree growth and acidification in response to 30 years of experimental nitrogen loading on boreal forest. Global Change Biology, 12: 489–499.

Hole L.R., Tørseth K. (2002): Deposition of Major Inorganic Compounds in Norway 1978–1982 and 1997–2001: Status and Trends. Kjeller, Norwegian Institute for Air Research: 73.

Hyvönen R., Persson T., Andersson S., Olsson B., Ågren G.I., Linder S. (2008): Impact of long-term nitrogen addition on carbon stocks in trees and soils in Northern Europe. Biogeochemistry, 89: 121–137.

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. Canadian Journal of Forest Research, 31: 899–909.

Jacobson S., Pettersson F. (2010): An assessment of different fertilization regimes in three boreal coniferous stands. Silva Fennica, 44: 815–827.

Jandl R., Lindner M., Vesterdal L., Bauwens B., Baritz R., Hagedorn F., Johnson D.W., Minkkinen K., Byrne K.A. (2007): How strongly can forest management influence soil carbon sequestration? Geoderma, 137: 253–268.

Kukkola M., Saramäki J. (1983): Growth response in repeatedly fertilized pine and spruce stands on mineral soils. Communicationes Instituti Forestalis Fenniae, 114: 1–55.

Laitakari E. (1929): Männyn juuristo: morfologinen tutkimus. Summary: The root system of pine (*Pinus sylvestris*): A morphological investigation. Acta Forestalia Fennica, 33: 1–380.

Mälkönen E., Kukkola M. (1991): Effects of long-term fertilization on the biomass production and nutrient status of Scots pine stands. Fertilizer Research, 27: 113–127.

Martínez-Vilalta J., Vanderklein D., Mencuccini M. (2007): Tree height and age-related decline in growth in Scots pine (*Pinus sylvestris* L.). Oecologia, 150: 529–544.

Miller H.G., Miller J.D. (1976): Analysis of needle fall as a means of assessing nitrogen status in pine. Forestry, 40: 57–61.

Nilsen P. (2001): Fertilization experiments on forest mineral soils: a review of the Norwegian results. Scandinavian Journal of Forest Research, 16: 541–546.

Nilsen P., 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.

Pettersson F., Högbom L. (2004): Long-term growth effects following forest nitrogen fertilization in *Pinus sylvestris* and *Picea abies* stands in Sweden. Scandinavian Journal of Forest Research, 19: 339–347.

Saarsalmi A., Mälkönen E. (2001): Forest fertilization research in Finland: a literature review. Scandinavian Journal of Forest Research, 16: 514–535.

Saarsalmi A., Tamminen P., Kukkola M. (2014): Effects of long-term fertilisation on soil properties in Scots pine and Norway spruce stands. Silva Fennica, 48: 1–19.

Tamm C.O. (1991): Nitrogen in terrestrial ecosystems: questions of productivity, vegetational changes, and ecosystem stability. Ecological Studies 81. Berlin-Heidelberg, Springer-Verlag: 115.

Tveite B., Braastad H. (1981): Bonitering for gran, furu og bjørk. Norsk Skogbruk, 27: 17–22.

Received for publication October 24, 2014
Accepted after corrections December 10, 2014

Corresponding author:

Dr. Ph. Oddvar Haveraaen, Norwegian University of Life Sciences, Department of Ecology and Natural Resource Management, P.O. Box 5003, NO-1432 Ås, Norway; e-mail oddvar.haveraaen@nmbu.no