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Effects of Frequency of Fertilisation on Production, Foliar Chemistry and Nutrient Leaching in Young Norway Spruce Stands in Sweden

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There is a great need to increase the production in Swedish forests to meet future demand from the forest industry and the bio-energy sector. One option to increase the production is to supply nutrients to young stands of Norway spruce. For the practical application it is important to develop and optimise fertilisation regimes in terms of production, economy and leaching of nutrients. The frequency of fertilisation is one important variable in the fertilisation regime, and this study aimed to study effects of different fertilisation frequencies on production and leaching of nitrogen. In 2001, five field experiments were established in southern, central and northern Sweden. Young stands of Norway spruce were fertilised every year, every second year and every third year. In addition, fertilisation with sludge pellets and wood-ash combined with nitrogen was investigated. The current annual increment after five years of treatment was significantly larger in fertilised than in unfertilised treatments. The difference in production between fertilisation every year and every second year was insignificant, while fertilisation every third year resulted in lower production. Sludge pellets and wood-ash fertilisation gave significantly lower production than fertilisation every second year even though approximately the same amount of nitrogen was applied. There was relatively little leaching of nitrate to ground water in all treatments; 0.6–1 kg N ha^{-1} a^{-1} from plots with fertilisation every year or every second year; and 2.7 kg N ha^{-1} a^{-1} from plots with fertilisation every third year. Most of the leaching was after the first fertilisation, in all treatments at all sites.

Keywords sludge, wood-ash, boreal, N, P, K
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1 Introduction

The forest industry in Sweden consumes ca 100 million m^3 of wood every year, while the practicable harvest volume is only ca 80 million m^3 (Kempe 2005). The need to reduce emissions from fossil fuel will further increase the requirement for forest products for bio-energy purposes in the future. Other claims and restrictions on the forest resource are those of ecotourism, recreation, wildlife, biological diversity and the need for more forest land to be set aside for conservation. More wood must therefore be produced from a continuously shrinking area.

Improved silvicultural methods currently available probably enable the total annual increment in Sweden to be increased by 10–15% (Rosvall et al. 2004). The uptake of and demand for nutrients is highest in young stands, in which the nutrient-rich foliage mass must be built up (Miller 1988). It can take several decades before the canopies of boreal and cold-temperate Norway spruce stands are fully closed, if ever (Bonan 1993). Growth and development of needles in boreal and cold-temperate coniferous forests can be considerably increased by frequent fertilisation of young stands (Bergh et al. 1999). Fertilisation of young stands not only increases production, it also shortens the initial phase of low production at the beginning of the rotation period (Bergh et al. 2005). The demand for nutrients decreases when canopies start to close and the horizontal expansion of the crowns ceases. The decreased demand is also an effect of increased shading in closed canopies, which causes increased mortality of needles (see van Cleve et al. 1991 and references therein) and recirculation of nutrients through retranslocation of nutrients and mineralization of litter (Berg and Staaf 1981). This does not necessarily mean that the effect of fertilisation is less or uncertain in middle- and old-aged stands, but the amount and frequency of fertilisation can probably be considerably reduced.

In earlier experiments, nutrients were added every year in young stands of Norway spruce (Linder 1995, Bergh et al. 1999). This interval must in practical forestry be extended to every second or every third year for economic reasons (Nilsson and Fahlvik 2006), but it is uncertain if it is possible to achieve the same production with 2- or 3-year intervals as with fertilisation every year. Fertilisation every second year and third year probably requires a larger supply of nutrient, in order to achieve the same production. Increased amounts applied at one time might increase the risk of leaching of nutrients to groundwater.

Waste products such as sludge and wood-ash can be used in intensively cultivated forests as a supplement or replacement for conventional fertilisers. Sludge pellets are a product with a low water content, which are easy to handle and contains no disease-causing organisms (Hånell and Magnusson 1996). Sludge or wood-ash alone results in a small or non-existent effect on production, because of the low nitrogen content (Sikström et al. 2001, Magnusson 2006). Sludge and wood-ash supplemented with nitrogen (N) and/or phosphorus (P), potassium (K) and magnesium (Mg) would probably increase the effect and hence the interest from the forestry sector.

To test how different fertilisation frequencies influence production of stem-wood and nutrient leaching to groundwater, five field experiments were established in 2001. Effects of practical application of wood ash and sludge were also studied. In the present paper, results from these five sites on foliar chemistry, nutrient leaching and production of stem wood during the first five years are presented. The tested hypotheses are:

1) Volume production is negatively correlated to decreased frequency of fertilisation.
2) Leaching of nutrients is positively correlated to decreased fertilisation frequency with higher N-doses.
3) Sludge and wood-ash with added nitrogen has the same effect on production as fertilisation with mineral nutrients, provided that the same amount of nitrogen is added.

2 Material and Methods

2.1 Site and Stand Characteristics

The experimental sites are located in south-eastern (Ebbegärde), central (Mölnbacka, Grängshammar, Valbo) and northern (Bräcke) Sweden (Table 1). All were planted with Norway spruce (*Picea abies* (L.) Karst.) of different provenances on former forest land (see Table 1 for detailed information). Bräcke was planted in 1983 and Ebbegärde in 1991, while the other sites were planted in 1988. The length of the vegetation period ranges from ca 155 days for Bräcke to 200 days for Ebbegärde, while the amount of precipitation ranges from 500 mm for Ebbegärde to ca 800 mm for Mölnbacka.

The soil at Bräcke is a podzol (FAO, 1988) on a coarse shallow glacial till with frequent stones and boulders. At Valbo and Grängshammar the soil is podzol on a sandy glacial till, while at Mölnbacka it is clay silt sediments. At Ebbegärde the soil is podzol on a coarse sandy glacial till. The initial standing volume varied between 5.1 m^3 ha^{-1} for Valbo to 11.8 for Bräcke and Grängshammar. Site index varied between G22 for Bräcke to G29 for Ebbegärde (Table 1), according to Hägglund and Lundmark (1977).

2.2 Experimental Design

The treatments were (C) control with no treatment, (F1) fertilisation every year, (F2) fertilisation every second year, (F3) fertilisation every third year, (A/NP) wood-ash combined with N and P, and (S/N) sludge pellets combined with N (see Fig. 1 for further information). Ash and sludge were supplied every fifth year in A/NP and S/N-treatment, while N supply followed the F2-treatment (see Fig. 1 for further information). There were no treatments with wood-ash and sludge pellets in Bräcke, but a treatment was added with a larger supply of nutrients every year compared to F1 and without restrictions on nutrient leaching (Maximum). Treatments were replicated three times and each replicate consisted of two 50 × 50 m plots, except for Ebbegärde and Bräcke, where the plot size was 40 × 40 m. Each plot contained a net plot (1000 m^2) surrounded by a buffer zone. The solid fertiliser was applied in May. The total area of each site was ca 4.5 ha at Mölnbacka, Grängshammar and Valbo, while it was ca 3 ha for Ebbegärde and Bräcke.

2.3 Fertilisation Regimes

The amount of N supplied on each occasion was determined from needle N-concentration and monitoring of N in the soil water. The supply of other macro- and micronutrients was adjusted to initial target ratios of each element to N (Linder 1995). If the ratio of a nutrient element to N was below its target value, an extra amount was added on the next occasion. Threshold leaf concentrations and proportions of the essential nutrient elements for the attainment of unlimited growth were determined in earlier laboratory (Ericsson and Kähr 1993) and field experiments (Linder 1990, Stockfors et al. 1997). These proportions correspond with recommendations given by Braekke (1994). A main aim of the fertilisation regimes is to avoid N leaching to ground water. If a significant amount of N is detected in the soil water below the rooting zone, the supply must be reduced next time. This means that the F2- and

Table 1. Latitude, longitude, altitude, climate and site index (dominant height at 100 years) for the five different sites.

Experimental site	Latitude	Longitude	m.a.s.l. (m)	Precipitation (mm a–1)	Runoff (mm a–1)	Vegetation period (days)	Mean annual temperature (ºC)(	Site index H100)
Ebbegärde	56º53’N	16º15’E	35	500	150	200	6.5	G29
Mölnbacka	59º36’N	13º34’E	90	800	250	180	5	G26
Grängshammar	60º21’N	15º31’E	200	700	300	170	4	G24
Valbo	60º34’N	17º11’E	40	700	300	175	5	G24
Bräcke	62º43’N	15º51’E	390	650	300	155	2	G22

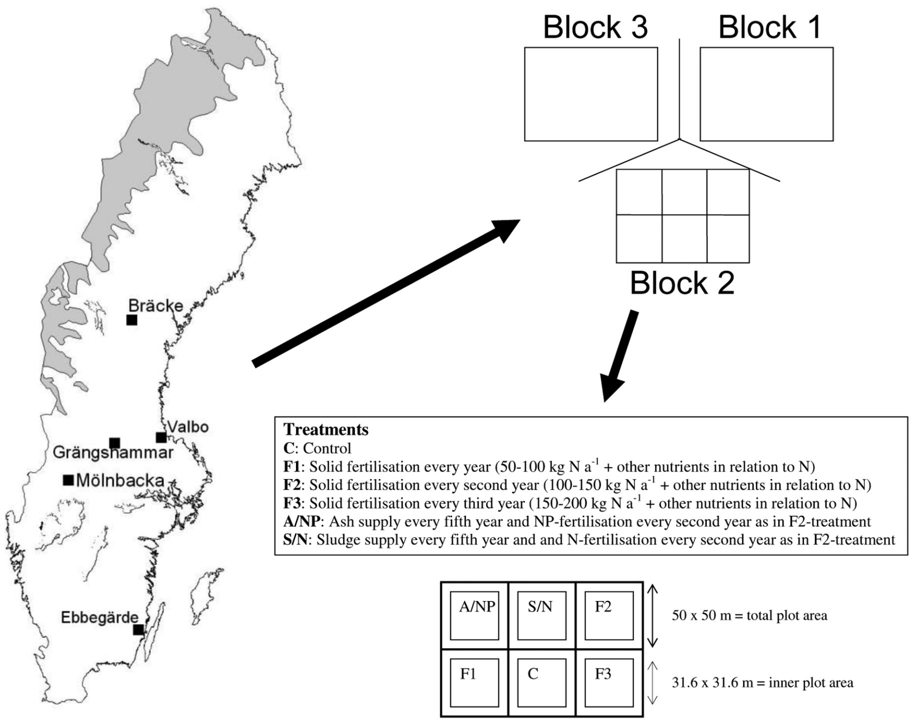

Fig. 1. Location and experimental design for the different sites in the fertilisation frequency experiment in young stands of Norway spruce. The experiment consisted of untreated control plots (C) and treatments with fertilisation every year (F1), fertilisation every second year (F2), fertilisation every third year (F3), sludge supplemented by nitrogen (S/N), and ash supplemented by nitrogen and phosphorus (A/NP). Bräcke had no ash and sludge treatments. Each treatment was replicated three times.

F3-treatments will receive a smaller amount of nutrients than the F1-treatment.

In 2002 for Mölnbacka, Valbo, Grängshammar and Bräcke the amounts of N for F1-, F2- and F3-treatment were 100, 150 and 180 kg N ha^{-1} respectively (Appendix A). In Ebbegärde the amounts were 75 kg N ha^{-1} for F1, 125 kg for F2 and 150 kg for F3 (Appendix A). Sludge and wood-ash were supplied in Mölnbacka, Valbo, Grängshammar and Ebbegärde with almost the same amount of N as in the F2-treatment. Sludge pellets and wood-ash were supplied later in July 2002 to avoid N-losses. Thereafter, nitrogen was supplied every second year in the sludge and wood-ash treatment. The F1-treatment in Mölnbacka, Grängshammar and Valbo received 100 kg N ha^{-1} in 2003 and 2004 and 75 kg N in 2005 and 2006, while F2 was reduced from 150 to 125 kg N ha^{-1} and F3-treatment from 180 to 150 kg N ha^{-1} in 2005 and 2006 (Appendix A).

Ebbegärde followed the same fertilisation regime but the supply was in general 25% lower compared with the other sites. Bräcke had the same rate of supply of fertiliser as in Mölnbacka, Grängshammar and Valbo, except for the F1-treatment in 2005, in which the supply was 33% higher in Bräcke (Appendix A).

The fertiliser used in F1-, F2- and F3-treatments was a conventional fertiliser produced by Yara AB. Sludge pellets were obtained from Himmerfjärdsverket in Stockholm and were heated and dried to produce a product with a low water content and no disease-causing products. The ash was a wood-ash from Falun, which had been treated with water and crushed. The amounts of wood-ash and sludge pellets supplied in 2002 were five and three tons, respectively. Nitrogen was also supplied in 2002 for these treatments and the total amount of nutrients supplied can be seen in Appendix A. Samples of wood-ash and sludge pellets were taken and content of different mineral nutrients was analysed (data not shown) to calculate the total amount supplied.

2.4 Needle Sampling and Analysis

Shoots for nutrient analysis in one-year-old (C+1) needles were sampled in October–November each year for the five different sites. Ten shoots from each plot were taken from the upper third of the canopy, and samples were dried at 85 °C for 48 hours before they were sent to the laboratory for nutrient analysis. Needles were dried (70 °C, 48 h) and ground in a cyclone mill (Cyclotec 1093 sample mill, Tecator, Sweden). Sub-samples were then dried in a vacuum (70 °C, 24 h). For element analysis a part of each sub-sample was wet-digested in nitric and perchloric acid in an open digestion system, and then analyzed on ICP/MS (Elan 6100, PerkinElmer, Norwalk, CT, USA). Between 4 and 7 mg of each sub-sample was weighed into tin capsules. These samples were analysed for percent N (%) and C (%) in a continuous flow isotope ratio mass spectrometer (model 20–20 Stable Isotope Analyzer, Europa Scientific Ltd, Crewe, UK) interfaced with an elemental analyser unit (ANCA-NT solid/liquid preparation module, Europa Scientific Ltd).

2.5 Lysimeter Sampling and Analysis

Soil water at 50 cm soil depth was extracted once every autumn from six ceramic cup suction lysimeters (P80) installed at all sites in 2001 and 2002 by augering from above in each parcel and refilling with soil in the same order. The lysimeters were evacuated to about –70 kPa and sucked in soil water until the next day when the water from the plastic sampling bottles was collected. A simple sub-sampling was done in the field: 100 ml from each lysimeter was mixed in a 1-L bottle pre-rinsed with de-ionized water and then 100 ml was saved as the parcel sample. Within a day the samples were deep frozen, until analysis. All soil water samples were analyzed for NO_3-N (colometrically determined using FIA). From 2005 the analysis was extended to pH (potentiometry), electrical conductivity, NH_4^+-N and PO_4-P (colometrically determined using FIA), total nitrogen by oxidation in alkali by peroxydisulphate and analysis on FIA, F^-, Br^-, Cl^-, SO_4^{2-} using ion chromatography (Dionex, Sunnyvale, CA), total (TC) and inorganic (IC) carbon using a total organic carbon analyzer (TOC-5000, Shimadzu, Tokyo, Japan), and Li, B, Na, Mg, Al, Si, P, S, K, Ca, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Mo, Cd and Pb on ICP/MS (Elan 6100, PerkinElmer, Norwalk, CT, USA).

2.6 Measurements and Growth Estimates

At the sites, tree height and diameter at breast height (DBH) were measured in 2001, 2002, 2005 and 2006, in order to calculate both the standing volume and the current annual increment. DBH was measured on all trees in the net plots, but height of a smaller number of trees (ca 13% of the total number) selected from the diameter distribution in the stands. Volume over bark was estimated for the sample trees with height measurements using volume functions developed by Brandel (1990). Regressions between volume and DBH for each treatment and site, based on data from the standing sample trees, for which both diameter and height had been measured, were derived to assign a volume to the remaining diameters.

2.7 Statistical Analysis

An analysis of variance (ANOVA) was made for untransformed stem volume production data for each site, using SAS statistical software (version 9.1, SAS Institute, Cary, NC); to test if there were any significant differences between the treatments. The following model was used for analysing the statistical significance of the differences in stem volume among the treatments:

$$Y_{ij} = m + A_i + B_j + \beta X_{ij} + e_{ij}$$

where m is the general mean, A_i the effect of block, B_j the effect of treatments, and β regression coefficient. The initial differences among the plots

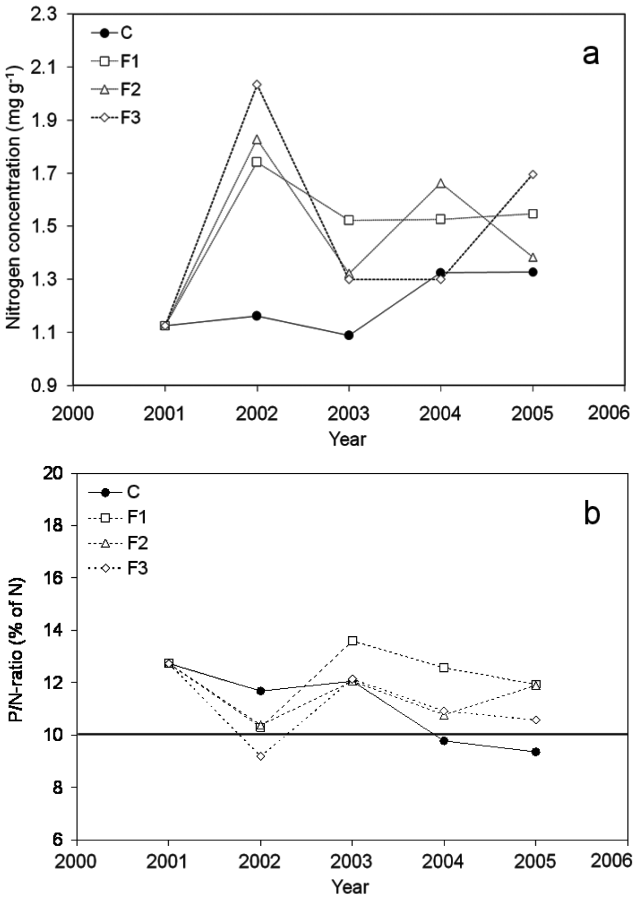

Fig. 2. Nitrogen concentration in mg g^{-1} (a) and P/N-ratio in percent of N (b) in one-year-old (C + 1) needles for C-, F1-, F2- and F3-treatment in the frequency experiment. Values are mean values for all five experiments ; the target value (10%) is marked in the figure.

were removed by applying a continuous covariate X_{ij}, i.e. stand volume at the onset of the treatments in 2001. Differences among class means were evaluated with Tukey's honestly significant difference (HSD) mean separation test when fertilisation treatments were significant ($p = 0.05$) in the analysis of variance.

3 Results

3.1 Foliar Chemistry

Foliar nitrogen concentrations in earlier field experiments normally varied between 10–15 mg g^{-1} (Linder 1995, Sikström et al. 1998) and reported target values i.e. for P, K, Mg and B, are 10%, 35%, 4% and 0.05%, respectively (Braekke 1994, Linder 1995, Stockfors et al. 1997, Bergh and Linder 2006). Average needle nitrogen concentration was 11.1 mg g^{-1} before the treatments started in spring 2002 (Fig. 2a), and varied between 10.2–12.3 mg g^{-1} for the

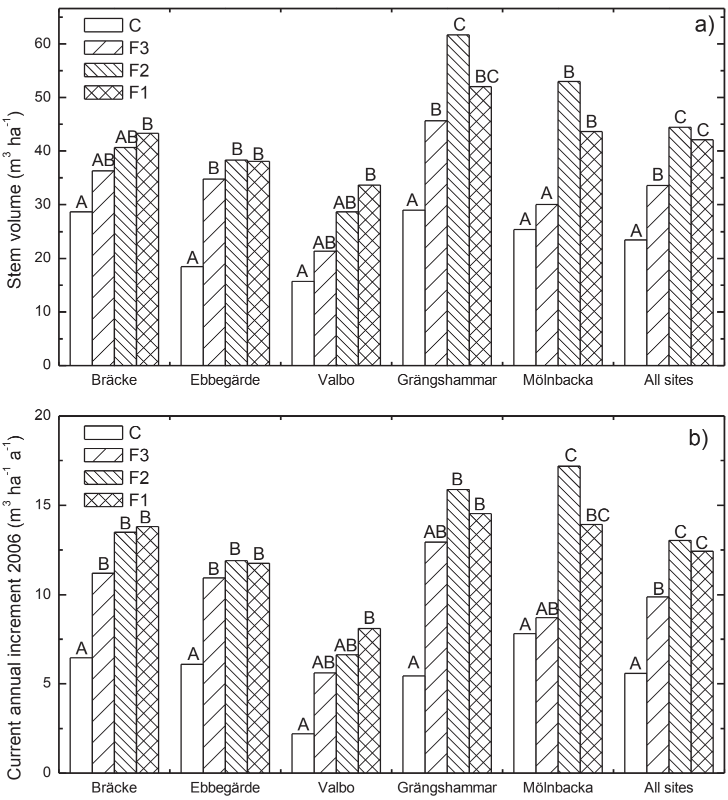

Fig. 3. Standing stem volume (a) and current annual increment (CAI) of stem volume (b) in 2006 for young stands of Norway spruce at Ebbegärde, Mölnbacka, Valbo, Grängshammar and Bräcke. The treatments were untreated control plots (C), fertilisation every year (F1), fertilisation every second year (F2) and fertilisation every third year (F3). Treatments commenced in 2002. Columns with different letters are significantly different ($p<0.05$).

five different experiments (data not shown). The largest variation in needle N concentration was 17.4–25.6 mg g^{-1} for the F3-treatment in 2002, while the smallest was 13.1–14.9 for F2-treatment in 2005. Needle nitrogen concentration increased significantly during the first growing season for all fertilisation treatments. After the first growing season, the high N concentration decreased for all treatments but fluctuated more for the F2- and F3-treatments than for the F1-treatment (Fig. 2a). The P/N-ratio decreased for all treatments after fertilisation in spring 2002. Thereafter the P/N-ratio was above the target value for all treatments in terms of mean values for all sites. However, in Ebbegärde the P/N-ratio was below the target value and the supply of nutrients had no effect on the P/N-ratio (data not shown). The ratio of potassium (K) to N was also rather low in the experiment (Bergh and Linder 2006) and Mölnbacka had K/N-ratios between 25–35% for the different treatments (data not shown). The ratio of boron (B) to N was also low in these experiments.

3.2 Production of Stem-Wood

In the autumn of 2006, stem volume was significantly higher in the fertilised treatments than in the untreated control (Fig. 3a). Average standing stem volume was 42 m^3 ha^{-1} and 44 m^3 ha^{-1} in the F1- and F2-treatments, respectively, while it was significantly less (34 m^3 ha^{-1}) in the F3-treat-

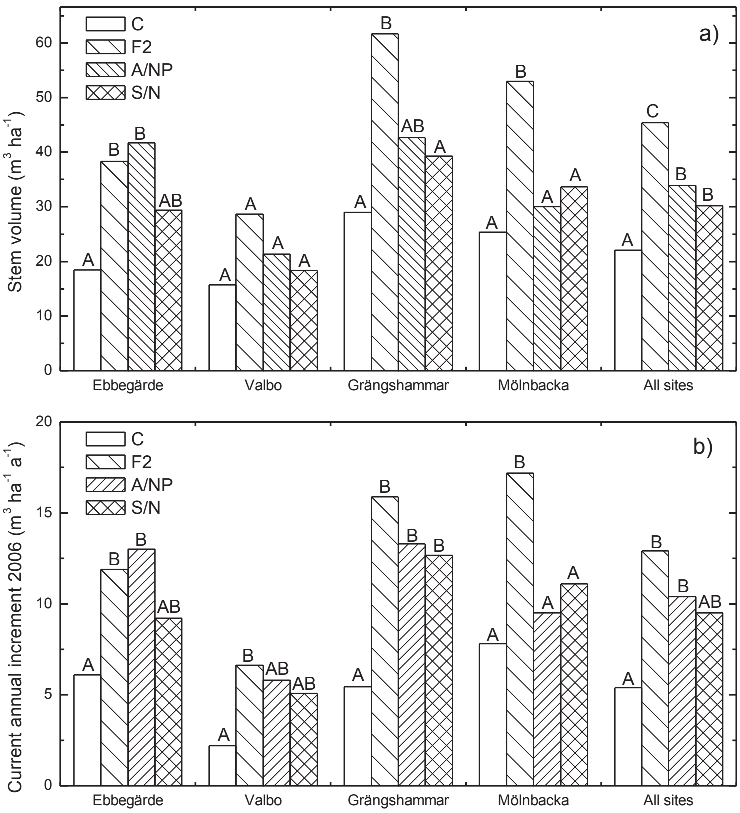

Fig 4. Standing stem volume (a) and current annual increment (CAI) of stem volume (b) in 2006 for young stands of Norway spruce at Ebbegärde, Mölnbacka, Valbo and Grängshammar. The treatments were untreated control plots (C), fertilisation every second year (F2), sludge supplemented by nitrogen (S/N), and ash supplemented by nitrogen and phosphorus (A/NP). Treatments commenced in 2002. Columns with different letters are significantly different ($p<0.05$).

ment (Fig. 3a). The absolute values of standing stem volume varied between sites but the ranking between treatments was relatively constant. Current annual increment (CAI) during 2006 was significantly lower in the untreated control than in fertilised treatments (Fig. 3b). CAI for the F1- and F2-treatments was significantly higher than for the F3-treatment. Both absolute values of CAI and ranking between treatments varied between sites. The untreated control had lowest CAI on all sites while the difference between fertilised treatments was not significant on some sites (Fig. 3b).

Standing volumes in the ash- and sludge treatments were significantly lower than in the F2-treatment which had received approximately the same amount of N (Fig. 4a). The absolute values of standing volume and relative difference between treatments varied between sites. The F2-treatment was significantly higher than the ash- and sludge treatments only in Mölnbacka. Current annual increment (CAI) during 2006 was not significantly different between the F2-treatment and the ash- and sludge treatments (Fig. 4b).

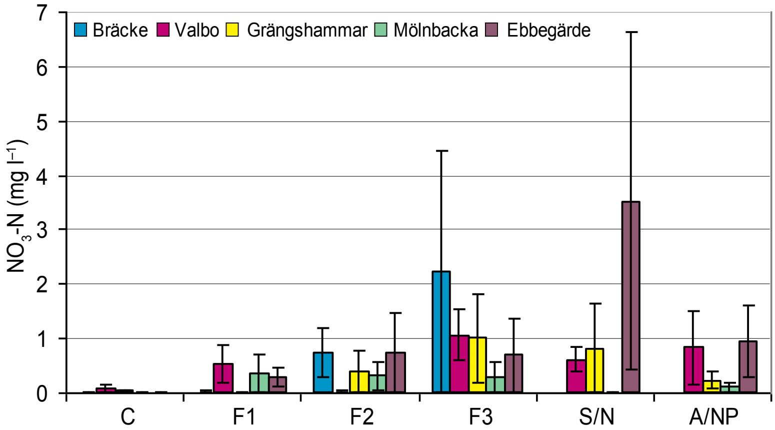

Fig. 5. Average concentration (±se between blocks) of NO_3-N (mg L^{-1}) in soil water for Bräcke, Valbo, Grängshammar, Mölnbacka and Ebbegärde during 2002–2005. The treatments are control (C), fertiliser every year (F1), fertiliser every second year (F2), fertiliser every third year (F3), sludge supplemented by nitrogen (S/N), and ash supplemented by nitrogen and phosphorus (A/NP).

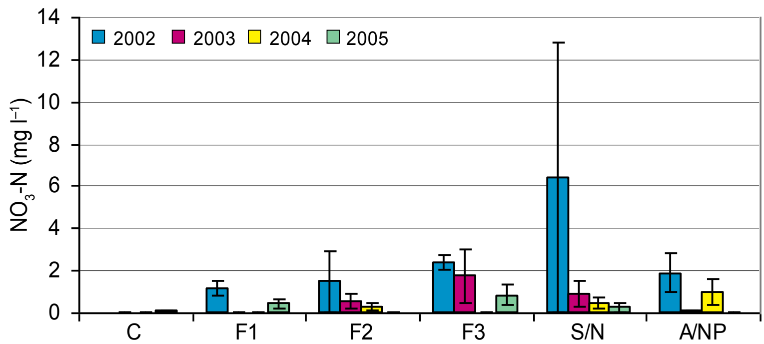

Fig. 6. Average concentration (±se between sites and blocks) of NO_3-N (mg L^{-1}) in soil water over the years 2002–2005 and the sites Bräcke, Valbo, Grängshammar, Mölnbacka and Ebbegärde. The treatments are control (C), fertiliser every year (F1), fertiliser every second year (F2), fertiliser every third year (F3), sludge supplemented by nitrogen (S/N), and ash supplemented by nitrogen and phosphorus (A/NP).

3.3 Nitrate Leaching

There were large variations in nitrate concentration in soil water at 50 cm soil depth between experimental sites, between treatments, and between years (Fig. 5). Therefore, treatment effects on nitrate concentration in soil water were not statistically significant ($p>0.05$). Soil water samples from fertilised treatments had higher average nitrate concentration (0.7 mg N l^{-1}) than the control treatment (0.02 mg N l^{-1}), and the nitrate concentration was lower in the F1-treatment (0.2 mg N l^{-1}) than in the F3- and A/NP-treatments, 1.0 and 1.4 mg N l^{-1}, respectively (Fig. 5). The difference in mean nitrate concentrations between experimental sites was not significantly different. During the treatment period the average nitrate concentration for the fertilised treatments decreased from 2.6 (2002) to 0.3 (2005) mg N l^{-1} (Fig. 6).

4 Discussion

Nitrogen concentrations varied more for the F2- and F3-treatments than for the F1-treatments, indicating that it may be difficult to maintain a high concentration of nitrogen in needles with decreased fertilisation frequency as well as for the sludge and wood-ash treatment. The same tendency was found for the ratios of the other nutrients to N. It was mainly the P/N- and K/N-ratios that were below their target value; the most severe deficiency was found in P/N-ratios at Ebbegärde.

Even if the N concentration in needles fluctuated in the F2-treatment, compared with the F1-treatment, it might not have influenced leaf area development enough to cause a significant effect on production. For the F3-treatment, the total amount of nutrients supplied was less, 325 kg (F3) compared to 425 kg (F2) and 450 kg (F1) N per ha^{-1} (Appendix A), and was probably insufficient to maintain the same leaf area development as the F1- and F2-treatments. Therefore, stem volume production were probably lower than in the F1- and F2-treatments. These results both support and reject hypothesis 1 since F3-treatment is significantly lower than F1- and F2-treatments, while there is no difference between F1- and F2-treatments. These tendencies in production indicate that fertilisation every second year will be economically preferable compared with fertilisation every year (Nilsson and Fahlvik 2006). However, fertilisation every third year may still be an option for practical forestry if losses in potential production do not further increase. Previous application frequency (2–13 yrs) experiments, in mature and old stands of Scots pine and Norway spruce, have shown no significant differences in stem wood production between fertilisation frequencies (Pettersson 1990, Jacobson and Pettersson 2001). A likely explanation might be the greater potential need for nutrients in young stands (Miller 1988) and the fact that mature stands are not able to utilise the nutrients if application is every fifth year or more frequently.

Fertilisation with sludge combined with N, and wood-ash combined with N and P, resulted in lower standing stem volume than the F2-treatment. Some of the supplied N may have been lost through denitrification (Maljanen et al. 2006), and nutrients may have been immobilised to a greater extent compared with the conventional fertiliser used in the F1-, F2- and F3-treatments (Hånell and Magnusson 2005). However, current annual increment for ash- or sludge treatment was not significantly different from the F2-treatment, suggesting that such treatments may be an interesting alternative way of increasing production. The third hypothesis cannot be rejected yet, even if there is a large difference in terms of production.

When comparing production in these five sites with earlier intensive fertilisation experiments i.e. Stråsan, Flakaliden and Asa (Bergh and Linder 2006), the climatic conditions should be comparable. Therefore Ebbegärde was compared with Asa; Mölnbacka, Grängshammar and Valbo were compared with Stråsan; and Bräcke was compared with Flakaliden. The production in F1- and F2-treatments was equal or slightly higher at all frequency sites compared with Stråsan, Flakaliden and Asa, except for Ebbegärde which had lower production. The lower production in Ebbegärde compared to Asa was probably caused by P-deficiency in Ebbegärde, which the intensive fertilisation treatments failed to compensate for. P-deficiency was observed in the Asa experiment in the treatment in which only nitrogen was supplied (Bergh and Linder 2006). Another explanation might be the lower precipitation and coarser soil texture at Ebbegärde (ca 500 mm a^{-1}) than at Asa (ca 600 mm a^{-1}), or the year to year differences in precipitation.

The nitrate concentration in soil water may be approximated to amount of leaching by multiplying the concentration by the water flux, which may be approximated by the mean runoff for the area. Using runoff values from Table 1 gives leaching of <0.1–4.7 kg ha^{-1} a^{-1} for fertilisation every year and every second year, and <0.1–20 kg ha^{-1} a^{-1} for fertilisation every third year (cf. Fig. 6). The nitrate concentration decreases with time in all treatments. It might therefore have been more efficient to start the stand treatment with a lower fertilizer amount. N doses higher than 125–150 kg N per ha^{-1} increased nitrate leakage considerably and must be avoided. It is therefore impossible to supply the same amounts of N in F2- and F3-treatments as in the F1-treatment.

Earlier experiments in young stands of Norway spruce showed very small losses of N through leaching (Grip 2006). Nitrogen losses from forest land are less than 1.5 kg ha^{-1} a^{-1} and most of the leaching during a rotation period originates from clear-felling (Ring 1995, Ring et al. 2003).

According to this experiment, the most important nutrients to supply in young stands of Norway spruce in order to prevent nutrient deficiencies are N, P and K. In terms of production and economy it seems preferable to fertilise every second year but fertilisation every third year may also be a cost-effective option. Furthermore, N-leaching to soil water has been kept at a low level in all treatments. The very preliminary conclusion from the experiment is that longer intervals between fertilisation with larger single applications of fertilizer may increase nitrogen leaching. Hypothesis 2 is therefore still valid. From this perspective, it may be advantageous to begin a fertiliser regime with a low dosage and then increase it to the planned level. However, this experiment must be evaluated further in the future before definite conclusions can be drawn and guidelines for practical forestry can be given. The frequency experiment will provide important information on which a fertilisation programme for young Norway spruce stands can be based.

References

Berg, B. & Staaf, H. 1981. Leaching, accumulation and release of nitrogen in decomposing forest litters. In: Clark, F.E. & Rosswall, T. (eds.). Terrestrial nitrogen cycles. Processes, ecosystem strategies and management impacts. Swedish Natural Science Research Council (NFR). Ecological Bulletins 33: 405–426.

Bergh, J. & Linder, S. 2006. Grundläggande försök med balanserad näringstillförsel i ungskog av gran (Basic experiments with balanced nutrient supply in young spruce stands). In: Bergh, J. & Oleskog, G. (eds.). Slutrapport för fiberskogsprogrammet.SLU, Southern Swedish Forest Research Centre. Rapport 27: 1–17. ISBN 91-576-7161-3. (In Swedish).

— , 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. The potential production for Norway spruce in Sweden. Forest Ecology and Management 204: 1–10.

Bonan, G.B. 1993. Importance of leaf area index and forest type when estimating photosynthesis in boreal forests. Remote Sensing of Environment 43: 303–314.

Braekke, F. 1994. Diagnostiske grensverdier for näringselementer i gran- och furunåler. – NISK, 15–94, 11 p. (In Norwegian).

Brandel, G. 1990. Volume functions for individual trees, Scots pine (Pinus sylvestris), Norway spruce (Picea abies) and birch (Betula pendula & Betula pubescens). Department of forest yield research. Report 26. 72 p.

Ericsson, T. & Kähr, M. 1993. Growth and nutrition of birch seedlings in relation to potassium supply. Trees 7: 78–85.

Grip, H. 2006. Miljöeffekter av intensivodling. Effekter på näringsläckage. (Environmental effects of intence forestry. Effects on nutrient leakage). In: Bergh, J. & Oleskog, G. (eds.). Slutrapport för fiberskogsprogrammet. SLU, Southern Swedish Forest Research Centre. Rapport 27: 38–60. ISBN 91-576-7161-3. (In Swedish).

Hägglund, B. & Lundmark, J.-E. 1977. Site index estimation by means of site properties of Scots pine and Norway spruce in Sweden. Studia Forestalia Suecica 138: 1–33.

Hånell, B. & Magnusson, T. 1996. Pelleterat slam (Sludge pellets). FaktaSkog 6/96. ISSN 1400-7789. (In Swedish).

— & Magnusson, T. 2005. An evaluation of land suitability for forest fertilization with biofuel ash on organic soils in Sweden. Forest Ecology and Management 209: 43–55.

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(5): 899–909.

Kempe, G. 2005. Forest statistics 2005. Department of Forest Resource Management. 108 p. ISSN 0280-0543.

Linder, S. 1990. Nutritional control of forest yield. In: Nutrition in trees. The Marcus Wallenberg Foundation Symposia Proceedings 6: 62–87. ISSN 0282-4647.

— 1995. Foliar analysis for detecting and correcting nutrient imbalances in Norway spruce. Ecological Bulletins 44: 178–190.

Magnusson, T. 2006. Slam och aska i intensivodling (Use of sludge and wood-ash in intensive forest management). In: Bergh, J. & Oleskog, G. (eds.). Slutrapport för fiberskogsprogrammet. SLU, Southern Swedish Forest Research Centre. Rapport 27: 1–17. ISBN 91-576-7161-3. (In Swedish).

Maljanen, M., Jokinen, H., Saari, A., Strömmer, R. & Martikainen, P.J. 2006. Methane and nitrous oxide fluxes, and carbon dioxide production in boreal forest soil fertilized with wood ash and nitrogen. Soil Use and Management 22(2): 151–157.

Miller, H.G. 1988. Long-term effects of application of nitrogen fertilizers on forest sites. In: Cole, D.W. & Gessel, S.P. (eds.). Forest site evaluation and long-term productivity. University of Washington Press, Seattle. p. 97–106.

Nilsson, U. & Fahlvik, N. 2006. Ekonomisk analys av praktisk produktionsoptimering i granplanteringar (Economical analysis of operational use of nutrient optimisation in young stands of Norway spruce). In: Bergh, J. & Oleskog, G. (eds.). Slutrapport för fiberskogsprogrammet. SLU, Southern Swedish Forest Research Centre. Rapport 27: 1–17. ISBN 91-576-7161-3. (In Swedish).

Pettersson, F. 1990. Growth effects of refertilisation with different nutrients. [In Swedish with English summary.] Institutet för skogsförbättring, Uppsala Inf. Växtnäring-skogsprod. 1 1990/91.

Ring, E. 1995. Nitrogen leaching before and after clear-felling of fertilised experimental plots in a Pinus sylvestris stand in central Sweden. Forest Ecology and Management 72: 151–166.

— , Bergholm, J., Olsson, B.A. & Jansson, G. 2003. Urea fertilizations of a Norway spruce stand: effects on nitrogen in soil water and field-layer vegetation after final felling. Canadian Journal of Forest Research 33: 375–384.

Rosvall, O., Jacobson, S., Karlsson, B. & Lundström, A. 2004. Ökad avverkningspotential med intensivare skogsskötsel (Increased harvesting potential with more intensive forest management). Skogforsk Results 10. ISSN 1103-4173. (In Swedish).

SAS System for Windows, Version 6.12. SAS Institute, Cary, NC, USA.

Sikström, U., Nohrstedt, H.-Ö., Pettersson, F. & Jacobson, S. 1998. Stem-growth response of Pinus sylvestris and Picea abies to nitrogen fertilization as related to needle nitrogen concentration. Trees 12: 208–214.

— , Albrektsson, A., Näsholm, T. & Bergh, J. 2001. Effekter på skogsproduktion av markförsurning och motåtgärder. Skogsstyrelsens temaserie: Markförsurning & Motåtgärder, 11F:2001. ISSN 1100-0295. (In Swedish).

Stockfors, J., Aronsson, A. & Linder, S. 1997. Effects of long-term fertilization and growth on micronutrient status in Norway spruce trees. In: Acta Universitatis Agriculturae Sueciae, Silvestria 20. Swedish University of Agricultural Sciences, Uppsala. 41 p.

van Cleve, K., Chapin III, F.S., Dyrness, C.T. & Viereck L.A. 1991. Element cycling in taiga forests: State-Factor Control. BioScience 41(2): 78–88.

Total of 29 references

Appendix A. Supply rates of N, P and K, in kg ha^{-1} for the different treatments for the period 2002–2006 in Mölnbacka, Grängshammar, Valbo (left in table), Bräcke (middle) and Ebbegärde (right).

Treatment and year	Mölnbacka, Grängshammar, Valbo			Bräcke			Ebbegärde		
	N	P	K	N	P	K	N	P	K
F1									
2002	100	15	25	100	15	25	75	11	19
2003	100	42	160	100	42	160	75	31	120
2004	100	42	160	100	42	160	75	31	120
2005	75	20	20	100	27	27	75	20	20
2006	75	20	20	75	20	20	75	20	20
Total	*450*	*139*	*385*	*475*	*146*	*392*	*375*	*113*	*299*
F2									
2002	150	23	38	150	23	38	125	19	31
2003									
2004	150	63	240	150	63	240	125	52	200
2005									
2006	125	34	34	125	34	34	100	27	27
Total	*425*	*120*	*312*	*425*	*120*	*312*	*350*	*98*	*258*
F3									
2002	180	27	45	180	27	45	150	23	38
2003									
2004									
2005	150	40	40	150	40	40	125	34	34
2006									
Total	*330*	*67*	*85*	*330*	*67*	*85*	*275*	*57*	*72*
Ash + NP									
2002	151	35	250				126	35	250
2003									
2004	150	26					150	26	
2005									
2006	125	34	34				100	27	27
Total	*426*	*95*	*284*				*376*	*88*	*277*
Sludge + N									
2002	232	108	5				207	108	5
2003									
2004	150	26					150	26	
2005									
2006	125	34	34				100	27	27
Total	*507*	*168*	*39*				*457*	*161*	*32*