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Growth of *Pinus sylvestris* after the Application of Wood Ash or P and K Fertilizer to a Peatland in Southern Sweden

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The effects of the application of wood ash and of fertilizer regimes including phosphorus (P) and potassium (K), with and without simultaneous addition of nitrogen (N), were investigated on a stand of Scots pine (*Pinus sylvestris* L.) saplings growing on a drained oligotrophic peatland site in southern Sweden. A randomized block design was used. Tree growth and concentrations of various elements in the needles were measured. The addition of similar doses of P (approx. 40 kg P ha^{-1}) from different sources resulted in similar growth responses, amounting to 1.6–1.9 m^3 ha^{-1} yr^{-1} of stem wood over the 26-year study. The P source was either wood ash (2500 kg d.w. ha^{-1}) or PK-fertilizer (raw phosphate and potassium chloride). In response to several treatments there were both increased numbers of trees and increased growth of individual trees. The high PK-dose (40 kg P ha^{-1} and 80 kg K ha^{-1}) appeared to result in a larger growth increase than the low dose (20 kg P ha^{-1} and 40 kg K ha^{-1}). The N treatment had no additional effect on growth. In the control plots, tree growth was more or less negligible (0.04 m^3 ha^{-1} yr^{-1}). After almost 26 years, concentrations of P and K in the needles of treated plants were still higher than in the untreated control plants. Nevertheless, in spite of the elevated P concentration, P appears to limit the growth of Scots pine. In conclusion, after sufficient drainage of this type of peatland site, it is possible for a forest stand to develop to the pole stage if wood ash or PK-fertilizer is applied.

Keywords ammonium nitrate, fertilization, forest yield, needle element concentrations, nitrogen, potassium chloride, raw phosphate, wood ash
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1 Introduction

Several studies have shown that the growth of Scots pine (*Pinus sylvestris* L.) trees on peat soils generally increases after the addition of phosphorus (P) and potassium (K), either in the form of fertilizers (e.g. Almqvist 1990, Moilanen 1993) or ash (e.g. Silfverberg and Huikari 1985, Moilanen et al. 2005b). Silfverberg (1991) suggested that, if similar doses of P and K are applied, ash and fertilizer applications result in similar growth increases. Moilanen et al. (2004) concluded that wood ash is a good alternative to commercial PK-fertilizer in Scots pine stands on drained mires. There are examples of additional growth amounting to an increased wood volume of c. 100 m^3 over a period of 30–40 years after ash addition (Silfverberg 1996, Silfverberg and Issakainen 1996). Usually, the growth increase following ash addition lasts longer than that after PK-fertilizer application (Silfverberg and Moilanen 2001, Moilanen et al. 2004). A closed forest stand can be established, following drainage by ditches and ash application, on peatlands where there are few if any saplings or trees initially (Silfverberg and Huikari 1985, Silfverberg and Hotanen 1989).

The prerequisites for increased growth after PK-addition include sufficient drainage of the peat and an adequate supply of plant-available nitrogen (N) (Silfverberg and Huikari 1985, Moilanen 1993). The magnitude and the duration of the growth increase depend on the amounts of P and K added, as well as the supply of plant available N at the site (Silfverberg 1996). The addition of nitrogen at sites that are already well supplied with this element does not result in any increased growth (Silfverberg and Hotanen 1989). At some peat sites levels of plant available N can be so low that tree growth is limited (Kaunisto 1982). However, there are reports of increased tree growth after ash addition on quite N-poor peat sites in southern Finland (Silfverberg and Huikari 1985), which probably is a result of larger amounts of extractable nutrients (e.g. N) in southern than in northern Finland in a corresponding peatland site type (Starr and Westman 1978). In addition, application of ash may increase the decomposition of the peat (Karsisto 1979, Moilanen et al. 2002), and possibly affect the N mineralization.

Paavilainen and Päivänen (1995) recommended a dose of 40–50 kg P ha^{-1}, corresponding to an ash dose of 2000–5000 kg d.w. ha^{-1}, if the ash originates from biofuels. Silfverberg (1996) suggested a practical ash dose of 5000 kg d.w. ha^{-1}. In general, doses less than 2000 kg d.w. ha^{-1} result in small or negligible growth responses (Silfverberg 1996).

Today, a substantial proportion of energy production in Finland and Sweden is from biofuels, and the intention is for this to increase (Hansen et al. 2006, KOM 2008). Burning biofuel generates ash. In many cases, the biomass harvested for biofuel use includes the tops and branches (including needles) of the trees; thus substantially more nutrients are exported from the forest than if only the tree stems are harvested (Weetman and Webber 1972, Mälkönen 1976). The need to compensate for nutrient loss is probably greater in peat soils than mineral soils. This is due to the low levels of extractable P and K in the peat (Clymo 1983) and the fact that a large proportion of these nutrients is located within the trees (cf. Egnell et al. 1998). Ash may be used as a compensatory fertilizer at quite low doses in order to sustain forest production on peat soils after intensive forest harvesting. At quite high doses ash may also be used as a fertilizer on peat soils in order to increase tree growth substantially.

Few reports on the effects of ash on tree growth on peat soils relate to Sweden, and to our knowledge, none compare ash applications with PK-fertilizers. In addition, the few reports that do describe the effects of ash in the field (e.g. Malmström 1943) are based on experiments that did not include replication. At the beginning of the 1980s, the Forestry Research Institute of Sweden (Skogforsk) established an experiment in the southern part of Sweden, in order to compare growth responses following ash and PK-fertilizer applications. The experiment is unique for Swedish conditions and it is a valuable complement to the numerous field studies conducted in Finland, because it is located in an area with a more southerly climate.

In this paper, we evaluate stem growth of the trees in this experiment 26 years after the nutrient additions. Three hypotheses were tested. 1) Applications of ash or PK-fertilizer result in similar

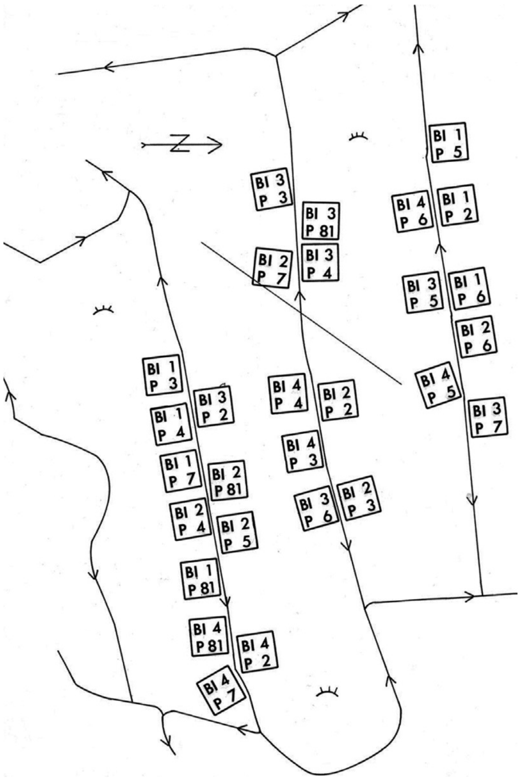

Fig. 1. The experimental plots within Skogforsks experiment 168 Perstorp. The lines with arrows represent the ditches. The values within plots indicate the numbers of the blocks (Bl) and the treatments (P). An individual sample plot measures 25 × 25 m^2.

growth responses, if they deliver similar doses of P and K; simultaneous addition of N does not affect this response. 2) A high dose of P and K results in a larger growth increase than a low dose if the same amount of N is applied. 3) There is higher growth if N is applied at the same time as P and K (in the form of ash or inorganic fertilizer) than if they were added without N. In addition to the growth study, element concentrations in the needles were measured.

2 Materials and Methods

2.1 The Experimental Site and Design

The Skogforsk experiment, known as 168 Perstorp, was established at a site in the southern part of Sweden (56°12'N, 13°17'E, 90 m.a.s.l.). The mean annual temperature is 7.2 °C and the mean annual precipitation is 795 mm at the 6306 Ljungbyhed climate station, 12 km away from the experimental site (means for the period 1961–1990; Alexandersson et al. 1991). The monthly mean temperature in January is –1.2 °C and in July it is 16.0 °C. The temperature sum is 1520 day-degrees (threshold 5 °C) (Odin et al. 1983).

The experimental site was located on an oligotrophic peatland, with peat that was originally more than 1 m deep. The area was ditched and drained in 1981 (Fig. 1). In 2007, in the control plots, the degree of humification of the peat was classified as H3–6, H4–6 and H4–6 according to the von Post classification at depths of 0–5, 5–20 and 20–30 cm, respectively (M. Ernfors, pers. comm.). The corresponding average pH values in the control plots were 4.9, 5.1 and 4.8 (measured on fresh soil in soil:H_2O suspensions of 1:10 by weight). The total-N content of the peat was 1.6%, 1.2% and 1.0% (combustion in an elemental analyser; Model: EA 1108 CHNS-O, Fison, Italy) (R. Björk, pers. comm.) at the same depths and the corresponding C/N ratios were 30, 39 and 47.

The vegetation was classified as a Heather-*Sphagnum magellanicum*-bog type (Påhlsson 1998). The field-layer was dominated by *Calluna vulgaris* L., *Erica tetralix* L. and *Eriophorum vaginatum* L. The bottom layer was dominated by *Sphagnum capillifoilum* and *S. magellanicum*, and *Hypnum cupressiforme*, *Pleurozium schreberi* and *Mylia anormala* were also present.

At the start of the experiment, the tree layer consisted mainly of Scots pine saplings with some birch (*Betula* sp.), and occasional solitary Norway spruce (*Picea abies* L. Karst.). There were, on average, 1330 conifer trees ha^{-1} and 500 birches ha^{-1} (height ≥ 0.5 m) across the 24 experimental plots. Their mean heights were 1.3 m for conifers and 1.2 m for birches. When all trees were included, i.e. including those shorter than 0.5 m,

Table 1. Treatments at the 168 Perstorp experimental site.

Treatment (kg ha^{-1})	Notation in text	Notation in Fig. 1
Control (untreated)	Control	P81
2500 ash[a]	Ash	P2
2500 ash[a] + 100 N[b]	Ash+100N	P3
40 P[c] + 80 K[d]	40P80K	P4
40 P[c] + 80 K[d] + 0.6 B + 100 N[e]	40P80K+100N	P5
20 P[c] + 40 K[d] + 0.6 B + 100 N[e]	20P40K+100N	P6
2[f] × (20 P[c] + 40 K[d] + 0.6 B +100 N[e])	2×(20P40K+100N)	P7

[a] Measured elemental concentrations: P 17, K 58, Ca 220, Mg 21 (g kg^{-1}), Cd 37, Cu 450, Zn 3460, B 344 (mg kg^{-1}).
[b] NH_4NO_3 (34.5% N).
[c] Raw phosphate (about 14% P).
[d] Potassium chloride (49.8% K).
[e] NH_4NO_3 incl. boron (34.5% N and 0.2% B).
[f] Re-fertilized after five years.

the mean density was 2960 trees ha^{-1}.

The experiment was based on a randomized complete block design, involving four blocks and seven treatments. The blocks were designated on the basis of the number of trees per plot and their mean heights. The treatments consisted of an untreated control and six different nutrient regimes (Table 1). The size of the experimental plots was 25 × 25 m^2. The ash treatments used a wood ash containing the following elemental concentrations: P 17 mg g^{-1}, K 58 mg g^{-1}, Ca 220 mg g^{-1}, Mg 21 mg g^{-1}, and Cd 37 μg g^{-1}, Cu 450 μg g^{-1}, Zn 3460 μg g^{-1}, B 344 μg g^{-1}. The ash dose applied corresponded to 42 kg P ha^{-1} and K 145 kg K ha^{-1}. This was about the same amount of P and almost the double amount of K as in the high PK-fertilizer treatment. The ash and fertilizer were applied on 10 June 1982. In the 2×(20P40K+100N) treatment plots (Table 1) fertilizer was also applied on 6 May 1987.

2.2 Growth Assessments and Calculations

In mid July 2007, 26 years after the initial treatments, the dominant trees (hereafter referred to as "main trees") within a circular plot (radius = 7.5 m, centred in each experimental plot) were selected and measured. The objective was to select 32–34 trees per plot (1800–1920 trees ha^{-1}); however, in practice, between 17 and 35 trees were selected. The diameter of the main trees was determined by cross callipering (D26 (diameter after 26 years) in mm; 1.3 m above the ground) and the height (H) of the main trees was measured (cm). The basal area (BA) was calculated and the stem volume (including bark) (V) was estimated using the empirical functions of Andersson (1954) (tree diameter ≤ 50 mm) or Näslund (1947) (tree diameter > 50 mm).

In addition, the internodes of some of the main trees were measured in order to reconstruct height growth over the previous 14 years; from these data, the annual total mean heights (1993–2007; Period 2) and mean height increments (1994–2007) were calculated. One quarter of the *Pinus sylvestris* main trees were selected for height reconstruction; only trees that had not suffered obvious damage during the previous 14 years were included. The aim was to assess 8–10 trees per plot, and the actual range was 4–11 trees. The main reason for measuring fewer trees than intended was the difficulty in finding trees with distinct internodes representing the previous 14 years. The 14-year period reflected the difficulty in finding trees with distinct undamaged internodes older than this. Height reconstruction was not possible for the trees in the control plots due to their very slow growth and, thus, the absence of distinct internodes.

In an earlier survey, conducted in October 1987, the 44 most important trees per plot (radius = 7.5 m, centred in each experimental plot) were measured (i.e. 2500 main trees ha^{-1}). It was intended that the total height and the annual height growth back to the time of the original treatment (1982) would be calculated. However, it was only possible to reconstruct the total height back to 1983 (Period 1; 1983–1987), and, thus, the annual growth during each of the previous four years

(1984–1987). These data are presented herein (Table 3, Figs. 2–3). Height reconstruction during this earlier survey was also not possible for the trees in the control plots because of their very slow growth and indistinct internodes.

In order to estimate stem growth (BAI and VI) over the whole experimental period, the basal area (BA0) and stem volume (V0) in the control plots at the time of establishment were determined by quotient estimation. Height data pertaining to the main trees in the control plots from the surveys in 2007 (H26) and in 1987 (H6) were used. The height in the control plots when the experiment was established in 1982 (H0) was calculated as H0 = H6 – (6 × ((H26 – H6) / 20)). Then BA0 and V0 in the control plots were estimated using the ratios between the height and BA or V, e.g. BA0 = (BA26 / H26) × H0. Finally, the estimated value for the control plot at the time of establishment was subtracted from the values for all plots recorded at the time of the latest survey (2007). This procedure was undertaken for each block, i.e. first reconstructing H0, BA0 and V0 for the control plot within a block and then subtracting this estimated initial control value from the values recorded during the last assessment (2007) for all the plots within the same block.

2.3 Concentrations of Elements in the Needles

Current-year (C+0) and one-year-old needles (C+1) were sampled in January 2007 from trees in the Control, Ash, Ash+100N, 40P80K, 40P80K+100N treatments. Samples were collected from eight main trees growing immediately outside the 7.5 m radius circle in the centre of each plot. Twigs from the upper third of the crown on the south side of the tree were brought down using a shotgun and collected for analysis. Similar quantities of needles from each of the eight trees were pooled into single samples, with the exception of C+1 needles from the control plots since these needles were not present on all sampled trees. Prior to chemical analysis, each composite sample was dried overnight at 70°C, ground and mixed thoroughly. The samples were treated with a mixture of HNO_3 and $HClO_4$ (10:1) before the concentrations of P, K, Ca, Mg, S, Mn, Fe, Zn, Al, B and Cu were determined by inductively coupled plasma (ICP) analysis (JOBIN YVON JY-70 Plus; Instruments S.A. Longjumeau France). The nitrogen concentration in each sample was determined using an NA 1500 elemental analyser (Carlo Erba) after dry-combustion. The chemical analyses were performed by the Department of Ecology and Environmental Research of the Swedish University of Agricultural Sciences, Uppsala, Sweden.

2.4 Groundwater Level

In mid June 1987, one groundwater tube was installed in the centre of each experimental plot. From then on, over the following five years (1987–1991), the groundwater level was recorded every second week from April/May until October.

2.5 Statistical Analyses

Data on the stem density (STHA26), BA26, V26, mean annual BAI and the mean annual VI during the 26-year period, as well as concentrations of elements in the needles (C+0 and C+1; sampled in January 2007), were analysed using the following linear model:

$$y_{ij} = \mu + \alpha_i + \beta_j + c(g_{ij} - \overline{g}) + e_{ij} \qquad \text{(Eq. 1)}$$

where: μ = the overall mean; α_i = the fixed effect of the treatment, i = 1,..., 7; β_j = the fixed effect of the block, j = 1,…, 4; e_{ij} = the random error, normally and independently distributed $(0, \sigma_e^2)$. For STHA26, BA26, V26 and the growth variables on an area basis (BAI and VI), some covariates $[c(g_{ij} - \overline{g})]$ were tested individually within the model; c = regression coefficient, g_{ij} = the value of the measured covariable on observation ij, and $\overline{g}$ is the mean value of the covariable. The covariates (g) examined were the number of coniferous seedlings ≥0.5 m at the time that the experiment was established, their mean height, and the total number of seedlings at the outset. In general, the contribution of covariates to the statistical model was moderate to weak (p = 0.11–0.79). The only exception was the model for STHA26, where the total number of seedlings before treatment was a

Table 2. Number of stems ha^{-1} (STHA26), basal area (BA26; m^2 ha^{-1}) and volume (V26; m^3 ha^{-1}) 26 years after treatment, as well as mean annual basal area increment (BAI; m^2 ha^{-1} yr^{-1}) and mean annual volume increment (VI; m^3 ha^{-1} yr^{-1}) for the dominant trees ("main trees") in the 168 Perstorp experiment over 26 years. Mean values of four blocks and standard errors (SE). Values followed by different letters within a row differ significantly ($p < 0.05$) from each other. The treatments are outlined in Table 1.

Variable	ANOVA *p*-value, treatment	Means							SE
		Control	Ash	Ash +100N	40P80K	40P80K +100N	20P40K +100N	2×(20P40K+ 100N)	
STHA26[1]	0.0003	790 b	1830 a	1920 a	1760 a	1600 a	1720 a	1430 a	120–130[1]
BA26	0.0020	2.30 b	10.9 a	9.82 a	11.6 a	9.60 a	7.10 ab	10.2 a	1.27
V26	0.0011	7.4 b	46 a	37 a	50 a	38 a	24 ab	43 a	5.8
BAI	0.0034	0.012 b	0.34 a	0.30 a	0.37 a	0.29 a	0.20 ab	0.32 a	0.049
VI	0.0023	0.039 b	1.5 a	1.2 a	1.7 a	1.2 a	0.68 ab	1.4 a	0.22

[1] Least-square means; the total number of trees before treatment was included as a covariate in the statistical model, i.e. giving variable estimates of the standard error for different treatments.

quite strong covariate ($p = 0.038$), and, hence, was included in the statistical model. The GLM procedure within the SAS® program (SAS Institute Inc. 1999) was used for the calculations.

Annual total height, annual height increment and groundwater levels were analysed using a mixed linear model and treated as repeated measures in the model:

$$y_{ijk} = \mu + \alpha_i + \beta_j + p_{ij} + t_k + (\alpha t)_{ik} + e_{ijk} \qquad \text{(Eq. 2)}$$

where: μ, α_i, β_j are the same as in Eq. 1 (see above); p_{ij} = the random plot effect; t_k = the fixed effect of time, $k = 1,\ldots, n$, e_{ijk} = the random error.

The analyses were carried out with PROC MIXED (SAS Institute Inc. 1999) using the spatial power covariance structure, where the covariance structure describes the relationship between measurements at different times within the same plot. The spatial power models the covariance between two measurements at times t_1 and t_2 as $\mathrm{cov}(y_{t1}, y_{t2}) = \sigma^2 \rho^{|t1-t2|}$ where ρ is an autoregressive parameter and σ^2 is the variance.

A level of $p < 0.05$ was considered to be statistically significant when evaluating differences among treatments with Tukey's test.

3 Results

3.1 Growth

3.1.1 Stand Density, Basal Area and Volume Increment

The density of main trees was, on average, 81–143 % significantly higher in the treated plots than in the control (Table 2). In general, the timber stock in 2007, in terms of both BA and V, was significantly higher in the treated plots than in the control (Table 2). The one exception was the low-dose PK treatment (20P40K+100N). The growth rate of the main trees in the control plots was very low during the observation period (BAI = 0.01 m^2 ha^{-1} yr^{-1} and VI = 0.04 m^3 ha^{-1} yr^{-1}) (Table 2). In the treated plots, the annual BAI was in the range 0.20–0.37 m^2 ha^{-1} yr^{-1}, and the VI was 0.7–1.7 m^3 ha^{-1} yr^{-1}. All the nutrient regimes were significantly different from the control, except for the (20P40K+100N) treatment (Table 2). For all growth variables, there were no significant differences between the tested nutrient regimes (Table 2).

3.1.2 Height and Height Growth

In the years 1983–1987 (Period 1), the mean tree height in the Ash+100N treatment plots was significantly higher than in the 40P80K+100N plots (Fig. 2; Table 3).

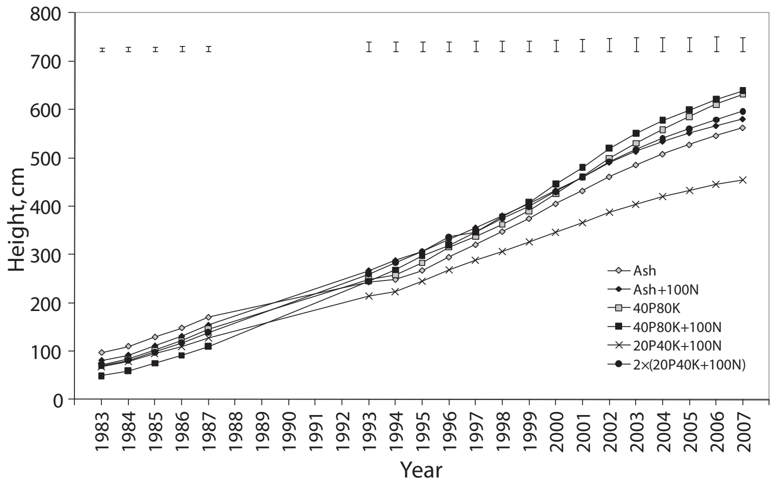

Fig. 2. Annual mean height of four blocks in the different treatments in the 168 Perstorp experiment (except for the untreated control, which could not be measured due to insufficient height growth). The results of the statistical analysis are presented in Table 3. The treatments are outlined in Table 1. In 2007, the mean height of the Scots pines in the control plots was 166 cm. Error bars at the top represent standard errors.

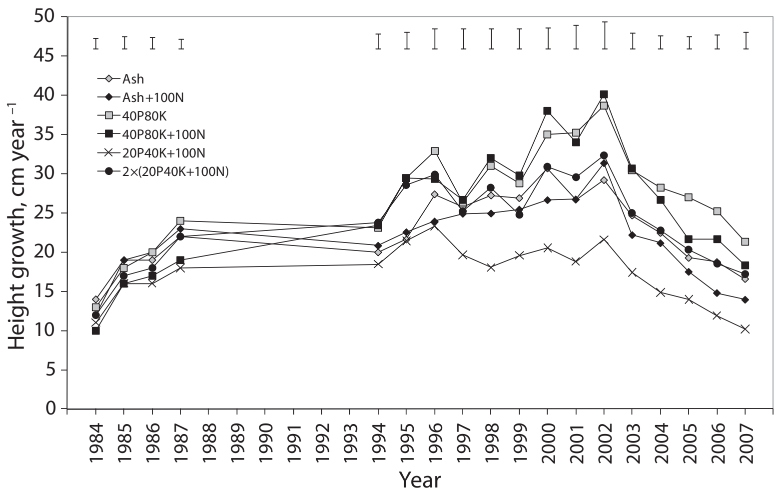

Fig. 3. Annual mean height growth of four blocks for the different treatments in the 168 Perstorp experiment (except for the untreated control; see the explanation in Fig. 2). The results of the statistical analysis are presented in Table 3. The treatments are outlined in Table 1.

There were no significant differences in tree height among the tested nutrient regimes for data in the years 1993–2007 (Period 2), as well as for all data (Period 1+2) included in the analysis. However, in 1993–2007, the single high-dose PK treatment including N (40P80K+100N), tended ($p = 0.11$) to be associated with taller trees than the single low-dose PK treatment (20P40K+100N) (Fig. 2; Table 3).

During 1984–1987, the mean annual height growth was in the range 0.10–0.24 m under the nutrient regimes tested (Fig. 3). There were no

Table 3. ANOVA tables from the statistical analyses (mixed models; repeated measurement) of the annual total height and the annual height growth of the dominant Scots pine trees ("main trees") in the 168 Perstorp experiment. Per 1 refers to height data during the period 1983–1987 (height growth 1984–1987), Per 2 to 1993–2007 (height growth 1994–2007), and Per 1+2 to both periods. The annual mean values (n = 4) for the different treatments are presented in Figs. 2 and 3.

Effect	Per 1				Per 2				Per 1+2			
	Num DF	Den DF	F-value	p-value	Num DF	Den DF	F-value	p-value	Num DF	Den DF	F-value	p-value
Height (H)												
Block	3	15	6.12	0.006	3	15	0.41	0.748	3	15	0.25	0.857
Treatment	5	15	3.18	0.037	5	15	2.19	0.110	5	15	1.57	0.230
Year	4	72	1004	<0.001	14	252	270	<0.001	19	342	298	<0.001
Treatment×Year	20	72	1.83	0.033	70	252	2.14	<0.001	95	342	2.05	<0.001
Height growth (HG)												
Block	3	15	0.67	0.583	3	15	1.47	0.262	3	15	0.67	0.584
Treatment	5	15	1.80	0.173	5	15	10.9	<0.001	5	15	11.5	<0.001
Year	3	54	157	<0.001	13	234	24.3	<0.001	17	306	32.1	<0.001
Treatment×Year	15	54	1.62	0.100	65	234	1.21	0.154	85	306	1.35	0.035

Lsmeans for the different treatments during the respective periods (m):
H, Per 1: Ash (1.31); Ash+100N (1.14); 40P80K (1.05); 40P80K+100N (0.77); 20P40K+100N (0.95); 2×(20P40K+100N) (1.01).
H, Per 2: Ash (4.02); Ash+100N (4.31); 40P80K (4.33); 40P80K+100N (4.46); 20P40K+100N (3.42); 2×(20P40K+100N) (4.32).
H, Per 1+2: Ash (3.34); Ash+100N (3.52); 40P80K (3.51); 40P80K+100N (3.54); 20P40K+100N (2.80); 2×(20P40K+100N) (3.49).
HG, Per 1: Ash (0.18); Ash+100N (0.18); 40P80K (0.19); 40P80K+100N (0.15); 20P40K+100N (0.15); 2×(20P40K+100N) (0.17).
HG, Per 2: Ash (0.24); Ash+100N (0.23); 40P80K (0.30); 40P80K+100N (0.29); 20P40K+100N (0.18); 2×(20P40K+100N) (0.26)
HG, Per 1+2: Ash (0.23); Ash+100N (0.22); 40P80K (0.27); 40P80K+100N (0.26); 20P40K+100N (0.17); 2×(20P40K+100N) (0.24)

significant differences between the regimes. During the last 14 years of the study (1994–2007), the annual mean height growth varied between 0.10 and 0.40 m (Fig. 3). For this period, all nutrient regimes including a high dose of PK, except for treatment Ash+100N, were associated with a significantly higher increment (0.06–0.12 m annually) than the single low dose PK treatment (20P40K+100N). In addition, the PK-fertilizers (40P80K; 40P80K+100N) were associated with a significantly larger increment (0.06–0.07 m annually) than one of the wood ash treatments (Ash+100N).

When all data pertaining to height growth were included (Period 1+2), the results were similar as for the period 1993–2007.

For the tested variables (height and height growth) and periods (Period 1, Period 2 and Period 1+2) sampling year had a significant effect (Table 3). For all data sets pertaining to height and for the height growth dataset that included all data, there was a significant interaction between treatment and sampling year.

3.2 Concentrations of Elements in Needles

After almost 26 years, some concentrations of elements in the needles were elevated (P, K, Mg, Mn, Al), some unaffected (Ca, S, Fe, B, Cu) and some were reduced (N, Na, Zn) by the nutrient additions, in comparison to the control (Table 4).

The P-concentration was significantly higher than the control (by 12–28%) in both C+0 and C+1 needles (sampled in January 2007), with the exception of the C+1 needles from the Ash+100N treatment (Table 4). Both the PK treatments were also associated with significantly higher P concentrations than the Ash+100N treatment.

For K, the concentrations in the C+0-needles were significantly higher or nearly so (Ash+100N; $p = 0.06$) than the control (+ 17–31%; Table 4). In the C+1 needles, the K-concentration was significantly elevated (40P80K; $p < 0.05$) or nearly so (40P80K+100N; $p = 0.09$) in the PK-fertilizer treatments.

Only the PK-alone treatment resulted in higher Mg-concentrations than the control, with levels of +24% and +38% in the C+0 and C+1 needles, respectively (Table 4). These concentrations were

Table 4. Elemental concentrations in current (C+0) and one-year old (C+1) Scots pine needles in the 168 Perstorp experiment sampled in January 2007. Mean values of four blocks and standard errors (SE). Values followed by different letters within a row differ significantly ($p < 0.05$) from each other. The treatments are outlined in Table 1.

Element	ANOVA p-value, treatment	Means Control	Ash	Ash +100N	40P80K	40P80K +100N	SE
C+0							
N (mg g^{-1})	0.0006	17 a	14 b	14 b	13 b	13 b	0.47
P (mg g^{-1})	<0.0001	0.78 c	0.91 ab	0.87 b	0.97 a	0.97 a	0.020
K (mg g^{-1})	0.0021	3.5 b	4.4 a	4.1 ab	4.6 a	4.2 a	0.14
Ca (mg g^{-1})	0.23	1.2 a	1.4 a	1.2 a	1.2 a	1.1 a	0.069
Mg (mg g^{-1})	0.0040	0.92 b	0.96 b	0.92 b	1.14 a	1.09 ab	0.038
Mn (mg g^{-1})	<0.0001	0.25 b	0.46 a	0.42 a	0.18 b	0.17 b	0.017
S (mg g^{-1})	0.58	0.87 a	0.86 a	0.85 a	0.82 a	0.82 a	0.024
Na (μg g^{-1})	<0.0001	480 a	300 b	290 b	320 b	210 b	24
Fe (μg g^{-1})	0.80	44 a	40 a	42 a	41 a	40 a	1.6
Zn (μg g^{-1})	0.12	52 a	53 a	50 a	53 a	48 a	1.6
Al (μg g^{-1})	0.0075	74 b	91 ab	87 ab	96 ab	108 a	5.0
B (μg g^{-1})	0.15	14 a	15 a	14 a	16 a	15 a	0.59
Cu (μg g^{-1})	0.16	2.8 b	3.2 a	3.1 ab	3.2 ab	3.2 ab	0.098
C+1							
N (mg g^{-1})	0.0044	18 a	14 b	14 b	13 b	13 b	0.76
P (mg g^{-1})	0.0001	0.67 c	0.78 ab	0.72 bc	0.86 a	0.84 a	0.020
K (mg g^{-1})	0.033	2.9 b	3.4 ab	3.3 ab	3.7 a	3.5 ab	0.16
Ca (mg g^{-1})	0.44	1.6 a	2.1 a	1.8 a	1.9 a	1.6 a	0.16
Mg (mg g^{-1})	0.0049	0.77 b	0.78 b	0.82 b	1.06 a	0.92 ab	0.048
Mn (mg g^{-1})	<0.0001	0.26 b	0.61 a	0.60 a	0.24 b	0.22 b	0.029
S (mg g^{-1})	0.88	0.84 a	0.88 a	0.86 a	0.85 a	0.84 a	0.026
Na (μg g^{-1})	0.0088	790 a	520 b	470 b	470 b	490 b	57
Fe (μg g^{-1})	0.52	66 a	60 a	61 a	61 a	59 a	2.6
Zn (μg g^{-1})	0.0042	62 a	55 ab	51 b	62 a	50 b	2.1
Al (μg g^{-1})	0.0080	69 a	85 ab	83 ab	93 a	96 a	4.5
B (μg g^{-1})	0.99	15 a	15 a	14 a	14 a	15 a	0.96
Cu (μg g^{-1})	0.33	2.4 a	2.8 a	2.6 a	2.7 a	2.7 a	0.11

also higher than both the treatments involving wood ash applications. In the C+0-needles, there was a tendency ($p = 0.06$) towards increased Mg-concentrations in trees in the 40P80K+100N treatment, compared with the control and the Ash+100N treatment.

In the two wood ash-treatments, the Mn-concentrations in the needles were higher, especially in the C+1 needles (131–135%), than in all the other sampled treatments (Table 4). There was a tendency ($p = 0.06$–0.08) for lower C+0 needle Mn concentrations in the PK-treatments compared with the control. In contrast, the Al-concentration was significantly elevated or tended ($p = 0.06$) to be elevated (30–46%) after PK-fertilization.

In all nutrient regimes sampled, the concentrations of N in the needles were reduced by 18–28% and Na concentrations were reduced by 33–56% compared with the control (Table 4). The reductions were similar in both C+0 and C+1 needles. In the C+1 needles, Zn was reduced by 18–19% when 100N had been applied (Table 4).

3.3 Groundwater Level

The groundwater table varied greatly over the five-year sampling period from 1988 to 1992. It ranged from being at the ground surface to a depth lower than 0.3 m (Fig. 4). The 40P80K treatment was associated with a mean level of 0.18 m, which was significantly lower than the

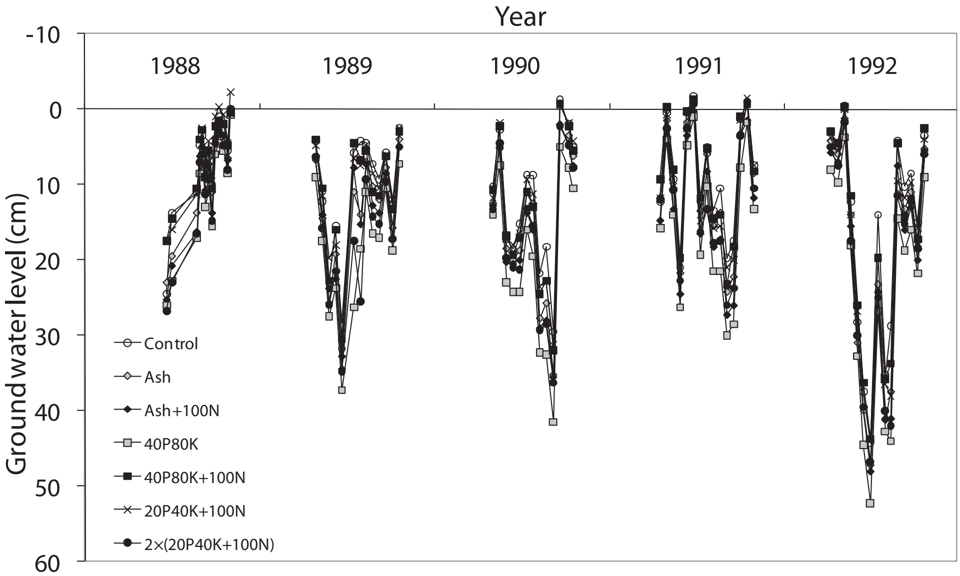

Fig. 4. Groundwater levels at the 168 Perstorp experimental site during the years 1988–1992. Means for the different treatments are based on four blocks.

mean levels associated with the untreated control and all the other treatments (mean levels of 0.11–0.15 m; Table 5), except for the level in treatment 2×(20P40K+100N) plots. In addition, the level in both the wood ash treated plots (Ash; Ash+100N), as well as in the 40P80K and 2×(20P40K+100N) plots was significantly lower than in the control. Furthermore, the Ash+100N and 2×(20P40K+100N) treatment plots had significantly lower ground water levels than the 40P80K+100N and 20P40K+100N plots. There was a significant effect of sampling date (Table 5).

Table 5. ANOVA table from the statistical analyses (mixed models; repeated measurement) of the ground water level in the 168 Perstorp experiment. Data from the years 1988–1992. The mean values (n = 4) for the different treatments at each sampling date are presented in Fig. 4.

Effect	Num DF	Den DF	F-value	p-value
Block	3	18	14.2	<0.001
Treatment	6	18	15.2	<0.001
Date	68	1428	217	<0.001
Treatment×Date	408	1428	0.97	0.629

Lsmeans for the different treatments during the observation period (m):
Control (0.11); Ash (0.14); Ash + 100N (0.15); 40P80K (0.18); 40P80K + 100N (0.12); 20P40K + 100N (0.12); 2 × (20P40K + 100N) (0.15).

4 Discussion

4.1 Growth

The addition of 2500 kg wood ash ha^{-1} produced a similar growth response to the application of PK-fertilizer containing a similar dose of P. This was the case both with and without the simultaneous addition of N. Thus, our first hypothesis, that the application of wood ash and PK-fertilizer results in similar growth responses if the doses of P and K are similar, was supported. Our data support the conclusion of Moilanen et al. (2004) that wood-ash is an adequate alternative to PK-fertilizers on drained peatlands. An ash dose of less than 2000 kg ha^{-1} usually results in small or negligible increases in tree growth (Silfverberg 1996). Our ash dose was only a little higher than this, but the P-concentration in the ash was quite high, thus supplying an adequate amount of P (cf.

Paavilainen and Päivinen 1995). Other studies have also reported similar growth responses to wood-ash and PK-fertilizers (Silfverberg 1996, Moilanen et al. 2004). Moilanen et al. (2004) found that, initially, PK-fertilizers may cause more growth, but a more long-lasting effect may be produced by ash application. However, our results somewhat contradict this suggestion, as indicated by an initial superiority in height growth in the ash treated plots including N (1984–1987; Ash+100N > 40P80K+100N), and a superiority in height growth in the high-dose PK plots during the second recording period (1994–2007; 40P80K and 40P80K+100N > Ash+100N) (Fig. 3). One possible explanation is that the loose ash may initially release nutrients more rapidly than the raw-phosphate. In the longer-term, the rather low dose of highly soluble ash is likely to promote less growth than the raw-phosphate, which is probably less soluble. With respect to the short-term effects (Period 1), there is some uncertainty associated with the data because plants in the experiment were browsed by moose (see below).

All in all, the results indicate that the second hypothesis, that a high PK dose results in a greater growth increase than a low dose, cannot be rejected. All the nutrient regimes including a high PK fertilizer dose (40 kg P ha^{-1} and 80 kg K ha^{-1}), as well as the pure ash treatment, resulted in a significantly larger height growth response than the low PK dose (20 kg P ha^{-1} and 40 kg K ha^{-1}) in Periods 2 and 1+2. In addition, there was a tendency ($p = 0.11$) towards the production of taller trees in Period 2 in the high dose PK treatment plots (40P80K+100N) than in the low dose PK treatment plots (20P40K+100N). The VI and the standing volume at the time of the last assessment (2007) were estimated to be about 0.5–1.5 times higher in the two single high-dose PK-treatments (40P80K and 40P80K+100N) than in the low PK-dose treatment (20P40K+100N), although the difference was not statistically significant. The lack of significance of these last differences was probably due to a large variation in growth and standing volume among the low dose PK-plots (data not shown). On the other hand, the difference might have been somewhat overestimated, since two of the plots supported a considerably lower standing volume than the other plots at the time of the most recent assessment. The reason might, at least partly, be linked to earlier damage by moose browsing (see below).

The lower growth rates during Period 2, especially over the last 10 years, in the low PK-treatment, suggest that the fertilization effect had a shorter duration. Under the other nutrient regimes, the height growth rates seemed to peak in 2002, followed by a decline in height growth (Fig. 3). This suggests a declining growth effect 20 years after these nutrient additions. Previous studies of the fertilization of Scots pine stands, usually at the pole stage, deficient in P and K and growing on drained peatlands with deep peat have shown that the effects of fertilizer applied at doses recommended for practical purposes (40–50 kg P ha^{-1} and c. 80 kg K ha^{-1}; Paavilainen and Päivänen 1995) last 15–30 years (e.g. Heikurainen 1973, Huikari 1973, Paavilainen and Päivänen 1995). In general, the growth response to P is more long-lasting than to K (e.g. Kaunisto 1989, Moilanen 1993, Silfverberg and Hartman 1999, Rautjärvi et al. 2004, Moilanen et al. 2005a, Pietiläinen et al. 2005). This concurs with the changes in nutrient concentrations in the needles. Several studies have shown that the P status of Scots pine can be improved for more than 30 years with a single fertilizer application, and that the duration of the effects of K application is usually shorter (10–20 years) (Silfverberg and Moilanen 2008 and references therein), although the duration of increased K concentrations may be prolonged somewhat by the application of a compound of potassium of low solubility such as biotite (Moilanen et al. 2005a).

The third hypothesis was that if N is applied at the same time as PK, there is greater tree growth than if PK is applied alone (irrespective of whether it is in the form of inorganic fertilizer or ash). In our study there was no such additional growth. The vegetation type indicated a nutrient-poor site and low site quality following drainage (Hånell 1986). These facts could indicate a limited supply of plant-available N, leading us to expect increased growth when N was added. However, the high N concentration in the needles (cf. Braekke 1994; Silfverberg and Moilanen 2008) and the total-N content in the upper layer of the peat (1.4%) (cf. Silfverberg and Huikari 1985; Silfverberg 1996), suggest a small or negligible effect of added N, and that the application of P and

K alone was sufficient to increase tree growth. For Nordic conditions, the experimental site has quite favourable climatic conditions, which, according to Silfverberg and Huikari (1985), is also indicative of sufficient N availability. In addition, the site is located in a region that has received a substantial N-deposition over a period of several decades (http://www.krondroppsnatet.ivl.se/innehall/resultatdata/depositionskartor/kvave.4.2f3a7b311a7c8064438000825358.html; Lövblad et al. 1995). However, the effect of air-borne N deposition on tree growth remains unclear (cf. Sikström 2002) and has not, as far as we know, been studied in peatland sites.

The tree growth in the control plots was very slow; in contrast all the nutrient regimes tested clearly increased tree growth. If the main trees present are considered, a maximum timber stock volume of 50 m^3 ha^{-1} had been built up over the 26-year period. An estimate of the total stock of trees in the sample plots was also done, i.e. including all coniferous trees (diameter > 10 mm; 1.3 m above the ground) and all birches (diameter > 20 mm) (data not shown). In the different nutrient regimes tested, the mean number of stems was 60–100% higher and the mean stocking (BA and V) rates were 4–20% higher compared with the analysis of only main trees. Similar statistical differences between the treated plots and the control plots were recorded, thus not changing the main conclusions. The reported growth rates and stocks are within the same range as earlier findings relating to similar fertilization regimes tested in Scots pine stands, predominantly at the sapling and pole stages, growing on sites where plant available N is not the main growth limiting factor (Silfverberg and Huikari 1985, Moilanen et al. 2005a, Moilanen et al. 2005b, Pietiläinen et al. 2005). However, much higher growth rates and stocks have been reported than those recorded in this study, for example with higher doses of ash (Silfverberg and Huikari 1985; Moilanen et al. 2002).

The growth increase in this study was an effect of both the increased number of trees and the higher growth rate of individual trees, compared with the control. The influence of nutrient addition on stem density was probably an effect of both more vital trees being present and a reduction in the length of time it took for seedlings to reach a "critical height", at which the probability of survival increases substantially. Our data indicating increased numbers of trees are supported by several reports on afforestation of more or less tree-less peatlands following drainage and nutrient addition (e.g. Silfverberg and Huikari 1985, Silfverberg and Hotanen 1989, Moilanen 1993). If the control plots had contained the same number of trees of the critical height as the treated plots, their potential growth and standing volume may have been somewhat greater.

There are some uncertainties in the estimates of standing volume and growth, due to the moose browsing that occurred at the beginning of the experimental period. In addition, since that time there has been little inspection and recording of damage (only in 1987). According to the survey in 1987, all plots that had received nutrient additions seemed to be more or less equally affected. The mean frequencies of browsed main trees per treatment were 11%–16%. One consequence of this damage is an overall underestimate of potential standing volume and growth. Browsing and stem-breakage may also explain some of the outlier plots that contained a much lower standing volume at the time of the last assessment (two plots for the 20P40K+100N treatment and one plot for the 2×(20P40K+100N) treatment).

The differences in ground water levels among some of the treatments, 3–7 cm on average for all values recorded, should be interpreted with care. These results could be interpreted as a treatment effect, i.e. the increased growth following fertilization lead to increased evapotranspiration and, thus, lowered the ground water level. However, there does not seem to be any obvious connection between the mean ground water levels and the tree growth responses. For example, the level in the control plots does not clearly deviate from all the other treatments, despite the substantially different growth patterns. Another interpretation is that initially better drainage conditions in some plots/treatments resulted in more favourable growing conditions. However, this is not likely, since the experiment involved four replicates of each treatment and there were no obvious deviations in water level data associated with any of the plots. Furthermore, at this stage of stand development, especially when the ground water levels were recorded, the ditches had a greater influence on water level (i.e. the 'technical drainage') than the vegetation could through evapotranspiration (i.e. the 'biological drainage') (Paavilainen and Päivänen 1995).

The data on ground water levels is most useful in highlighting the fact that the site is not optimally drained. Drainage could have been improved, with respect to both the distance between ditches and the maintenance of the ditches during the experimental period (cf. Heikurainen 1973). Drainage improvement might have yielded even better tree growth at Perstorp after the nutrient additions, due to improved growing conditions and as a result of the positive feedback between increased tree growth and water table drawdown, as suggested by Hökkä et al. (2008).

4.2 Concentrations of Elements in the Needles

The K-concentration in the C+0 pine needles (sampled in January 2007) from the control plots was at a level that suggested severe deficiency (Braekke 1994; cf. Silfverberg and Moilanen 2008). In the treated plots, somewhat higher concentrations in the needles were still recorded 26 years after treatment. Ten to twenty years after PK-fertilization, K often becomes growth limiting for Scots pine on peatlands (Kaunisto 1982, 1989, Moilanen 1993, Silfverberg and Moilanen, 2008 and references therein). The duration of the P effect is usually somewhat longer (Moilanen 1993, Silfverberg and Hartman 1999, Silfverberg and Moilanen 2008 and references therein). However, our data indicate that P has been (see control plot values) and presently is the element that limits tree growth. The P concentrations in needles were well below the suggested severe deficiency level for Scots pine (Braekke 1994; cf. Silfverberg and Moilanen 2008). This was the case for all the nutrient regimes examined, despite the higher P-concentrations than in the control needles. The P concentration in the needles was somewhat higher in the trees from the high PK-treatment plots than from the ash treatments, but this was not reflected in any increased growth.

The N-concentration in the needles from the trees in the control plots was quite high and close to optimal for maximum growth according to Braekke (1994) or within the optimal interval (cf. Silfverberg and Moilanen 2008). This is in line with the lack of growth response associated with added N. The reduced N-concentrations in needles from trees in the treated plots may be a dilution effect due to a larger total needle biomass and larger individual needles; this effect has been reported elsewhere (cf. Silfverberg and Moilanen 2008). Larger individual needles and greater needle biomass were observed in the treated plots during the most recent assessment, but these variables were not measured at the time.

4.3 Conclusion

In the peatland studied, sufficient drainage combined with the addition of ash or PK-fertilizer can result in the production of a pole stage Scots pine stand. However, it is not known whether the long-term growth of the stand is sustainable. The concentrations of elements in the needles indicated that P was the primary nutrient limiting growth, both when the experiment was established and after 26 years. However, the addition of K was, presumably, also necessary for increased tree growth. The needle N concentration indicated that there was sufficient supply of plant available N present at the site for the Scots pine trees to grow; this is in line with the lack of growth response as a result of N fertilization.

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