Effects of Different Phosphorus Fertilisers on the Nutrient Status and Growth of Scots Pine Stands on Drained Peatlands

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Silfverberg, K. & Hartman, M. 1999. Effects of different phosphorus fertilisers on the nutrient status and growth of Scots pine stands on drained peatlands. Silva Fennica 33(3): 187–206.

The aim of the study was to compare the effects of phosphorus fertilisers of different solubility and different phosphorus doses. The material was collected from 8 field experiments situated on drained peatlands in southern and central Finland (60°–65° N). The sites were drained, oligotrophic pine fens and pine bogs, which had been fertilised between 1961 and 1977 with different combinations of N, K and P. In 1991–94 stand measurements and foliar and peat sampling were carried out on 162 sample plots.

Apatite, rock phosphate and superphosphate affected basal area growth to a rather similar extent. However, apatite slightly surpassed superphosphate and rock phosphate at the end of the study period in two hollow-rich *S. fuscum* bogs. Higher doses of phosphorus did not significantly increase the basal area growth. The foliar phosphorus concentrations clearly reflected the effect of the P fertilisation. Especially on the pine bogs basic fertilisation with 66 kg P/ha maintained the needle phosphorus concentrations at a satisfactory level for more than 25 years after fertilisation. The amount of phosphorus in the 0–20 cm peat layer was not significantly increased either by basic fertilisation or refertilisation. The phosphorus reserves in the peat in the individual experiments were between 88 and 327 kg/ha. There was a strong correlation between the amounts of phosphorus and iron in the peat. Large amounts of iron in peat may reduce the solubility and availability of phosphorus.

According to the foliar phosphorus concentrations in the basic-fertilised plots, the need for refertilisation seems to be unnecessary during the 25-year postfertilisation period at least. None of the basic fertilisation treatments seriously retarded the basal area growth compared to the refertilised treatments. There seems to be a greater shortage of potassium than of phosphorus, because the foliar potassium concentrations and the amounts of potassium in the 0–20 cm peat layer were very low in several of the experiments.

Keywords drainage, phosphorus, fertilisation, peat, Scots pine, needles, stand growth
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Received 19 February 1999 **Accepted** 8 September 1999

1 Introduction

As a result of intensive forest drainage, particularly in the 1960's and 70's, over 5 million hectares of peatland have been drained for forestry purposes in Finland. The annual increment of stem volume growth due to drainage is over 10 million m^3 (e.g. Paavilainen and Päivänen 1995).

About 1.37 million hectares of peatland forest are situated on oligo-mesotrophic peatland (Keltikangas et al. 1986), where the nitrogen resources are generally satisfactory. On these sites the pine stands often need additional phosphorus and potassium in order to maintain a balanced nutrient status and good growth (e.g. Kaunisto and Tukeva 1984, Kaunisto et al. 1993, Moilanen 1993). The duration of phosphorus fertilisation is, in addition to that of potassium, a key factor in maintaining sustainable timber production on drained peatland sites with sufficient N, but poor in other macronutrients (Paarlahti and Karsisto 1968, Paavilainen 1977, Paavilainen and Päivänen 1995).

Forests on drained peatlands should preferably be able to grow without fertilisation. On many sites, however, the application of nutrients with long- (e.g. apatite; Kaunisto et al. 1993) or short-term (e.g. wood ash; Ferm et al. 1992) effects will be needed in order to ensure the development of existing stands. Evaluation of the need for nutrient application in peatland forests with a low or lowered productivity is thus an urgent task (see e.g. Moilanen 1992, Veijalainen 1992, Moilanen et al. 1996). About 1.6 million hectares of peatlands have been fertilised at least once, mainly with phosphorus and potassium, although nitrogen and micronutrients have also been applied.

Phosphorus has been recognized as the most important growth-limiting mineral nutrient in drained peatland forests (Lukkala 1955, Huikari 1973, Paarlahti et al. 1971, Reinikainen et al. 1998). On mesotrophic sites especially, the store of phosphorus is often sufficient compared to that of potassium, but there is often a shortage of phosphorus in relation to nitrogen (Kaunisto and Paavilainen 1988, Laiho 1997).

Paarlahti and Veijalainen (1988) found that the effect of phosphorus on a drained low-sedge bog was more important than that of nitrogen or potassium in improving volume growth. The stem volume and basal area development of (NK)P-fertilised Scots pine stands in northern Finland have been intensively studied by Moilanen (1993). The volume growth of PK and NPK-fertilised plots exceeded that of the control by 2–4 m^3/ha/a and the effect lasted for at least 7 years when N_{tot} in the surface peat exceeded 2.1 %. 20–44 kg P per hectare was sufficient for at least 10 years. The effect of phosphorus in refertilisation was generally weaker than that of the basic fertilisation (Moilanen 1993). Veijalainen (1994) reported annual growth increments of 2–2.5 m^3/ha compared to unfertilised stands during the 28-year period after phosphorus fertilisation alone in southern Finland. Finér (1986) reported equal stem volume increases for different P fertilisers – including rock phosphate and superphosphate – after 18 years.

The finely ground PK fertiliser for peatlands used in the 1960's and 70's did not contain water-soluble phosphorus. The leaching of phosphorus from peatlands fertilised with finely ground PK was initially low, but increased with time (Ahti 1983). However, the rapid leaching of phosphorus from the more recent granulated PK fertiliser with 20 % of the phosphorus in soluble form, caused great environmental concern (Paarlahti and Ahti 1988, Nieminen and Ahti 1993). Kaunisto and Paavilainen (1988) observed that high phosphorus doses had probably led to substantial leaching of phosphorus from the site. Possible leaching problems therefore emphasize the importance of the solubility of phosphorus in fertilisers.

In the 1960's a series of experiments with different P-fertilisers, primarily apatite, rock phosphate and superphosphate, were established in Finland (Huikari 1973). The fall in fertilisation costs strongly stimulated the interest in phosphorus fertiliser studies in the 1960's (Huikari 1998). Early reports from some of these experiments (Paarlahti and Karsisto 1968, Karsisto 1976, 1977) revealed that superphosphate gave the strongest initial height growth in Scots pine stands. On the other hand, Paavilainen (1977) found that, within the 10-year period after fertilisation on an oligotrophic site, superphosphate did not increase the radial growth as much as finely ground rock phosphate. According to Penttilä and Moilanen (1987) the origin, water solubility and particle size of the phosphorus fertiliser seemed to be of less importance. Kaunisto et al. (1993) reported that apatite increased growth more slowly than rock phosphate; however, both fertilisers increased the height growth of Scots pine.

High foliar phosphorus concentrations in P-fertilised Scots pine stands support the results of growth measurements, indicating considerably long-term, similar effects for rock phosphate and apatite (Kaunisto et al. 1993, Moilanen 1993). In Sweden, Carlsson and Möller (1985) and Sundström (1995) reported an increase in foliar and peat P concentrations and stand growth, as in the Finnish experiments.

The aim of this study is to determine whether there are any long-term differences (15–34 years) between different types and doses of phosphorus fertilisers 1) in the growth development of Scots pine stands, 2) in the present nutrient status of the tree stands as based on foliar analysis and 3) in the amounts of phosphorus in the surface peat.

2 Material and Methods

2.1 Field Experiments

Eight field experiments, located between latitudes 60° and 65° N and drained for the first time between 1939 and 1976 were chosen for this study (Table 1). The original ditching strip width varied between 20 and 100 m, and the site types from hollow-rich *S. fuscum* bog to tall-sedge pine fen. When fertilised for the first time the sites had been recently drained or in the transitional stage of post-drainage succession. The peat thickness in most cases exceeded one meter. The mean total nitrogen content in the surface peat (0–10 cm) of the control plots varied from 1.05 to 2.61 % (Table 1). At the time of fertilisation the tree stands consisted almost solely of naturally regenerated Scots pine (*Pinus sylvestris* L.) with a median $d_{1,3}$ age of 6–43 years**.** The mean height of the stands varied between 1–15 m, and the current volume growth between 1.8 and 8.1 m^3/ha. There was an admixture of downy birch (*Betula pubescens* Ehrh.) and an undergrowth of Norway spruce (*Picea abies* (L.) Karst. in some of the experiments. Thinnings were not carried out during the study period. Considerable natural removal occurred in the Rautavaara experiment as a result of fungal diseases and nutritional growth disorders. The older pine stands (Heinola, Rautavaara, Kettula) had suffered from damage by a fungus (*Ascocalyx abietina*).

The experimental designs followed the randomized block concept. The basic fertilisations were carried out between 1961 and 1977 (Tables 1 and 2). In all the experiments nitrogen and potassium fertilisation was carried out simultaneously with the phosphorus fertilisation in order to eliminate or prevent a deficiency of nitrogen and potassium. The amounts of different phosphorus fertilisers applied in basic fertilisation were 200–802 kg per hectare, corresponding to 22–66 kg elemental P/ha. Three experiments were fertilised only once and the others twice (Table 2).

The macronutrients applied in refertilisation 1975 (in five experiments) were the same as those in the basic fertilisation. In addition, the plots were given micronutrients (Tables 1, 2). The refertilised experiments in Häädetjärvi, Heinola and Rautavaara form a homogenous group with respect to site type, fertilisation age, drainage and also have an identical experimental design. The lay-out of the Alkkia 2 and Kettula experiments was a split-plot design. The refertilisations were applied on entire plots (Heinola, Häädetjärvi, Rautavaara) or by dividing the original plots into four equal-sized subplots (Alkkia 2, Kettula). The treatments of the experiments were randomized totally or blockwise. The number of replications within the individual experiments varied from 1 to 12.

The types and amounts of fertilisers used are presented in Table 2. The phosphorus in superphosphate was over 90 % water soluble The corresponding figure for apatite was less than 0.1 % and for rock phosphate 0 (J. Issakainen, unpublished). The phosphorus in the multinutrient fertiliser was probably superphosphate. The solubility of phosphorus in polyphosphate is not known. Most of the phosphorus fertilisers were a non-granulated powder consisting of particles with a diameter of less than 1 mm.

Table 1. Basic information about the experiments.

Experiment	Alkkia 66	Puras	Jylkky	Heinola	Häädetjärvi	Rautavaara	Alkkia 2	Kettula
Coordinates (N, E), km	6904 280	7198 619	7199 458	6783 448	6888 276	7026 584	6904 280	6705 319
Elevation a.s.l., m	157	225	71	100	150	200	157	93
Temperature sum, d.d. > 5 °C	1119	888	1134	1275	1131	1024	1119	1286
Peat depth, m	1.5+	1+	1+	1+	2+	2+	1.5+	0.5–1.5
Site type [1]	hollow-rich S. fuscum bog	tall-sedge pine fen	tall-sedge pine fen	dwarf-shrub pine bog	dwarf-shrub pine bog	Carex globularis pine swamp	hollow-rich S. fuscum bog	dwarf-shrub pine bog
Fertility class [2]	6	3–4	3	5	5	4	6	5
N_{tot} in peat (0–10 cm), %	1.41	1.24	2.61 °	1.94	1.22	1.29	1.21	1.05
N_{tot} in peat (10–20 cm), %	1.31	1.62	2.86 °	1.76	1.45	1.65	1.19	0.74
Stand height, m	n.d.	1–5	1–4	3–15	7–10	6–12	6–7	3–11
Stand age ($D_{1.3}$), years *	n.d.	15	20	35	60	40	30	n.d.
Basic drainage	1940	1976	1939	1938	1939	1963	1940	1959
Strip width, m	20	20–30	20	80	70	65–100	20	35–40
First fertilisation	VI–VII 1968	XI 1977	VI 1975	VI 1966	VII 1965	VI 1965	VII 1961	V 1961
Treatments	4	4	9	5	5	5	6	6
Replications	12	3	3	3	3	3	2–3	1–4
Plot area, m^2	100	650–1340	400	400	400	400	600	250, 500
Plots	48	12	27	15	15	15	17	13
Refertilisation	none	none	none	V 1975	VII 1975	VI 1975	VII 1975	V 1972, 75

[1] Laine and Vasander 1990
[2] Huikari 1952

$D_{1.3}$ = breast height at 1.3 m
n.d. = not determined

* = when measured
° = all plots

Table 2. Types and amounts (gross kg/ha) of fertilisers used.

Fertiliser	Particles Ø mm	Element %	Alkkia 66	Puras	Jylkky	Heinola	Häädetjärvi	Rauta-vaara	Alkkia 2	Kettula
Basic fertilisation										
KCl	0.2–0.5	K 49.8	200	100	62 124 187	65 130 195	65 130 195	65 130 195	200	100 200
Urea	1–3	N 46.3	200	-	81 162 243	200	200	200	-	-
Amm. nitrate with lime	3	N 25	-	-	-	-	-	-	400	400
Montan saltpetre	2.8	N 26	-	-	-	-	-	-	-	385
Multinutrient fertiliser (Mf)	3	15-8.8-7.5	-	-	125–750	-	-	-	-	-
Superphosphate (Ps) x)	2.6	P 8.3–8.8	600	500	-	535 802	535 802	535 802	267 535 802	630
Rock phosphate (Pr) y)	0.2–1.0	P 14.5	360	300	-	304 457	304 457	304 457	-	-
Apatite	0.1–0.3	P 11.3	350	386	-	-	-	-	267 535 802	-
Polyphosphate (Pp)	n.d.	P 15.2	-	-	75–450	-	-	-	-	-
Refertilisation										
KCl	0.2–0.5	K 49.8	-	-	-	200	200	200	200	200
Urea	1–3	N 46.3	-	-	-	216	216	216	216	216
Superphosphate	2.6	P 8.8	-	-	-	500	500	500	250 500 750	375
Rock phosphate	0.2–1.0	P 14.5	-	-	-	304	304	304	150 300 450	235
Apatite z)	0.3–1.0	P 10	-	-	-	-	-	-	216	-
Micronutrient mixture	n.d.	Mn Cu B	-	-	-	33	33	33	50	50

x) = powder 0.3–0.6, granules 2.6 y) Morocco z) Sokli, Finland

Rock phosphate and superphosphate were compared in all the experiments except that in Jylkky. Apatite was included in Alkkia 2, Alkkia 66 and in Puras. Polyphosphate, especially imported from France, and a multinutrient ("normaali super Y" containing N, P and K) fertiliser from Kemira Ltd were used only in Jylkky.

2.2 Sampling, Chemical Analyses and Statistical Treatment of the Material

When the experiments were evaluated, in 1993–94, 15 to 34 years had elapsed since the first fertilisation. The total number of sample plots (stand measurement, needle and peat samples) was 162. *Peat sampling* was carried out in autumn 1993. One sample consisted of 5 volumetric subsamples, four of which were taken along the diagonals of the plot and one at the crossing point. Ditch spoil and hummocks were avoided. The peat samples were taken from the 0–10 (humus layer included) and 10–20 cm layers. In Heinola and Kettula the humus layer was sampled separately, but added to the 0–10 cm peat layer. The samplers were of a type used in peat sampling at the Finnish Forest Research Institute (e.g. Kaunisto et al. 1993). The total peat sample volume [area × 10(depth) × 5(subsamples)] per plot varied, depending on the sampler, between 912 and 1237 cm^3. After drying and weighing, the bulk density and nutrient concentrations of the peat samples were determined according to Halonen et al. (1983). The total nitrogen concentration was determined by the Kjeldahl method. Total K, Ca, Mg, Mn, Fe, Zn, Cu, and Al concentrations were analysed by dry digestion followed by determination by AAS and for P and B spectrophotometrically. Soluble phosphorus (extracted with 1M ammonium acetate pH 4.65) was determined by ICP/AES. The nutrient concentrations were expressed per dry mass of peat. The nutrient amounts per hectare were calculated using the (dry) bulk density of the peat samples.

Foliar sampling was mainly carried out in March 1993 and 1994, and at Alkkia 66 already in 1991. Current needles from 4–10 Scots pines per plot were taken from the topwhorls of dominant and co-dominant pines according to Veijalainen (1992). The needles were dried for 24 hours at 65 °C. The N (Kjeldahl), K Ca, Mg, Fe, Mn, Zn, and Cu (AAS), P and B (spectrophotometrically) concentrations were determined according to Halonen et al. (1983).

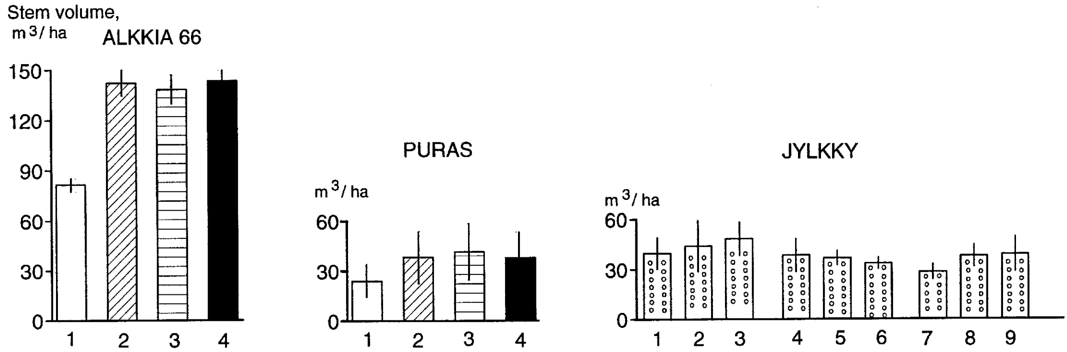
Measurements of the tree stands were carried out in 1993 and 1994. All trees with $d_{1.3} > 4.5$ cm were tallied. Total height and the height growth durig 5-year periods were measured with an accuracy of 10 cm. $D_{1,3}$ was measured crosswise to an accuracy of 1 mm, and increment cores were taken from the sample trees. The stem number per hectare varied from 100 to 2400, and the number of sample trees was 2–23 per plot. In some experiments the small size of the plots and the lack of buffer zones made sampling difficult and reduced the number of sample trees. The age at breast height was determined in five experiments by boring into the heartwood of every 5th sample tree. Circular plots were used in some cases in Puras and in Kettula (r = 10 and 7 m).

BMDP, Systat and SPSS programs were used in the statistical analysis. The results were analyzed both jointly and separately for each experiment using analysis of variance. The pairwise comparison of treatment means was made with the Bonferroni test. Current stem volume and growth (m^3/5 years/ha) were calculated using the KPL programme (Heinonen 1994). Basal area growth was tested for the whole and for the last 5 years of the study period. The basal area growth preceding fertilisation was also tested as a covariate.

3 Development of the Tree Stands

3.1 Experiments Fertilised Once

The *stem volume* of the tree stands in the fertilised treatments in Alkkia 66 and Puras (after 25 and 15 years) were clearly higher than in the control plots (Fig. 1). The differences between apatite, rock phosphate and superphosphate were, however, non-significant. In Jylkky the total stem volume varied between 28.4 and 48.3 m^3/ha. The differences between the individual fertilisation treatments and the three types of phospho-



Treat-ment	1968 N (kg/ha)	K	P
1 Control	-	-	-
2 Apatite	92	100	52
3 Pr	92	100	52
4 Ps	92	100	52

Treat-ment	1977 K (kg/ha)	P
1 Control	-	-
2 Apatite	50	44
3 Pr	50	44
4 Ps	50	44

Treatment	1975 N (kg/ha)	K	P
1 Mf	37	31	22
2 Mf	75	62	44
3 Mf	112	93	66
4 Pp+KCl+Urea	37	31	22
5 Pp+KCl+Urea	75	62	44
6 Pp+KCl+Urea	112	93	66
7 Pp+Mf	19	16	22
8 Pp+Mf	38	32	44
9 Pp+Mf	57	48	66

Fig. 1. Current stem volume ($\bar{x}$ ± S.E.) in the experiments fertilised once. For abbreviations, see Table 2.

rus fertilisers were statistically also non-significant in Jylkky. There was no significant interaction between the phosphorus levels (including N and K) and type of phosphorus fertiliser.

The *basal area growth* in Alkkia 66 was highest with apatite, particularly during the last five years (Fig. 2). In Puras, apatite was inferior to rock phosphate and superphosphate (Fig. 2). The basal area growth (18 years) in Jylkky was lowest in the treatments with the lowest P and NK doses. The multinutrient fertiliser increased basal area growth at all three phosphorus levels more than polyphosphate (Fig. 2). Polyphosphate (P = 22 kg/ha) was the weakest individual treatment. The effect of the polyphosphate + multinutrient fertiliser mixture was intermediate.

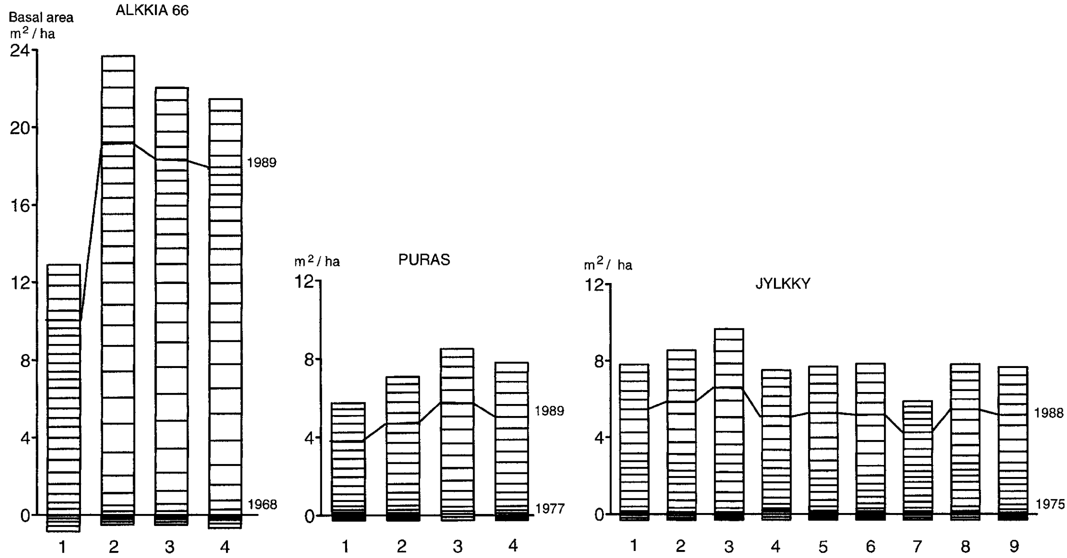
There were no significant differences between the treatments, in either total post-fertilisation basal area growth or during the last five years, at Alkkia 66, Puras and Jylkky.

3.2 Refertilised Experiments

The current *stem volume* in the three experiments with an identical fertilisation design (Heinola, Häädetjärvi, Rautavaara) showed considerable variation both between and within the individual experiments (Fig. 3). After 25 years, the effects of the fertilisation treatments non-significant. Only in Rautavaara the stem volumes were throughout higher than in the control plots. Refertilisation seemed to increase the stem volume of the superphosphate-fertilised stands, but not in the stands fertilised with rock phosphate.

The post-fertilisation *basal area development,* as well as that during the last five years, revealed no significant differences between the fertilisation treatments (Fig. 4). Refertilisation increased tree growth on the superphosphate plots only slightly more than on the rock phosphate plots (Häädetjärvi, Rautavaara).

In the early 1980s’ the tree growth was impaired by *Ascocalyx abietina,* especially on the fertilised plots (also Kaunisto 1989). It should be noted that the tree stands in Heinola, Häädetjärvi and Rautavaara have a relatively high mean age (Table 1). The generally low basal area growth in Heinola is also due to the fact that birch and



Treatment	1968 N kg / ha	1968 K kg / ha	1968 P kg / ha
1 Control	-	-	-
2 Apatite	92	100	52
3 Pr	92	100	52
4 Ps	92	100	52

Treatment	1977 K kg / ha	1977 P kg / ha
1 Control	-	-
2 Apatite	50	44
3 Pr	50	44
4 Ps	50	44

Treatment	1975 N kg / ha	1975 K kg / ha	1975 P kg / ha
1 Mf	37	31	22
2 Mf	75	62	44
3 Mf	112	93	66
4 Pp+KCl+Urea	37	31	22
5 Pp+KCl+Urea	75	62	44
6 Pp+KCl+Urea	112	93	66
7 Pp+Mf	19	16	22
8 Pp+Mf	38	32	44
9 Pp+Mf	57	48	66

Fig. 2. Cumulative basal area development for Scots pine in the experiments fertilised once.

spruce were omitted from the calculations.

The *stem volume* in Alkkia 2 reflect the importance of applying phosphorus in the basic fertilisation. The plots that received no phosphorus in the 1975 refertilisation had higher stem volumes than the NK plots. The stem volume on the control and NK-fertilised plots was 76 and 98 m^3/ha, while on the apatite plots it was 168 and on the superphosphate plots 132 m^3/ha (Fig. 3). The refertilised apatite plots had a lower stem volume than the unrefertilised ones, while the opposite was true for superphosphate (Fig. 3).

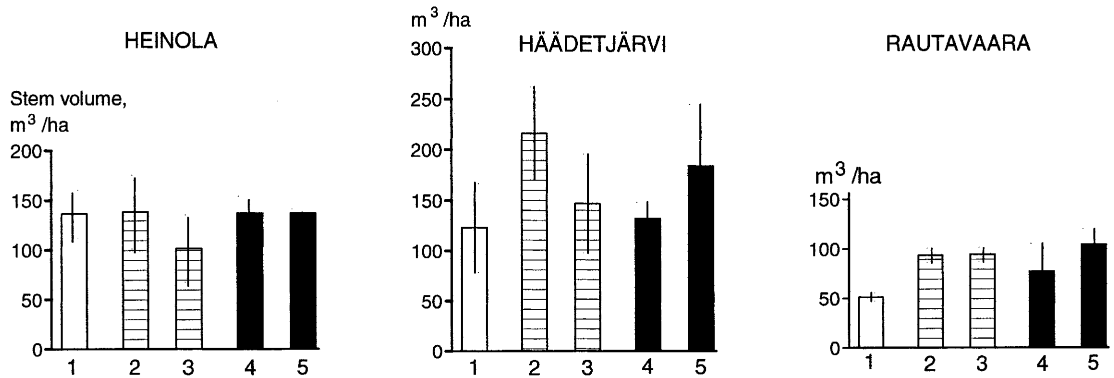
The volumes in the different treatments *Kettula* varied between 24 and 120 m^3/ha. Phosphorus fertilisation only slightly increased the stem volume compared to NK. On the average the stem volumes were 54, 37 and 49 for the control, NK and NK+P, respectively (Fig. 3).

The *basal area growth* with apatite and superphosphate in Alkkia 2 before refertilisation in 1975 was almost equal. The effect of apatite given in basic fertilisation probably continued as the refertilisation did not increase growth (Fig. 4). After refertilisation, the growth increased the most on the superphosphate plots. The difference (1975–1992) between apatite and superphosphate, as well as in the last five years' growth, was still non-significant.

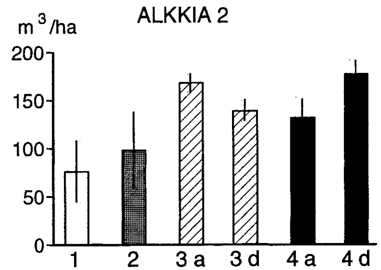
4 Foliar Nutrient Concentrations

4.1 Experiments Fertilised Once

The foliar phosphorus concentrations in *Alkkia 66* and *Puras* were significantly higher on the apatite, rock phosphate and superphosphate plots

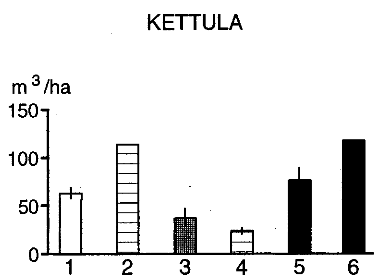


Treat-ment	1965 N	1965 K (kg/ha)	1965 P	1975 N	1975 K (kg/ha)	1975 P
1 Control	-	-	-	-	-	-
2 Pr	92	96	66	100	100	-
3 Pr	92	64	44	100	100	44
4 Ps	92	96	66	100	100	-
5 Ps	92	64	44	100	100	44



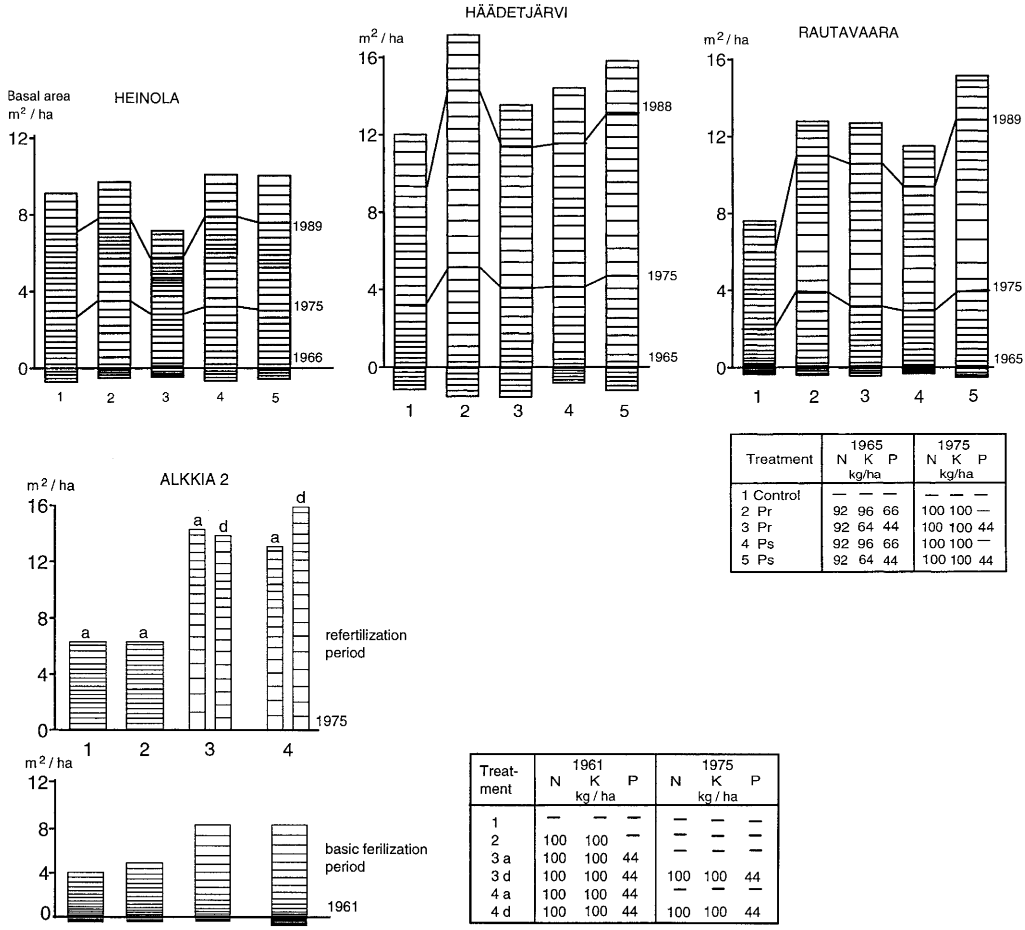
Treat-ment	1961 N	1961 K (kg / ha)	1961 P	1975 N	1975 K (kg / ha)	1975 P
1	-	-	-	-	-	-
2	100	100	-	-	-	-
3 a	100	100	44	-	-	-
3 d	100	100	44	100	100	44
4 a	100	100	44	-	-	-
4 d	100	100	44	100	100	44

3 = apatite; 4 = Ps



Treat-ment	1961 N	1961 K (kg / ha)	1961 P	1975 N	1975 K (kg / ha)	1975 P
1 Control	-	-	-	-	-	-
2 Pr	-	-	-	100	100	33
3 NK	100	50	-	-	-	-
4 Pr	100	100	-	100	100	33
5 Ps	100	100	52	-	-	-
6 Ps	100	100	52	100	100	33

Fig. 3. Current stem volume ($\bar{x} \pm$ S.E.) in the refertilised experiments.



Treatment	1965 N	K	P kg/ha	1975 N	K	P kg/ha
1 Control	—	—	—	—	—	—
2 Pr	92	96	66	100	100	—
3 Pr	92	64	44	100	100	44
4 Ps	92	96	66	100	100	—
5 Ps	92	64	44	100	100	44

Treat-ment	1961 N	K	P kg / ha	1975 N	K	P kg / ha
1	—	—	—	—	—	—
2	100	100	—	—	—	—
3 a	100	100	44	—	—	—
3 d	100	100	44	100	100	44
4 a	100	100	44	—	—	—
4 d	100	100	44	100	100	44

3 = apatite 4 = superphosphate

Fig. 4. Cumulative basal area development for Scots pine in the refertilised experiments. At Alkkia 2 P 44 kg/ha is the mean of 22, 44 and 66 kg P/ha levels.

than on the control plots, 23 and 15 years after fertilisation. The phosphorus concentrations were still relatively low. The differences between the phosphorus fertilisers were statistically non-significant (Table 3).

The potassium and especially the nitrogen concentrations in Alkkia 66 were high, indicating good nitrogen availability. Fertilisation significantly lowered the manganese, zinc and boron concentrations, but increased the magnesium concentrations. In Puras the stands suffered from N and K deficiency.

In *Jylkky* the foliar phosphorus concentrations increased along with the phosphorus dose. Plots given 22 kg P/ha had foliar phosphorus concentrations under the deficiency limit, 1.13 g/kg. The 44 and 66 kg P/ha levels resulted in significantly higher foliar phosphorus concentrations, 1.36 and 1.57 g/kg, respectively. Polyphosphate increased foliar P concentrations to a somewhat lower extent than the multinutrient fertiliser (Table 3). No interaction was found between the fertiliser type and the phosphorus dose.

The foliar nitrogen concentrations were between 1.22 and 1.53 % (Table 3), thus indicating a relatively low supply of nitrogen. Despite the potassium application the K concentrations were in all cases below the severe potassium deficien-

Table 3. Foliar nutrient concentrations in the experiments fertilised once. Underlining means significant deviation from the control. * = p < 0.05, ** = p < 0.01 and *** = p < 0.001.

Fertilisation (kg/ha)	N	K	P	N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	B
				%	g/kg				mg/kg				
Alkkia 66													
1 Control	-	-	-	1.89	1.18	3.96	2.23	1.27	n.d.	482	68	3.7	12.1
2 Apatite	92	100	52	1.66	1.32	3.79	2.19	1.36	n.d.	408	55	3.5	8.4
3 Pr	92	100	52	1.71	1.41	3.63	2.19	1.52	n.d.	393	57	3.6	10.0
4 Ps	92	100	52	1.58	1.44	3.99	2.35	1.48	n.d.	354	58	3.5	9.5
F-value				4.72**	4.52**	1.80	0.57	4.70**	n.d.	3.37*	4.85**	0.56	4.89**
Puras													
1 Control	-	-	-	1.18	1.46	4.27	1.92	1.15	47	368	57	3.4	14.8
2 Apatite	-	50	44	1.26	2.15	4.89	2.16	1.22	42	267	49	3.2	20.4
3 Pr	-	50	44	1.22	2.17	5.05	1.94	1.12	44	216	47	3.2	15.6
4 Ps	-	50	44	1.23	1.79	4.38	1.75	1.19	42	283	48	3.0	15.7
F-value				0.98	4.44*	2.10	0.74	0.77	1.14	1.57	2.19	0.46	0.28
Jylkky													
1 Mf	37	31	22	1.41	1.22	2.89	1.18	1.11	36	199	41	3.1	13.9
2 Mf	75	62	44	1.35	1.48	3.18	1.11	1.06	35	172	34	2.6	14.3
3 Mf	112	93	66	1.34	1.63	2.96	1.16	1.07	31	150	32	2.6	12.1
4 Pp+KCl+U	37	31	22	1.53	1.10	3.21	1.19	1.05	32	177	44	3.1	11.2
5 Pp+KCl+U	75	62	44	1.49	1.20	2.95	1.35	1.09	33	191	40	2.8	11.6
6 Pp+KCl+U	112	93	66	1.22	1.56	3.12	1.10	0.97	40	141	36	2.7	7.3
7 Pp+Mf	19	16	22	1.40	1.07	2.68	1.32	1.19	30	250	40	2.8	14.5
8 Pp+Mf	38	32	44	1.23	1.42	2.67	1.13	1.11	30	169	33	2.5	13.1
9 Pp+Mf	57	48	66	1.30	1.54	2.59	1.03	1.00	30	169	31	2.8	13.1
F-value				1.86	5.48**	2.58*	0.92	1.29	0.86	1.86	2.58*	0.93	2.41

cy limit (Veijalainen 1992, Sarjala and Kaunisto 1993).

4.2 Refertilised Experiments

The foliar phosphorus concentrations in the fertilised treatments (*Heinola*, *Häädetjärv*i and *Rautavaara* combined) were significantly higher than those on the control plots (cf. Table 4). Significant differences between the experiments were observed, but no interaction between fertilisation and the experiment. The differences between rock phosphate and superphosphate were statistically non-significant. The foliar phosphorus concentrations were still above the deficiency limit (Paarlahti et al. 1971), 25 years after fertilisation. The refertilised (rock and superphosphate) plots did not have significantly higher foliar phosphorus concentrations than the corresponding basic-fertilised treatments or control plots (Table 4).

The foliar nitrogen concentration on the control plots at Heinola was sufficient, but lower in Häädetjärvi and Rautavaara (Table 4) and indicated nitrogen deficiency (< 1.3 mg/g, Reinikainen et al. 1998) The potassium concentrations were at a satisfactory level and no significant changes caused by basic or refertilisation were observed.

In Alkkia 2 severe phosphorus deficiency (P 1.12 and 1.14 g/kg) was found on the control and NK plots (Table 4). Plots given apatite and superphosphate in the basic fertilisation still had higher needle phosphorus concentrations (1.27 and 1.24 g/kg) than the control and NK treatments. On the refertilised (apatite, superphos-

Table 4. Foliar nutrient concentrations in the refertilised experiments. Time elapsed since basic fertilisation is more than 25 years. Underlining means significant deviation from the control. * = p < 0.05, ** = p < 0.01 and *** = p < 0.001.

Fertilisation treatment	1966			1975			N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	B
	N	K	P	N	K	P	%	g/kg				mg/kg				
Heinola																
1 Control	-	-	-	-	-	-	1.44	1.37	4.52	2.21	1.11	28.4	213	41.1	3.0	22.6
2 Pr	92	96	66	100	100	-	1.48	1.54	4.68	2.54	1.12	27.1	240	38.6	2.5	23.1
3 Pr	92	64	44	100	100	44	1.52	1.53	4.61	2.16	1.05	28.3	192	31.8	2.6	20.0
4 Ps	92	96	66	100	100	-	1.51	1.50	4.81	2.51	1.03	30.0	194	40.4	2.8	21.8
5 Ps	92	64	44	100	100	44	1.42	1.54	4.64	2.07	0.99	29.1	171	35.6	2.6	17.0
F-value							0.33	2.60	0.10	0.64	2.98	0.51	0.35	0.61	0.37	1.21
Häädetjärvi																
1 Control	-	-	-	-	-	-	1.23	1.29	3.88	1.41	1.12	26.9	192	38.5	3.2	19.0
2 Pr	92	96	66	100	100	-	1.31	1.48	4.31	1.46	1.09	28.8	198	32.8	2.7	17.2
3 Pr	92	64	44	100	100	44	1.35	1.54	4.25	2.03	1.28	26.2	183	34.5	2.9	18.4
4 Ps	92	96	66	100	100	-	1.34	1.48	4.34	1.52	1.03	27.5	158	36.3	2.9	18.4
5 Ps	92	64	44	100	100	44	1.27	1.46	4.28	1.44	1.02	24.4	151	31.1	2.4	17.8
F-value							1.53	3.17	0.95	4.81*	0.63	1.27	0.58	1.47	2.36	0.13
Rautavaara																
1 Control	-	-	-	-	-	-	1.15	1.59	4.76	2.40	1.16	26.8	448	49.2	3.5	23.3
2 Pr	92	96	66	100	100	-	1.30	1.89	4.76	2.35	1.29	25.9	320	46.4	3.4	20
3 Pr	92	64	44	100	100	44	1.17	1.81	4.76	2.49	1.27	27.1	347	43.1	3.3	17.4
4 Ps	92	96	66	100	100	-	1.16	1.58	4.50	2.29	1.14	25.7	328	46.2	3.1	20.4
5 Ps	92	64	44	100	100	44	1.25	1.74	4.54	2.28	1.21	25.6	275	42.5	3.3	18.8
F-value							0.30	0.67	1.06	0.30	1.31	0.71	1.27	1.62	0.02	0.53
Alkkia 2																
1 Control	-	-	-	-	-	-	1.54	1.12	4.44	1.81	0.90	33.6	263	53.2	3.5	17.3
2 NK	100	100	-	-	-	-	1.55	1.14	4.29	1.76	0.82	37.3	313	54.6	3.5	15.2
3 a Apatite	100	100	44	-	-	-	1.49	1.27	3.89	1.56	0.96	36.7	190	47.2	4.0	15.4
3 d Apatite	100	100	44	100	100	44	1.46	<u>1.56</u>	3.81	1.46	0.91	33.2	<u>127</u>	35.4	2.5	13.1
4 a Ps	100	100	44	-	-	-	1.51	1.24	3.58	1.54	0.98	37.2	<u>166</u>	43.6	2.9	14.8
4 d Ps	100	100	44	100	100	44	1.45	<u>1.54</u>	3.80	1.58	0.93	36.0	<u>171</u>	37.6	2.4	<u>12.0</u>
F-value							0.11	8.60**	2.27	0.90	2.64	0.45	13.8***	2.26	2.89	3.75*
P 44 is the mean of 22, 44 and 66 kg P/ha levels																
Kettula																
1 Control	-	-	-	-	-	-	1.21	1.10	3.66	2.22	1.22	50.6	314	73.7	4.4	20.5
2 Pr	-	-	-	100	100	33	1.39	1.44	4.23	1.66	1.07	39.0	262	61.7	2.6	15.9
3 NK	100	50	-	-	-	-	1.22	1.24	4.17	1.93	1.30	41.1	284	66.3	3.9	20.4
4 Pr	100	100	-	100	100	33	1.30	1.39	3.31	1.77	1.26	40.6	298	57.2	3.0	19.1
5 Ps	100	100	52	-	-	-	1.28	1.49	4.14	2.45	1.40	51.0	245	62.5	4.0	22.1
6 Ps	100	100	52	100	100	33	1.40	1.30	3.43	2.00	1.41	38.2	296	77.3	3.4	16.8

phate 44 kg/ha) plots the concentrations were higher than those on the unrefertilised plots. The plots at Kettula not given phosphorus (P–) had needle phosphorus concentrations below the deficiency limit and were lower than those on the (P+) plots (Table 4).

According to the site type and nitrogen concentration in the surface peat (*Sphagnum fuscum* bog, 1.05 % and dwarf shrub pine bog, 1.21 %) Alkkia 2 and Kettula were infertile. The relatively high foliar nitrogen concentrations in the pine stands at Alkkia 2 indicated that they were not suffering from nitrogen deficiency (Table 4). The K, Mn and B concentrations were lower in the apatite and superphosphate treatments than in the control and NK treatment, while the differences between the two P-fertilised treatments were small.

The range of the foliar nitrogen concentrations at Kettula was 1.21–1.40 % (Table 4). The needle potassium concentrations were in most cases below the deficiency limit.

5 Nutrients in the Peat

5.1 Experiments Fertilised Once

The fertilised plots at Alkkia 66 and Puras had approximately the same amounts of phosphorus as the control (Fig. 5). The fertilised plots at Alkkia 66 contained 65–157 kg P/ha, while the average was 105 kg for the control plots (Appendix 1). Thus, there was apparently little surplus phosphorus left in the P-fertilised plots 23 years

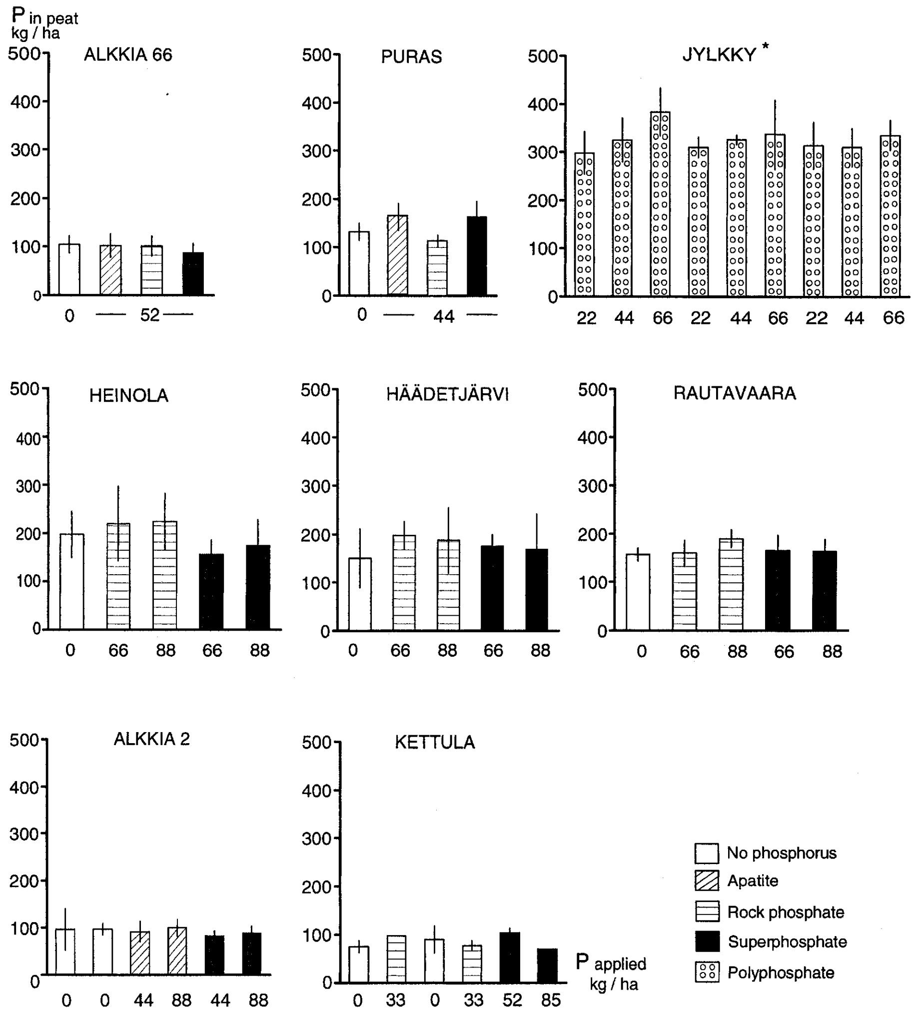


Fig. 5. Total amounts of phosphorus, $\bar{x}$ ± S.E. by treatment, in the peat layer 0–20 cm. * = no control plots.

after fertilisation. About 20 % of the total phosphorus was in a soluble form (Appendix 1). At Puras the range for the fertilised plots was 106–192 P kg/ha, and 132 kg for the control.

The nitrogen stores in the control plots at Alkkia 66 and Puras were about 2500 kg/ha, and that of potassium 84 and 51 kg/ha (Appendix 1). The potassium store was lower in the fertilised plots than in the control plots.

In *Jylkky* the amounts of phosphorus were high, over 300 kg/ha, and they correlated well with the phosphorus doses applied (22, 44 and 66 kg/ha; Fig. 5). The multinutrient fertiliser increased the phosphorus stores more than polyphosphate. The amounts of soluble phosphorus were extremely low in all the treatments, probably due to the large amounts of iron in peat (between 2000 and 4000 kg/ha, Appendix 1).

The nitrogen concentration in peat (0–20 cm) in Jylky exceeded 2,5 %, corresponding to 8500 kg N/ha and was by far the highest in this study (see Fig. 6)., The potassium stores were in sharp contrast to nitrogen, very low, 36–53 kg/ha. The amounts of Ca, Mg and the microelements B, Mn and Zn were the lowest in this study. Despite fertilisation Jylkky is still a site with strong nutrient imbalances in the soil.

5.2 Refertilised Experiments

The range in the amount of phosphorus in the fertilised plots at *Heinola*, *Häädetjärvi* and *Rautavaara* was 102–309 kg *P* /ha in the 0–20 cm peat layer (Appendix 1). Basic fertilisation (P = 66 kg/ha) did not significantly increase the amount of phosphorus compared to the control. The refertilised (P 44+44 = 88 kg/ha) treatments did not differ significantly from the basic fertilisation treatments or the control (Fig. 5).

The whole range of nitrogen was 2121–5745 kg/ha and of potassium 50–231 kg/ha (Appendix 1).

At *Alkkia 2* the control plots contained 96, and the fertilised plots 69–112 kg P/ha. The amounts of P in the basic and refertilised plots were at the same level as in the control plots (Fig. 2). The whole nitrogen range was 1550–2924 kg/ha. The amount of potassium was 80 kg/ha in the control plots and 29–152 kg in the fertilised plots (Appendix 1).

The control plots at *Kettula* had 75 and the NK plots 97 kg P/ha, which was approximately the same as the P-fertilised plots (Fig. 5). The range of nitrogen was 1000–2595 and that of potassium 35–138 kg/ha (Appendix 1).

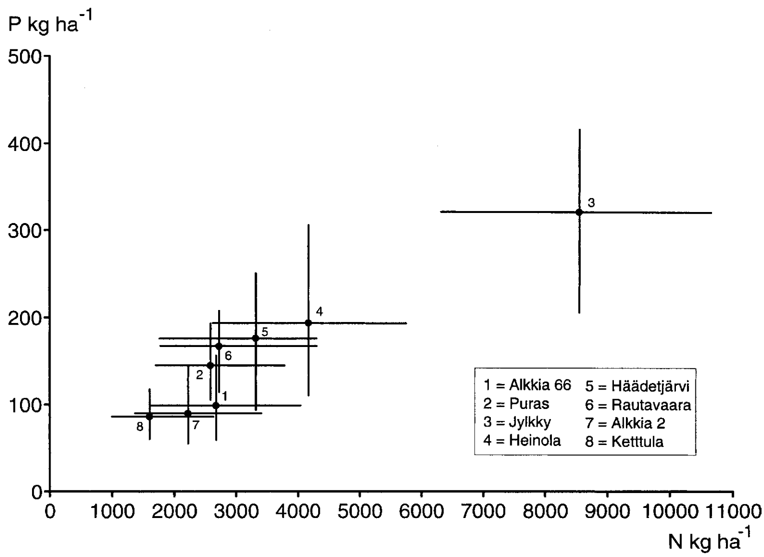


Fig. 6. The amount of N_{tot} and P_{tot} in the 0–20 cm peat layer. Means, min. and max. (for plots) are marked.

Table 5. Correlations for current basal area growth (m^2/ha/5a) versus peat (kg/ha 0–10 cm) and foliar nutrients. For site types, see Table 1.

Field		Alkkia 66	Jylkky	Häädetjärvi
Peat	P_{sol}	-	–.381*	-
	Ca_{tot}	.357*	.583***	-
	Fe_{tot}	-	–.663***	-
Foliar	P	-	.672***	-
	Ca	-	-	–.538*
	B	–.549***	-	-

Significance levels:
- not significant. * 5%; ** 1% and *** 0.1%.

Only a few peat and foliar nutrients correlated positively with the basal area growth during the last five years. The significant correlations between the current basal area growth and the nutrient variables are presented in Table 5. The experiment at Jylkky had the most and the strongest correlations. The positive correlations with calcium are due to the fact that the Ca content of rock phosphate is 38 % and of (Siilinjärvi) apatite 22 % (Paavilainen 1979, Karsisto 1976).

The amounts of total P and N in the peat correlated strongly with each other, both within the indidvidual experiments and in the whole material (Fig. 6).

Discussion

The sites studied represent nutrient-poor drained peatlands in Finland (Huikari 1952, Keltikangas et al. 1986). The very low infertility and scarce nitrogen resources in most of the experiments was a disadvantage, despite the nitrogen fertilisation(s), when performing this study. The effect of different phosphorus fertilisers is not easy to evaluate when nitrogen (and potassium), instead of phosphorus, is the growth-limiting element.

The design of the experiments did not include treatments with only phosphorus fertilisation and there were only a few with NK alone. Evaluation of the effects of the basic fertilisation was also complicated by the refertilisations in 1975 with N, P, K and microelements. The study on the duration of basic fertilisation was hampered by this in some of the experiments.

This study did not reveal any major differences between the effects of apatite, rock phosphate and superphosphate. There were only a few significant differences between the phosphorus fertilisers with respect to tree growth, and foliar and peat nutrients. Apatite seemed to be equal to rock phosphate and superphosphate particularly during the last five years of the study period (see also Penttilä and Moilanen 1987). Apatite thus seems to be a suitable source of phosphorus, (also Kaunisto et al. 1993) and is used as the phosphorus compartment in PK-fertilisers by Kemira Ltd. The solubility of the phosphorus in the fertilisers seems to be of minor importance as regards stand development. Superphosphate was almost as effective as rock phosphate and apatite even at the end of the study period. Superphosphate has not been recommended in peatland forests because of the rapid leaching of phosphate after application (e.g. Karsisto 1968).

Karsisto (1977) developed a model for the duration of the fertilisation effect of phosphorus fertilisers containing different proportions of water soluble phosphorus. This concept does not completely fit with the growth results obtained here, particularly in the case of superphosphate, as the differences between the P fertilisers used were non-significant. Foliar nutrient deficiencies and imbalances (N, P, K) and a need for refertilisation primarily occurred on the originally open mire sites.

Potassium, rather than phosphorus, seemed to be the critical element, according to both the foliar analyses and the low amounts of K in the surface peat. The potassium given in both the basic and refertilisation probably had a transitory effect on foliar concentrations (see Kaunisto 1988, Kaunisto and Tukeva 1984, Moilanen 1993). The use of biotite might ensure a sufficient, and long-lasting availability of potassium (Kaunisto 1992).

The response to the fertilisation treatments was strongest in the needles, weaker in tree growth and negligible in the surface peat. Foliar analysis seems to be a reliable method for evaluating the nutritional status of pine stands (Paarlahti et al.

1971, Veijalainen 1992, Reinikainen et al. 1998). Basal area growth, however, generally did not correlate with foliar nutrient concentrations and amounts in the peat. Stand growth does not correlate with the foliar concentrations of individual nutrients, if other nutrients are minimum growth factors (Paarlahti et al. 1971). It is difficult to determine the optimum time of refertilisation with respect to current growth, as there were few clear signs of decreasing growth on the basic-fertilised plots.

Phosphorus + NK fertilisation increased tree growth in most of the experiments. Unfortunately, a simple P+ vs P– comparison was possible only in Alkkia 2. A surprisingly high stem volume was obtained with basic fertilisation (1961–1993) on this hollow-rich *S. fuscum* bog. Compared to NK fertilisation the increase resulting from apatite (44 kg/ha) alone was 2.1 m^3/ha per year. The oligotrophic pine bogs generally had a weak growth response to fertilisation. The experiments on the pine fens (Puras, Jylkky) were too young to permit conclusions to be drawn on the duration of the effect influence, and this should be followed up.

Refertilisation with rock phosphate and apatite in most cases only slightly increased the basal area growth. Even repeated fertilisation with N, P and K (N 192, K 164 and P 88 kg/ha) gave only a non-significant increase in basal area growth and stem volume. The stands fertilised for the first time with apatite seemed to gain less benefit from refertilisation than the superphosphate plots. The current basal area growth on the unrefertilised plots does not reveal any substantial weakening in the growth response, despite the low foliar nutrient concentrations and the low nutrient reserves in the surface peat. The growth is only slightly lower than on the refertilised plots. This indicates that apatite has a long-lasting growth effect (see also Kaunisto et al. 1993). Somewhat surprisingly, superphosphate seemed to increase growth in a similar manner as rock phosphate and apatite. Within 20 or more years after basic phosphorus fertilisation there will probably not be a need for phosphorus refertilisation.

A deficiency of phosphorus in the needles was found on the control plots of all the experiments, except that at Rautavaara. The effect of phosphorus fertilisation on the foliar phosphorus concentrations was strong and long-lasting. At Puras 44 kg P/ha provided enough phosphorus for at least 15 years, but at Jylkky only the highest dose (66 kg P/ha), maintained a sufficient foliar phosphorus concentration 18 years after fertilisation. On the basic fertilised (66 kg P/ha) pine bog plots only slight signs of phosphorus deficiency were observed after 28 years. On the hollow-rich *S. fuscum* bogs phosphorus deficiency occurred 23 and 31 years after basic fertilisation (P 52 and 44 kg/ha). On the refertilised (1975) plots the foliar phosphorus concentrations were insignificantly or not higher than those on the unrefertilised plots.

The foliar nitrogen concentrations on the unfertilised plots were sufficient only at Alkkia 66, Jylkky and Heinola. A deficiency of potassium was found on originally open or sparsely treed mires (Alkkia 66, Alkkia 2, Jylkky), as well as at Häädetjärvi and Kettula. Thus the initial N and K-fertilisation was highly necessary in these experiments. However, fertilisation with potassium probably had only a weak or transitory effect on the potassium concentrations (Kaunisto and Tukeva 1984, Moilanen 1993). Scots pine stands on drained, nutrient-poor pine bogs are generally not considered very susceptible to micronutrient deficiencies (Kolari 1983). The foliar Mn, Zn, Cu and B concentrations were at a satisfactory level, because even the control plots received micronutrients in 1975. In several experiments phosphorus fertilisation lowered the concentrations of Zn in particular.

The range of total nutrients in the whole material (by plots, 0–20 cm) was 63–440 for P, 1000–10712 for N and 29–231 kg/ha for K. The relationship between nitrogen and phosphorus was linear along the trophic gradient. There were only a few significant differences between the treatments, although the amounts given were often considerable compared to the amounts in the unfertilised plots. A slight surplus of phosphorus and potassium after fertilisation was found in the surface peat of the younger, once fertilised experiments and also in the refertilised treatments. The figures obtained for P agree rather well with earlier results for drained peatlands (e.g. Kaunisto and Paavilainen 1988, Laiho and Laine 1995).

The antagonism between elements in the soil that affects the foliar concentrations of nutrients, particularly phosphorus, was most evident at Jylkky. The large amount of iron (about 3000 kg/ha) was probably the reason for the low concentrations of foliar P and soluble P in the surface peat, despite the high amounts of total phosphorus (> 300 kg/ha). Increasing iron amounts in the peat reduce the leaching of phosphorus (Nieminen and Jarva 1996), but simultaneously reduces its solubility in peat and uptake by the trees. There was also a strong negative correlation between stand growth and iron in peat at Jylkky.

17 to 55 years had elapsed since the first drainage at the time of peat sampling; 32 years had passed since the first basic fertilisation and 18 years since refertilisation. Consequently, there was also a certain amount of variation due to the drainage age. The overall trend was that poor site types with a long drainage history had little surplus phosphorus in the surface peat on the fertilised plots, while more fertile sites had some additional – evidently fertiliser – phosporus in the fertilised plots compared with the controls. The amount of phosphorus in the surface peat can, however, hardly be used as a measure when evaluating the growth prospects for Scots pine on drained peatlands.

Acknowledgements

We gratefully acknowledge the cooperation of the following persons and institutions in carrying out this study: Jorma Issakainen, Markku Tiainen and Heikki Takamaa supervised the field work. Hilkka Granlund assisted in the data processing and preparation of the manuscript; Raija Linnainmaa drew the figures together with Airi Piira, who also made the stand data calculations. Mikko Kukkola gave us useful advice in the calculations. Professor Seppo Kaunisto supported us in many ways during all stages of this work, John Derome improved our English and Kemira Ltd provided us with information about the composition of the differerent fertilisers.

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Appendix 1. Nutrients in the 0–20 cm peat layer. Means are given for the control plots and range for individual plots. The raw humus layer is included.

Element	Experiments fertilised once					Refertilised experiments									
	Alkkia 66		Puras		Jylkky	Heinola		Häädetjärvi		Rautavaara		Alkkia 2		Kettula	
	Control	Fertilised	Control	Fertilised	Fertilised	Control	Fertilised	Control	Fertilised	Control	Fertilised	Control	Fertilised	Control	Fertilised
	Mean	Range	Mean	Range	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
N	2745	1626–4063	2322	1668–3774	6381–10712	4086	2842–5745	2835	2153–4364	2576	2121–3628	2420	1550–2924	1495	1000–2595
$P_{(tot)}$	105	65–157	132	106–192	257–440	198	121–309	150	102–249	157	128–212	96	69–112	75	63–129
$P_{(sol)}$	21	15–37	21	26–36	5–13	24	15–30	34	30–46	28	23–41	21	20–40	22	18–45
K	84	29–135	51	46–71	36–53	74	50–160	110	90–231	79	62–95	80	29–152	86	35–138
Ca	397	224–586	536	386–1699	186–347	514	383–898	208	235–356	269	240–449	359	244–571	321	209–510
Mg	76	33–93	116	89–229	19–38	46	22–47	68	58–87	62	53–64	57	32–68	57	34–86
Fe	662	328–1093	41	32–191	1792–4160	348	208–546	306	218–458	331	234–654	565	324–567	140	72–260
Mn	8	4–14	5	2–13	3–4	6	3–7	7	4–11	7	3–12	6	3–13	4	3–18
Zn	6	3–8	3	2–5	2–3	4	2–6	6	4–11	5	3–69	4	3–10	10	6–13
Cu	0.7	0.5–1.1	0.4	0.3–0.6	0.8–1.8	3.9	1.0–10.2	3.6	1.5–4.1	3.7	1.1–6.7	1.0	0.5–8.4	0.7	0.7–3.3S
B	0.7	0.2–1.4	0.4	0.3–0.8	0.2–0.5	0.4	0.3–0.9	0.9	0.6–1.8	0.4	0.3–0.5	0.7	0.2–1.2	0.3	0.2–0.4