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Long-term effects of apatite and biotite on the nutrient status and stand growth of Scots pine (*Pinus sylvestris* L.) on drained peatlands

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Phosphorus and potassium deficiencies are common in Scots pine stands growing on drained peatlands. In this study, the foliar nutrient concentrations and stand growth were monitored after the application of phosphorus and potassium fertilisers of different solubility in four experiments on thick-peated drained peatlands in northern central Finland. The studied stands involved three fertilisation treatments: (i) unfertilised control, (ii) rock phosphate and potassium chloride, and (iii) apatite and biotite. The growth of stands was monitored 20–25 years after the fertilisation. Needles were sampled four times: 4–9, 11–14, 16–19 and 21–24 years after the fertilisation. According to foliar analyses, the trees on the control plots suffered from severe phosphorus and potassium deficiencies. Rock phosphate and apatite fertilisation increased the foliar phosphorus concentrations above the deficiency limit, and the effect was still noticeable 21–24 years after the application. Both potassium sources, that is, the slowly soluble biotite and the water-soluble potassium chloride increased the foliar potassium concentration to an adequate level. Potassium chloride increased the concentrations faster and stronger than biotite during the first years (4–9) after the applications. The situation was reversed when 11–14 years or more had passed from the fertilisation: the biotite fertilised stands had higher potassium concentrations. The fertilisation treatments decreased the foliar nitrogen, zinc, manganese, copper and boron concentrations. The fertiliser applications increased the stand volume growth considerably. Raw phosphate and potassium chloride increased the volume growth significantly already during the first five-year period. The effect of the apatite and biotite treatment was weaker during the first 10 years, but became stronger with time. During the period 19–24 years after the fertilisation, the stand growth on the biotite plots was equal to that of the plots fertilised with potassium chloride. However, during the whole study period the differences between the treatments remained insignificant. The results showed that slowly soluble apatite and biotite are suitable sources of phosphorus and potassium for pines on drained peatlands. However, to avoid boron deficiency, also boron should be added simultaneously.

Keywords: Fertilisation, nutrient deficiency, nutrient status, drained peatland, phosphorus, potassium, rock phosphate, potassium chloride.

Introduction

About 5.7 million hectares of mires and paludified mineral soil forests have been drained for forestry in Finland. In the national forest inventory (1986–1994), 4.6 million hectares of the drained areas were still classified as peatlands. This is 53% of the total peatland area (Hökkä et al. 2002).

Tree growth on drained peatlands is often restricted by the lack of plant available phosphorus (Paarlahti et al. 1971, Huikari 1973, Silfverberg & Hartman 1999). Furthermore, the amounts of potassium and boron may be low in peat soils with respect to the amount bound in the tree biomass (Huikari 1977, Braekke 1979, Kaunisto & Paavilainen 1988, Finér 1989, Laiho & Laine 1995). Potassium deficiencies, as well as those of phosphorus, are most common on thick-peated, originally treeless fens (Kaunisto & Tukeva 1984). It has been suggested that more than 1 million hectares (ca 20% of the total drainage area) suffer from potassium shortage and can be considered as potential potassium deficiency areas in Finland.

In practical forestry, the potassium-phosphorus fertilisation (PK) has been widely used as an amelioration method in drained peatlands. Trees benefit from phosphorus fertilisation on the majority of peatlands that have relatively high total nitrogen concentration (Edwards 1959, Paarlahti & Karsisto 1968, Karsisto 1968, 1977, Dickson 1971, Moilanen 1993). In peatland forestry, phosphorus was applied as super or rock phosphate until the late 1980´s in Finland. Since then, a water-insoluble, native apatite ($Ca_5(PO_4)_3(OH,F,Cl)$) has been used as the phosphorus component in peatland forest fertilisers to minimise the risk of phosphorus leaching. Super phosphate, with its high amount of water-soluble phosphorus, affects tree growth more rapidly, but the long-term effect is usually of the same order as that of the rock phosphate or apatite (Karsisto 1977, Vasander & Lindholm 1992, Kaunisto et al. 1993, Silfverberg & Hartman 1999).

The effect of phosphorus fertilisation on tree growth — regardless of the solubility of the phosphorus compound — may last over 30 years on drained peatlands (Silfverberg & Hartman 1999, Pietiläinen & Kaunisto 2003, Rautjärvi et al. 2004). The effect of the water-soluble and easily leached potassium chloride (KCl), on the other hand, lasts only for some 15 years (Kaunisto & Tukeva 1984, Kaunisto 1989, 1992).

In forest fertilisation, potassium has been given mainly as water-soluble potassium chloride. In the last decades, also slowly soluble forms of potassium compounds (e.g. biotite and phlogopite) have been available as an alternative peatland forest fertiliser. The results from earlier short-term experiments showed that biotite increased the potassium concentration of the tree's needles slower than potassium chloride (Vasander & Lindholm 1992, Kaunisto et al. 1993). The results reported so far have been promising but cover only the first 15 years after fertilisation (Kaunisto et al. 1993, 1999). Thus, we do not know if the duration of the slow soluble potassium fertilisers is longer than that of the fast dissolving potassium compounds.

As with phosphorus, also the applied potassium should be slowly dissolving to minimise the losses by leaching and thus extend the duration of the fertilisation effect. In practical forestry, it would be reasonable to minimise the number of fertilisation applications and leaching during the rotation time. If the effect of biotite is as long as that of apatite phosphate, the number of fertilisations can be reduced in those peatland stands suffering from phosphorus and potassium deficiencies.

Biotite is an interesting alternative, which has been used in agriculture as a fertiliser in organic farming and as a soil amendment in conventional farming. It is a silicate forming large platy mineral ($K(Fe,Mg)_3AlSi_3O_{10}(F,OH)_2$). These potassium silicate minerals contain no water-soluble potassium. Potassium ions are tightly fixed in the interlayer positions of mica and are only partly released by cation exchange reactions that depend on the amounts of cations (K^+, Ca^{++}, Mg^{++}, Na^+, Al^{+++}, H^+) present in the soil solution.

This investigation aims to clarify the long-term effects of apatite and biotite fertilisations on the phosphorus and potassium nutrition by monitoring in detail the development of the foliar phosphorus and potassium concentrations, as well as the growth increment in the stands in a 21 to

25 year period after the fertilisations. The main objective is to find out whether the responses in the foliar potassium concentration and stand growth following slowly dissolving biotite application last longer than those achieved with more water soluble potassium chloride.

Materials And Methods

Experimental design

The material consisted of four fertilisation experiments located in the northern central Finland (64º, 53' N; 26º, 06' I) (Table 1). Preliminary results cover 11–19 years from the fertilisation of the same experiments, which have been presented by Kaunisto et al. (1993, 1999). The previous studies contained 12 experiments; of these, four were included into this follow-up study. We restudied the long-lasting effects of fertilisation with a more homogenous set of experiments, since some experiments in the original data did not have nutrient deficiencies (see Kaunisto et al. 1993, 1999). The experiments included in the present study represented a relatively uniform trophy level, all of which suffered from phosphorus and potassium deficiencies according to previous studies.

The studied sites represented the most typical site types of peatlands drained for forestry according to Keltikangas et al. (1986) (Table 1). The site fertility ranged from tall-sedge pine fen to cottongrass sedge pine fen (the site classification is according to Laine & Vasander 1996). Naturally born Scots pine (*Pinus sylvestris* L.) stands were mixed with (less than 15%) of pubescent birch (*Betula pubescens* Ehrh.) and Norway spruce (*Picea abies* Karst). When the experiments were established in 1977–81, the tree stands were in a pole stage with a dominant height of 4 to 5 m (Table 1).

The oldest drainage was done in the 1930's, and the most recent one in the 1970's. Ditch spacing varied from 20 to 25 m in the experiments. The ditches were cleaned prior to the fertilisation in the majority of the experiments (Table 1). The ditch network functioned well on all sites.

The fertilisation treatments were as follows: control with no fertilisation (0), fertilisation with rock phosphate (Rp) and potassium chloride (KCl), and fertilisation with apatite (Ap) and biotite (Bi). The phosphorus and potassium compounds and their nutrient concentrations are shown in Table 2. The phosphorus dose was equal to that given in peatland forest fertilisation recommendations for practical forestry in Finland. The potassium dose in biotite varied from 55 to 128 kg ha^{-1} and in potassium chloride from 71 to 83 kg ha^{-1} (recommendation 80 kg ha^{-1}).

The experimental lay-out followed the randomised block design, with 2–4 replicates of each treatment (Rp+KCl, Ap+Bi). The size of the experimental plots varied from 0.04 to 0.16 ha. Unfertilised plots were included in all the experiments.

Table 1. Some basic site and stand characteristics on the studied experiments at the time of their establishment on drained peatlands.

Taulukko 1. Lannoituskokeiden kasvupaikkaa ja puustoa kuvaavia tunnuksia eri ojitusalueilla.

Experiment (number, name)	Site type [1]	Peat depth	Peat N, % [2]	Ditching, years	Ditch spacing, m	Stand height, m
1. Oisava 1/79	VSR	>1.0	2.58	1975	20	5
2. Itkusuo 171B	VSR	0.7– >1.0	2.05	1932, -78	20	4
3. Aittokangas 248	TSR	0.6– >1.0	1.86	1971, -80	20	5
4. Jylkky 235	VSR	0.7	2.27	1939, -79	25	5

[1] Site types: VSR = tall-sedge pine fen, TSR = cottongrass-sedge pine fen (see Laine & Vasander 1996). [2] Surface peat (0–10 cm layer).

Data collection and analyses

The nutrient status of the pine stands was determined with foliar analyses. Each plot was sampled four times (except the experiment 3, which was sampled three times): 4–9 years, 11–14 years, 16–19 years and 21–24 years after the fertilisation (Table 3, for the first three sampling see also Kaunisto et al. 1993, 1999). Current needles were collected from upper whorls of trees between December and March, during dormancy. One composite sample consisted of 8 dominant trees per plot uniformly distributed over the plot, each on a minimum distance of 2 metres from the plot edge. The samples were stored at 21 °C. The dry mass of 100 needles was weighed. The nitrogen concentration was determined using the Kjeldahl method. After dry combustion and dissolving in hydrochloric acid, K, Ca, Mn, Zn, and Cu concentrations were determined using an atomic absorption spectrophotometer (Hitachi 100-40). The concentrations of B were determined with a spectrophotometer (Shimadzu UV-2401 PC) using the azomethine-H method, and those of P using the vanado-molybdate method as outlined by Halonen et al. (1983).

To determine the richness of the site, the total nitrogen concentration was analysed from the top 10 cm layer of the peat of the unfertilised plots, sampled in autumn 1990. One composite sample consisted of 5 subsamples from the 0–10 cm layer, which were distributed uniformly over the plot, excluding a 2.5 m wide edge area. The living vegetation and undecomposed plant material of the peat cores were discarded from the analyses. The samples were separated into plastic bags and stored at –21 °C. After thawing, drying (at 70 °C for 48 hours) and weighing, the total nitrogen concentration was determined by the Kjeldahl method (Halonen et al. 1983). In the surface peat, the N concentrations varied from 1.86 to 2.58% of dry matter (Table 1).

The stand measurements were carried out in 2000 and 2001, when 20–25 years had elapsed since the fertilisation, depending on the experiment. For the tree stand measurements, one measurement circle with a radius of 8 or 12 metres was marked, depending of the shape and size of

Table 2. The fertilisation treatments, nutrient sources and dosages, and nutrients amounts applied in the experiments. Control = no fertilisation, PK-fertiliser = combined fertiliser containing rock phosphate and potassium chloride, PapatO = grinded apatite ore, PapatR = enriched apatite, Prock = rock phosphate, Kpot = potassium chloride, Biot = biotite.

Taulukko 2. Tehdyt lannoituskäsittelyt, ravinnelähteet, lannoitteiden käyttömäärät ja ravinteiden annostus alkuaineina kokeittain. Control = lannoittamaton, PK-fertiliser = Suometsien PK-lannos (sis. raakafosfaattia ja Kpot = kalisuola l. kaliumkloridi, Biot = biotiitti.

Exp.	Treatment	—— Nutrients applied as elements, kg ha^{-1} ——				Code
		P	K	Ca	B	
1	Control	-	-	-	-	0
1	PK-fertiliser[1] 400	35	73	87	0.8	Rp+KCl
1	PapatO 2100 + Biot 800	37	128	152	0.0	Ap+Bi
2	Control	-	-	-	-	0
2	PK-fertiliser 400	35	73	87	0.0	Rp+KCl
2	PapatR 200 + Biot 1500	41	61	156	0.0	Ap+Bi
3	Control	-	-	-	-	0
3	Prock 310 + Kpot 140	44	71	109	0.0	Rp+KCl
3	PapatR 230 + Biot 1330	45	55	159	0.0	Ap+Bi
4	Control	-	-	-	-	0
4	PK-fertiliser[1] 500	44	83	109	1.0	Rp+KCl
4	PapatR 200 + Biot 1550	42	66	165	0.0	Ap+Bi

[1] Treatment contained also water-soluble borate fertiliser, 20% of P was in the form of super phosphate.

the plot. However, in the experiment 1, the tree stand was measured on the whole plot, excluding a 7.5 m wide edge area in cross direction of the ditches. In the measuring area (0.02–0.05 ha), all the trees were counted by the species and breast-height diameter classes (at 1.3 m, minimum diameter class 5 cm). The height (dm) and diameter at breast height (d1.3, mm) were measured from 20–25 randomly chosen pines. The height increment measurements of the sample trees were focused on five-year periods prior to and after the fertilisation. Increment cores were drilled at the breast height from each sample tree to determine the development of the annual radial growth during the study period microscopically with the accuracy of 0.01 mm. The development of the tree stand volume was calculated with the taper curve and volume functions for Scots pine (Laasasenaho 1982).

Data processing and statistical analyses

Two-way analysis of variance and covariance was applied to test for the effects of fertilisation treatments on the foliar nutrients and on the absolute annual and five-year periodic volume growth of the tree stand. The average pre-treatment (three years) volume growth was used as a covariate when analysing the stand growth. The treatment effects and the interactions between the treatments and experiments were analysed with the two-way ANOVA-model:

$$Y = F + E + FE + \mu, \qquad (1)$$

where Y is the value of the response, F is the fertilisation treatment, E is the experiment, and μ is a random variable (error). In addition, one-way analysis of variance was calculated separately for each experiment as regards the nutrient concentrations and growth of the stand. The statistical significance of the differences between the treatments for each year were analysed using Bonferron's paired t-test.

The differences in the nutrient concentrations of pine needles at different sampling times (4–9, 11–14, 16–19, 19–24 years after fertilisation) were tested with ANOVA. Treatment effects and interactions between treatment and experiment within the groups were analysed using the one-way analysis of variance. The statistical calculations (one- and two-way analysis of variance) were followed by the general linear models procedure associated with the SPSS statistical software package. The treatment means were compared using Bonferron's or Tukey's multiple range tests. For the foliar nutrient concentrations collected four times in experiments 1, 2 and 4, the statistical analyses were carried out using the ANOVA repeated measures model, in order to reveal the significance of time factor of the fertilisation response.

Results

Nutrient concentrations and needle dry mass

The foliar phosphorus and potassium concentrations on the control plots were below the severe deficiency level, 1.4 mg g^{-1} and 3.5 mg g^{-1}, respectively (the deficiency limits according to Paarlahti et al. 1971, Reinikainen et al. 1998, Sarjala & Kaunisto 1993), in almost all of the sampling occasions (Tables 4–5). During the last period, the phosphorus status on the control plots

Table 3. The points of time for tree stand measurements and for needle samples by experiments, a = autumn, s = spring.
Taulukko 3. Puustomittausten ja neulasnäytteiden keruun ajankohdat lannoituskokeittain, a = syksy, s = kevät.

Experiment	Time of fertilisation	Treatments × replicates = plots	Stand measure	Needle samples (month/year)
1	s1977	3 × 3 = 9	a2001	3/1984, 12/1990, 3/1996, 3/2001
2	s1980	3 × 2 = 6	s2001	3/1984, 12/1990, 3/1996, 3/2001
3	s1981	3 × 3 = 9	s2001	12/1990, 3/1996, 3/2001
4	s1979	3 × 4 = 12	a2001	3/1985, 12/1990, 3/1996, 3/2001

was more or less at the same level (1.1–1.2 mg g^{-1}) as in the first sampling, whereas the potassium concentration had improved from 3.3 to 3.8 mg g^{-1}. Deficiencies were not observed in the other studied nutrients on the control plots at any time.

The foliar phosphorus concentrations in the fertilised plots differed significantly from the control at all samplings, and were mostly above the severe deficiency level (1.4 mg g^{-1}) (Tables 4–5). The response to rock phosphate (RP) and apatite (Ap) continued throughout the study period. However, on several fertilised plots, the phosphorus concentrations were slightly below the slight deficiency limit (1.7 mg g^{-1}). The differences between rock phosphate and apatite were only minor.

Both potassium sources, potassium chloride (KCl) and biotite (Bi), increased the potassium concentration significantly compared with the controls, KCl up to 14 years and Bi up to 24 years. The potassium concentration was at a sufficient level at the first sampling time (Table 4). During this first period, KCl increased the potassium concentration more than Bi, but at the latter sampling times, the situation was opposite (Fig. 1, Tables 4–5). At the third and fourth samplings (16–19 and 21–24 years, respectively), the effect of KCl was almost non-existent, whereas Bi kept the potassium concentrations at an adequate level, which were significantly higher than those of the control.

The nitrogen status remained satisfactory (foliar N > 13 mg g^{-1}, see Paarlahti et al. 1971, Kaunisto 1984) both on the control and the ferti-

Table 4. Two-way ANOVA results for the nutrient concentrations of Scots pine needles 4–9 and 11–14 years from application (mean nutrient concentrations of experiments 1–4). Differences between the values marked with same letters are not statistical within the period in Bonferron's test (p > 0.05) (treatments in detail see Table 2).

Taulukko 4. Männyn neulasten ravinnepitoisuudet 4–9 ja 11–14 vuoden kuluttua lannoitteiden levityksestä (kokeiden 1–4 keskiarvot, 2-suuntainen varianssianalyysi). Samoilla kirjaimilla merkityt tietyn ravinteen pitoisuudet eivät käsittelyjen välillä eroa toisistaan tilastollisesti merkitsevästi (Bonferronin testi) (käsittelyt tarkemmin taulukossa 2).

	Years after fertilisation					
	4–9 years			11–14 years		
Nutrient	Control	Rp+KCl	Ap+Bi	Control	Rp+KCl	Ap+Bi
N, mg g^{-1}	15.6 a	13.2 b	14.0 b	14.7 a	13.1 b	13.3 b
P, mg g^{-1}	1.08 a	1.53 b	1.40 c	1.11 a	1.67 b	1.52 c
K, mg g^{-1}	3.28 a	4.50 b	4.12 c	3.42 a	3.94 b	4.25 b
Ca, mg g^{-1}	1.81 a	1.93 ab	2.13 b	2.03 a	1.95 a	2.19 a
Mn, mg kg^{-1}	409 a	270 b	264 b	373 a	281 b	274 b
Zn, mg kg^{-1}	54 a	42 b	50 a	63 a	43 b	54 c
Cu, mg kg^{-1}	3.09 a	2.54 b	2.91 a	3.5 a	2.8 b	3.2 a
B, mg kg^{-1}	12.02 a	11.98 a	8.05 b	11.8 a	10.0 a	7.3 b
Dry mass of 100 needles, g	1.72 a	2.32 b	2.07 b	1.53 a	1.96 b	1.94 b
p-values of ANOVA:						
Nutrient	Experiment	Treatment	Exp. × Treat.	Experiment	Treatment	Exp. × Treat.
N	0.000	0.001	0.264	0.000	0.001	0.114
P	0.000	0.000	0.199	0.000	0.000	0.100
K	0.001	0.000	0.097	0.618	0.000	0.440
Ca	0.008	0.013	0.040	0.018	0.077	0.310
Mn	0.000	0.000	0.007	0.000	0.000	0.001
Zn	0.000	0.001	0.728	0.000	0.000	0.113
Cu	0.000	0.000	0.944	0.000	0.002	0.197
B	0.000	0.001	0.002	0.000	0.002	0.008
Needle mass	0.000	0.000	0.222	0.000	0.002	0.942

lised plots. However, both fertiliser treatments lowered foliar nitrogen concentrations during the periods of 4–9 and 11–14 years after application (Tables 4–5). The effect weakened towards the end of the study period.

The concentrations of micronutrients generally decreased after fertilisation. Especially the treatment containing KCl decreased manganese, zinc and copper concentrations (Tables 4–5). Correspondingly, the treatment including Bi decreased the boron concentration below the deficiency level (< 7.0 mg kg^{-1}, see Veijalainen et al. 1984) at the third and fourth sampling times. The "dilution effect" was most visible at the first and the second sampling times, and weakened at the end of the study period.

By the first sampling period, both fertiliser treatments increased the 100-needle dry mass significantly. The effect was still seen at the end of the study period (Tables 4–5).

Interactions between the fertilisation treatments and the experiments were seen for some elements and sampling times: phosphorus and zinc in the 3rd, nitrogen in the 4th, calcium in the 1st, manganese and boron in the 1st, 2nd and 3rd, and copper in the 3rd and 4th samplings (see Tables 4–5). Thus, the fertilisation effects on nutrient concentrations other than K, and on needle mass were not generally parallel regardless of the experiment.

In the ANOVA of the repeated measures, the temporary variation of the foliar potassium concentration turned out to be significant, and there was a significant interaction effect between ferti-

Table 5. The results of two-way ANOVA for the nutrient concentrations of Scots pine needles 16–19 and 19–24 years from application (mean nutrient concentrations of experiments 1–4). Differences between the values marked with same letters are not statistical within the period in Bonferron's test ($p > 0.05$) (fertilisation treatments in detail, see table 2).

Taulukko 5. Männyn neulasten ravinnepitoisuudet 16–19 ja 19–24 vuoden kuluttua lannoitteiden levityksestä (kokeiden 1–4 keskiarvot, 2-suuntainen varianssianalyysi). Samoilla kirjaimilla merkityt tietyn ravinteen pitoisuudet eivät käsittelyjen välillä eroa toisistaan tilastollisesti merkitsevästi (Bonferronin testi) (lannoituskäsittelyt tarkemmin taulukossa 2).

	Years after fertilisation					
	16–19 years			19–24 years		
Nutrient	Control	Rp+KCl	Ap+Bi	Control	Rp+KCl	Ap+Bi
N, mg g^{-1}	15.7 a	13.4 b	14.7 a	15.7 a	14.6 a	15.3 a
P, mg g^{-1}	1.19 a	1.39 b	1.49 b	1.22 a	1.62 b	1.54 b
K, mg g^{-1}	3.48 a	3.78 a	4.40 b	3.81 a	3.90 a	4.46 b
Ca, mg g^{-1}	1.80 a	1.83 a	1.99 a	2.22 a	2.25 a	2.37 a
Mn, mg kg^{-1}	367 a	294 b	258 b	426 a	384 a	291 b
Zn, mg kg^{-1}	51 a	39 b	46 a	61 a	49 b	54 a
Cu, mg kg^{-1}	3.8 a	3.1 b	3.0 b	3.0 a	2.8 a	2.9 a
B, mg kg^{-1}	10.9 a	9.6 b	6.9 b	12.3 a	9.9 a	5.7 b
Dry mass of 100 needles, g	2.09 a	2.11 a	2.27 a	1.67 a	2.01 b	2.11a
p-values of ANOVA: Nutrient	Experiment	Treatment	Exp. × Treat.	Experiment	Treatment	Exp. × Treat.
N	0.000	0.000	0.171	0.000	0.095	0.012
P	0.000	0.000	0.000	0.000	0.000	0.464
K	0.000	0.000	0.081	0.009	0.002	0.943
Ca	0.000	0.219	0.628	0.151	0.211	0.170
Mn	0.001	0.000	0.015	0.030	0.003	0.076
Zn	0.001	0.000	0.025	0.001	0.005	0.794
Cu	0.000	0.000	0.000	0.083	0.219	0.038
B	0.001	0.001	0.037	0.121	0.000	0.057
Needle mass	0.301	0.210	0.713	0.205	0.003	0.894

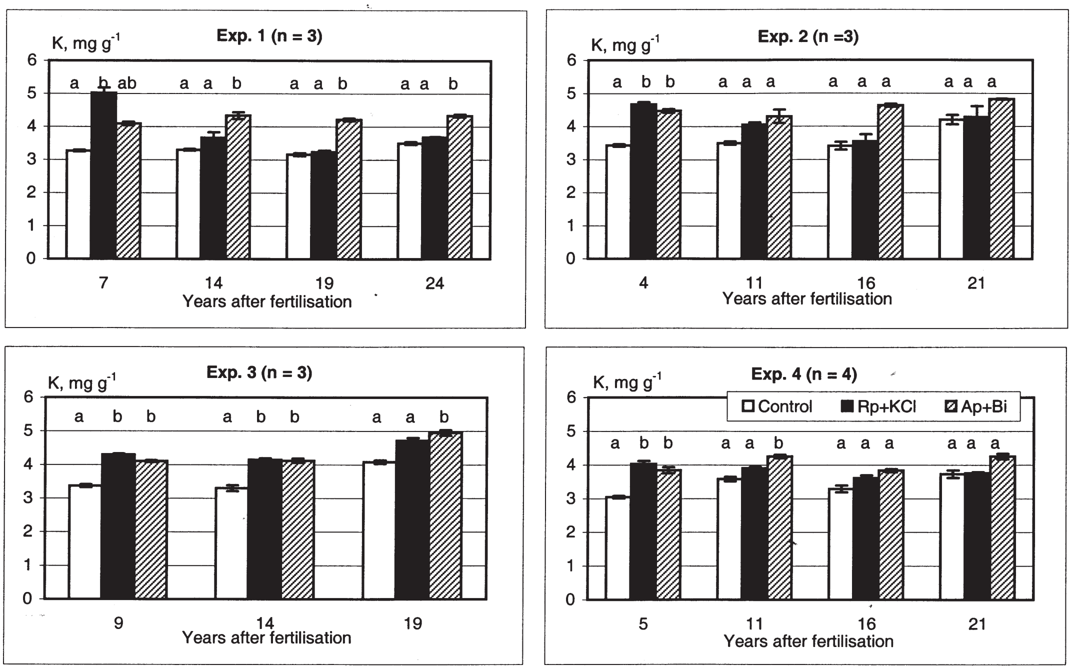

Fig. 1. The foliar potassium concentration of Scots pine at different sampling times following fertilisation treatments (mean values with standard error bars). Differences between the values marked with same letters are not statistical within the period in Bonferron's test ($p > 0.05$).

Kuva 1. Männyn neulasten K-pitoisuus kokeittain ja käsittelyittäin eri ajankohtina lannoituksen jälkeen pylväät = toistojen keskiarvo, jana= keskiarvon keskivirhe). Samoilla kirjaimilla merkityt tietyn ravinteen pitoisuudet eivät käsittelyjen välillä eroa toisistaan tilastollisesti merkitsevästi (Bonferronin testi).

lisation and time (Table 6). For the other tested nutrients (nitrogen, phosphorus, and boron), the repeated ANOVA model did not reveal any interactions.

Stand volume growth responses

Both fertiliser applications improved stand volume growth significantly in experiments 1, 3 and 4, but the timing and the magnitude of the responses varied conspicuously. Raw phosphate (Rp) and potassium chloride (KCl) increased the growth significantly already during the first five-year period in experiments 3 and 4. During the first 1–15 years, the effect of apatite and biotite (Ap+Bi) was generally weaker than that of Rp+KCl, but the response strengthened with time (Fig. 2, Table 7). After 16–20 years, Ap+Bi-application yielded equal or greater growth increases than Rp+KCl-application. However, during the third five-year period the fertilisation effects of KCl and Bi treatments were significant only in experiments 1 and 3. In experiment 2 there were no statistical differences between treatments, although Ap+Bi seemed to be increased stand growth towards the end of the study period. Unfortunately, only two replicates for treatments were used in experiment 2, which caused more uncertainty to the statistical tests.

The differences in the stand growth between the fertilised and the control plots became more pronounced in the course of time. During the first five-year period the differences were 0.0–0.9 ha^{-1} a^{-1}, depending on the experiment and treatment. During the period of 16–20 years after fertilisation, the stand growth on Rp+KCl-plots was from 0.9 to 2.0 m^3 ha^{-1} a^{-1}, and on Ap+Bi-plots from 1.4 to 3.3 m^3 ha^{-1} a^{-1} greater than on control plots, respectively (Table 7).

Pre-treatment volume growth — three years

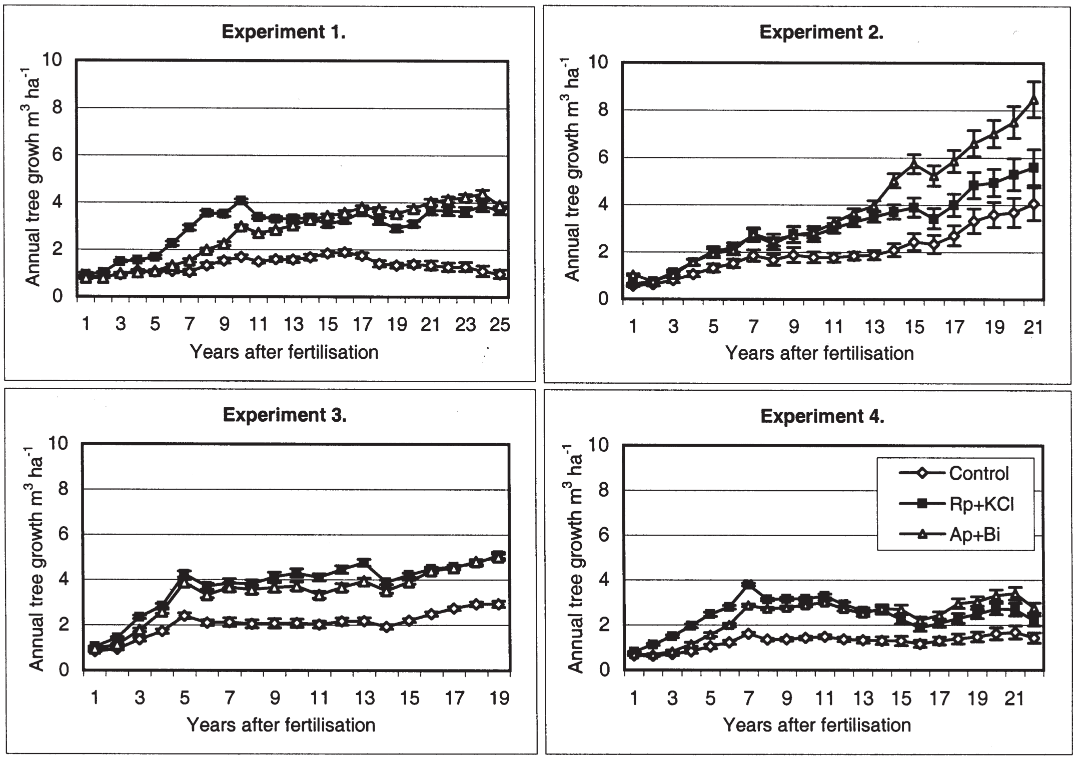

Fig. 2. The annual development of stand growth in the experiments 1–4. The values are covariance adjusted with standard errors of mean. Pair wise comparisons between the treatments are for each year and experiment (statistical difference: p-value < 0.05 in Bonferron's test).

Kuva 2. Männyn vuotuinen tilavuuskasvun kehitys (havaintopiste = toistojen keskiarvo; jana = keskiarvon keskivirhe) lannoituskäsittelyittäin ja kokeittain. Käsittelyjen parittainen vertailu tehty kullekin vuodelle erikseen (Bonferronin testi).

before fertilisation — was significant as a covariate in all of the experiments. It was verified as a significant interaction between experiment and treatment only during the 2nd and 4th to 7th years after the fertilisation. There was no interaction during the latter part of the monitoring period, which means that the fertilisation effect was similar in every experiment (Table 8).

Discussion

This study involves four experiments that represent peatlands with a sufficient total nitrogen concentration in the peat for pine growth in northern central Finland. The total nitrogen concentration in the surface peat should be over 1.5% in a climatic region of this investigation in order to produce satisfactory nitrogen nutrition for Scots pine (Pietiläinen & Kaunisto 2003, see also Kaunisto 1982, 1987). The total nitrogen concentration in peat was adequate for normal tree growth (range in N concentration 1.86–2.58%). The nitrogen concentrations in the needles were also satisfactory in all experiments. Since the lack of nitrogen was not a growth-limiting factor, the differences in the effects of the studied phosphorus and potassium compounds were more easily observed.

Phosphorus and potassium shortage was quite evident on all of the unfertilised plots. Both phosphorus sources (Rp and Ap) and potassium sources (KCl and Bi) increased the foliar phosphorus and potassium concentrations over the severe deficiency level in all experiments. During the monitoring period (19–25 years) both fertilisation treatments increased the stand growth equally.

Only small differences were observed in the foliar phosphorus concentrations and stand growth between the phosphorus sources. The result is in accordance with the earlier reports, e.g. by Silfverberg & Hartman (1999). However, in the experiments 1 and 4, during the first 10 years after application, the Rp+KCl-treatment increased stand growth more than the Ap+Bi-treatment. The reason for this could have been that 20% of the phosphorus in the PK-fertiliser that was used was water soluble super phosphate, which has been noted to increase tree growth faster than the other P-fertilisers immediately after its application (e.g. Karsisto 1968). The effect of a single nutrient on tree growth was not determined since the scope of the study was to clarify the long-term effects of apatite and biotite.

Table 6. The results of the Greenhouse-Geisser test. F-, p-, and adjusted df-values of time factor (Time), experiment factor (Exp) and fertilisation treatment (Fert) with their main effects and interactions for experiments 1, 2, and 4 (ANOVA, repeated measures). Testing variables foliar nitrogen (N), phosphorus (P), potassium (K), and boron (B) concentration.

Taulukko 6. Aika (Time) -, koe (Exp)- ja lannoituskäsittelytekijälle (Fert) määritetyt pää- ja yhdysvaikutukset (Greenhouse-Geisser-testi, toistettujen mittausten ANOVA-analyysi). Testimuuttujina neulasten N-, P-, K- ja B-pitoisuudet.

	Nitrogen		
	F	p	df
Time	29.5	0.000	2.62
Time × Exp	36.7	0.000	5.24
Time × Fert	2.50	0.084	2.62
Time × Exp × Fert	1.42	0.242	5.24
	Phosphorus		
	F	p	df
Time	26.9	0.000	2.40
Time × Exp	3.68	0.001	4.81
Time × Fert	2.17	0.125	2.40
Time × Exp × Fert	2.63	0.046	4.81
	Potassium		
	F	p	df
Time	8.47	0.000	1.79
Time × Exp	2.67	0.000	3.58
Time × Fert	12.1	0.000	1.79
Time × Exp × Fert	2.25	0.005	3.58
	Boron		
	F	p	df
Time	8.38	0.001	2.38
Time × Exp	3.34	0.018	4.76
Time × Fert	0.42	0.698	2.38
Time × Exp × Fert	2.10	0.097	4.76

The effect of slowly soluble phosphorus fertilisers on the nutrient status proved to be longer lasting than that of water-soluble potassium chloride. Earlier results agree fairly well with the results obtained in this study. When using the potassium dose recommended for practice — about 80 kg ha^{-1} — the effect of the fertilisation lasts 10–15 years (Kaunisto & Tukeva 1984, Kaunisto 1989, 1992, Moilanen 1993, Rautjärvi et al. 2004). However, the effect of the phosphorus fertilisers can be still seen 25–32 years from the application (Silfverberg & Hartman 1999, Pietiläinen & Kaunisto 2003).

The slowly soluble potassium fertiliser, biotite, increased the foliar potassium concentration and stand growth slower than water-soluble potassium chloride. On the other hand, the response in the foliar concentration and growth seemed to continue for a longer period of time. Sarjala and Kaunisto (1993, 1996) and Vasander & Lindholm (1992) reported similar results. Our results are consistent with the preliminary results from the same experiment set presented by Kaunisto et al. (1993, 1999). According to Kaunisto et al. (1993) potassium chloride increased trees growth more than biotite in the first 10-year period, after which the differences levelled out. In the present study, the differences between the effects of potassium sources had levelled out after 11–14 years from the fertilisation, and reversed when 16–19 years or more had passed.

The results suggest that biotite had a longer lasting effect than potassium chloride on the potassium concentrations and possibly stand growth of Scots pine. It is also probable that the effect of biotite and apatite on the potassium and phosphorus status of the stand is of the same duration. In practical forestry, potassium losses might be reduced by substituting potassium chloride

Table 7. The mean annual growth increase (m^3 ha^{-1} a^{-1}, standard error given in parentheses) achieved with fertilization by experiments during the five-year periods and during the whole monitoring period. The difference between control and fertilization treatment significant within the period in Bonferron's test ($p < 0.05$) marked with asterisk.

Taulukko 7. Lannoituskäsittelyjen aiheuttama puuston keskimääräinen vuotuinen kasvunlisäys (m^3 ha^{-1} a^{-1}, suluissa keskiarvon keskivirhe) 5-vuotisjaksoittain ja koko tutkimuskauden aikana. Lannoittamattoman vertailun ja lannoituskäsittelyn välillä oleva tilastollisesti merkitsevä ero (Bonferronin testi) merkitty tähdellä.

Experiment	Years from application				Whole study period
	1–5	6–10	11–15	16–20	
	Raw phosphate:				
1	0.4 (0.06)	1.9* (0.19)	1.7* (0.21)	1.7* (0.23)	1.6* (0.15)
2	0.3 (0.21)	0.8 (0.52)	1.5 (0.51)	1.4 (1.02)	1.0 (0.56)
3	0.9* (0.13)	1.9* (0.35)	2.2* (0.26)	-	1.7* (0.21)
4	0.8* (0.12)	1.8* (0.12)	1.4* (0.26)	0.9 (0.37)	1.2 * (0.23)
	Apatite + biotite:				
1	0.0 (0.04)	0.7 (0.14)	1.4* (0.14)	2.1* (0.16)	1.4* (0.10)
2	0.4 (0.21)	0.8 (0.52)	2.3 (0.51)	3.3 (1.02)	1.8 (0.56)
3	0.6* (0.13)	1.5 (0.35)	1.6* (0.26)	-	1.4* (0.21)
4	0.2 (0.12)	1.3 * (0.12)	1.4* (0.26)	1.4 (0.38)	1.1* (0.22)

with biotite. This would also affect practical peatland forest fertilisation, because during a rotation, two fertilisations could ensure an adequate potassium and phosphorus nutrition for the trees on peatlands with substantial nitrogen supplies. On the other hand, spreading costs would become higher, as a larger dose would be needed because the potassium concentration of biotite is lower than that of potassium chloride. In any case, the results show that biotite is a reasonable potassium source for pines on drained peatlands.

In our study the foliar boron concentrations dropped close to or below the deficiency limit, 7 µg/g given by Veijalainen et al. (1984). The "dilution effect" occurs frequently in stands fertilised only with the main nutrients (N, P, K), as Huikari (1977) and Veijalainen (1977) observed earlier. Of the other micronutrients, also copper, manganese and especially zinc concentrations behaved quite similarly with that of boron — mostly decreasing after the fertilisation. It is quite obvious that at least boron, but possibly zinc too, should be added into apatite and biotite based fertilisers, as zinc is very scarce in Finnish peat soils (Kaunisto & Paavilainen 1988).

Table 8. The results of two-way ANOVA analysis of covariance for the annual development of stand growth in the experiments 1–4.

Taulukko 8. Kaksisuuntaisen kovarianssianalyysin (koe, käsittely) testitulokset pää- ja yhdysvaikutuksille. Testimuuttujana puuston vuotuinen tilavuuskasvu lannoituksen jälkeen.

Years from appl.	Experiment		Treatment		Exp. × Treat.	
	F	p	F	p	F	p
1	1.89	0.160	3.80	0.038	0.71	0.644
2	2.24	0.111	10.95	0.000	2.75	0.036
3	9.29	0.000	14.31	0.000	2.52	0.051
4	14.55	0.000	9.60	0.001	3.46	0.014
5	26.56	0.000	8.24	0.002	3.48	0.013
6	14.20	0.000	13.98	0.000	2.76	0.036
7	13.08	0.000	19.53	0.000	3.17	0.021
8	3.38	0.036	31.33	0.000	2.16	0.084
9	3.71	0.026	27.67	0.000	1.17	0.355
10	1.85	0.167	41.79	0.000	0.84	0.553
11	5.81	0.004	50.05	0.000	0.96	0.472
12	10.49	0.000	46.39	0.000	0.82	0.568
13	13.02	0.000	33.24	0.000	1.13	0.375
14	13.32	0.000	33.61	0.000	0.83	0.559
15	14.15	0.000	19.91	0.000	0.67	0.677
16	16.11	0.000	16.53	0.000	0.59	0.733
17	18.22	0.000	17.64	0.000	0.60	0.726
18	18.37	0.000	14.32	0.000	0.37	0.890
19	17.00	0.000	11.33	0.000	0.39	0.879

Conclusions

On drained peatland with low nutrient stores and with an adequate nitrogen supply, the slowly soluble apatite and biotite are good sources of phosphorus and potassium for pine stands. Biotite affects the tree's potassium status longer than water-soluble potassium chloride. This facilitates peatland forestry on "nitrogen-rich" sites suffering from P and K deficiency. The rates of 200–230 kg ha^{-1} of enriched apatite (containing 37–45 kg P ha^{-1}) and 1100–1200 kg ha^{-1} of biotite (containing 60–70 kg K ha^{-1}) result in adequate or even good phosphorus and potassium nutrition of pines for at least 25 years. Furthermore, boron, and possibly zinc, should be added into the apatite and biotite based fertiliser.

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Tiivistelmä:

Apatiitin ja biotiitin pitkäaikaisvaikutukset männyn tilavuuskasvuun ja neulasten ravinnepitoisuuksiin ojitetuilla rämeillä

Paksuturpeisilla soilla puusto kärsii usein kaliumin puutoksista. Pintaturpeen kaliumvarat ovat yleensä niukat suhteessa puustoon sen kiertoaikana sitoutuviin kaliummääriin. Kalium myös pidättyy turpeeseen löyhästi, ja on siten altis huuhtoutumaan. Potentiaalisten kaliumpuutosalueiden määräksi on arvioitu n. 1 milj. ha, mikä on n. 20 % maamme koko ojituspinta-alasta. Suometsiin kehitetyissä PK-lannoitteissa (esim. Metsän PK) lannoitteissa fosfori on apatiittifosforia, kun se vielä 1980-luvulla oli raakafosfaattifosforia. Näistä etenkin apatiitti on hidasliukoinen. PK-lannoksen kalium sen sijaan on vesiliukoista kaliumkloridia eli kalisuolaa. Hidasliukoiset ja turpeen rauta- ja kalsiumyhdisteisiin sitoutuvat fosforiyhdisteet vaikuttavat puiden fosforitalouteen pitemmän ajan kuin helppoliukoiset kaliumyhdisteet puiden kaliumtalouteen. Näin ollen on perusteltua selvittää, voitaisiinko kaliumkloridin sijasta käyttää hitaammin liukenevia kaliumyhdisteitä ja samalla jatkaa lannoituksen vaikutusaikaa. Näin säästettäisiin myös lannoituskustannuksissa.

Tässä työssä tutkittiin erilaisten fosfori- ja kaliumyhdisteiden vaikutusta männyn (*Pinus sylvestris* L.) neulasten ravinnepitoisuuksiin ja kasvuun. Tärkein tavoite oli vahvistaa aiemmissa selvityksissä saatuja ennakkotuloksia, joiden mukaan biotiitin vaikutusaika muodostuu kalisuolan vaikutusaikaa pitemmäksi.

Aineisto kerättiin neljältä rämemännikön lannoituskokeelta, jotka sijaitsivat Metlan tutkimusalueessa Muhoksella. Muuttuma-turvekangasvaiheessa olevat tutkimuskohteet edustivat lähinnä suursaraista kasvupaikkatyyppiä (Taulukko 1). Kohteilla tehtiin kunnostusojitus ennen lannoituskäsittelyitä. Kaikissa koemetsiköissä puusto oli lähes puhdasta männikköä, jonka valtapituus kokeita perustettaessa vaihteli välillä 4–5 m.

Koejärjestelyt toteutettiin arvottujen lohkojen periaatteiden mukaisesti. Lannoituskäsittelyjä olivat (i) lannoittamaton vertailu, (ii) raakafosfaatin ja kalisuolan yhdistelmä (Rp+KCl) ja (iii) apatiitin ja biotiitin yhdistelmä (Ap+Bi) (Taulukko 2). Käsittelyjen sisältämät fosfori- ja kaliumannostukset olivat lähellä nykyisten käytännön metsänlannoitussuositusten mukaisia annostuksia. Lannoituskäsittelyillä oli toistoja 2–4 kokeesta riippuen (Taulukko 2).

Neulasnäytteet kerättiin 4–9 vuoden, 11–14 vuoden, 16–19 ja 21–24 vuoden kuluttua lannoituksesta (Taulukko 3). Neulasista analysoitiin N-, P-, K-, Ca-, Mn-, Zn-, Cu- ja B-pitoisuudet ja määritettiin neulasten kuivamassa (100 kpl). Puusto mitattiin, kun levityksestä oli kulunut kokeesta riippuen 20–25 vuotta (Taulukko 3). Puuston tilavuuskasvu selvitettiin taannehtivasti koepuista mitattujen säde- ja pituuskasvujen avulla. Vertailukoealoilta kerätyistä turvenäytteistä analysoitiin pintaturpeen (10 cm:n kerros) kokonaistyppipitoisuus.

Tutkimusmetsiköt edustivat kohtalaisen runsastyppisiä kasvupaikkoja. Pintaturpeen typpipitoisuus vaihteli kokeittain välillä 1,9–2,6 %. Myös neulasten korkeahko typpipitoisuus osoitti, ettei puilla ollut typen vajausta millään kokeella.

Lannoittamattomat puustot kärsivät kaikissa tutkimusmetsiköissä ankarasta fosforin (neulasten P-pitoisuus < 1,4 mg g^{-1}) ja ankarasta tai lievästä kaliumin puutoksesta (neulasten kaliumpitoisuus < 4,0 mg g^{-1}) koko tutkimusjakson ajan (Taulukko 4). Muiden ravinteiden puutoksia ei neulasanalyysin perusteella ollut todettavissa. Molemmat lannoituskäsittelyt kohottivat neulasten fosfori- ja kaliumpitoisuudet puutosrajan yläpuolelle (Taulukot 4–7). Myös neulasten kuivamassa kasvoi. Raakafosfaatti ja apatiitti vaikuttivat fosforipitoisuuksiin samalla tavoin; molemmilla vaihtoehdoilla vaikutus jatkui vielä tutkimusjakson lopussa. Kalisuola kohotti neulasten kaliumpitoisuutta enemmän kuin biotiitti ensimmäisellä tarkastelujaksolla (4–9 vuotta), mutta myöhemmin tilanne kääntyi päinvastaiseksi (Kuva 1). Kun levityksestä oli kulunut 16–24 vuotta, kalisuolan vaikutus oli hävinnyt, mutta biotiittia saaneiden puiden kaliumtila oli edelleen tyydyttävällä tasolla. Lannoituskäsittelyt yleensä alensivat puiden hivenravinnepitoisuuksia: kalisuolaa saaneilla puilla alentuminen todettiin mangaanilla, sinkillä ja kuparilla. Biotiittikäsittely puolestaan alensi neulasten booripitoisuutta, kalisuolalannoitteessa booria oli mukana

Molemmat lannoitusvaihtoehdot lisäsivät männyn tilavuuskasvua merkitsevästi. Kasvureaktio voimistui koko tutkimusjakson ajan. Rp+KCl-käsittelyn vaikutus oli Ap+Bi-käsittelyn vaikutusta suurempi levitystä seuranneella ensimmäisellä 10-vuotisjaksolla. Kun levityksestä oli kulunut 16–20 vuotta tai enemmän, tuotti Ap+Bi-yhdistelmä suuremman lisäkasvun kuin Rp+KCl-yhdistelmä (Kuva 2, Taulukko 9). Jaksolla 16–20 vuotta lannoituksesta Rp+KCl-käsittely lisäsi tilavuuskasvua kokeesta riippuen 0,1–2,0 m^3 ha^{-1} a^{-1} ja Ap+Bi-käsittely 1,4–3,3 m^3 ha^{-1} a^{-1}. Koko tutkimuskauden aikana saavutettu puuston kasvunlisäys oli keskimäärin samaa suuruusluokkaa molemmilla lannoiteyhdistelmillä.

Hidasliukoinen biotiitti parantaa puiden kaliumtilaa kauemmin (yli 20 vuoden ajan) kuin nopealiukoinen kalisuola, jonka vaikutus rajoittuu 15 vuoteen. Todennäköistä on, että Ap+Bi-yhdistelmällä saatu Rf+KCl-yhdistelmää voimakkaampi puuston kasvureaktio tutkimusjakson lopussa on nimenomaan biotiitin ansiota, sillä fosforilannoitelajien (raakafosfaatti vs. apatiitti) väliset erot neulasten fosforitilaan jäivät hyvin vähäisiksi. Todennäköisesti kaliumin huuhtoutumista voitaisiin vähentää korvaamalla kalisuola biotiitilla suometsien lannoituksessa. Toisaalta se lisäisi levityskustannuksia, koska biotiitin kaliumpitoisuus on vain noin kymmenesosa kalisuolan kaliumpitoisuudesta. Apatiitin ja biotiitin lannoituskäyttö edellyttää myös boorin ja mahdollisesti myös sinkin samanaikaista lisäämistä ko. hivenravinteiden puutosten ennaltaehkäisemiseksi.

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