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Nutrient status and growth of Scots pine (*Pinus sylvestris* L.) on drained peatlands after potassium fertilisation

Pekka Pietiläinen, Mikko Moilanen & Heikki Vesala

Pekka Pietiläinen, Mikko Moilanen & Heikki Vesala, Finnish Forest Research Institute, Muhos Research Station, Kirkkosaarentie 7, FIN-91500 Muhos, Finland. Tel.: +358 8 010 211 3744, fax: +358 8 010 211 3701 (e-mail: pekka.pietilainen@metla.fi).

The effects of potassium (K) fertilisation on the nutrient status and growth of Scots pine (*Pinus sylvestris* L.) stands on drained peatlands were studied on three field experiments in northern central Finland. The Scots pine stands were at a sapling or pole stage with a dominant height of 3–8 m when the experiments were set up. The stands differed from each other in their nutritional status, for example, the foliar K concentration varied considerably between the experiments. The experiments were fertilised with potassium chloride, rock phosphate (P 42 kg ha^{-1}) and urea (N 46 kg ha^{-1}) between 1979 and 1980. The potassium doses in terms of elemental K, were 50, 100, 200 and 400 kg ha^{-1}. The foliar samples were taken three times during the study period: 7–9 years, 14–15 years and 19–20 years after fertilisation. The stand measurements were done 19–22 years after the fertilisation. The rate and magnitude of stand response due to fertilisation depended essentially on the nutritional status of the trees. The strongest effect of PK-fertilisation was obtained on a nitrogen-rich peatland, where the stands suffered from severe phosphorus and potassium deficiencies (foliar P concentration < 1.2 mg g^{-1}, K concentration < 3.5 mg g^{-1}). During the study period, the annual stand volume growth on fertilised plots ranged from 3.9 to 5.4 m^3 ha^{-1} a^{-1}, and that of the unfertilised plots was 0.78 m^3 ha^{-1} a^{-1}. In other sites, where the lack of phosphorus and potassium was not so drastic, nor did the trees suffer from shortage of nitrogen, the effect of PK-treatment on tree growth was weak or almost non-existent. The foliar K concentrations rose with the amount of potassium chloride applied. The fertilisation effect of the dose of 100 kg K ha^{-1} lasted 15–20 years, after which the foliar K concentration dropped close to the deficiency limit. The effect of the larger doses (200–400 kg K ha^{-1}) on the needle K concentration was more pronounced and still visible at the end of the study period. However, the stand growth responses gained with larger potassium applications were not essentially greater than those with the 100 kg ha^{-1} dose.

Keywords: Fertilisation, drained peatland, growth increment, needle analysis, nutrient concentration, nutrient deficiency, *Pinus sylvestris*, potassium chloride,

Introduction

The peat of drained peatlands generally contains only small amounts of mineral nutrients, e.g. phosphorus and potassium (Paavilainen 1980, Kaunisto & Paavilainen 1988, Kaunisto & Moilanen 1998). Especially the amounts of potassium may become too small in the root layer to meet the requirements of the trees. Already during the first stand rotation (80–100 years), substantial amounts of the potassium reserves from the substrate are bound into the trees (Kaunisto & Paavilainen 1988, Finér 1992, Laiho & Laine 1994). Thus, tree growth on drained peatlands may often be restricted by a shortage of phosphorus and potassium (Kaunisto 1982, 1987, Kaunisto & Tukeva 1984, Moilanen & Issakainen 1990, Kaunisto 1992, Moilanen 1993, Silfverberg & Hartman 1999). On the other hand, Westman and Laiho (2003) showed that the nutrient resources in the soil did not decrease as the drainage area aged.

On ombro-oligotrophic sites, also nitrogen limits the growth of trees, at least in the climatic conditions of northern Finland (Kaunisto 1977, Kaunisto & Paavilainen 1977, Kaunisto 1982, Moilanen & Issakainen 1990, Moilanen 1993, Pietiläinen & Kaunisto 2003). E.g. Kaunisto and Pietiläinen (2003) found that in a climatic region where the annual temperature sum was on average 850 d.d., nitrogen was still the limiting factor for tree growth as late as 30 years after basic fertilisation and 20 years after refertilisation.

Potassium deficiencies are most common on originally wet meso-oligotrophic thick-peated peatlands (Kaunisto & Tukeva 1984, Kaunisto & Paavilainen 1988, Kaunisto 1989, 1992, Moilanen et al. 1996). The potassium both in the soil solution as well as in humus colloids exists freely or only weakly bound to the cation exchange sites. Therefore, it is easily available to trees, but as a mobile element it also leaches easily (Ahti 1983, Malcolm & Cuttle 1983, Wells & Williams 1996). Severe shortage of potassium may cause leader dieback and even death of trees on drained peatlands (Kaunisto & Tukeva 1984).

Nutrient deficiencies and imbalances can be amended with fertilisation (Kaunisto 1972, Kaunisto & Paavilainen 1977, Kaunisto 1982, Kaunisto & Tukeva 1984, Moilanen 1993, Kaunisto et al. 1993). In practical peatland forestry, potassium has been applied as water-soluble potassium chloride together with water-insoluble rockphosphate (= PK treatment). The fertilisation effect of the used phosphorus rate (P 45 kg ha^{-1}) on tree growth and nutrient status lasts at least over 30 years (Moilanen 1993, Silfverberg & Hartman 1999, Pietiläinen & Kaunisto 2003). The duration of the effect of potassium chloride with the rate 100 kg ha^{-1} (recommended in forest fertilisation practise) is shorter, only 10 to 20 years on nitrogen-rich sites (Kaunisto 1989, 1992, Kaunisto et al. 1999, Rautjärvi et al. 2004). The reason for the short effect is probably the higher leaching losses of potassium compared with those of phosphorus fertilisers (Ahti 1983, Kaunisto 1992).

Presently the practical peatland forestry recommends remedial fertilisation, which increases the growth of trees by improving the nutrient status of the soil. The degenerating development of the stand, caused by the imbalanced nutritional state of the soil, has to be recovered by adding the specific nutrient or nutrients to overcome the shortages which are limiting stand growth. The fertilisation requirement, dose and composition have to be determined by the prevailing deficiency symptoms, growth disturbances and foliar analyses.

In the previous fertilisation studies, the results on the effects of potassium doses on Scots pine growth have been partly contradictory. Kaunisto (1992) showed that most of the water-soluble fertiliser potassium chloride, when applied in large amounts, could not be used by trees. By contrast, Moilanen (1993) found that by increasing the dose the fertilisation reaction in the stand increased.

In this study, we aim to clarify the long-term role of potassium fertilisation on the foliar K status and growth of Scots pine on drained peatlands. We also compare the duration of the response of the potassium fertilisation on the foliar potassium concentration with that of phosphorus fertilisation. We hypothesise that the response of fertilisation depends on the site type and the nutritional status of the trees, as well as on the fertiliser dose.

Material and methods

Experiments

The three field experiments studied were located in Sievi (63° 53' N; 24° 26' I), Muhos (64° 52' N; 26° 06' I) and Rovaniemi (66° 28' N; 26° 40' I), in the northern boreal coniferous forest zone in northern central Finland. The experiments were established between 1979 and 1980 on pine peatlands drained in 1935, 1939 and 1961 (Table 1). Ditch spacing varied between 20 and 25 m. The site fertility ranged from tall-sedge pine fen to herb-rich birch-pine fen (site classification according to Laine and Vasander 1996). The peat thickness varied from 50 cm to over 100 cm.

The stands were naturally born and at a sapling or pole stage when the experiments were set up, with a dominant height of 3–8 m. The dominant tree species was Scots pine with a mixture (less than 15% of stem volume) of pubescent birch (*Betula pubescens* Ehrh.) and Norway spruce (*Picea abies* (L.) Karst). The stands differed from each other in their nutritional status. Visible potassium deficiency symptoms, yellow or yellowish needles (Reinikainen et al. 1998) were seen in experiment 1 (Sievi) distinctly and in experiment 2 (Muhos) weakly, whereas in experiment 3 (Rovaniemi) the trees showed no visible symptoms of nutrient deficiency.

The fertilisers — rock phosphate, potassium chloride and urea were spread in 1979–1980. The phosphorus dose was equivalent to that of the present recommendation in forest fertilisation practise in Finland (Paavilainen and Päivänen 1995) (Table 2), but the nitrogen dose was only a half of the recommendation. The potassium doses were 50 (K_{50}), 100 (K_{100}), 200 (K_{200}) and 400 kg ha^{-1} (K_{400}) (300 kg ha^{-1} in Muhos) as elemental potassium. Moreover, a micronutrient mixture containing boron, copper and manganese was used in Sievi and Muhos. Rovaniemi was fertilised in 1969 as a whole (including control plots) with a PK fertiliser, before the potassium rate experiment was set up. An additional remedial drainage was included in the treatment.

The experimental layout followed the randomised block design with three or four replications. Unfertilised plots were included in each of the experiments as one treatment. The size of the experimental plots varied from 0.05 to 0.09 ha.

Sampling, measurements, and chemical analyses

To determine the site fertility of the experiments, peat samples were collected from the unfertilised plots in autumn 1988. One composite sample consisted of five sub-samples from the surface peat layer (0–10 cm), which were distributed uniformly over the plot, excluding a 5 meters wide edge area. The samples were put into plastic bags and stored at –21 °C. After thawing, the living vegetation and the undecomposed plant material in the peat cores was discarded from the analyses. The peat samples were dried at 70 °C for 48 hours and weighed, and the total nitrogen con-

Table 1. Basic information on the experiments at the time of the establishment in 1979–80.
Taulukko 1. Kokeiden perustamisajankohdan yleistietoja.

Experiment (number, name)	Coordinates (N, E)	Altitude (m a.s.l.)	Temp. sum (d.d)	Site type [1)]	Peat thickness (m)	Years of ditching	Stand volume (m^3ha^{-1})
1. Sievi 9/79	63° 53'; 24° 26'	110	1032	RhSR	0.7	1935, 1980	8
2. Muhos 164	64° 52'; 26° 06'	71	1023	VSR	0.5–0.7	1939, 1979	16
3. Rovaniemi 1/80	66°28'; 26 °40'	180	860	VSR	>1.0	1961, 1980	29

[1)] Original site type in pristine stage according to Laine and Vasander 1996; RhSR = herb-rich birch-pine fen, VSR = tall-sedge pine fen.

centration was determined by the Kjeldahl method (Halonen et al. 1983). In the surface peat, the nitrogen concentrations (of dry matter) were 2.0% (Sievi), 2.3% (Muhos) and 1.7% (Rovaniemi).

The Scots pine needles were sampled three times during the study period: 7–9 years, 14–15 years and 19–20 years after the fertilisation, depending on the experiment. Current needles were sampled in the winter (February–April) from six dominant trees per plot from the sun-exposed upper whorls of the tree crowns. Branches with current needles were put into plastic bags and kept frozen at –20 °C until the analyses. Needles were thawed and dried at 60 °C. The dry mass was determined after drying at 105 °C for 24 hours. The nitrogen concentrations of the needle samples were determined using the Kjeldahl method as outlined by Halonen et al. (1983). After dry combustion and dissolving the ash in hydrochloric acid, potassium concentrations were determined using an atomic absorption spectrophotometer (Hitachi 100-40). The concentrations of boron were determined using the azomethine-H method, and that of phosphorus using the vanadomolybdate method with a spectrophotometer (Shimadzu UV-2401 PC) as outlined by Halonen et al. (1983).

The stand measurements were done 19–22 years after the fertilisation in 2000–2001. The measurements were carried out on one circular (radius 10–11 m) sub-sample plot (Muhos, Rovaniemi) or within a rectangular sample plot (Sievi), with a minimum distance of 5 metres from the edge of the fertilisation plot. In the subsample plots, all of the trees were counted by the species and the breast-height diameter class (at 1.3 m, with the minimum diameter class 5 cm). Furthermore, the height (dm) and the diameter at breast height (d1.3, mm) were measured from 20–25 randomly chosen pine sample trees in each plot. The height increment measurements of these sample trees were focused on five-year periods before and after the fertilisation. Increment cores

Table 2. The treatments, used fertilisers, doses, and nutrient amounts applied in 1979–80. Nu = Urea (N 46%), Prf = rock phosphate (P 14%), KCl = potassium chloride (K 50%). Exp.1 = Sievi; Exp. 2 = Muhos; Exp. 3 = Rovaniemi.

Taulukko 2. Lannoituskäsittelyt, käytetyt lannoitteet, annostukset ja käytetyt ravinnemäärät alkuaineina. Nu = Urea, Prf = raakafosfaatti, KCl = kaliumkloridi (kalisuola). Koe 1 = Sievi; Koe 2 = Muhos; Koe 3 = Rovaniemi.

		Nutrients applied as elements, $kg\ ha^{-1}$						
Exp.	Treatment	K	P	N	Ca	Mn	Cu	B
1	Control	-	-	-	-	-	-	-
1[a)]	Nu+Prf+KCl	50	42	46	104	10	2.5	2.1
1[a)]	Nu+Prf+KCl	100	42	46	104	10	2.5	2.1
1[a)]	Nu+Prf+KCl	200	42	46	104	10	2.5	2.1
1[a)]	Nu+Prf+KCl	400	42	46	104	10	2.5	2.1
2	Control	-	-	-	-	-	-	-
2[a)]	Nu+Prf+KCl	50	42	46	104	10	2.5	2.1
2[a)]	Nu+Prf+KCl	100	42	46	104	10	2.5	2.1
2[a)]	Nu+Prf+KCl	200	42	46	104	10	2.5	2.1
2[a)]	Nu+Prf+KCl	300	42	46	104	10	2.5	2.1
3[b)]	Control	-	-	-	-	-	-	-
3[b)]	Nu+Prf+KCl	50	42	-	104	-	-	-
3[b)]	Nu+Prf+KCl	100	42	-	104	-	-	-
3[b)]	Nu+Prf+KCl	200	42	-	104	-	-	-
3[b)]	Nu+Prf+KCl	400	42	-	104	-	-	-

[a)] Additionally, each plot — apart from control — was fertilised at the same time with borate fertilizer (B 14%) 15 $kg\ ha^{-1}$, copper sulphate (Cu 25%) 15 $kg\ ha^{-1}$ and manganese sulphate (Mn 26%) 40 $kg\ ha^{-1}$. [b)] The whole study area — including the control plots — was fertilized with PK fertilizer for peatlands (P 10%, K 15%, Ca 30%) 400 $kg\ ha^{-1}$ in 1969.

were taken at breast height from the sample trees to determine the development of annual radial growth, with the accuracy of 0.01 mm. The tree stand volume was calculated with the taper curve and volume functions for Scots pine (Laasasenaho 1982).

The two-way analyses of variance was performed for all of the stand growth data, including (i) three experiments and (ii) all of the fertilisation treatments with varying potassium doses, as well as a control for each year following the fertilisation. Moreover, a one-way analysis of variance, with the one-year absolute periodic volume growth as the response variable, was carried out separately in each experiment. The statistical significance of the differences between the treatments versus unfertilised control was studied using Tukey's paired t-test.

A repeated measures ANOVA model was applied to test the effect of fertilisation treatment on nutrient concentrations 7–9, 14–15 and 19–20 years after the fertilisation. A two-way analysis of variance was also applied to evaluate the foliar nutrient concentrations at the different sampling dates.

Results

Foliar nutrient concentrations

The effect of fertilisation on the nutrient concentrations was rather similar in all three experiments (Table 3). However, sig1nificant ($p < 0.05$) interactions between treatment and experiment were observed with phosphorus (19–20 years after application), potassium (14–15 years after application) and boron (Table 4). Therefore, the results for nutrient concentrations are presented by experiment.

In Scots pine needles, the deficiency limit for phosphorus has been interpreted to be 1.3–1.4 mg g^{-1}, for potassium 3.5 mg g^{-1}, for nitrogen 12 mg g^{-1} and for boron 7 mg kg^{-1} of dry mass (Paarlahti et al. 1971, Veijalainen et al. 1984, Reinikainen et al. 1998). The trees on the control plots in Sievi suffered from phosphorus and potassium deficiencies. The foliar potassium concentration in the control plots decreased to 3.12 mg g^{-1}, indicating that the stands were in a very severe state of potassium deficiency at the end of the study. In the fertilised plots, the nutrient deficiencies disappeared within 9 years after the fertilisation, and the effect of the fertilisation on the foliar K concentration was still visible at the end of the study (Fig. 1, Table 4).

In Sievi, all of the treatments, apart from the K_{50} dose, differed statistically from the control as regards the foliar concentrations. The increase in the potassium concentration was in proportion to the K dose given. When 9 years had passed from the fertilisation, the potassium concentrations were adequate in all fertilised plots. At the end of study period, 20 years from the fertilisation, only the highest K_{400} dose kept the concentration clearly above the deficiency level. The temporary variation in foliar potassium concentration was significant, and there was also a sig-

Table 3. P-values of two-way (Exp., Treat.) analysis of variance for the nutrient concentrations of pine needles during the study period. For fertilisation treatments, see Table 2.

Taulukko 3. Kaksisuuntaisen varianssianalyysin havaitut merkitsevyystasot (p-arvo) neulasten ravinnepitoisuuksille, selittävinä muuttujina koe ja käsittely (lannoituskäsittelyt, ks. Taulukko 2).

	7–9 years after fertilisation		
Nutrient	Exp.	Treat.	Exp. × Treat.
N	0.000	0.344	0.199
P	0.005	0.000	0.072
K	0.000	0.000	0.074
B	0.000	0.050	0.031
	14–15 years after fertilisation		
Nutrient	Exp.	Treat.	Exp. × Treat.
N	0.000	0.384	0.875
P	0.809	0.000	0.069
K	0.719	0.000	0.000
B	0.000	0.268	0.013
	19–20 years after fertilisation		
Nutrient	Exp.	Treat.	Exp. × Treat.
N	0.789	0.854	0.943
P	0.000	0.000	0.032
K	0.000	0.000	0.225
B	0.000	0.083	0.022

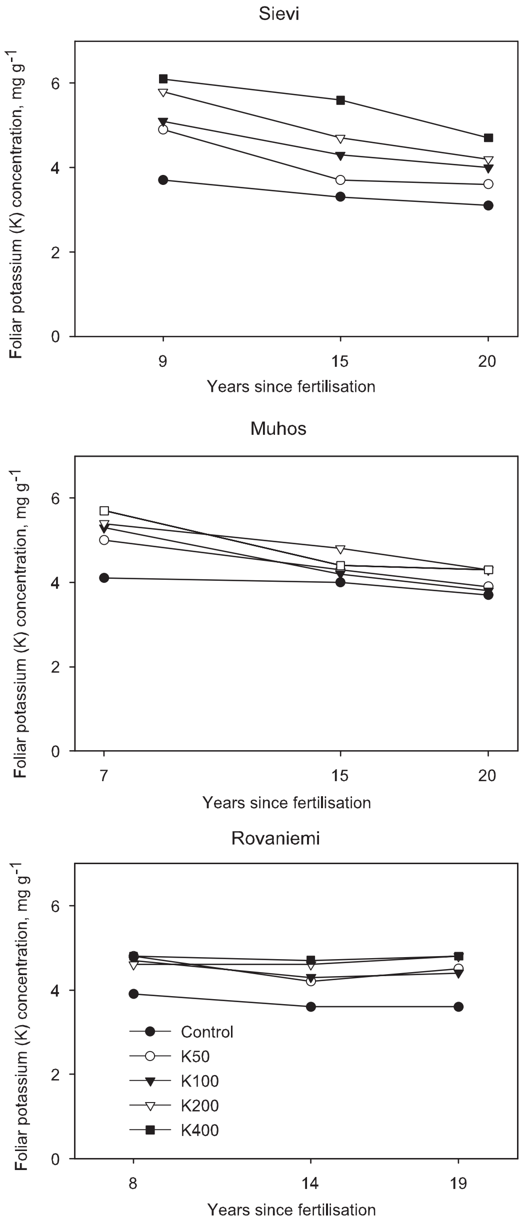

Fig. 1. Foliar potassium concentration by experiments and treatments. For fertilisation treatments in detail, see Table 2.

Kuva 1. Männyn neulasten kaliumpitoisuudet eri ajankohtina kokeittain ja lannoituskäsittelyittäin (käsittelyt tarkemmin ks. Taulukko 2).

nificant interaction effect between fertilisation and time (= the date of the needle sampling) (Table 5).

In Sievi, the PK treatment increased the foliar phosphorus concentration to a sufficient level (1.8 mg g^{-1}) in 9 years, and the effect was significant 20 years after the application (Table 4). The foliar nitrogen and boron concentrations of the tree stands were in the same order of magnitude in all treatments. During the study period, the needle nitrogen concentration increased, and on the control plots reached its maximum (1.56%) after ten years. On the PK-fertilised plots, the foliar nitrogen concentration increased more slowly, and it was at the same level with the control plots 20 years after the fertilisation. The foliar boron concentrations were above the deficiency limit during the entire period.

In Muhos, as in Sievi, there was a severe phosphorus deficiency on the control plots throughout the study period. The potassium concentration on the control plots also decreased below the deficiency limit and showed insufficient concentrations 20 years later (Fig. 1). The temporary variation in the potassium concentrations was significant (Table 4). The foliar nitrogen and boron concentrations were adequate. In the fertilised plots, the boron concentration was higher than in the control plots 7 years after the fertilisation, though not significantly. The PK-fertilisation increased the foliar phosphorus and potassium concentration above the deficiency limits (Table 4). The differences in the phosphorus concentration between the control and the PK-treatments remained statistically significant throughout the whole study period. All of the used potassium chloride doses had increased the foliar potassium concentration when 7 years had passed from fertilisation (Fig. 1). Later on, only the K_{200} and K_{300} doses seemed to have increased the foliar potassium concentration. However, there were no statistical differences between the treatments 20 years after the fertilisation (Table 4).

In Rovaniemi, the potassium status of the trees on the sample plots that were not refertilised proved to be insufficient (Table 4). PK-treatments, including various potassium chloride doses, increased the foliar potassium concentration by 0.8–0.9 mg kg^{-1}. The differences between unrefertilised and refertilised plots were significant at the 2^{nd} and 3^{rd} sampling. However, the differences between the various doses were not conspicuous, even though the potassium concentrations were highest on the plots, which had received the K_{200} and K_{400} doses. The temporary variation in the foliar potassium concentrations was significant (Table 5).

The nitrogen concentrations in Rovaniemi — regardless of the treatment — were near the deficiency limit after 8 or 14 years. However, after 19 years the nitrogen status was at an adequate level. In the control plots (with only the basic fer-

Table 4. Foliar nitrogen (N), phosphorus (P), potassium (K) and boron (B) concentrations in 1987–1989, 1995 and 2000 in varying potassium dose treatments in the experimental areas (for fertilisation treatments in detail, see Table 2). Differences between the treatments marked with same letters are not statistical in Tukey's test ($p > 0.05$) within a given time point.

Taulukko 4. Männyn neulasten N-, P-, K- ja B-pitoisuudet vuosina 1987–89, 1995 ja 2000 lannoituskäsittelyittäin (lannoituskäsittelyt ks. Taulukko 2). Samoilla kirjaimilla merkityt pitoisuudet eivät poikkea merkitsevästi toisistaan käsittelyjen välillä tiettynä ajankohtana (Tukeyn testi, Cont = vertailu).

Sievi	Cont	K_{50}	K_{100}	K_{200}	K_{400}
1989 N %	1.56 a	1.26 a	1.33 a	1.33 a	1.26 a
1995 N %	1.48 a	1.33 a	1.37 a	1.38 a	1.33 a
2000 N %	1.34 a	1.30 a	1.40 a	1.38 a	1.35 a
1989 P mg g^{-1}	1.00 a	1.83 b	1.82 b	1.82 b	1.81 b
1995 P mg g^{-1}	0.99 a	1.74 b	1.54 b	1.72 b	1.66 b
2000 P mg g^{-1}	0.99 a	1.51 b	1.57 b	1.53 b	1.52 b
1989 K mg g^{-1}	3.70 a	4.85 b	5.10 b	5.77 b	6.14 b
1995 K mg g^{-1}	3.28 a	3.70 ab	4.34 bc	4.68 cd	5.64 e
2000 K mg g^{-1}	3.12 a	3.59 ab	4.04 bc	4.15 bc	4.70 cd
1989 B mg kg^{-1}	13.1 a	19.7 a	20.8 a	20.5 a	16.3 a
1995 B mg kg^{-1}	16.2 a	13.8 a	15.4 a	15.0 a	16.5 a
2000 B mg kg^{-1}	14.4 a	14.7a	19.0 b	11.7 a	11.7 a
Muhos	Cont	K_{50}	K_{100}	K_{200}	K_{300}
1987 N %	1.41 a	1.51 a	1.46 a	1.43 a	1.48 a
1995 N %	1.33 a	1.33 a	1.32 a	1.29 a	1.33 a
2000 N %	1.35 a	1.42 a	1.34 a	1.41 a	1.31 a
1987 P mg g^{-1}	1.17 a	1.62 a	1.65 a	1.54 a	1.66 a
1995 P mg g^{-1}	1.26 a	1.64 a	1.80 a	1.58 a	1.56 a
2000 P mg g^{-1}	1.20 a	1.56 a	1.47 a	1.47 a	1.47 a
1987 K mg g^{-1}	4.11 a	5.04 b	5.32 b	5.39 b	5.65 b
1995 K mg g^{-1}	4.04 a	4.26 a	4.23 a	4.77 b	4.40 a
2000 K mg g^{-1}	3.69 a	3.88 a	3.79 a	4.26 a	4.31 a
1987 B mg kg^{-1}	14.4 a	35.3 a	32.7 a	42.0 a	42.6 a
1995 B mg kg^{-1}	12.4 a	15.0 a	18.9 a	20.3 a	18.5 a
2000 B mg kg^{-1}	10.1 a	11.6 a	15.9 a	17.5 a	13.3 a
Rovaniemi	Cont	K_{50}	K_{100}	K_{200}	K_{400}
1989 N %	1.24 a	1.24 a	1.10 a	1.22 a	1.20 a
1995 N %	1.23 a	1.13 a	1.11 a	1.21 a	1.15 a
2000 N %	1.33 a	1.44 a	1.42 a	1.36 a	1.37 a
1989 P mg g^{-1}	1.67 a	1.96 a	1.79 a	1.76 a	1.67 a
1995 P mg g^{-1}	1.39 a	1.69 a	1.50 a	1.66 a	1.59 a
2000 P mg g^{-1}	1.60 a	2.04 b	1.75 a	1.87 b	1.71 a
1989 K mg g^{-1}	3.93 a	4.75 a	4.67 a	4.59 a	4.78 a
1995 K mg g^{-1}	3.60 a	4.20 a	4.27 b	4.55 b	4.71 b
2000 K mg g^{-1}	3.63 a	4.46 b	4.41 b	4.76 b	4.84 b
1989 B mg kg^{-1}	7.8 a	4.3 a	8.4 a	4.6 a	6.3 a
1995 B mg kg^{-1}	9.0 a	5.8 a	7.4 a	4.6 b	5.5 a
2000 B mg kg^{-1}	9.1 a	5.8 a	6.7 a	6.0 a	5.8 a

tilisation), the phosphorus concentrations were well over the deficiency limit. PK-refertilisation did not increase the foliar phosphorus concentration significantly. The boron concentrations were at the deficiency level in the refertilised plots. However, the differences between the fertilisation treatments were insignificant.

Stand volume growth

All treatments, except for the K_{50} dose, increased the stand volume growth already during the first five-year period. The differences between the control and the fertilised plots gradually became more pronounced in the course of time (Fig. 2). However, the fertilisation effect depended also on the potassium dose used. The increase in annual growth was greatest with the K_{100}, K_{200} and K_{400} doses. The effect of the K_{50} dose was insignificant.

The experiments differed from each other with respect to their volume growth. Moreover, a significant interaction appeared between the experiment and the treatment during the latter part of the study period (two-way ANOVA, results not shown). The greatest stand growth responses were found in Sievi, and the smallest in Rovaniemi (Fig. 2).

In Sievi, in the annual increment for the control stands was, on average, 0.8 m^3 ha^{-1} a^{-1} for the period of 22 years. In stands fertilised with the K_{50} dose — about a half of the recommendations in forest practise — the average annual increment was 3.3 m^3 ha^{-1} for 22 years. In stands that received K_{100} or more, the annual increment was 4.9 m^3 ha^{-1}. In the one-way analysis of variance performed within the experiment, the fertiliser effect was statistically significant. At its maximum, the fertilised trees grew 7-fold compared to the unfertilised trees.

In Muhos, the effect of the fertilisation was weaker than in Sievi and not statistically significant, even though the volume growth on the fertilised sample plots was considerable higher than that on the unfertilised ones. Differences in the stand growth control versus fertilised plots varied between 0.5–2.0 m^3 ha^{-1} a^{-1}, depending on the K dose.

In Rovaniemi, there were only minor growth reactions in the tree stand after the refertilisation. During 20 years, the volume growth increased from 1.3 m^3 ha^{-1} a^{-1} to 4.0 m^3 ha^{-1} a^{-1} and was in the same order of magnitude irrespective of the treatment.

Table 5. Results of Greenhouse-Geisser tests in repeated measures ANOVA. Df-values, F-, and adjusted p-value of the time factor and the fertilisation treatment with their main effects and interactions. The testing variable is the foliar potassium concentration.

Taulukko 5. Toistettujen mittausten ANOVA-analyysin Greenhouse-Geisser-testin testisuureet aikatekijälle (time) ja lannoituskäsittelyille (Fert.) pää- ja yhdysvaikutuksineen. Testisuureena männyn neulasten K-pitoisuus.

Experiment	df	F	p
Sievi			
Time	1.80	63.7	0.000
Time × Fertilization	7.20	2.71	0.041
Muhos			
Time	1.06	10.53	0.008
Time × Fertilization	4.20	50.61	0.679
Rovaniemi			
Time	1.85	4.34	0.025
Time × Fertilization	7.39	0.78	0.610

Discussion

All of the experiments represented oligo-mesotrophic peatland site types. According to the peat and foliar analyses, the nitrogen status of the peat soil and the pine trees was adequate (N_{peat} > 2.0%, N_{foliar} > 1.30% of dry matter) in Sievi and Muhos (Kaunisto 1987, Pietiläinen & Kaunisto 2003). In Rovaniemi, the peat nitrogen concentration was lower than in the two other experiments, and we can assume that the pines suffered from a nitrogen deficiency.

The different nutritional conditions, as well as the forest management history of the experimental stands had an effect on the magnitude and duration of the fertilisation effect. The effects on the nutrient concentrations and the tree growth were most pronounced on those sites where the shortage of nitrogen was not the limiting factor (but where the trees evidently suffered from phosphorus and potassium deficiencies). The fertilisation effect was highest in Sievi, which was a nitrogen-rich and thick-peated site. There, according to the needle analysis, the growth-limiting factor was the shortage of phosphorus and potassium. The potassium status of the unfertilised trees weakened throughout the study period.

The results of Sievi were consistent with the earlier results obtained from similar peatland sites: PK-fertilisation improves the growth of the stands most on peatlands originated from thick-peated sites (Kaunisto 1989, Moilanen 1993). In Sievi, the effect of phosphorus was still evident 20 years after the fertilisation. Also in previous studies the fertilisation effect of phosphorus has proved to be long-lasting — over 30 years (Silfverberg & Hartman 1999, Pietiläinen & Kaunisto 2003). The fertiliser effect on tree growth in Sievi increased in magnitude with the applied potassium dose. This agrees with the results of Moilanen (1993). Presumably the effect will continue for at least 30 years with the highest potassium doses.

Also in Muhos the tree stand suffered from phosphorus and potassium deficiencies, and the fertilisations increased the foliar nutrient concentrations and improved tree growth. However, the nutritional situation was not as critical as in Sievi, and the responses remained moderate and not significant.

In Sievi and Muhos, the potassium concentrations in the needles were highest 5–10 years after the fertilisation. The fertilisation effect of the K_{100} dose lasted 10–15 years, after which the potassium concentration in the needles dropped close to the deficiency limit. The fertilisation effect of the higher doses on the potassium concentration in needles lasted at least 20 years. By increasing the potassium dose, the nutritional state of the trees seems to be improved for a longer time.

On the other hand, the stand growth responses produced by the potassium applications equivalent to the present recommendation were essentially similar to those produced by the larger amounts. This is consistent with Kaunisto (1992), who showed that fertilisation with potassium chloride increased tree growth for 8–22 years. Kaunisto (1992) assumed that the majority of the

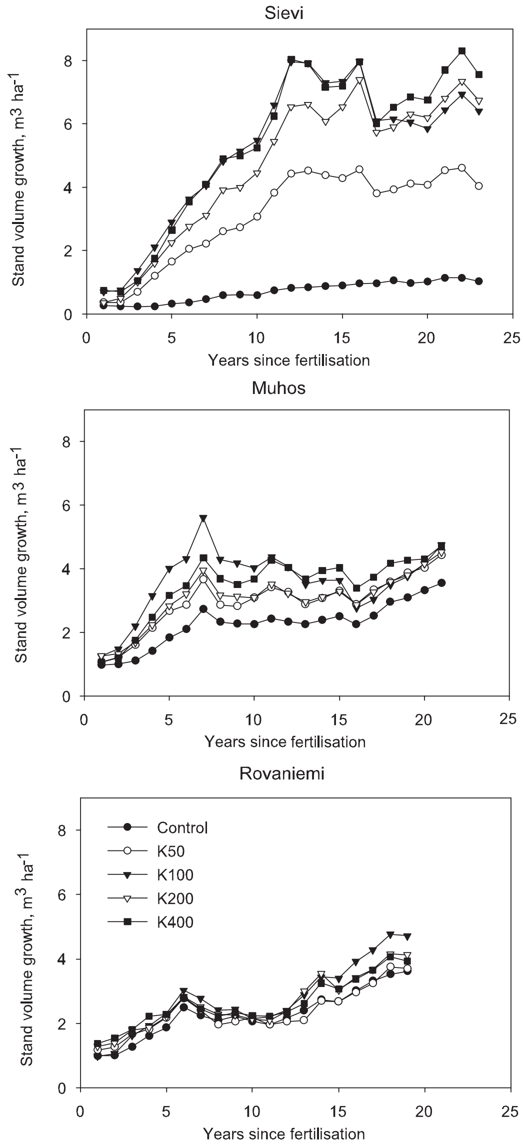

Fig. 2. The annual growth development of Scots pine in varying potassium dose treatments by the experimental areas. For fertilisation treatments in detail, see Table 2. Pairwise comparisons between the treatments are tested for each year (statistical difference: p-value < 0.05 in Tukey's test). Statistical differences in Sievi: Control vs. K100: years 10–12, 14–15. Control vs. K200: year 23. Control vs. K400: years 8, 10–12, 14–15, 17–18, 22–23.

Kuva 2. Puuston tilavuuskasvun vuotuinen kehitys kokeittain ja lannoituskäsittelyittäin. Käsittelyjen väliset erot testattu erikseen kullekin vuodelle.

water soluble potassium fertilisers leached below the root system and, therefore, could not be used by the trees. Our results agree with the previous studies concerning the long-lasting duration of the potassium fertilisation effects (Kaunisto & Tukeva 1984, Kaunisto et al. 1999, Rautjärvi et al. 2004).

In Rovaniemi, the effect of the refertilisation in 1979 was weak, both on the foliar nutrient concentrations and the stand growth, because the basic fertilisation in 1969 ensured an adequate phosphorus status, also on those plots not refertilised. Moilanen (1993) found that the effect of the refertilisation was weak if it was done 10–15 years after the basic fertilisation (see also Rautjärvi et al. 2004). The differences in the potassium concentrations between the refertilised and unrefertilised trees increased with time. Evidently this means that the effect of the basic fertilisation was weakening and the foliar nutrient concentrations started to respond to the refertilisation.

In Rovaniemi, the nitrogen concentration of the peat was low compared to Sievi and Muhos, and the foliar nitrogen concentrations were also low. The result is consistent with those obtained by Pietiläinen and Kaunisto (2003) in similar climatic conditions (annual temperature sum < 900 d.d.). According to Moilanen and Issakainen (1990) and Moilanen (1993), nitrogen fertilisation was a prerequisite for obtaining additional growth on nitrogen poor site types by applying other fertilisers. Most likely, the shortage of nitrogen was the growth-limiting factor for the pines in Rovaniemi. In the other experiments the foliar nitrogen concentrations were satisfactory.

The foliar potassium concentrations decreased with time and were at the lowest level at the end of the study period. Concern has been expressed frequently that the nutrient ratios become unfavourable in peatland stands as drainage areas age and the stands bind a major part of the scarse mineral nutrients — especially potassium — of the peat into their biomass (Kaunisto & Tukeva 1984, Kaunisto & Paavilainen 1988). Our results from all three experiments support the previously presented estimate from this point of view.

The temporary variation in foliar potassium was significant in every experiment. Furthermore, significant interactions between time and the fertilisation treatment were observed in Sievi. The latter suggests that the temporal foliar responses to the different treatments were not similar: the effect of the K_{50} and K_{100} doses ceased within 10–15 years, whereas the effect of biggest doses were still continuing. In Muhos and Rovaniemi, the interaction between treatment and time was not significant.

The foliar boron concentrations were well over the deficiency level in all experiments. Due to the micronutrient addition, the boron concentrations increased in Sievi and Muhos. The boron concentrations have been found to improve rapidly with water-soluble boron fertilisers (e.g. Paavilainen & Pietiläinen 1983, Kolari 1983, Veijalainen 1983, 1984). In Rovaniemi — where no micronutrients were applied — the foliar boron concentration decreased in the PK refertilised plots. This “dilution effect” occurs frequently in stands that are fertilised with only the main nutrients (N, P, K) as earlier observed by Huikari (1977) and Veijalainen (1977).

Conclusions

Our results indicate that on drained thick-peated pine peatlands, where potassium and phosphorus deficiencies are common the shortage of potassium and phosphorus restrict stand growth. PK-fertilisation ensures a balanced nutrient status and increases stand growth considerably. The ameliorative effect is especially strong in stands suffering from a severe potassium deficiency (K < 3.5 mg g^{-1}). The potassium dose equivalent to those of the recommendations in practical forestry (100 kg ha^{-1}) cures the nutrient deficiencies for about 15–20 years. The foliar response is stronger and longer-lasting with higher doses (200–400 kg K ha^{-1}), but the stand response is, however, in the same range of magnitude as with a 100 kg ha^{-1} dose. Refertilisation with PK is unnecessary if only 10 years has passed from the previous PK-fertilisation and if the growth-limiting factor is the shortage of another nutrient, e.g. nitrogen.

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Tiivistelmä:

Kaliumlannoituksen vaikutus männyn neulasten ravinnepitoisuuksiin ja tilavuuskasvuun ojitetuilla rämeillä

Kaliumin (K) niukkuus ja fosforin (P) heikko saatavuus rajoittavat yleensä puiden kasvua ojitetuilla soilla. Karuilla kasvupaikoilla — etenkin Pohjois-Suomessa — puut kärsivät usein myös typen (N) puutoksesta. P- ja K-puutoksia esiintyy etenkin saraturvevaltaisten, alkuaan vähäpuustoisten nevaisten ja märkien soiden ojitusalueilla, kun puusto on ehtinyt riukuvaiheeseen tai saavuttanut ensiharvennusiän. Ravinteiden puutokset korostuvat paksuturpeisilla ja runsastyppisillä kohteilla. Fosforilannoitus korjaa puiden P-taloutta ja lisää puuston kasvua ainakin 30 vuoden ajan. Kaliumlannoituksen vaikutusaika rajoittuu 10–20 vuoteen. On arveltu, että käyttämällä suurempia kaliumannostuksia myös lannoituksen vaikutus puiden kasvuun suurenisi ja lannoituksen vaikutusaika pitenisi. Toisaalta on esitetty arveluita, että kaliumannostuksella ei ole olennaista merkitystä lannoitusreaktioon, koska suurin osa kaliumista huuhtoutuu juuristokerroksen alapuolelle puiden ulottumattomiin.

Tässä työssä selvitettiin männyn (*Pinus sylvestris* L.) ravinnetilaa ja lannoituksen aiheuttamia puustoreaktioita. Lähtökohtana olivat hypoteesit, joiden mukaan lannoitusvasteen voimakkuus määräytyy joko käytetystä kaliumannostuksesta tai puuston ravinnetilasta lannoitushetkellä. Aineisto kerättiin kolmelta rämemännikön lannoituskokeelta Pohjois-Suomesta (Sievi, Muhos, Rovaniemen maalaiskunta). Muuttuma- tai turvekangasvaiheessa olevat tutkimuskohteet on ojitettu 1930- ja 1960-luvuilla ja ne edustavat suursaraisia ja ruohoisia kasvupaikkatyyppejä (Taulukko 1). Tutkimuskohteilla tehtiin kunnostusojitus ennen lannoituskäsittelyitä. Kaikissa koemetsiköissä puusto oli lähes puhdasta männikköä, jonka valtapituus vaihteli kokeiden perustamishetkellä välillä 3–8 m. Puiden ravinnetila vaihteli kokeiden välillä selvästi. Sievin ja Muhoksen kokeilla männyn neulasten keltakärkisyys indikoi ankaraa tai lievää kaliuminpuutosta, kun taas Rovaniemen kokeella ei silmin havaittavia ravinnepuutoksia esiintynyt. Koejärjestelyt toteutettiin arvottujen lohkojen periaatteiden mukaisesti. Lannoituskäsittelyjä olivat lannoittamaton vertailu ja NPK-käsittelyt, joissa käytetty fosforin ja typen määrä oli vakio, mutta kaliumannostus vaihteli välillä 50–400 kg ha^{-1}. Lannoitteina käytettiin kaliumkloridia (kalisuola), raakafosfaattia ja ureaa, ja lannoituskäsittelyt toistettiin kokeesta riippuen 3 tai 4 kertaa (Taulukko 2). Muista kokeista poiketen Rovaniemen tutkimusmetsikkö oli lannoitettu kertaalleen Suometsien PK-lannoksella jo ennen kokeen perustamista vuonna 1969.

Neulasnäytteet kerättiin 7–9 vuoden, 14–15 vuoden ja 19–20 vuoden kuluttua lannoituksesta. Neulasista analysoitiin typen, fosforin, kaliumin, ja boorin pitoisuudet ja määritettiin neulasten kuivamassa (100 kpl). Puusto mitattiin, kun levityksestä oli kulunut 19–22 vuotta (Taulukko 3). Puuston tilavuuskasvu selvitettiin taannehtivasti koepuista mitattujen säde- ja pituuskasvujen avulla. Vertailukoealoilta kerätyistä turvenäytteistä analysoitiin pintaturpeen (10 cm:n kerros) kokonaistyppipitoisuus.

Pintaturpeen typpipitoisuus oli Sievissä 2 %, Muhoksella 2,3 % ja Rovaniemellä 1,7 %. Neulasanalyysien mukaan puiden N-tila oli Sievissä ja Muhoksella tyydyttävä; Rovaniemellä sitä vastoin typen niukkuus rajoitti puiden kasvua.

Lannoitusvaikutuksen suuruus riippui puuston ravinnetilasta. Sievissä, jossa lannoittamattomat vertailupuut kärsivät ankarasta fosforin ja kaliumin puutoksesta (K-pitoisuus < 3.5, P-pitoisuus < 1.4 mg g^{-1}) ja jossa K-pitoisuudet vertailualoilla edelleen heikkeni tutkimusjakson aikana, lannoitus kohotti ko. ravinteiden pitoisuudet neulasissa hyvälle tai tyydyttävälle tasolle (Kuva 1, Taulukko 5). Ravinnelisäyksen vaikutus näkyi Sievissä tilastollisesti merkitsevänä kaikkina tutkittuina ajankohtina. Myös Muhoksen kokeella lannoituskäsittelyt kohottivat männyn neulasten fosfori- ja kaliumpitoisuuksia, vaikka puiden ravinnepuutokset eivät olleet yhtä voimakkaita kuin Sievissä. Rovaniemen kokeella –ilmeisesti aiemman lannoituksen vuoksi– ravinnepitoisuuksien muutokset näkyivät lähinnä vain kaliumpitoisuuksien kohoamisena.

Neulasten kaliumpitoisuus oli sitä korkeampi, mitä enemmän kaliumia lannoituskäsittely sisälsi. Annoksen suurentaminen myös pidensi vaikutusaikaa. Kun lannoituksesta oli vähemmän kuin 10 vuotta, kaikki käytetyt kaliumtasot (50, 100, 200, 400 kg ha^{-1}) riittivät turvaaman puiden riittävän kaliumin saannin. Nykyistä lannoitussuosituksen mukaista annostusta (100 kg ha^{-1}) käytettäessä vaikutusajaksi muodostui n. 15 vuotta. Käsittelyt, jotka sisälsivät kaliumia 200–400 kg ha^{-1}, säilyttivät puiden neulasten kaliumpitoisuuden tyydyttävällä tasolla (> 4.0 mg g^{-1}) vielä tutkimusjakson lopussa 19–20 vuoden kuluttua levityksestä (Kuva 1, Taulukko 5).

Lannoituskäsittelyt (lukuun ottamatta kaliumannosta 50 kg ha^{-1}) lisäsivät koko aineistossa puuston tilavuuskasvua merkitsevästi, kun lannoituksesta oli kulunut 2–4 vuotta (Taulukko 7). Kokeittaisessa tarkastelussa lannoituksen vaikutus puuston kasvuun oli merkitsevä vain Sievin kokeella: vaikutus voimistui lannoitusta seuranneen 15 vuoden ajan, ja säilyi sen jälkeen suurin piirtein samalla tasolla tutkimusjakson loppuun saakka (Kuva 2). kaliumannokset, joissa kaliumin käyttömäärä vaihteli välillä 100–400 kg ha^{-1}, lisäsivät puuston tilavuuskasvua Sievissä lähes yhtä paljon: 22 vuoden aikana kasvunlisäys oli keskimäärin lähes 5 m^3 ha^{-1} a^{-1}. Sen sijaan Muhoksen ja Rovaniemen kokeilla, joilla fosforin ja kaliumin puutokset eivät olleet yhtä ankaria kuin Sievissä, lannoituksen vaikutus puuston kasvuun jäi selvästi pienemmäksi, eivätkä erot lannoittamattomaan olleet merkitseviä. Rovaniemellä puiden heikkoa kasvuvastetta selittänee se, että puiden fosforitila oli edellisen lannoituksen ansiosta vielä kunnossa, ja että kasvua rajoitti myös typen heikko saatavuus.

Tulosten perusteella voidaan päätellä, että PK-lannoituksen vaikutuksen suuruus ja kestoaika määräytyy sekä kohteen viljavuuden (typen runsaus) että kivennäisravinteiden puutostilan voimakkuuden perusteella. Lannoituksen puustovasteen kesto on pitkä eli yli 20 vuotta silloin, kun turpeen typpipitoisuus on yli 2 % ja kun neulasten fosfori- ja kalium-arvot ovat ankaran puutosrajan tuntumassa tai sen alla. Kaliumlisäys kalisuolana poistaa kaliumin puutoksen 15–20 vuoden ajaksi. Nykysuositusta korkeammalla kalisuola-annostuksella voidaan pidentää lisääntyneen neulasten kaliumpitoisuuden kestoaikaa, mutta puiden absoluuttiseen kasvuun käyttömäärän lisääminen ei juuri vaikuta.

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JÄRJESTÖASIOITA

Suoseura
Finnish Peatland Society

Hyvä Suoseuran jäsen,

Vuoden 2005 kolmas jäsenkokous pidetään Suoseuran ja Metsänparannussäätiön yhteisen opintoretkeilyn yhteydessä 4.10.2005, Suomusjärvellä, Kettulassa. Metsänparannussäätiön 50-vuotisjuhlan kunniaksi säätiö tekee Suoseuran kanssa yhteisen opintoretken Lounais-Suomeen, Suomusjärven ympäristöön.

Seuran syysvuosikokous 22.11.2005

Neljäs esitelmäkokous ja samalla syysvuosikokous pidetään 22. 11. 2005 Helsingissä, Tieteiden talolla, Kirkkokatu 6.

Ohjelmassa:

1) Sääntömääräiset vuosikokousasiat, mm. seuraavat:

—Toimintassuunnitelman hyväksyminen vuodelle 2006

—Talousarvio vuodelle 2006

—Suoseura ry:n uuden hallituksen valinta vuodelle 2006

—Jäsenasiat: Uudet jäsenet

—Muut asiat

2) Esitelmät:

Esitelmien ajankohtaisena aiheena ovat **suot matkailukohteena**, joista kertovat mm. Mari Wiiskanta (Helsingin yliopisto) ja Lea-Elina Nikkilä (Leivonmäen kansallispuisto). Luvassa mm. Suo-animaatio-esitys!
Tervetuloa!

Syysterveisin,

Leila Korpela
Sihteeri
Metsäntutkimuslaitos, Metla/Vantaa
Pl 18, 01301 Vantaa
p. 0102112629,
sähköposti: Leila.Korpela@metla.fi