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Long-term nutrient status of PK fertilized Scots pine stands on drained peatlands in North-Central Finland

PK-lannoituksen vaikutus männyn ravinnetilaan Pohjois-Pohjanmaan ojitusalueilla

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The low availability of usable phosphorus (P), as well as the scarcity of potassium (K), are often limiting tree growth on peatlands. Approximately one third of the 5.5 million ha of peatlands drained for forestry in Finland has been fertilized during the last 50 years. The aim of this study was to determine the long-term effect of PK fertilization on the nutrient status of Scots pine on different site types of drained peatlands. Changes in nutrient concentrations (N, P, K) and dry mass of current needles was used for examining the effect of fertilization. The material included 82 fertilization experimental stands comprising a total of 892 needle samples; 434 from PK-fertilized and 458 from unfertilized control stands. The needles were collected and analyzed between 1980 and 2002. Depending on the experiment, a time period of 1–35 years had elapsed between fertilization and needle sampling. More than half (54%) of the control stands had P concentration below the deficiency limit 1.3 mg g^{-1}, and correspondingly, 48% had K concentration below 4.0 mg g^{-1}. Fertilization increased considerably the needle dry mass and foliar P and K concentration raised above the deficiency limits. The lower the concentrations of foliar P and K and the higher the concentration of N were in control trees, the more pronounced the effect of PK fertilization was. Compared to control, the needle P concentration was still noticeably higher on the fertilized stands after 21–35 years of the fertilization. However, K concentration had decreased and was at the same level as in the control trees. The effect of fertilization was strongest on sites which had been treeless or sparsely forested before drainage and which had severe nutrient shortages or imbalances. The response to fertilization was very similar regardless of the temperature sum of the year the needles first appeared. The results of this study show that the P status of Scots pine could be improved for over 30 years with a single fertilization. On the other hand, ensuring the K status will require 1–2 refertilization treatments during the rotation period.

Key words: needle analysis, fertilization, peatland, site type, nutrient deficiencies

Introduction

Finland is home to one third of the world's 15 million hectares of peatlands drained for forestry (Paavilainen & Päivänen 1995). Initially, drainage in Finland was carried out primarily on genuine forested sites, but as it became mechanized during the 1950s and 1960s, it was expanded to open fens and oligotrophic bogs, which have thick peat layer. In such sites stand yield is limited by scarcity or imbalance of nutrients in the growing substrate (Keltikangas et al. 1986).

In contrast to mineral forest soil, peat contains abundantly nitrogen, but a low amount of mineral nutrients. Total nitrogen and phosphorus contents of peat are adequate for forest trees (Laiho & Laine 1994, Laiho & Alm 2005), but their mineralization into a usable form, especially in the case of phosphorus, is often slower than trees would require. The low availability of usable phosphorus and the scarcity of potassium are often limiting factors for tree growth on drained peatlands (Veijalainen 1992, Moilanen 1992, Hytönen & Kokko 2006).

The importance of potassium is pronounced on thick-peated sites, where it is especially scarce, and where a significant part of the surface peat's potassium can become bound in the tree stand (Kaunisto & Tukeva 1984, Kaunisto & Paavilainen 1988, Laiho & Laine 1994, Moilanen et al. 1996a, Kaunisto & Moilanen 1998). It has not always been possible to detect depleting potassium stores even in old drainage areas (Laiho & Laine 1994, Laiho et al. 1999), thus, predicting changes in potassium content of peat during longer periods has been difficult. The compaction and settling of peat over time may result in an improved potassium status, especially on thin-peated sites where the root system is able to reach the subsoil for mineral nutrients (Moilanen et al. 1996b, Saarinen 1997).

Pine trees growing on oligotrophic drained peatlands also suffer from low availability of nitrogen. The scarcity of nitrogen limits tree growth especially in Northern Finland, and particularly during cold growing seasons (Starr & Westman 1978, Westman 1979, Sundström et al. 2000, Pietiläinen & Kaunisto 2003).

The aim of fertilization is to improve stand yield by ensuring the trees a balanced amount of nutrients available. Approximately one third of the 5.5 million ha of peatlands drained for forestry has been fertilized with PK or NPK fertilizers during the last 50 years. A considerable part of that area has been refertilized later. Fertilization was especially active during the 1970s, when nutrients were often added as part of first-time drainage. The activity peaked in 1974, when 117 000 ha of recently ditched peatlands were fertilized, but experienced a sharp decline during the 1980s, and by the 1990s, annual fertilization amounts were very low. By 2000, the annual spreading areas had risen to 5000–10 000 ha. The highest increases have been with so-called vitality fertilizations, which are partly funded by the government (KEMERA, Act on the Financing of Sustainable Forestry in Finland since 1996).

The nutrient status of the tree stand is firmly dependent on the nutrient status of the soil. There are several methods for estimating the site fertility status and nutrient status of peatlands drained for forestry. Fertilization instructions for practical forestry are based on site type classification which is based on the composition of plant species in the bottom and field layers (Huikari 1952, Vasander & Laine 2008). Site type classification - as peat chemical analysis - has been used to evaluate especially the total amount and availability of nitrogen in the soil substrate. The higher the nitrogen content in peat, the higher is the potential productivity of the tree stand (Kaunisto & Pietiläinen 2003, Pietiläinen & Kaunisto 2003, Korkalainen et al. 2007). The nutrient status and deficiencies of the stand can be assessed by observing visual symptoms of nutrient deficiencies in the tree stand (e.g. changes in colour of leafs and needles, abnormal growth of shoots) (Reinikainen 1967, Veijalainen et al. 1984, Hytönen & Wall 2006).

Needle analysis has been widely used as a standard method to assess the nutrient status in peatland forests. Analyses of the nutrient concentrations of living needles enable an accurate evaluation of the nutrient status at a certain point of time. In Finland, needle analysis has been used especially in studies involving the nutrient requirements and deficiencies of Scots pine on drained peatlands (e.g. Paarlahti et al. 1971, Veijalainen 1984, 1992, Hytönen & Kokko 2006).

After fertilization, the nutrient concentrations in the living parts of the trees (needles, leaves, bark, root system) and in the wood rise within 1–2 years, depending on e.g. fertilizer type and dose, site type and tree species (e.g. Paavilainen & Pietiläinen 1983, Veijalainen 1984, Kaunisto 1987, Finér 1992, Kaunisto et al. 1993, Moilanen et al. 1996b, Penttilä & Moilanen 1997, Finér & Kaunisto 2000). An improved nutrient status also results in an increased number of living needle age classes (Moilanen et al. 2002).

Although there have been many studies on the nutrient status of peatland forests, there still is a lack of knowledge about the factors involved in the fertilization reaction. The majority of studies based on needle analysis and stand measurements have been done on trouble spots, where nutrient deficits have been apparent already at the time of fertilization (e.g. Kaunisto & Tukeva 1984, Rautjärvi et al. 2004). Determining the need for fertilization has been difficult in practical forest planning—more precise guidelines are needed for choosing the target sites and also for carrying out the application itself.

The main aim of this study was to determine the magnitude and duration of the fertilization response in the foliar N, P and K concentrations of Scots pine (*Pinus sylvestris* L.) stands growing on different types of peatland sites. It was assumed that nutrient status of trees and the changes in it after PK fertilization are connected to 1) the original mire type (genuine forested sites, sparsely forested composite sites and treeless sites), 2) site fertility type (N rich/N poor), and 3) the temperature conditions at the time of new needle growth. Also, it was evaluated whether the P and K deficiency limits presented in current guidelines for needle analysis are suitable for determining fertilization needs and assessing fertilization results in practical forestry.

Material and methods

Experiments

The long-term fertilization experiments in stands on drained peatlands monitored by Metla (Finnish Forest Research Institute) were used in this study. The oldest experiments had been established in early 1960s and the newest in late 1990s. A single experiment generally consisted of 15–30 sample plots (stands) and 5–8 fertilization treatments. Each experiment followed a randomized block design. The fertilization treatments included primary nutrients (N, P, K) in different combinations and dosages, usually with 2–4 replicates.

This study included only Scots pine (*Pinus sylvestris* L.) dominated stands that had received a single PK treatment and had an unfertilized control. A further criterion was that the dosage was in line with current recommendations (P 40–45 kg ha^{-1}, K 80–100 kg ha^{-1}). The material included 82 experiments, of which a total of 892 needle samples had been analyzed between 1980 and 2002 (Table 1).

The majority of the studied experiments were located in the Southern boreal aapa mire zone (Ruuhijärvi 1983) in Northern Ostrobothnia. The northernmost experiment was located in Sodankylä municipality (ca. 100 km above the Arctic Circle) in Northern boreal aapa mire zone, the southern and westernmost on the coast of the Gulf of Bothnia, in zone of eccentric bogs and the easternmost (in Southern boreal aapa mire zone) near the Russian border, in Kainuu (Fig. 1). Background information of the sites within the experiments (site type, drainage information, time of cuttings) was derived from the archives of Metla, establishment documents and previous publications. The following information was available for every experiment: 1) location (coordinates) and the elevation from sea level (m), 2) the original mire site type (according to Vasander & Laine 2008), 3) site fertility type (eutrophic, herb-rich, tall-sedge, low-sedge, dwarf-shrub/cottongrass, *Sphagnum*) (according to Huikari 1952), 4) the year of fertilization and treatment details, and 5) time elapsed between initial drainage or ditch maintenance and needle sampling (years).

The experimental stands had been drained mainly in 1960s and 1970s, but the earliest drainage had been carried out in 1930s. On average, 33 years (ranging 1–74 years) had elapsed between drainage and needle sampling. Ditch maintenance had been carried out latest 25 years after first drainage in almost all of the stands, so the drainage was assessed to be good or satisfactory throughout the post-drainage period. The dominant tree species was Scots pine with a low admixture of downy birch (*Betula pubescens* Ehrh.) and/or Norway spruce (Picea abies (L.) Karst.) (5–25% of the total stand volume). At the fertilization event the stands within the experiments were mostly in the young thinning stand stage, the mean height of Scots pine varied between 4–10 m depending on the stand. One tenth of the sites were thin-peated i.e. the thickness of peat layer was less than 30 cm. More than half (56%) of the needle samples were collected from sites with a peat layer thickness of more than 1 meter.

The elemental composition of the PK-fertilizers varied. At the beginning, during 1960s, PK fertilizers were mixtures of raw or fine phosphate and potassium sulfate or chloride. 'Suometsien PK-lannos' was the standard fertilizer in the 1970s and 1980s, and 'Metsän PK' (P 9–11%, K 13–18%) in the 1990s. In PK treatments, 35–50 kg^{-1} ha^{-1} of P and 60–100 kg^{-1} ha^{-1} of K were applied.

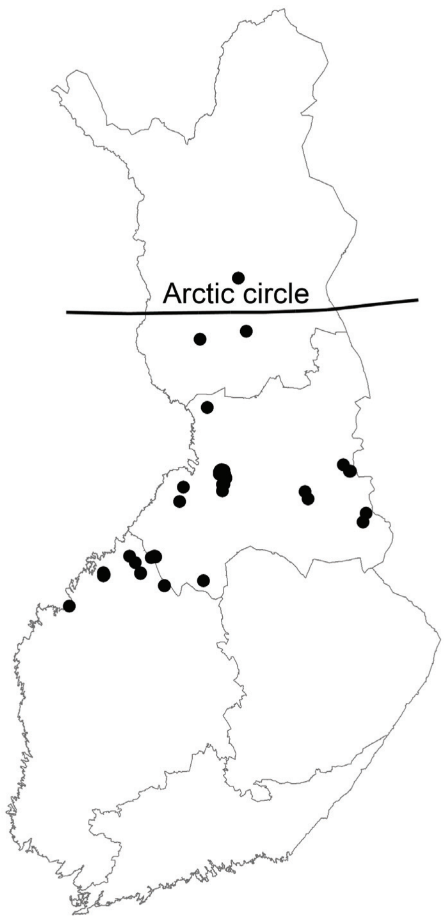


Fig. 1. Areas where the experimental stands are located.

Kuva 1. Koemetsiköiden sijaintialueet.

Table 1. Number of needle samples in 82 experiments (stands) by original natural mire site type groups and time passed since fertilization. PK = PK fertilized (n = 434 plots), - = control (n = 458 plots). For the site classification, see Vasander & Laine (2008).

Taulukko 1. Neulasnäytteiden määrä 82 tutkimusmetsikössä alkuperäisen suotyyppien pääryhmän ja lannoituksesta kuluneen ajan mukaan luokiteltuna. PK = PK-lannoitus (n = 434 koealaa), - = vertailu (n = 458 koealaa). Kasvupaikkaluokitus esitetty Vasander & Laine (2008) mukaan.

	Years since fertilization						Total
	1–10		11–20		21–35		
Fertilization	PK	-	PK	-	PK	-	
Genuine forested sites	34	36	35	34	8	7	154
Sparsely forested sites	132	154	82	85	25	36	514
Treeless sites	38	37	47	41	33	28	224

Sampling and analysis of needles

Changes in needle nutrient concentrations and dry mass were used as the gauge for examining the effect of fertilization. The needles had been generally collected at dormant period between November and March, as recommended (Paarlahti et al. 1971, Reinikainen et al. 1998). At the time of the sampling, 12 years on average (range 1–36 years) had elapsed from the fertilization. One sample was collected from each unfertilized control stand and each fertilized stand. A sample consisted of 1–2 lateral growths from the previous summer per tree (6–8 trees per stand). The branches were collected with a branch cutter from the southern side of the upper third of the green crown. Samples were not collected from trees growing close to the ditches (< 3 m). More than 10 years had passed from any stand operations (thinning) in all cases.

Around one fifth (17%) of the needle samples were from originally genuine forested mire site types (KR spruce-pine swamp, KgR paludified pine forest, IR dwarf-shrub pine bog, for classification see Vasander & Laine 2008). The majority (58%) were from former sparsely forested composite mire site types characterized by a mosaic of hummock - lawn - hollow vegetation (RhSR herb-rich sedge birch-pine fen, VSR tall-sedge pine fen, LkR low-sedge *S. papillosum* pine fen, TR cottongrass pine bog), and a quarter (25%) from former treeless site types (RhSN herb-rich sedge fen, VSN tall-sedge fen, VRiN flark fen, LkKaN low-sedge *S. papillosum* fen) (Table 1). The most common site fertility type was tall-sedge type (42% of all samples). Low-sedge and cottongrass types both accounted for 28% of the samples. The most fertile (eutrophic) and the least fertile (*Sphagnum*) site types both were represented only by around ten samples each.

The needles were dried at 60 °C for 48 hours, after which they were grounded and burned in a muffle furnace at 500 °C for 24 hours. From the ashes, the total nutrient concentrations were analyzed with HCl extract (2 M-HCl), phosphorus spectrophotometrically with vanadomolybdate method, and K with atomic absorption spectroscope (AAS). Nitrogen was analyzed spectrophotometrically (salicylate method) from a sample decomposed with the Kjeldahl-method (see Halonen et al. 1983). Most of the samples were also weighed for dry mass (per 100 needles) before grinding.

Data analysis

Weather conditions in the experiments were derived with models that are based on the geographical location and elevation above sea level (Ojansuu & Henttonen 1983). The models were used to calculate an effective temperature sum (threshold +5 °C) for the growing season when the needles appeared. . The annual temperature sums in 1980–2002 varied between 800 and 1292 d.d.

Interpretation of the needle analyses is based on previous studies of Scots pine growing on peatlands, and the recommendations on the deficiency limits and optimal concentrations of the different primary nutrients. Following nutrient concentration values (mg g^{-1}) for weak, adequate and optimal nutrient status were used in the interpretation of the needle analyses (according to Paarlahti et al. 1971 and Reinikainen et al. 1998):

Nutrient	Weak	Adequate	Optimal
P	<1.3	1.3–1.6	>1.6–2.2
K	<4.0	4.0–4.5	>4.5–5.5
N	<12	12–13	>13–18

The data was grouped into classes in order to examine the reaction of fertilization of trees in different stands having different nutrient status, as well as examine the relationship between the reaction and the temperature sum of the growing season. Two fertility classes were used in the calculations: "fertile", including the nitrogen-rich eutrophic, herb-rich and tall-sedge sites (31 experiments and 379 samples), and "barren", including the nitrogen-poor low-sedge, cottongrass and *Sphagnum* sites (51 experiments and 513 samples). The temperature sums from the summer preceding the sample collection (the year the needles first appeared) were divided into three categories (< 950 d.d., 951–1050 d.d. and > 1050 d.d.).

The analysis of variance (SPSS 14.0 for Windows) was used to examine the differences in needle nutrient concentrations, dry mass and nutrient contents (= dry mass*concentration) between fertilized and control stands. The calculation unit used was the mean needle nutrient concentration for N, P or K for both PK fertilized and unfertilized control stands in each experiment. Foliar stand-specific N, P and K concentrations, and needle dry mass during three different periods after fertilization were used as dependent variables (post-drainage age 1–10, 11–20 and 21–35 years). The independent variables in analysis of variance were thus fertilization treatment by (i) the original site type (genuine forested, sparsely forested, treeless), (ii) fertility class or (iii) temperature sum class of growing season. Bonferroni test was used as a follow-up in the pair comparison (significance level $p < 0.05$).

Regression analysis was used to examine the timing of the needles' reaction to fertilization, and its dependency on the nutrient status of the trees in the control stands. The variations in nutrient concentrations, needle dry mass and nutrient content of 100 needles between the fertilized stands and control stands during given time period were used as dependent (y) variables. The nutrient concentration or content in the control stands were used as independent (x) variables. Regression analysis (curve estimation) was carried out by direct inverse model $y = a + b*(1/x)$.

Changes in the nutrient status of the trees were also examined by vector analysis, based on visual examination of diagrams of the changes in needle nutrient concentrations and dry mass (e.g. Timmer & Stone 1978, Timmer & Ray 1988, Haase & Rose 1995). A vector diagram depicts the relative changes in needle nutrient concentrations and content after a particular application with the control considered as the comparison level, simultaneously for several nutrients. The method illustrates the connections between different nutrients and points out the ones affecting tree growth most. It also allows the identification of different nutrient status and fertilization responses (dilution, luxury consumption, deficiency, sufficient or excessive levels) in a more complete way than the use of nutrient concentration alone.

Results

The variability of the nutrient status in fertilized and control stands

Needle nitrogen (N) concentration in control stands (n = 458) varied between 6.8 and 22.3 mg g^{-1}, phosphorus (P) 0.76–2.18 mg g^{-1} and potassium (K) 2.09–6.26 mg g^{-1}. In fertilized stands (n = 434 samples) the concentrations were: N 9.4–19.9 mg g^{-1}, P 1.00–2.71 mg g^{-1} and K 2.49–7.49 mg g^{-1}.

There were considerably more cases of needle P and K deficiencies on the unfertilized control stands than on the fertilized stands (Table 2). More than half of the unfertilized stands had the needle P below the deficiency limit 1.3 mg g^{-1}, and almost half had the needle K below 4.0 mg g^{-1}. Deficiencies of P and K mostly appeared together: 75% of the K-deficient stands also suffered from deficiency of P. The effect of PK treatment on the needle N status of the trees was insignificant (Table 2).

During the first 10-year period after the application PK fertilization improved the nutrient status of the stands and significantly increased foliar P and K concentration and needle dry mass (Fig. 2). Especially the increase in P concentrations due to fertilization was long-lasting and did not cease during the study period (35 years) in contrast to K concentrations which sunk almost to control level in 20 years.

Table 2. Nutrient deficiencies in the experimental stands (% of samples) by fertilization treatments (n= 892 needle samples) with the statistically significance values of Pearson Chi-square test.

Taulukko 2. Ravinnepuutosten yleisyys (% näytteistä) koealuemetsiköissä lannoituskäsittelyittäin (n = 892 neulasnäytettä). Tilastolliset merkitsevyydet ovat Pearson X^2-testin mukaan.

Needle concentration	Control	Fertilized	Pearson Chi-square test p-value
P <1.3 mg g^{-1}	9	54	0.000
K <4.0 mg g^{-1}	30	48	0.016
N <12 mg g^{-1}	27	24	0.588

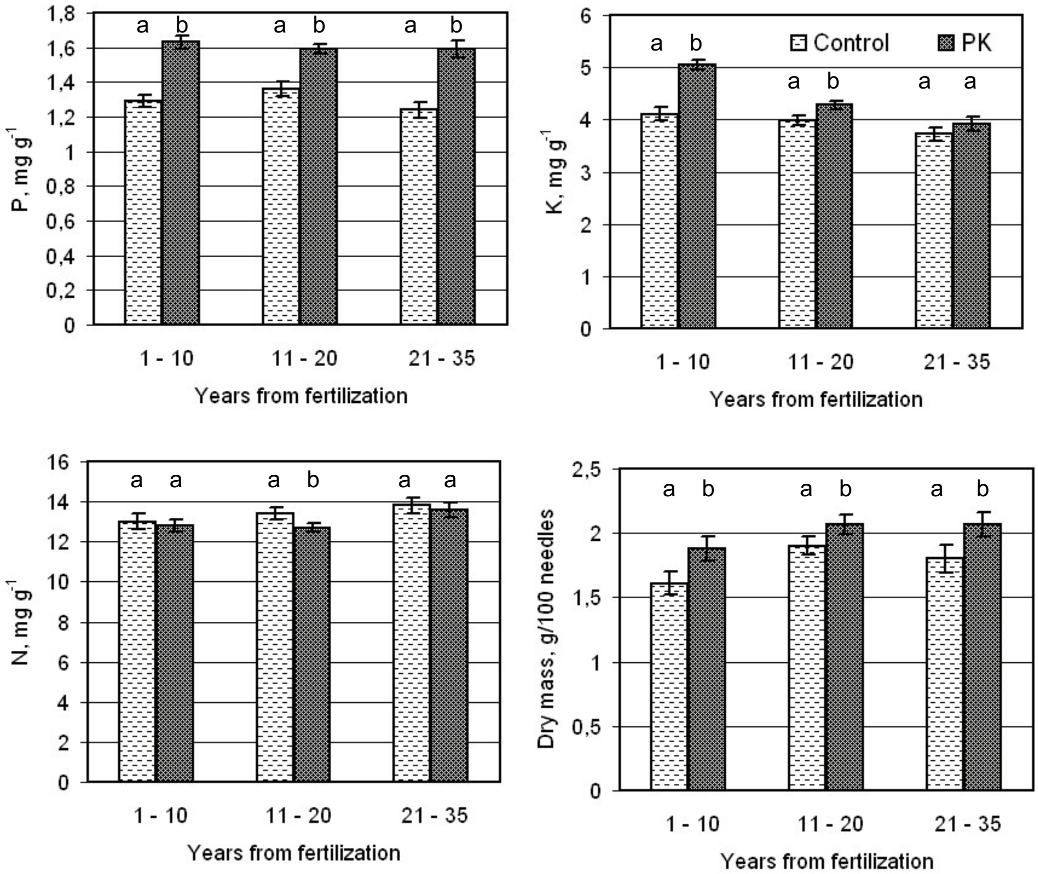


Fig. 2. Needle nutrient concentrations and dry mass in unfertilized and fertilized stands by time elapsed from the fertilization (mean values with standard errors of mean). Differences between the columns marked with same letters are not statistically significant within the period according to Bonferroni's test ($p > 0.05$).

Kuva 2. Neulasten ravinnepitoisuudet ja kuivapaino eri ajankohtina lannoituksen jälkeen (keskiarvot ja keskiarvon keskivirheet). Samalla kirjaimella merkityt pylväiden arvot eivät poikkea merkitsevästi toisistaan lannoitusikäluokan sisällä.

Effect of fertilization on different site types

Original site type

On originally (before drainage) genuine forested sites the mean needle K concentration was significantly higher ($p = 0.005$) and mean P concentration almost significantly higher ($p = 0.085$) than on former treeless or sparsely forested composite sites (Bonferroni test including all the unfertilized stands). The mean needle N concentration, however, were significantly lower on genuine forested sites than on the other sites ($p = 0.025$) (Table 3).

PK fertilization raised foliar P concentrations and improved the P status of trees in all site types (Table 3). There were no significant interactions between fertilization treatment and site type in two-way variance analysis. In all site types also the K status improved remarkably after fertilization. The changes in mean foliar N concentrations were minor after the fertilization.

The overall mean of the needle dry mass (per 100 needles) was significantly ($p < 0.05$) higher on genuine forested sites (1.98 g) than on sparsely forested sites (1.76 g) and former treeless sites (1.66 g) (Bonferroni test including all the unfertilized stands). The effect of PK fertilization on the needle dry mass was statistically significant only on former treeless sites 11–20 years from fertilization (Table 3).

Site fertility

The mean needle K concentration was significantly lower on nitrogen-rich sites classified "fertile" than on nitrogen-poor "barren" sites ($p = 0.005$). The mean N concentration, however, was significantly higher on fertile sites ($p = 0.001$). On the control stands in barren sites, the status of P and K was generally satisfactory (Table 4).

Fertilization had improved needle P and K concentrations significantly on both fertile and barren sites (Table 4). In the two-way variance analysis no statistical interaction between fertilization treatment and site type class could be found. The improvement in the phosphorus status was detectable even on the oldest experiments (21–35 years). The fertilizer effect on the K concentration had ended within 11–20 years, especially on the fertile sites. The mean needle N concentration was only slightly lower in barren sites but the mean dry mass was higher on both fertile and barren sites on fertilized stands (Table 4).

Needle response in relation to the temperature sum

The fertilization reaction for the main (N, P, K) nutrients was largely unrelated to temperature sum of the growing season (Table 5). The two-way variance analysis revealed no interactions between fertilization treatment and temperature sum class. The mean needle P concentration was

Table 3. The means of the nutrient concentrations (mg g^{-1}) and dry mass (g per 100 needles) of Scots pine needles according to original natural mire site type and time since fertilization. * = significant deviation within corresponding time period from the unfertilised control plots (p value < 0.05 in Bonferroni test).

*Taulukko 3. Männyn neulasten ravinnepitoisuudet (mg g^{-1}) ja kuivapaino (g per 100 kpl) alkuperäisen suotyyppien pääryhmän ja lannoituksesta kuluneen ajan mukaan. * = merkitsevä poikkeama ko. lannoitusikäluokan vertailuun nähden (p < 0.05 Bonferroni).*

	Control			Fertilized		
	Time since fertilization (years)					
Site type group	1–10	11–20	21–35	1–10	11–20	21–35
			Phosphorus (P)			
Genuine forested	1.36	1.46	1.40	1.59*	1.61	1.66
Sparsely forested	1.28	1.33	1.29	1.64*	1.61*	1.60*
Treeless	1.26	1.28	1.16	1.64*	1.53*	1.56*
			Potassium (K)			
Genuine forested	4.15	4.34	4.46	5.04*	4.69	4.50
Sparsely forested	4.23	3.86	3.64	5.02*	4.19	4.00
Treeless	3.76	3.78	3.55	5.15*	3.91	3.67
			Nitrogen (N)			
Genuine forested	11.4	12.5	12.7	12.1	12.2	13.8
Sparsely forested	12.9	13.6	14.7	12.4	12.9	14.4
Treeless	14.2	13.8	13.5	14.2	13.0	13.2
			Dry mass			
Genuine forested	1.69	1.98	2.26	1.96	2.11	2.28
Sparsely forested	1.62	1.97	1.76	1.90	2.14	2.09
Treeless	1.52	1.61	1.73	1.79	1.88*	2.01

1.22–1.31-fold on the fertilized stands, and the mean concentration of K 1.21–1.25-fold compared to the control stands during the first 10-year period after fertilization. The changes in needle N concentration were minor.

Needle dry mass increased along with higher temperature sums for the year of needle appearance (Table 5). The mean dry mass was significantly higher in the highest temperature sum class (1051–1290 d.d.) than in other classes ($p < 0.013$; Bonferroni test including all the unfertilized stands). In all temperature sum classes the means of needle dry mass were only slightly higher on the fertilized stands compared to control stands (Table 5).

Needle response in relation to time of fertilization and natural foliar nutrient status

The strength of the response to fertilization (nutrient concentrations and needle dry mass) was dependent on the natural nutrient status of the stands (= control). The lower the concentrations of P and K were on the control stands, the more pronounced the effect of fertilization was (Figs. 3 and 4). While P concentration on control stands was below the deficiency limit (1.3 mg g^{-1}), the concentration on fertilized trees was on average at least 1.3-fold. In the regression analysis, control stand P concentration explained 36.6–53.5% of the P variation in fertilized trees (Fig. 3). With K, the corresponding dependency was pronounced during the first 10 years after fertilization, when control stand K concentration explained 61.4% of the variation in the fertilized trees (Fig. 4). The dependency weakened during the 11–20 year period, and disappeared after that almost completely (Fig. 4).

According to vector analysis, the effect of fertilization was detected in needle P and K concentration and content when 1–10 years had elapsed since treatment (Fig. 5). Also the N content of the needle mass was, on an average, slightly higher in the fertilized trees than on the

Table 4. The means of the nutrient concentrations (mg g^{-1}) and dry mass (g per 100 needles) of Scots pine needles on fertile and barren sites in 10 year time periods since fertilization. * = significant deviation within corresponding time period from unfertilized control plots (p value < 0.05 of Bonferroni test). For the site fertility classes, see Huikari (1952).

*Taulukko 4. Männyn neulasten pääravinnepitoisuudet (mg g^{-1}) ja kuivapaino (g per 100 neulasta) viljavilla ja karuilla kasvupaikoilla lannoituksesta kuluneen ajan mukaan. * = merkitsevä poikkeama ko. lannoitusikäluokan vertailuun nähden (p < 0.05 Bonferroni). Kasvupaikan viljavuusluokat (site fertility class) esitetty Huikarin (1952) mukaan.*

	Control			Fertilized		
	Time since fertilization (years)					
Site fertility class	1–10	11–20	21–35	1–10	11–20	21–35
			Phosphorus (P)			
Fertile	1.30	1.34	1.16	1.60*	1.61*	1.57*
Barren	1.28	1.37	1.33	1.65*	1.58*	1.60*
			Potassium (K)			
Fertile	3.86	3.76	3.49	4.99*	4.04	3.76
Barren	4.22	4.10	3.94	5.09*	4.40*	4.07
			Nitrogen (N)			
Fertile	14.1	14.1	14.6	13.3	13.2	13.6
Barren	12.5	13.0	13.0	12.5	12.5	13.6
			Dry mass			
Fertile	1.64	1.87	1.81	1.80	2.14	2.04
Barren	1.59	1.91	1.79	1.93	2.04	2.09

control stands during the first 10 years period. The response (deviation from the reference point) was more noticeable with P than with K, and with K more noticeable than with N. This implies that P and K were the minimum factors in stand nutrient status and key nutrients behind the increased needle mass. During the periods 11–20 and 21–35 years after the fertilization, the role of K in needle mass variation diminished, and the relative role of P became more pronounced (Fig. 5).

Discussion

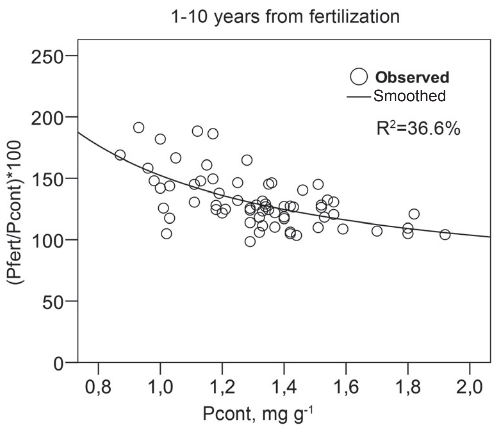
Representativeness of the material

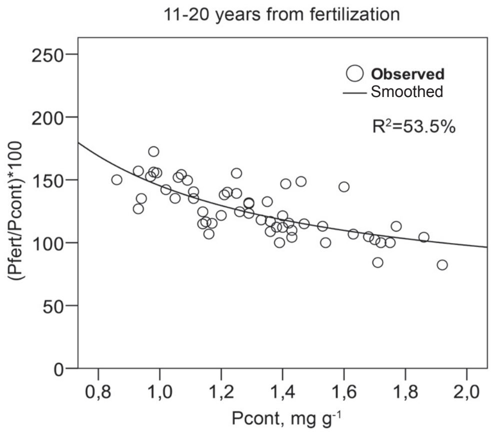
The number of experiments in the study is high, and includes considerable variation in climate conditions (between northern and southern experiments) as well as noticeably different years in terms of temperature conditions. However, the material represents only a part of the tree, habitat and geographical variation found in drained peatlands of Finland. Most of the experimental forests were located in Central Ostrobothnia, Kainuu and in Central and West Lapland. Thus, the results best represent the peatland complex type of the aapa mires of Ostrobothnia and southern Lapland, as well as the zone of southern boreal aapa mires (see Eurola & Kaakinen 1978, Ruuhijärvi 1983). Regarding habitat types, the material is focused on moderately fertile sites (low-sedge, tall-sedge, herb), which are often drained and transformed into *V. myrtillus* and *V. vitis-idaea* peatland forest types (see Vasander & Laine 2008).

Table 5. The means of the nutrient concentrations (mg g^{-1}) and dry mass (g per 100 needles) of Scots pine needles by the temperature sum of the needle birth year and by time since fertilization. * = significant deviation within corresponding time period from unfertilized control (Bonferroni test). a = insufficient data for statistical testing.

*Taulukko 5. Neulasten ravinnepitoisuudet (mg g^{-1}) ja kuivamassa (g per 100 neulasta) neulasten syntymävuoden lämpösumman ja lannoituksesta kuluneen ajan mukaan. * = merkitsevä poikkeama ko. lannoitusikäluokassa vertailuun nähden (Bonferroni). a = havaintoja liian vähän tilastolliseen testaukseen.*

	Control			Fertilized		
Temperature sum (d.d.)	Years since fertilization					
of the needle birth year	1–10	11–20	21–35	1–10	11–20	21–35
			Phosphorus (P)			
<950	1.23	1.50	1.02a	1.61*	1.65	1.50a
951–1050	1.31	1.36	1.26	1.68*	1.63*	1.53
>1050	1.30	1.32	1.25	1.59*	1.56*	1.61*
			Potassium (K)			
<950	4.09	4.05	3.07a	5.03*	4.24	3.64a
951–1050	4.26	3.94	3.58	5.17*	4.30*	3.76
>1050	3.92	4.00	3.80	4.90*	4.27	3.98
			Nitrogen (N)			
<950	14.6	12.6	17.0a	13.7	12.7	13.2a
951–1050	12.3	13.1	13.1	12.2	12.5	13.5
>1050	12.1	13.7	13.8	12.6	12.8	13.7
			Dry mass			
<950	1.41	1.67	1.16a	1.60	1.96	1.88a
951–1050	1.62	1.70	1.62	1.93	1.97	1.99
>1050	1.86	2.07	1.89	2.21	2.17	2.10





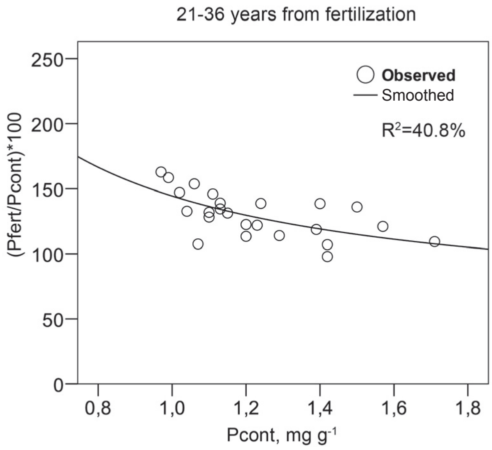


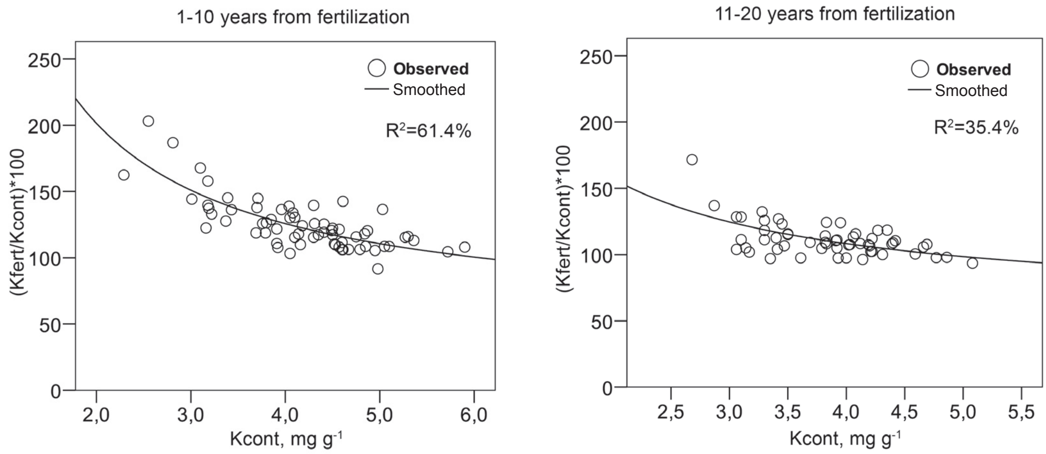
Fig. 3. The change in needle P concentration (Y-axis) following fertilization, in relation to unfertilized control stands. X-axis: P concentration on unfertilized stands (Pcont), Y-axis: Pfert/Pcont is the ratio of P concentrations in fertilized and unfertilized stands. Dot = one experimental stand. Time from fertilization: 1–10, 11–20 and 21–36 years. Regression analysis (curve estimation) made by direct inverse model y = a + b*(1/x).

Kuva 3. Neulasten fosforipitoisuuden muutos (pystyakseli) lannoituksen jälkeen suhteessa lannoittamattomaan. Vaaka-akselilla fosforipitoisuus lannoittamattomilla koealoilla (Pcont), Pfert/Pcont on lannoitettujen ja lannoittamattomien puiden fosforipitoisuuksien suhde. Yksi piste edustaa yhtä koemetsikköä. Lannoituksesta kulunut 1–10, 11–20 ja 21–36 vuotta.

Effect of PK-fertilization on different habitats/sites

The main result of this study — as was assumed — is that P and K deficiencies are more pronounced on originally sparsely forested and treeless sites, in comparison to genuine forested sites, as is also the effect of fertilization (e.g. Paavilainen & Päivänen 1995, Moilanen 2005). In addition, in nitrogen-rich sites the need for PK fertilization, as well as its effect, was greater than on nitrogen-poor sites. On former treeless or sparsely forested sites, fertilization improved needle P and K concentrations and mass noticeably more than on genuine forested sites. This is because stand nutrient status on genuine forested sites is naturally already better and more balanced (especially N/K ratio) than on other primary site types. The result is significant for assessing the need for fertilization and fertilization effect in practice. On peatlands that had been transformed from originally genuine forested site types, stand nutrient status may remain satisfactory for at least the first tree generation after drainage.

Fertilization improved needle P and K concentrations of Scots pine more on sites that had naturally lower P and K concentrations. The fertilization reaction increased rapidly when P was below 1.3 and K below 4.0 mg g^{-1}. These values have been considered “deficiency limits” also earlier (e.g. Reinikainen et al. 1998). The result shows that these values can also be used as deficiency limits when evaluating the strength of needle response to fertilization. The increment in foliar P and K concentration were also larger in stands with P and K deficiencies than in control



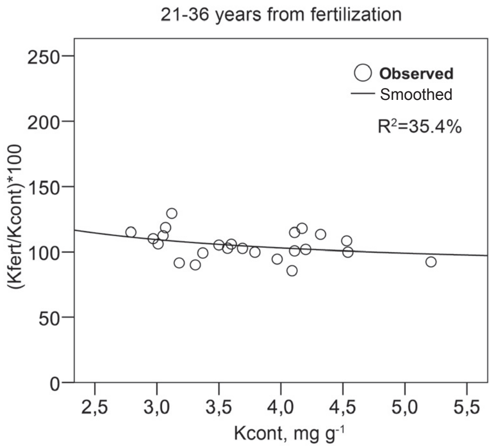


Fig. 4. The change in needle K concentration (Y-axis) following fertilization, in relation to unfertilized control stands. X-axis: K concentration on unfertilized stands (Kcont), Y-axis: Kfert/Kcont is the ratio of K concentrations in fertilized and unfertilized stands. Dot = one experimental stand. Time from fertilization: 1–10, 11–20 and 21–36 years. Regression analysis (curve estimation) made by direct inverse model y = a + b*(1/x).

Kuva 4. Neulasten kaliumpitoisuuden muutos (pystyakseli) lannoituksen jälkeen suhteessa lannoittamattomaan. Vaaka-akselilla fosforipitoisuus lannoittamattomissa metsiköissä (Kcont), Kfert/Kcont on lannoitettujen ja lannoittamattomien puiden fosforipitoisuuksien suhde. Yksi piste edustaa yhtä koemetsikköä. Lannoituksesta kulunut 1–10, 11–20 ja 21–36 vuotta.

stands. In stands where the natural nutrient status was satisfactory, gains with fertilization were relatively modest.

The fertility levels used in traditional mire site type classification reflect the peat's Ca and N contents (e.g. Valmari 1956, Starr & Westman 1978, Westman & Laiho 2003). The effect of PK-fertilization was stronger on nitrogen-rich sites than on nitrogen-poor sites. On "barren" sites, the effect of fertilization has remained slight also in earlier studies (e.g. Moilanen & Issakainen 1990, Moilanen 1993). The reason is probably the scarcity of N, which inhibits the growth increase that would be gained with PK fertilization. It has also been noted that fertilization may weaken the trees' N status by decreasing the foliar N concentration (e.g. Paarlahti et al. 1971, Raitio 1981, Kaunisto 1982, 1985, Pietiläinen et al. 1996, Silfverberg & Issakainen 2001, Pietiläinen & Kaunisto 2003). This is due to the so-called "dilution" effect, as the uptaken nitrogen gets distributed in the larger needle mass. In this study, this "dilution effect" was not clearly detectable and remained statistically insignificant. The amount of nitrogen in needles and the trees increased in all sites, as the needles grew more dry mass than they lost in their nitrogen concentration. Moreover, needle N concentration decreased never below the deficiency limit. It can be thus deducted that stand N status was not weakened by PK fertilization. On the other hand, the most barren or infertile peatland sites were not included in this study.

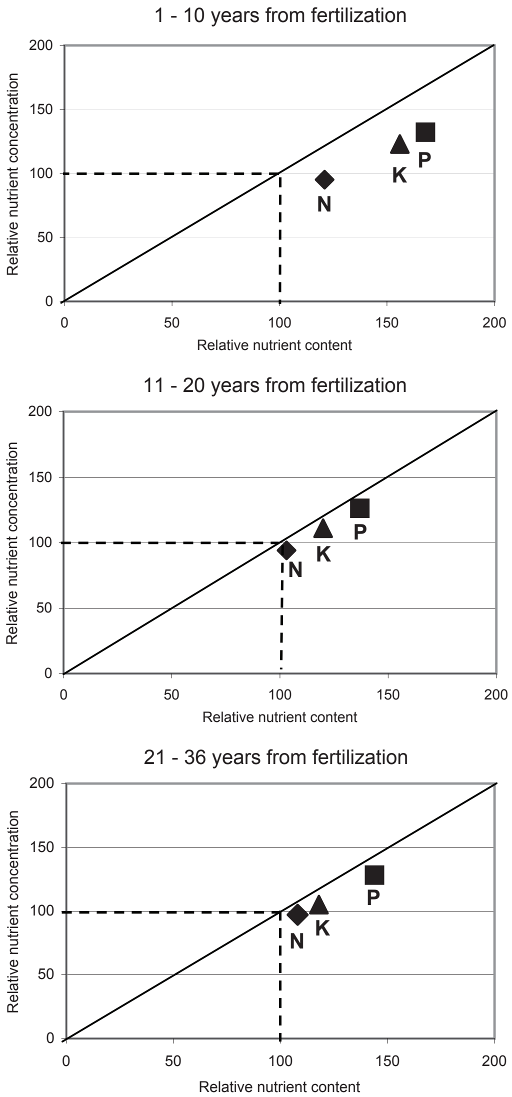


Fig. 5. The relative needle nutrient concentrations (the ratio of certain nutrient concentration between fertilized and unfertilized trees, Y-axis) and relative nutrient contents (the ratio of certain nutrient content between fertilized and unfertilized trees, X-axis) in different periods after the fertilization. Parallel (ratio 100) = unfertilized stands.

Kuva 5. Neulasten suhteelliset ravinnepitoisuudet (lannoitetun ja lannoittamattoman puuston välinen tietyn ravinnepitoisuuden suhde, y-akseli) ja suhteelliset ravinnesisällöt (lannoitetun ja lannoittamattoman puuston ravinnesisällön välinen suhde, x-akseli) eri ajankohtina lannoituksen jälkeen. Vertailukohtana (suhdeluku 100) = lannoittamattomat metsiköt.

Temperature sum of the needles' birth year

In this study, the needle mass increased considerably along with higher temperature sums. However, the needle response to PK fertilization was very similar regardless of the temperature sum of the growing season. Thus, this study does not agree with previous results concerning the minor fertilization effect in the low temperature conditions. The result implies that the temperature conditions in the growing season were also in Northern Finland adequate for the sufficient availability of nitrogen, which "provided" the needle responses also in P and K status by fertilization. It should be noted, however, that data on sums below 900 d.d. in the north, and below 1200 d.d. in the south was rather scarce.

It has been noted in earlier studies that PK fertilization improves Scots pine growth on drained mires, all the way to Arctic Circle (e.g. Paavilainen 1978). Nitrogen mineralization is, however, slower in Northern Finland, which means that scarcity of nitrogen is a limiting factor for tree growth even on relatively nitrogen-rich mires (Starr & Westman 1978, Sundström et al. 2000). To gain a fertilization response of a certain magnitude, therefore, requires more nitrogen in the site in Northern Finland than in the south. According to Pietiläinen and Kaunisto (2003) tree growth would not respond to PK fertilization because of shortage of available N, when the temperature sum is below 900 d.d. In low temperature sum areas, the effect of PK fertilization has remained modest, and the greatest increases have been gained with NPK and NP treatments (Seppälä & Westman 1976, Heikurainen & Laine 1985, Westman 1987, Sundström 1995).

The duration of the effect of PK fertilization

The effect of fertilization on foliar P concentration was noticeably longer-lasting than that of K. There were no cases of serious P deficiencies, and the fertilization response did not show signs of diminishing. Compared to unfertilized control stands, needle P concentration was still noticeably higher on the fertilized stands 21–35 years after fertilization. On the other hand, the concentration of K had decreased and dropped almost back to the level of the unfertilized control stands.

The results are in accordance with the earlier studies: phosphorus fertilizers have raised needle P concentration in Scots pine needles and improved the stem growth of trees on drained peatlands for at least 15–25 years (e.g. Penttilä & Moilanen 1987, Silfverberg &Hartman 1999, Moilanen et al. 2002, 2005, Pietiläinen et al. 2005). In most fertilizers, K is in the form of water-soluble KCl, which has been noted to improve needle K concentration already during the application year, and to improve stand nutrient status for 10–20 years, depending on the site (Kaunisto 1987, 1992, Finér 1994, Rautjärvi et al. 2004). It has also been noted, however, that a significant part of the readily soluble K leaches from the root-layer already during a couple of years since fertilization (Kaunisto & Paavilainen 1988, Kaunisto 1992).

In conclusion, our results suggest that in drained peatlands, where the trees suffered from the nutrient deficiencies, the P status of Scots pine could be improved for over 30 years with single fertilization. Instead, ensuring the K status over the rotation will require 1–2 refertilization treatments during the rotation period. The results also indicate that the magnitude of the tree response to the PK fertilization sharply depends on the original mire site type and the nitrogen amounts in the surface peat. On drained peatlands that have originally been genuine forested site types, stand nutrient status may remain satisfactory for at least the first post-drained tree generation. Instead, the need to cure nutrient deficiencies is most important on drained peatland sites, which have been sparsely forested or treeless in their natural (original) stage. The results of this study indicate that needle analysis makes it possible to estimate not only the need for fertilization but also how long and strong this effect will be.

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References

Eurola, S. & Kaakinen, E. 1978. Suotyyppiopas. WSOY, Porvoo-Helsinki-Juva. 87 p.

Finér, L. 1992. Nutrient concentrations in Pinus sylvestris growing on an ombrotrophic pine bog, and the effects of PK and NPK fertilization. Scandinavian Journal of Forest Research 7(2): 205–218.

Finér, L. 1994. The effects of fertilization on the growth of tree stand. The experiments at Ilomantsi. In: Effect of fertilization on forest ecosystem. Biological Research Reports from the University of Jyväskylä 38: 182–201.

Finér, L. & Kaunisto, S. 2000. Variation in stemwood nutrient concentrations in Scots pine growing on peatland. Scandinavian Journal of Forest Research 15: 424–432.

Haase, D. L. & Rose, R. 1995. Vector analysis and its use for interpreting plant nutrient shifts in response to silvicultural treatments. Forest Science 41(1): 54–66.

Halonen, O., Tulkki, H. & Derome, J. 1983. Nutrient analysis methods. Metsäntutkimuslaitoksen tiedonantoja 121. 28 p.

Heikurainen, L. & Laine, J. 1985. Duration of the height growth response of young pine stands to NPK-fertilization on oligotrophic pine bogs in Finland. Silva Fennica 19(2): 155–167.

Huikari, O. 1952. Suotyypin määritys maa- ja metsätaloudellista käyttöarvoa silmällä pitäen. Summary: On the determination of mire types, specially considering their drainage value for agriculture and forestry. Silva Fennica 75: 1–22.

Hytönen, J. & Kokko, A. 2006. Mäntyjen ravinnetila Kala- ja Pyhäjokilaaksojen suometsissä vuosina 1998–2005. Raportti Toimeentuloa metsästä -projektille. 12 p. (in Finnish).

Hytönen, J. & Wall, A. 2006. Foliar colour as indicator of nutrient status of Scots pine (*Pinus sylvestris* L.) on peatlands. Forest Ecology and

Management 237(1–3): 156–163.
Kaunisto, S. 1982. Development of pine plantations on drained bogs as affected by some peat properties, fertilization, soil preparation and liming. Communicationes Instituti Forestalis Fenniae 109. 56 p.
Kaunisto, S. 1985. Lannoituksen, ilman lämpösumman ja eräiden kasvualustan ominaisuuksien vaikutus mäntytaimikoiden kasvuun turvemailla. Summary: Effect of fertilization, temperature sum and some peat properties on the height growth of young pine sapling stands on peatlands. Folia Forestalia 616. 27 p.
Kaunisto, S. 1987. Effect of refertilization on the development and foliar nutrient contents of young Scots pine stands on drained mires of different nitrogen status. Communicationes Instituti Forestalis Fenniae 140. 58 p.
Kaunisto, S. 1992. Effect of potassium fertilization on the growth and nutrition of Scots pine. Suo — Mires and Peat 43(2): 45–62.
Kaunisto, S. & Moilanen, M. 1998. Kasvualustan, puuston ja harvennuspoistuman sisältämät ravinnemäärät neljällä vanhalla ojitusalueella. Metsätieteen aikakauskirja - Folia Forestalia 3/1998: 393–410. (in Finnish).
Kaunisto, S. & Paavilainen, E. 1988. Nutrient stores in old drainage areas and growth of stands. Communicationes Instituti Forestalis Fenniae 145. 39 p.
Kaunisto, S. & Pietiläinen, P. 2003. Peat nitrogen status and its effect on the nutrition and growth of Scots pine (*Pinus sylvestris* L.) on a afforested mire. Baltic Forestry 9(1): 33–42.
Kaunisto, S. & Tukeva, J. 1984. Kalilannoituksen tarve avosoille perustetuissa riukuvaiheen männiköissä. Summary: Need for potassium fertilization in pole stage pine stands established on bogs. Folia Forestalia 585. 40 p.
Kaunisto, S., Moilanen, M. & Issakainen, J. 1993. Apatiitti ja flogopiitti fosfori- ja kaliumlannoitteina suomänniköissä. Summary: Apatite and phlogopite as phosphorus and potassium fertilizers in peatland pine forests. Folia Forestalia 810. 30 p.
Keltikangas, K., Laine, J., Puttonen, P. & Seppälä, K. 1986. Vuosina 1930–1978 metsäojitetut suot: ojitusalueiden inventoinnin tuloksia. Summary: Peatlands drained for forestry during 1930–1978: results from field surveys of drained areas. Acta Forestalia Fennica 193. 94 p.
Korkalainen, T., Pietiläinen, P. & Colpaert, A. 2007. The effect of total peat nitrogen on the height and volume of Scots pine (*Pinus sylvestris* L.) stands in three fertilized and drained peatlands in northern Finland. Suo 58 (3–4): 75–85.
Laiho, R. & Laine, J. 1994. Changes in mineral element concentrations in peat soils drained for forestry in Finland. Scandinavian Journal of Forest Research 10: 218–224.
Laiho, R. & Alm, J. 2005. Turvemaiden ravinnevarat. In: Ahti, E., Kaunisto, S., Moilanen, M. & Murtovaara, I. (eds.). Suosta metsäksi. Suometsien ekologisesti ja taloudellisesti kestävä käyttö. Tutkimusohjelman loppuraportti. Metsäntutkimuslaitoksen tiedonantoja 947: 40–45. [In Finnish]
Laiho, R., Sallantaus, T. & Laine, J. 1999. The effect of forestry drainage on vertical distribution of major plant nutrients in peat soils. Plant and Soil 207: 169–181.
Moilanen, M. 1992. Suopuustojen ravinnetila Pohjois-Suomen vanhoilla ojitusalueilla. In: Valtanen, J, Murtovaara, I. & Moilanen Merja (eds) Metsäntutkimuspäivä Taivalkoskella 1991. Metsäntutkimuslaitoksen tiedonantoja 419: 58–65. [In Finnish]
Moilanen, M. 1993. Lannoituksen vaikutus männyn ravinnetilaan ja kasvuun Pohjois-Pohjanmaan ja Kainuun ojitetuilla soilla. Summary: Effect of fertilization on the nutrient status and growth of Scots pine on drained peatlands in Northern Ostrobothnia and Kainuu. Folia Forestalia 820. 37 p.
Moilanen, M. 2005. Suometsien lannoitus. In: Ahti, E., Kaunisto, S., Moilanen, M. & Murtovaara, I. (eds). Suosta metsäksi. Suometsien ekologisesti ja taloudellisesti kestävä käyttö. Tutkimusohjelman loppuraportti. Metsäntutkimuslaitoksen tiedonantoja 947: 134–166.
Moilanen, M. & Issakainen, J. 1990. PK-lannos ja typpilannoitelajit karuhkojen ojitettujen rämeiden lannoituksessa. Summary: PK fertilizer and different types of N fertilizer in the fertilization of infertile drained pine bogs. Folia Forestalia 754. 20 p.

Moilanen, M., Penttilä, T. & Issakainen, J. 1996b. Lannoituksen vaikutus kuusikoiden kasvuun ja ravinnetilaan ojitetuilla turvemailla Pohjois-Suomessa. Summary: Effects of fertilization on tree growth and nutrient status of Norway spruce stands on drained peatlands in northern Finland. Suo 47(3): 85–94.

Moilanen, M., Pietiläinen, P. & Issakainen, J. 2005. Long-term effects of apatite and biotite on the nutrient status and stand growth of Scots pine (*Pinus sylvestris* L.) on drained peatlands. Suo 56(3): 115–128.

Moilanen, M., Piiroinen, M-L & Karjalainen, J. 1996a. Turpeen ravinnevarat Metsähallituksen vanhoilla ojitusalueilla. In: Piiroinen, M-L & Väärä, T. (eds). Metsäntutkimuspäivä Kajaanissa 1995. Metsäntutkimuslaitoksen tiedonantoja 598: 35–54. (in Finnish).

Moilanen, M, Silfverberg, K. & Hokkanen, T.J. 2002. Effects of wood-ash on the tree growth, vegetation and substrate quality of a drained mire: a case study. Forest Ecology and Management 171(3): 321–338.

Ojansuu, R. & Henttonen, H. 1983. Kuukauden keskilämpötilan, lämpösumman ja sademäärän paikallisten arvojen johtaminen Ilmatieteen laitoksen mittaustiedoista. Summary: Estimation of the local values of monthly mean, effective temperature sum and precipitation sum from the measurements made by the Finnish Meteorological Office. Silva Fennica 17(2): 143–160.

Paarlahti, K., Reinikainen, A. & Veijalainen, H. 1971. Nutritional diagnosis of Scots pine stands by needle and peat analysis. Communicationes Instituti Forestalis Fenniae 74(5): 1–58.

Paavilainen, E. 1978. PK-lannoitus Lapin ojitetuilla rämeillä. Ennakkotuloksia. Summary: PK-fertilization on drained pine swamps in Lapland. Preliminary results. Folia Forestalia 343. 17 p.

Paavilainen, E. & Pietiläinen, P. 1983. Foliar responses caused by different nitrogen rates at the refertilization of fertile pine swamps. Communicationes Instituti Forestalis Fenniae 116: 91–104.

Paavilainen, E. & Päivänen, J. 1995. Peatland Forestry. Ecology and Principles. Ecological Studies 111. Springer-Verlag, Berlin -Heidelberg - New York. 241 p.

Penttilä, T. & Moilanen, M. 1987. Fosforilannoitteet suometsien lannoituksessa Pohjois-Suomessa. Metsäntutkimuslaitoksen tiedonantoja 278: 136–148.

Pietiläinen, P. & Kaunisto, S. 2003. The effect of peat nitrogen concentration and fertilization on the foliar nitrogen concentration of Scots pine (*Pinus sylvestris* L.) in three temperature sum regions. Suo 54(1): 1–13.

Pietiläinen, P., Moilanen, M. & Lähdesmäki, P. 1996. Peat inorganic nutrients and the concentration of soluble arginine in Scots pine needles. Humus 3(1): 4–13.

Pietiläinen, P., Moilanen, M. & Vesala, H. 2005. Nutrient status and growth of Scots pine (*Pinus sylvestris* L.) on drained peatlands after potassium fertilization. Suo 56(3): 101–113.

Raitio, H. 1981. Pääravinnelannoituksen vaikutus männyn neulasten rakenteeseen ja ravinnepitoisuuksiin ojitetulla lyhytkorsinevalla. Summary: Effect of macronutrient fertilization on the structure and nutrient content of pine needles on a drained short sedge bog. Folia Forestalia 456. 9 p.

Rautjärvi, H., Kaunisto, S. & Tolonen, T. 2004. The effect of repeated fertilizations on volume growth and needle nutrient concentrations of Scots pine (*Pinus sylvestris* L.) on a drained pine mire. Suo 55(2): 21–32.

Reinikainen, A. 1967. The appearance of nutrient deficiency in plants growing in the experimental area for forest fertilization at Kivisuo. Proceedings Vth Colloq For Fertiliz, Jyväskylä, Finland, Int Potash Inst, Bern, Switzerland: 345–361.

Reinikainen, A., Veijalainen, H. & Nousiainen, H. 1998. Puiden ravinnepuutokset — Metsänkasvattajan ravinneopas. Metsäntutkimuslaitoksen tiedonantoja 688. 44 p.

Ruuhijärvi, R. 1983. Suomen suoyhdistymätyypit. In: Laine, J. (ed.) Suomen suot ja niiden käyttö. Suoseura ry & IPS Suomen kansallinen komitea: 24–28.

Saarinen, M. 1997. Ojitusaluepuustojen kaliumin puutokset ja metsätalouden suunnittelu. Summary: Assessment of the potassium status of peatlands drained for forestry in connec-

tion with forest management planning. Suo — Mires and Peat 48(1): 21–25.
Seppälä. K. & Westman, C.J. 1976. Results of some fertilization experiments in drained peatland forests in North-Eastern Finland. Proceedings of 5th International Peat Congress, Poznan, Poland 1976. Vol. III: 199–210.
Silfverberg, K. & Hartman, M. 1999. Effects of different phosphorus fertilizers on the nutrient status and growth of Scots pine stands on drained peatlands. Silva Fennica 33(3): 187–206.
Silfverberg, K. & Issakainen, J. 2001. Puuntuhka ja kauppalannoitteet suomänniköiden ravinnetalouden hoidossa. Metsätieteen aikakauskirja 1/2001: 29–44.
Starr, M. & Westman, C.J. 1978. Easily extractable nutrients in the surface peat layer of virgin sedge-pine swamps. Silva Fennica 12: 65–78.
Sundström, E. 1995. The impact of climate, drainage and fertilization on the survival and growth of *Pinus sylvestris* L. in afforestation of open, low-production peatlands. Scandinavian Journal of Forest Research 10: 190–203.
Sundström, E., Magnusson, T. & Hånell, B. 2000. Nutrient conditions in drained peatlands along a north-south climatic gradient in Sweden. Forest Ecology and Management 126: 149–161.
Timmer, V. R. & Ray, P. N. 1988. Evaluating soil nutrient regime for black spruce in the Ontario Claybelt by fertilization. Forestry Chronicle 64: 40–46.
Timmer, V. R. & Stone, E. L. 1978. Comparative foliar analysis of young balsam fir fertilized with nitrogen, phosphorus, potassium, and lime. Soil Science Society of America Journal 42 (1978), pp. 125–130.
Valmari, A. 1956. Über den Edaphishen bonität von Mooren Nordfinnlands. Acta Agralia Fennica. 88: 1–126.
Vasander, H. & Laine J. 2008. Site type classification on drained peatlands. In: Korhonen, R., Korpela, L. & Sarkkola, S. (eds.), Finland - Fenland. Research and Sustainable Utilisation of Mires and Peat: 146–151. Finnish Peatland Society, Maahenki Ltd. ISBN 978-952-5652-47-5. Helsinki.
Veijalainen, H. 1984. Lannoitustarpeen määritys metsäojitusalueilla. Summary: Diagnosing nutrient deficiencies on drained peatlands. Suo 4–5: 94–97.
Veijalainen, H. 1992. Neulasanalyysituloksia suometsistä talvella 1987–88. Metsäntutkimuslaitoksen tiedonantoja 408. 28 p. (in Finnish).
Veijalainen, H., Reinikainen, A. & Kolari, K.K. 1984. Metsäpuiden ravinneperäinen kasvuhäiriö Suomessa. Summary: Nutritional growth disturbances of forest trees in Finland. Folia Forestalia 601. 41 p.
Westman, C.J. 1979. Climate dependent variation in nutrient content of the surface peat layer from sedge pine swamps. In: Classification of Peat and Peatlands. Proceedings of International Symposium on IPS. Hyytiälä, Finland, 17–21 September 1979: 160–170.
Westman, C. J. 1987. Site classification in estimation of fertilization effects on drained mires. Acta Forestalia Fennica 198. 55 p.
Westman, C.J. & Laiho, R. 2003. Nutrient dynamics of peatland forests after waterlevel drawdown. Biochemistry 63: 296–298.

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Tiivistelmä:

PK-lannoituksen vaikutus männyn ravinnetilaan Pohjois-Pohjanmaan ojitusalueilla

Ravinnetalouden seuranta ja hoito ovat olleet keskeinen osa suometsien tutkimusta ja käytännön toimintaa. Suomen viiden miljoonan hehtaarin metsäojitusalasta 1,7 miljoonaa on lannoitettu fosfori- ja kaliumlannoitteilla.

Tässä tutkimuksessa tarkasteltiin vuosina 1980–2002 Metsäntutkimuslaitoksen ojitettujen turvemaiden lannoituskokeilta kerättyjen männyn neulasnäytteiden ravinnepitoisuuksia. Aineistoon sisältyi analysoituja (N-, P-, K-pitoisuus/neulasmassa) näytteitä 892 kpl, jotka oli kerätty metsiköistä 82:lta koe-alueelta mustikka- tai puolukkaturvekankaan männiköistä. Näytteistä 434 kpl oli kerätty PK-lannoitetuilta koealoilta ja 458 kpl lannoittamattomilta vertailualoilta (taulukko 1). Näytteenottohetkellä lannoituksesta oli kulunut kohteesta riippuen 1–35 vuotta ja ensimmäisestä ojituksesta 1–74 vuotta. Näytepuut olivat pituudeltaan 3–16 metrisiä metsikön valtapuita. Näytteet kerättiin puiden lepokaudella talvisaikaan. Yhteen näytteeseen kerättiin nuorimman vuosikerran neulasia koealan 6–8 männystä. Valtaosa neulasnäytteistä oli peräisin Oulun läänin alueelta (kuva 1). Lannoituksissa annetut ravinnemäärät olivat käytännön lannoitussuosituksen mukaisia (fosforia 40–45 kg/ha, kaliumia 80–100 kg/ha).

Puiden ravinnetilaa kuvaavien pääravinnepitoisuuksien (N, P, K) ja neulasten kuivapainon vaihtelua tarkasteltiin ravinnekohtaisesti. Kasvupaikkatunnukset (suon alkuperäinen päämuoto, kasvupaikkatyyppi/ravinteisuusluokka) ja neulasten syntymävuoden lämpösumma olivat keskeisimmät selittävät luokkamuuttujat. Selitettäviä muuttujia tarkasteltiin lannoituksesta kuluneen ajan mukaan luokiteltuna. Luokkamuuttujien välisiä eroja testattiin yksi- ja kaksisuuntaisella varianssianalyysilla. Regressioanalyysiä käytettiin tarkasteltaessa neulasreaktioiden riippuvuutta puiden luontaisesta ravinnetilasta.

Aitojen rämeiden vertailualoilla puiden ravinnetaloudelliset ongelmat olivat vähäisempiä kuin muilla päämuodoilla. Alun perin puuttomilla tai vähäpuustoisilla (nevaisilla) soilla puilla esiintyi yleisesti fosforin ja kaliumin puutoksia. Neulasten typpipitoisuudet olivat tyydyttävällä tasolla. Karujen (niukkatyppisten) kasvupaikkojen vertailualoilla tavattiin lievää typen puutosta, viljavilla (runsastyppisillä) kohteilla tavattiin sekä fosforin että erityisesti kaliumin puutosta.

Lannoitetuissa puustoissa ravinnepuutokset olivat merkitsevästi vähäisempiä kuin vertailupuustoissa. PK-lannoituksen seurauksena männyn neulasten fosforin ja kaliumin pitoisuudet sekä neulasten kuivapaino kohosivat merkitsevästi kaikissa koemetsiköissä. P- ja K-pitoisuudet kohosivat sitä enemmän, mitä alemmat olivat vertailupuustojen ravinnepitoisuudet. Vaikutus ilmeni selvimmin lannoitusta seuranneella ensimmäisellä 10-vuotisjaksolla. Neulasten fosforipitoisuudet säilyivät lannoitetuilla aloilla merkitsevästi kohonneina ja puiden fosforitalous hyvänä vielä 20–35 vuotta lannoituksen jälkeen. Kaliumin pitoisuudet olivat laskeneet lannoittamattomalle vertailutasolle, kun lannoituksesta oli kulunut yli 20 vuotta.

Neulasten kuivapaino oli sitä suurempi, mitä korkeampi oli kasvukauden lämpösumma neulasten syntymävuonna. Lämpösumman vaikutus neulasten ravinnepitoisuuksiin oli kuitenkin pieni.

Tuloksista voi päätellä, että männyn fosforitalous saadaan ravinnepuutoksista kärsivissä metsiköissä vuosikymmeniksi kuntoon yhdellä lannoituksella. Puiden kaliumin saannin turvaaminen sitä vastoin edellyttää 1–2 jatkolannoitusta metsikön kiertoaikana ja on edelleen viljavien ojitusalueiden puunkasvatuksen suurin ravinnetaloudellinen haaste. Sitä vastoin aitojen metsäisten suotyyppien vanhoilla ojituskohteilla ravinnetalous säilynee tyydyttävänä ainakin ensimmäisen ojituksenjälkeisen puusukupolven ajan.

Neulasanalyysin avulla on mahdollista arvioida paitsi lannoitustarvetta myös lannoituksen voimakkuutta ja kestoaikaa.