© Suoseura — Finnish Peatland Society
Helsinki 2008

ISSN 0039-5471
Suo 59 (1–2): 9–26

Long term effects of mineral soil addition on the nutrient amounts of peat and on the nutrient status of Scots pine on drained mires

Kivennäismaalisäyksen vaikutus turpeen ravinnemääriin ja männyn ravinnetalouteen metsäojitetuilla soilla

Jyrki Hytönen, Mikko Moilanen & Klaus Silfverberg

Jyrki Hytönen, Finnish Forest Research Institute, Kannus Research Unit, P.O. Box 44, FI-69101 Kannus, Finland, e-mail: Jyrki.Hytonen@metla.fi
Mikko Moilanen, Finnish Forest Research Institute, Muhos Research Unit, Kirkkosaarentie 7, FI-91500 Muhos, Finland.
Klaus Silfverberg, Finnish Forest Research Institute, Vantaa Research Unit, P O Box 18, FI-01301 Vantaa, Finland.

Six field experiments on the use of mineral soil for amelioration of pine-dominated peatland forests were established in the 1920's and 1930's on drained mires in southern and central Finland. The treatments consisted of varying amounts of different textured mineral soil added on top of peatland. Soil samples were taken 52–74 years after the mineral soil application in 10 cm layers, up to 40 or 50 cm depth. The samples were analysed for pH, ash content, bulk density and nutrient concentrations. In two of the experiments, foliar samples of Scots pine were analysed 66 and 77 years after the mineral soil application, and in one experiment, tree growth was measured for the period of 31–60 years after the application. The mineral soil had a long term effect on the physical and chemical properties of the top peat layer. Ash content and bulk density of the peat increased along with increasing application amounts, as did soil total P, K, Ca, Mg, Zn, Fe and B. The changes caused by the mineral soil were mostly restricted to the top 30 cm layer. The higher the soil fine fraction was, so was the increase in peat total P, K, Ca and Mg amounts. The addition of mineral soil increased tree growth and improved nutrient deficiencies (P, K) of Scots pine on one experiment, but decreased the B concentrations near the deficiency level.

Key words: peatland, nutrients, mineral soil, fertilisation, foliar analysis
Avainsanat: turvemaa, ravinteet, kivennäismaa, lannoitus

Introduction

The peat substrate of drained peatlands generally contains only small amounts of mineral plant nutrients, e.g. phosphorus and potassium. Especially potassium stores in the root zone of trees are relatively low compared with the amounts bound in the tree stands, and potassium deficiencies are common especially on thick-peated and nitrogen-rich site types (Kaunisto & Paavilainen 1988, Laiho & Laine 1994, Kaunisto & Moilanen 1998, Westman & Laiho 2003). Also deficiencies of phosphorus are common in Scots pine stands growing on drained mires. PK-fertilisation of potassium and phosphorus deficient stands has increased the growth of stands on drained mires (Kaunisto & Tukeva 1984, Kaunisto 1989, Kaunisto 1992, Moilanen 1993, Moilanen et al. 2005, Pietiläinen et al. 2005). Phosphorus fertilisation may improve the phosphorus status of tree stands for 20–30 years (Moilanen 1993, Silfverberg & Hartman 1999). The effect of potassium fertilisation with potassium chloride (KCl) has been shorter, 10–20 years (Kaunisto 1992, Kaunisto et al. 1999, Rautjärvi et al. 2004, Pietiläinen et al. 2005).

The addition of mineral soil in the cultivation of peatland fields in Finland started during the second half of the 18th century (Valmari 1983). It was subsequently generally recommended (Isotalo 1952), and its use was common in the early 20th century (Pessi 1953, 1962, Valmari 1983). The application was especially intended to improve the nutrient status and thermal conditions of peat (Vesikivi 1933, Pessi 1953, 1961a, 1961b, 1962). In practice and in agricultural experiments, 100–400m^3 ha^{-1} of mineral soil was generally added (Anttinen 1957b, Pessi 1960, 1961a, 1961b, 1961c). During the cultivation of peatlands, mineral soil was mixed in the tilling layer (0–20 cm). Mineral soil addition usually increased hay and grain yields the more it was used (Anttinen 1957a, 1957b, Pessi 1961b). This positive effect was mainly attributed to the increase in soil potassium amounts, the decrease in peat acidity (pH), and improved thermal conditions (Vesikivi 1933, Anttinen 1957a, 1957b, Pessi 1953, 1956, 1962). In agriculture, the effect of mineral soil addition on the peat nutrient amounts, and also on physical properties, was noted to be long lasting (Anttinen 1957b, Pessi 1960, 1961a, 1961b). Even when agricultural peat soils are afforested, the changes caused by mineral soil application can be seen in the soil properties still for decades (Wall & Hytönen 1996, Hytönen & Wall 1997). Besides increasing bulk density and ash content, mineral soil addition has considerably increased the soil potassium, magnesium, manganese, iron and zinc amounts, and to a smaller extent, also phosphorus (Wall & Hytönen 1996).

Based on experiences from agriculture, field experiments on the use of mineral soil for the amelioration of peatland forests were initiated already in the 1920s in Finland and Sweden. Some preliminary results on the growth of trees were published in the 1950s and early 1960s (Lukkala 1951, 1955, Huikari 1961). According to the results, a 5 cm deep layer of mineral soil from fertile forest types, as well as clay, may considerably increase the wood production potential of peatlands drained for forestry. However, results on the long term effects of mineral soil addition on peat properties are still lacking.

In the afforestation of cut-away peatlands, mineral soil from the ditch spoil has been shown to be important for the short term nutrition of Scots pine trees, and has removed the need for fertilisation if it is fine textured (Kaunisto 1987, Aro et al. 1997). The mineral content of peat substrate may have importance also for the success of peatland forest regeneration. The amount of clear cuttings, and consequently regeneration areas in peatland forests is expected to increase considerably in the near future. Concern of the sufficiency of mineral nutrients for the next tree generation, especially on originally wet and thick-peated sites, has been raised (e.g. Saarinen 2005). If mineral soil addition has such long standing effects on peatland nutrition as has been shown to be the case in agricultural fields, its application could be feasible in conjunction with forest regeneration.

The aim of this investigation was to study the long term effects of mineral soil addition on the nutrient amounts of peat on mires drained for forestry. The movement of the nutrients and added material downwards to deeper layers in the soil profile were also studied. Moreover, the wood production and nutrient status of Scots pine after mineral soil application were investigated.

Material and methods

Experiments

The six field experiments used in this study were established in 1920s, 1930s and in 1950s on originally sparsely stocked sapling stands or even treeless peatland areas (Fig. 1, Table 1). The site types were classified as relatively unproductive (trophy classes ombro – oligotrophic) and represented the fertility levels from *Sphagnum fuscum* pine bog (RaR) to low-sedge *Sphagnum papillosum* fen (LkKaN) (site classification according to Laine and Vasander 1996). The sites had been drained 1–17 years before the establishment of the experiments. The average peat thickness varied from 60 to over 200 cm. The dominant tree species in all stands was Scots pine (*Pinus sylvestris* L.) with a mixture of pubescent birch (*Betula pubescens* Ehrh.).

The mineral soil used in the experiments originated mostly from upland forests near each of the experimental sites. The mineral soil treatments had only one replication per experiment, and usually no control plots were established. The control (untreated) plots were chosen as close to the experimental sites as possible from the same peatland site type.

The Vilppula experimental stand in Jaakkoinsuo was established in spring 1926 on a clear cutting area (Table 1). The mineral soil was taken from nearby *Calluna* type upland forest, and spread on three experimental plots (size 1800 m^2) aiming at three application amounts (2.5, 5.0 and 7.5 cm layers) (Lukkala 1951, 1955). In spring 1927, the treeless plots were afforested by sowing pine (*Pinus sylvestris* L.) seeds (1 kg ha^{-1}).

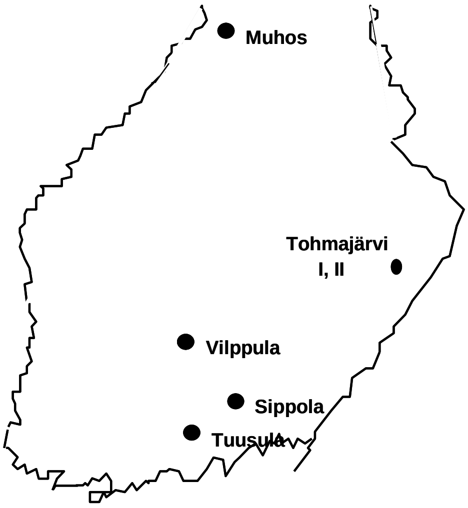

Fig. 1. Location of the experiments in southern and central Finland.

Kuva 1. Koemetsiköiden sijainti Etelä- ja Keski-Suomessa.

Table 1. The experimental site's site types, mean peat depth, date of ditching, date of mineral soil addition at the time of the establishment of the experiments and date of soil sampling 70–50 years later.

Taulukko 1. Tutkimuksessa käytettyjen koemetsiköiden kasvupaikkatunnukset, perustamistiedot ja maanäytteiden ottoajankohdat.

Experiment	Site type [1)]	Peat depth (m)	Years of ditching	Year of mineral soil addition	Date of soil sampling [2)]
Vilppula	IR	3.0	1909	1926	a2000
Tuusula	RaR	0.7	1926	1930	a2000
Sippola	RaR	>2.0	1947	1950	s2002
Tohmajärvi I	LkKaN	4.6	1927–28, -38	1930	a2000
Tohmajärvi II	LkKaN	4.9	1928–29, -38	1938	a2000
Muhos	LkN	0.6	1933	1934	a2000

[1)] Site types (Laine & Vasander 1996): IR = dwarf-shrub pine bog, RaR = *Sphagnum fuscum* pine bog, LkKaN = low-sedge *Sphagnum papillosum* fen, LkN = low-sedge bog. [2)] a = autumn, s = spring. *[1)] Suotyypit (Laine & Vasander 1996). [2)] a = syksy, s = kevät.*

According to Silfverberg (1984) the total increase in the stand volume growth on the plots that received mineral soil varied between 135–155 m^3 ha^{-1} (2.7–3.1 m^3 ha^{-1} a^{-1}) in the following 50 years.

The Tuusula experimental stand in Ruotsinkylä, established in 1930, consisted of only one experimental plot with the application of mineral soil aiming at a 5 cm layer on 400 m^2 (20x20 m) plot (Table 1). The Sippola experiment in Kaihlassuo was established in spring 1950 (Table 1). The application of mineral soil was done aiming at 0 (control), 2.5, 5 and 7.5 cm layers on 100 m^2 plots.

The Tohmajärvi experimental areas were originally treeless oligotrophic fen with *Sphagnum fuscum* hummocks. In 1930 (or 1931) mineral soil was added in four plots (size 400 m^2), aiming at 2.5 cm, 5 cm, 7.5 cm and 10 cm layers at the experiment of Tohmajärvi I. The experiment was afforested in spring 1931 with pine sowing. The total yield of the stand — including thinning removals in 1963 and 1989 — in 51 years on the plots that received mineral soil varied between 157–266 m^3 ha^{-1} (3.5–5.2 m^3 $ha^{-1}a^{-1}$) according to Tiainen (1990). In late autumn 1938 (or 1939), different textured mineral soils (clay, sand, gravel) were applied with the application rate of 5 cm layer on plots sized 400 m^2 at the experiment of Tohmajärvi II (Lukkala 1955). This experiment was sown with Scots pine in spring 1939. According Tiainen (1990 **)** the total increase in the stand growth — including thinning removals — varied between 138–350 m^3 ha^{-1} (2.3–5.8 m^3 $ha^{-1}a^{-1}$) in the following 60 years (Tiainen 1990).

The Muhos experimental stand at Leppiniemi was established in 1934. Two application amounts of mineral soil from *Calluna* type mineral soil forest were tested in two plots (plot size 500 m^2): 5 and 10 cm layers. The treeless fen was covered with pine and birch seedlings naturally in the first years after the mineral soil application in the 1930's. The tree stand was thinned in 1964 and 1988.

Soil and foliar sampling, analysis and stand measurements

The soil samples were taken from several peat layers (all experiments: 0–10, 10–20, 20–30, 30–40 cm, and in Tohmajärvi and Vilppula, also the 40–50 cm layer) with a soil corer (either 5.5 cm × 4.4 cm or 5.8 cm x 4.4 cm) in 2000–2002 (Table 1). At the date of the sampling, 52–74 years had elapsed since the mineral soil addition, depending on the experiment. One composite sample per plot and per each soil depth consisted of 9 (Vilppula, Sippola, Tohmajärvi I and II) or 12 (Muhos, Ruotsinkylä) subsamples, which were distributed uniformly over the plot, excluding a 5-meter-wide edge area. The living vegetation and undecomposed plant material of the peat cores were discarded from the analyses. The samples were frozen, and prior to analysis, defrosted and ground (2 mm), air-dried and stored at room temperature.

Soil pH was measured in distilled-deionised water from dried soil samples using a 1:2.5 soil solution suspension. After removing organic matter from the samples with H_2O_2, the particle-size distribution was determined by a dry-sieving and sedimentation method (Elonen 1971), and the soil texture was named according to the d50 method (Korhonen et al. 1974). The total N concentrations of the soil samples were determined by the Kjeldahl method. The soil samples were analysed for their total (HCl extraction of ignition residue; P, K, Ca, Mg, Zn, Fe) and acid ammonium acetate (pH 4.65) extractable (P, K, Ca, Mg) nutrient concentrations (Halonen et al. 1983). Boron was determined from H_3PO_4-H_2SO_4-extraction. The bulk density of the soil samples was calculated as the ratio of dry mass (dried at 105 °C) to the volume of the fresh sample. The concentration of organic matter was estimated as loss-on-ignition at 550 °C for 8 h. The amounts of nutrients at different soil depths were calculated on the basis of oven-dry (105 °C) weight of the fresh soil samples using bulk densities and expressed on an area basis for the sampling depth.

Needle samples were taken from Vilppula 77 years and from Muhos 66 years from the application of mineral soil. One sample consisted of current needles collected during dormant period from the upper whorls of 5 to 8 dominant pine trees per plot. Needle samples were also taken from nearby untreated stands. The nitrogen concentrations were determined using the Kjeldahl method. After dry combustion and dissolving in hydrochloric acid, K concentrations were determined using an atomic absorption spectrophotometer (AAS-method, Hitachi 100-40). The concentrations of B were determined using the azomethine-H method, and those of P using the vanado-molybdate method as outlined by Halonen et al. (1983).

Usually the sample plots treated with mineral soil were rather small (mostly 100–400 m^2) and in most experiments did not have unfertilized buffer areas between the plots. Thus, study on the effects of mineral soil on the growth of trees was considered feasible only in the Muhos experiment, where the information on cutting removals and the tree growth on the control plot was adequate.

The stand measurements were carried out at Muhos in 1994, when 60 years had elapsed since the application of mineral soil. In the measurement, all trees (50–68 per plot) were counted by species and breast-height (1.3 m) diameter classes (cm, minimum diameter class 5 cm). At each plot, the heights (dm) and diameters at breast height (d1.3, mm) were measured from 19–23 randomly chosen pines. The height increments of the sample trees were focused on ten-year periods retrospectively to the 1960s. Increment cores were extracted from breast height from each sample tree to determine the development of annual radial growth during the study period microscopically with the accuracy of 0.01 mm. The development of tree stand volume was calculated using the taper curve and volume functions for Scots pine (Laasasenaho 1982).

Data analysis

The amount of added mineral soil in each peat layer was calculated by subtracting the mineral soil mass of the untreated control plots from the mineral soil mass of the treated plots. At Tuusula, the soil samples from deepest layer, 30–40 cm, were not used in the analyses because they contained mineral soil from the subsoil at the bottom of the mire (ash content 20.6% on the control plot). The mass of mineral soil was converted into volume by using the value 1.1 kg dm^{-3} as the bulk density of mineral soil (Erviö 1970).

The added amounts of mineral soil expressed in the original research plans deviated considerably from those actually spread on the plots (Table 2). At Vilppula, the real application amounts were only 25–39% of those originally intended. At Tohmajärvi I, the calculated amounts were 190–260% of the amounts aimed at according to the research plan. At Tohmajärvi II, variation between the smallest and highest measured spreading amount was 29%. At Muhos, the plot with the smallest planned dose appeared to have received five-fold the intended amount, which was double the amount of the highest dose — both were higher than the application amount expressed in the research plan. Since the calculated mineral application amounts deviated considerably from those expressed in the original research plans, the calculated amounts were used in the analysis of the data.

Table 2. Calculated mineral soil addition compared with the planned addition rate (m^3 ha^{-1}) of the experimental sites.
Taulukko 2. Maa-analyysien perusteella arvioidut kivennäismaalisäykset (m^3 ha^{-1}) eri kokeilla.

Study site	Planned mineral soil addition, m^3 ha^{-1}						
	250 silt	500 silt	750 silt	1000 silt	500 fine sand	500 coarse sand	500
	Calculated mineral soil addition, m^3 ha^{-1}						
Vilppula	100	130	290	-	-	-	-
Tuusula	-	400	-	-	-	-	-
Sippola	350	520	1070	-	-	-	-
Tohmajärvi I	650	1210	1460	2600	-	-	-
Tohmajärvi II	-	-	-	-	640	740	570
Muhos	-	2530	-	1100	-	-	-

Also the added mineral soil texture differed considerably from that stated in the original research plan. The amount of fine fraction (<63 µm) in the 0–20 cm peat layer was highest at Vilppula (47%), Muhos (41%) and Tohmajärvi I (40%) and much lower at Tuusula (22%) and at Sippola (6%) (Table 3). At Tohmajärvi II, where different textured soil was used, the silt had fine fraction share of 79%, fine sand 28%, and coarse sand 34%. At the Tohmajärvi II experiment, the application amounts were close to each other, and it was possible to compare the effect of different textured soil on soil properties and nutrient amounts.

Correlation and regression analysis were used in determining the effects of mineral soil addition on peat bulk density (BD), soil ash content and pH, and conductivity and peat nutrient amounts in different layers in the combined data. In the Tohmajärvi II experiment, the effect of different mineral soil textures was compared separately.

Results

Effect of mineral soil on peat physical properties and acidity

On the control plots, the bulk density in the 0–20 cm peat layer was 87–142 g dm^{-3}, and ash content varied between 2 and 6%, except at Sippola, where it was 9–15%. After 52–74 years from the application on top of the peat, the mineral soil increased the bulk density and ash content of the uppermost peat layers (Fig. 2, Tables 4 and 5). The added mineral soil increased soil bulk density most (47 g dm^{-3}/100 m^3 ha^{-1} added mineral soil) in the 10–20 cm layer and least (3 g dm^{-3}/ 100 m^3 ha^{-1} added mineral soil) in the 30–40 cm peat layer. Correspondingly, 100 m^3 ha^{-1} of added mineral soil increased peat ash content in the 0–20 cm layer by 3–4 percentage points and in the 20–40 cm layer by 0.4 percentage points. The mineral soil addition rate correlated significantly with the bulk density and ash content even down to 30–40 cm depth. Mineral soil addition decreased soil conductivity in the 0–20 cm peat layer, but not significantly in deeper peat layers (Tables 4 and 5).

The soil pH in the topmost peat layer (0–20 cm) on the plots that received mineral soil was higher than in the neighbouring control plots. However, mineral soil addition increased soil pH significantly only in the 10–20 cm layer, by 0.03 pH units with every 100 m^3 ha^{-1} of mineral soil added (Table 5). The higher the application amount was, the deeper in the peat profile the change in pH was detectable. Soil pH correlated slightly better with soil ash content than with mineral soil addition rate (Table 4).

Effect of mineral soil on peat nutrient amounts

The addition of mineral soil increased the amounts of all measured total nutrients, except that of nitrogen. Nitrogen amount in the control plots in the 0–20 cm layer varied from 2740 kg

Table 3. The mean particle size distribution of mineral soil admixture in the 0–20 cm peat layer in the experimental sites.
Taulukko 3. Kivennäismaalajitejakauma pintaturpeessa (0–20 cm syvyydellä) eri koealueilla.

Particle size fraction (ì m)	Fraction %							
	Vilppula	Tuusula	Sippola	Tohmajärvi I	Muhos	Tohmajärvi II		
						Silt	Fine sand	Coarse sand
< 2	7.2	7.8	1.4	4.1	8.0	24.5	3.8	5.2
2–20	9.2	4.6	1.2	8.2	20.4	41.3	5.8	10.6
20–63	30.8	9.2	3.1	27.2	13.0	13.6	18.5	17.9
63–200	31.0	19.9	19.7	50.9	10.6	11.0	51.7	20.7
200–630	18.3	54.2	41.2	9.3	44.0	7.6	19.0	25.0
630–2000	3.5	4.3	33.4	0.3	4.0	2.0	1.2	20.6

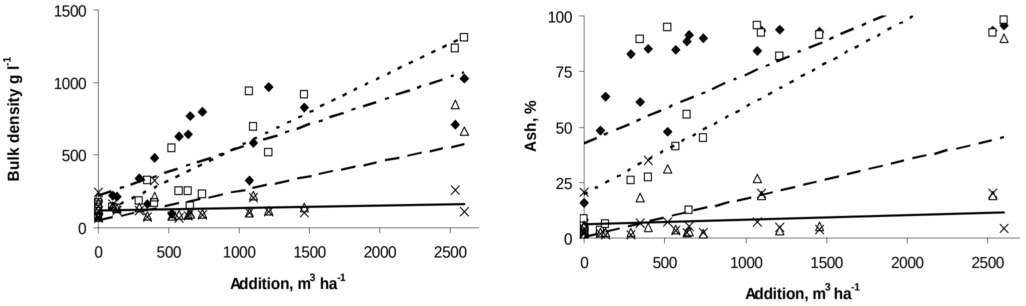

Fig. 2. Effect of mineral soil addition on peat bulk density and ash content in different peat layers in the combined data. Regression equations are presented in Table 5.

Kuva 2. Kivennäismaan lisäyksen vaikutus(Addition , m^{3}ha$^{-1)}$ turpeen tilavuuspainoon (Bulk density g l^{-1}) ja tuhkapitoisuuteen (Ash %) eri maakerroksissa, koko aineisto. Regressioyhtälöt on esitetty taulukossa 5.

ha^{-1} at Sippola to 5340 kg ha^{-1} at Muhos. The addition of mineral soil decreased the amount of total nitrogen in the top 20 cm layer of the peat (Tables 4 and 5). However, it did not have any effect on soil nitrogen amounts in the deeper layers.

Total phosphorus and potassium amounts in the control plots in the 0–20 cm layer varied from 114 (Sippola) to 241 kg ha^{-1} (Muhos) and potassium amounts from 80 (Vilppula) to 134 kg ha^{-1} (Sippola). The addition of mineral soil increased the soil total phosphorus and potassium amounts

Table 4. Correlations between mineral soil addition rate, bulk density (BD), soil ash content and pH, conductivity and peat nutrient amounts in different soil layers in the combined data. n = 21, except in layer 30–40 n = 19, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

Taulukko 4. Kivennäismaalisäyksen (Addition), maan tilavuuspainon (BD), tuhkapitoisuuden (Ash), happamuuden (pH), sähkönjohtokyvyn (conductivity) ja eri ravinteiden pitoisuuksien-keskinäiset korrelaatiot maakerroksittain koko aineistossa.

	0–10 cm			10–20 cm			20–30 cm			30–40 cm		
	Addition	BD	Ash	Addition	BD	Ash	Addition	BD	Ash	Addition	BD	Ash
Addition	1	0.77***	0.68**	1	0.93***	0.76***	1	0.79***	0.66**	1	0.46*	0.54*
BD	0.77***	1	0.83***	0.93***	1	0.84***	0.79***	1	0.59**	0.46*	1	0.75***
Ash, %	0.68**	0.83***	1	0.76***	0.84***	1	0.66**	0.59**	1	0.54*	0.75***	1
pH	0.46*	0.28	0.54*	0.51*	0.66**	0.69**	0.17	0.17	0.38	–0.17	–0.05	0.30
conductivity	–0.76***	–0.88***	–0.77***	–0.62**	–0.80***	–0.65**	–0.02	–0.31	–0.26	0.37	–0.22	–0.16
N tot	–0.53*	–0.27	–0.47*	–0.62**	–0.66**	–0.71***	–0.33	–0.07	–0.22	0.21	0.91***	0.67**
P tot	0.73***	0.90***	0.75***	0.90***	0.88***	0.63**	0.52*	0.81***	0.49*	0.38	0.88***	0.87***
P aac	–0.46*	–0.49*	–0.68**	–0.44*	–0.42	–0.66**	–0.14	–0.12	–0.43	0.28	–0.07	–0.29
K tot	0.53*	0.74***	0.67**	0.90***	0.84***	0.68**	0.81***	0.99***	0.58*	0.67**	0.86***	0.86***
K aac	0.06	–0.29	0.05	0.50*	0.38	0.29	0.84***	0.72***	0.51*	0.94***	0.53*	0.53*
Ca tot	0.62**	0.70***	0.65**	0.82***	0.79***	0.59**	0.73**	0.96***	0.49*	–0.02	0.26	0.03
Ca aac	–0.37	–0.32	–0.31	–0.28	–0.38	–0.26	0.005	–0.21	–0.02	0.24	–0.24	0.15
Mg tot	0.49*	0.74***	0.64**	0.92***	0.85***	0.67**	0.84***	0.97***	0.69***	0.78***	0.63**	0.50*
Mg aac	–0.13	–0.59	0.08	–0.05	–0.25	–0.11	0.14	–0.20	–0.22	0.55*	0.002	–0.19
Zn tot	0.63**	0.85***	0.67**	0.88***	0.87***	0.80***	0.79***	0.91***	0.72***	0.26	0.17	0.52*
Fe tot	0.49*	0.76***	0.83**	0.93***	0.90***	0.79***	0.84***	0.97***	0.72***	0.63**	0.69*	0.42
B tot	0.61**	0.89***	0.78***	0.75**	0.82***	0.74***	0.67**	0.88***	0.28	0.56*	0.61**	0.32

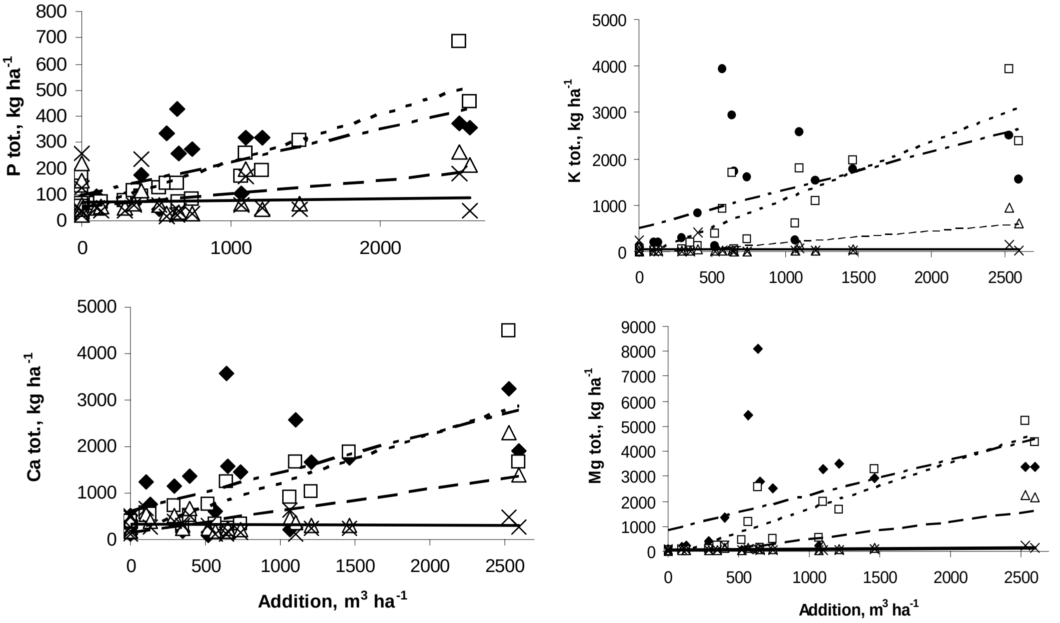

Fig 3. Effect of mineral soil addition on peat P^{tot}, K^{tot}, Ca^{tot} and Mg^{tot} amounts in different peat layers in the combined data. Regression equations are presented in Table 5.

Kuva 3. Kivennäismaan lisäyksen vaikutus turpeen fosfori- (P^{tot}), kalium- (K^{tot}), kalsium- (Ca^{tot}) ja magnesiumin (Mg^{tot}) määriin eri maakerroksissa, koko aineistossa. Regressioyhtälöt taulukossa 5.

considerably (Table 5 and Fig. 3). The effect of mineral soil addition was significant in the case of phosphorus up to the 20–30 cm layer, and for potassium even deeper, in the 30–40 cm layer. In the top layer (0–10 cm, 10–20 cm), 100 m^3 ha^{-1} of mineral soil increased the soil total phosphorus and potassium amounts by 13–18 kg ha^{-1} and 81–123 kg ha^{-1}, respectively. For potassium, the increase was much smaller (3 kg ha^{-1} per 100 m^3 ha^{-1} of mineral soil) in the deepest, 30–40 cm layer, but still significant. In contrast to total phosphorus, the mineral soil addition slightly decreased (by 0.2–0.3 kg ha^{-1} per 100 m^3 ha^{-1} mineral soil) the extractable phosphorus amount in the 0–20 cm peat layer. However, it increased soil extractable potassium amounts in all but the top, 0–10 cm layer (Table 5). Total potassium and phosphorus amounts correlated best with mineral soil addition rate in the 10–20 cm layer, but in deeper layers, the highest correlation coefficients were found with peat bulk density (Table 4).

The addition of mineral soil increased the soil total calcium and magnesium amounts many-fold compared to amounts in the control plots. For magnesium the increase was significant in all studied peat layers (Table 5 and Fig. 3), and for calcium in all except the deepest layer. Each 100 m^3 ha^{-1} addition of mineral soil increased the soil total calcium and magnesium amounts in the 0–10 and 10–20 cm layers by 83–104 kg ha^{-1} and 147–187 kg ha^{-1}, respectively. However, the mineral soil addition did not increase peat extractable calcium and magnesium amounts.

The addition of mineral soil increased the total iron and boron amounts in all studied peat layers (Table 5 and Fig. 4). In the control areas, zinc amounts in the 0–20 cm layer varied between 2.5–10 kg ha^{-1}. For zinc, the increases were significant up to the 20–30 cm peat layer, and for boron and iron, up to the 30–40 cm peat layer (Table 5).

Effect of mineral soil texture on soil characteristics

At Tohmajärvi experiment II, different textured soils were used: 640 m^3 ha^{-1} layer of silt, 740 m^3

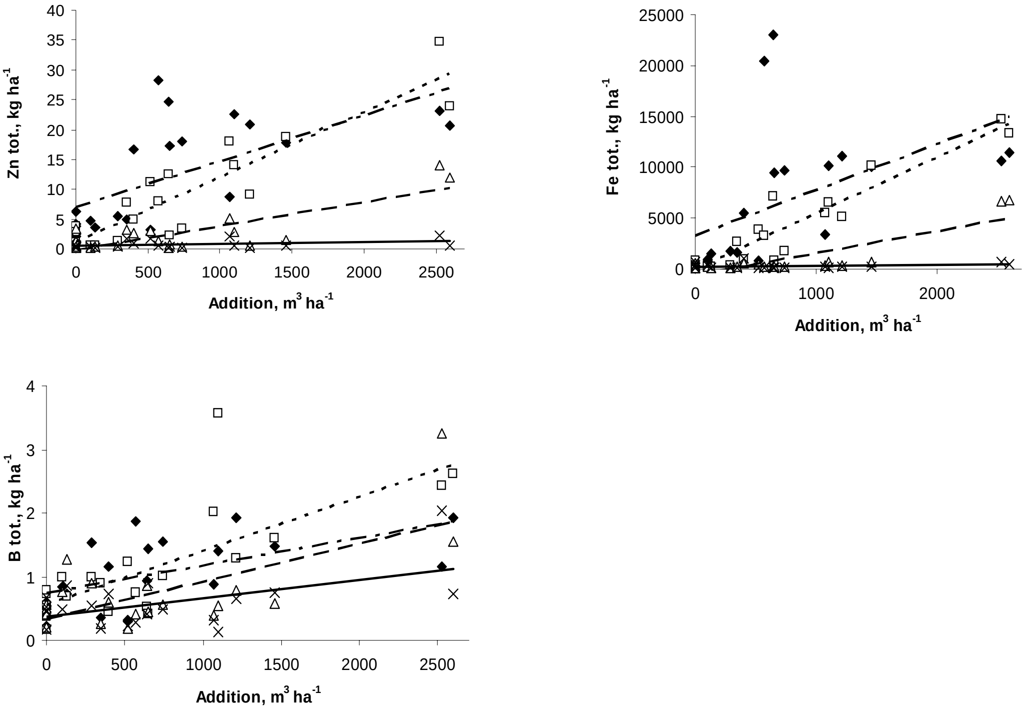

Fig 4. Effect of mineral soil addition on peat Zn^{tot}, Fe^{tot} and B^{tot} amounts in different peat layers in the combined data. Regression equations are presented in Table 5.

Kuva 4. Kivennäismaan lisäyksen vaikutus turpeen sinkki- (Zn^{tot}), rauta- (Fe^{tot}) ja boori- (B^{tot}) määriin eri maakerroksissa, koko aineisto. Regressioyhtälöt taulukossa 5.

ha^{-1} of fine sand, and 570 m^3 ha^{-1} of coarse sand. The added soils differed in their share of fine fraction so that coarse sand had a higher fine fraction than fine sand (silt: 80%, fine sand 28%, coarse sand 34%). The mineral soils used had a rather similar effect on the soil bulk density, ash content and pH. The use of fine sand resulted in the highest bulk density, owing to the highest addition amount.

Mineral soil addition increased the soil total phosphorus, potassium, calcium, magnesium, zinc and iron amounts many-fold compared to the control plots (Figures 5 and 6). Even though the added amount of fine sand was greater than that of other textured soil, it resulted in lower total nutrient amounts. Silt and coarse sand, having the highest share of fine fraction, increased the total potassium, phosphorus and magnesium amounts the most. Silt increased the total calcium amount many-fold compared to fine sand and coarse sand. Coarse sand increased calcium amount only slightly compared with the control plot. All soils decreased acid ammonium acetate extractable phosphorus and calcium amounts, but considerably increased those of potassium and magnesium (Fig. 5).

Effect of mineral soil on nutrient status and growth of Scots pine

At Muhos, Scots pines growing on control plots had severe phosphorus and potassium shortage (Table 6, Paarlahti et al. 1971, Reinikainen et al. 1998). Mineral soil addition increased the foliar phosphorus and potassium concentrations of Scots pine considerably at Muhos 66 years after application (Table 6). However, it had, on the other hand, decreased the concentrations of magnesium, zinc and boron. On the mineral soil treated plots, boron concentrations (6.2 – 6.8 mg kg^{-1}) were at

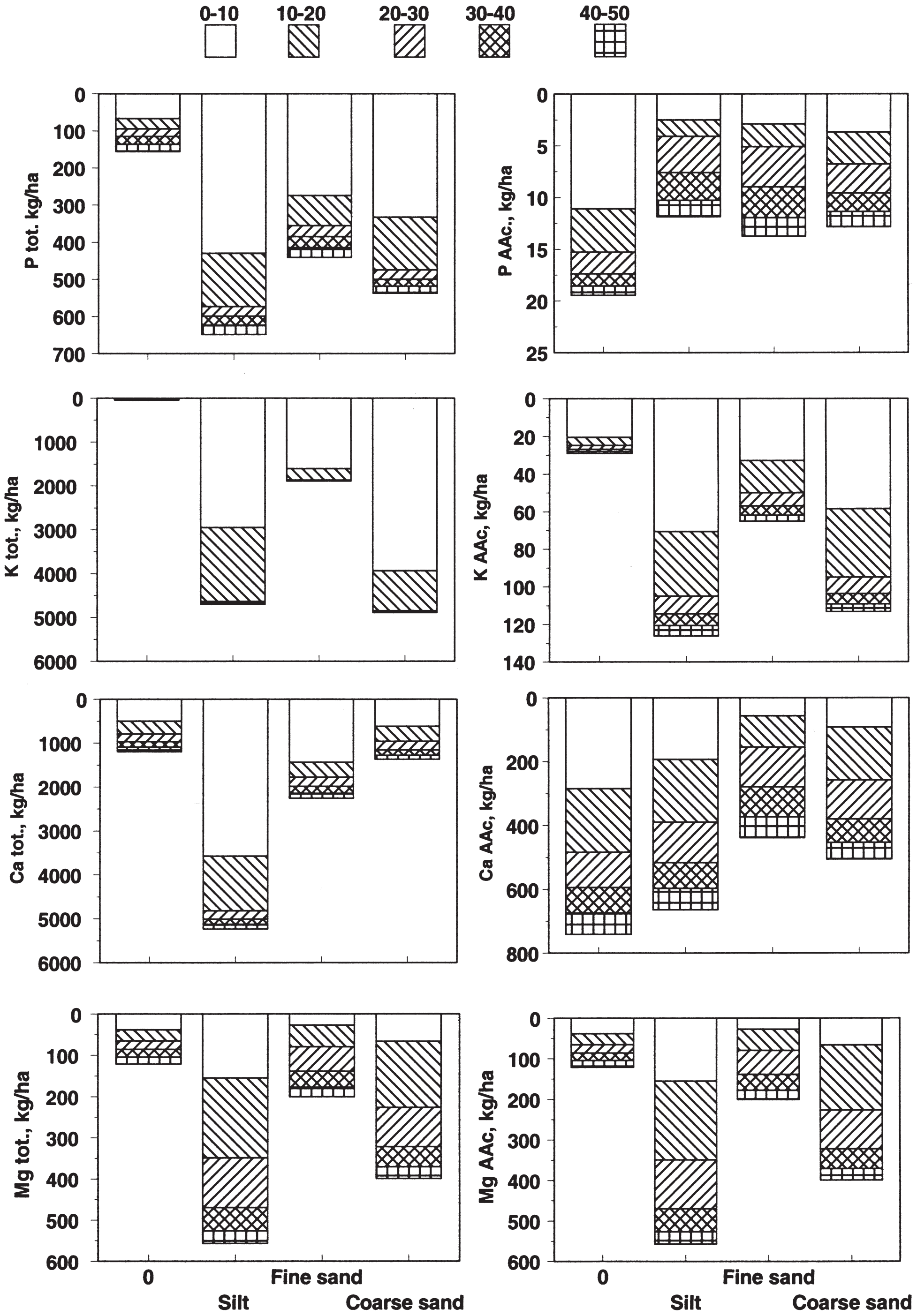

Fig 5. Effect of soil texture on total and ammonium acetate extractable phosphorus, potassium, calcium and magnesium amounts in different peat layers. Tohmajärvi II experiment.

Kuva 5. Kivennäismaan maalajin vaikutus kokonais- ja ammoniumasetaattiliukoisen fosforin (P^{tot}, P^{AAC}), kaliumin (K^{tot},K^{AAC}), kalsiumin (Ca^{tot},Ca^{AAC}) ja magnesiumin (Mg^{tot},Mg^{AAC}) kokonais- ja määriin eri maakerroksissa Tohmajärvi II -kokeessa.

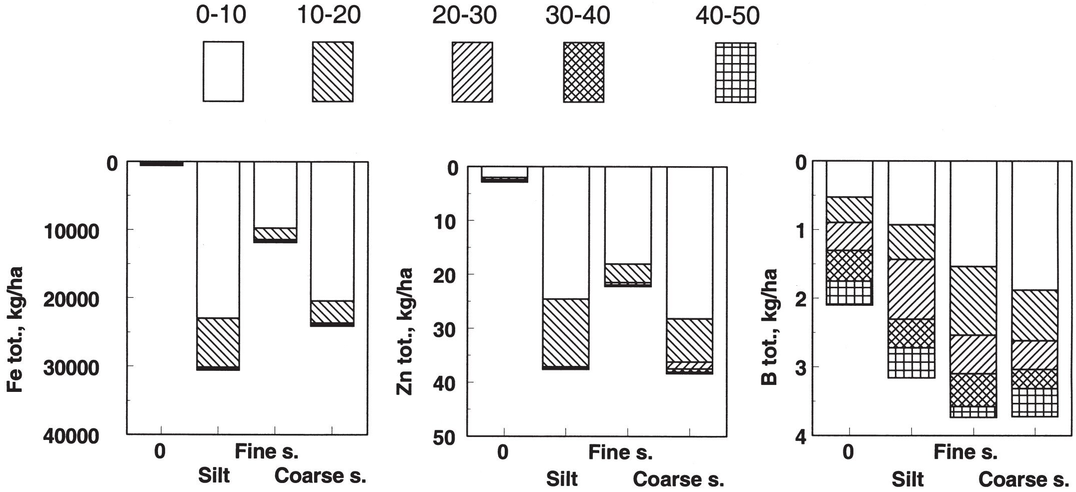

Fig. 6. Effect of soil texture on total zinc, iron and boron amounts in different peat layers. Tohmajärvi II experiment.

Kuva 6. Kivennäismaan maalajin vaikutus sinkin (Zn^{tot}), raudan- (Fe^{tot}) ja boorin- (B^{tot}) määriin eri maakerroksissa. Tohmajärvi II.

Table 5. Dependence of bulk density (BD, g dm^{-3}), ash content (%), pH-value, conductivity (ìS cm^{-1}) and total and extractable (AAc) nutrient amounts (kg ha^{-1}) (y) on the mineral soil addition rate (explaining variable x, 100 m^{3} ha^{-1}) in different soil layers (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm). r^{2} = coefficient of determination. Two outlier values for Fe and Mg in 0–10 cm layer are omitted from the analysis. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

*Taulukko 5. Maan tilavuuspainon (BD, g dm^{-3}), tuhkapitoisuuden (Ash, %), pH-arvon, sähkönjohtokyvyn (conductivity, ìS cm^{-1}) sekä kokonais (tot)- ja liukoisten (aac) ravinteiden määrän (y) riippuvuus kivennäismaa-annostuksesta (selittävä muuttuja x, 100 m^{3} ha^{-1}) eri maakerroksissa (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm), koko aineistossa. Yhtälöiden selitysaste (R^{2}) ja niiden tilastollinen merkitsevyys: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.*

	0–10 cm		10–20 cm		20–30 cm		30–40 cm	
y	equation	r2 (%)	equation	r2 (%)	equation	r2 (%)	equation	r2 (%)
BD	32.60x+220.13	59.5***	47.10x+87.23	87.3***	20.32x+48.58	60.0***	2.87x+94.66	21.0*
Ash	3.11x+42.53	45.8**	3.94x+19.45	58.0***	1.73x+0.30	44	0.38x+2.74	29.5*
pH	0.2x+3.94	21.1	0.03x+3.74	26.5*	0.01x+3.80	2.9	–0.01x+3.98	0.3
Conduct.	–6.58x+243.10	55.8***	–6.00x+223.20	37.8**	–0.18x+177.77	0	2.84x+137.81	13.7
N tot	–25.67x+1351.84	28.4*	–64.50x+1886.04	38.8**	–41.51x+2023.62	10.7	21.78x+24.37	4.5
P tot	12.64x+100.19	52.5***	18.22x+42.31	81.0***	5.10x+52.79	27.3*	2.29x+41.56	14.5
P aac	–0.31x+7.51	21.2*	–0.18x+5.10	18.9*	–0.03x+2.83	1.8	0.04x+1.57	7.5
K tot	81.69x+512.58	28.4*	123.31x–98.58	80.6***	24.68x–64.96	65.7***	2.65x+2.23	44.3**
K aac	–0.13x+47.00	0.4	0.78x+13.66	25.0*	0.72x+4.43	70.5***	0.44x+2.10	87.5***
Ca tot	83.3x+619.63	39.0**	103.97x+185.65	67.1***	46.74x+162.59	52.5***	–0.50x+309.35	0
Ca aac	–3.88x+125.75	9.5	–2.78x+122.85	8	0.06x+125.93	0	3.16x+95.59	0.6
Mg tot	147.29x+274.20	80.4***	187.00x–194.71	84.8***	70.74x–202.85	71.3***	4.89x+27.38	60.4***
Mg aac	–0.53x+39.05	1.6	–0.33x+50.58	0.3	0.53x+45.84	2	1.27x+31.97	26.4*
Zn tot	0.74x+7.31	39.7**	1.04x+1.44	87.6***	0.39x–0.03	62.5***	0.03x+0.60	6.6
Fe tot	456.32x+1567.03	63.2***	537.02x+48.46	85.7***	214.02x–534.05	71.0***	12.28x+124.70	36.1**
B tot	0.04x+0.75	36.9**	0.08x+0.57	55.7***	0.06x+0.35	45.1**	0.03x+0.35	30.8*

the deficiency limit. At Vilppula, 77 years after the application of much smaller amounts of mineral soil, no clear differences on pine foliar nutrient concentrations compared with control plot were noted. However, similarly to Muhos, also at Vilppula, increasing in foliar potassium concentrations could be seen.

At Muhos during the 57 years after the application, the total increases in the stem volume of the stand were 180 m^3 ha^{-1} (3.2 m^3 ha^{-1} a^{-1}) and 223 m^3 ha^{-1} (3.9 m^3 ha^{-1} a^{-1}) (5 and 10 cm layers, respectively). The increase of absolute annual growth due to mineral soil application was monitored in 1965–1994, when 31–60 years had elapsed since the treatments. During the monitoring period, the growth of stem volume was considerably greater on the plots that had received mineral soil than on the untreated control plot (Fig. 7 and Table 7). The stand response to the mineral soil application became stronger with time: after 60 years, the growth of mineral soil ameliorated trees was nearly three-fold that of the untreated trees (difference to control 5–6 m^3 ha^{-1} a^{-1}).

Discussion

In the experiments established in the 1920s and 1930s, the treatments were not replicated, and thus the statistical significance of the effects of the addition of mineral soil in each of the experiments could not be statistically tested. The application amounts deviated quite much from those expressed in the original experimental designs. This could be due to difficulties in measuring or spreading the mineral soil during winter using horse driven carriages. Since the variation in the actual application amounts was quite large, correlation and regression analyses was used to study the effect of mineral soil on peat characteristics. Due to the small size of the plots, the roots of tree stand probably had penetrated neighbouring plots, thus making the stand measurements inapplicable, apart from one experiment (Muhos). Also, some of the stands had been thinned several times during the experiments, and all harvest removals are not known. So it was not possible to study the effect of mineral soil addition on wood production in a more exact manner.

Table 6. The results of foliar analyses from Vilppula experiment 77 years and from Muhos experiment 66 years after mineral soil application.

Taulukko 6. Männyn neulasten ravinnepitoisuudet Vilppulan ja Muhoksen kokeilla 77 ja 66 vuotta kivennäismaan lisäyksen jälkeen.

	Mineral soil application rate, m^3 ha^{-1}						
	Muhos 66 a			Vilppula 77 a			
Nutrient	0	1100	2530	0	100	130	290
N, %	1.34	1.38	1.26	1.05	1.10	1.11	1.04
P, mg g^{-1}	1.17	1.46	1.48	1.15	1.20	1.21	1.07
K, mg g^{-1}	3.43	4.55	4.74	3.70	3.69	4.03	3.93
Ca, mg g^{-1}	1.99	2.27	1.86	2.27	2.08	2.34	2.20
Mg, mg g^{-1}	1.41	1.31	1.05	1.25	1.43	1.31	1.00
Fe, mg kg^{-1}	41	32	-	-	-	-	
Mn, mg kg^{-1}	269	238	200	-	-	-	-
Zn, mg kg^{-1}		43	41	35	-	-	-
-							
Cu, mg kg^{-1}	2.4	2.6	2.2	-	-	-	-
B, mg kg^{-1}	18.5	6.4	6.5	19.3	17.6	17.6	17.7

However, despite serious deficits in design, these long lasting field experiments give interesting results on the addition of mineral soil on the nutrition of peatland forest.

Addition of mineral soil changed the physical characteristics of the peat soils completely. Increases in ash content and bulk density were considerable. The soil bulk density and ash content on the plots with mineral soil application were considerably greater than on drained peatlands (Kaunisto & Paavilainen 1988, Laiho & Laine 1994, Westman & Laiho 2003). In some cases, the ash content in the top soil was close to that of mineral soil. This corresponds well with results from afforested arable peat soils (Wall & Hytönen 1996).

The amounts of many elements in the peat were noted to increase along with increased application amounts. Even moderate application rates of mineral soil led to considerable increases in soil total phosphorus, potassium, calcium, magnesium, iron and zinc amounts. Similarly Wall & Hytönen (1996) reported that mineral soil increased the potassium, magnesium, manganese, iron and zinc amounts considerably, and to a lesser extent, those of phosphorus on former arable peat fields. Also in accordance with results from Wall and Hytönen (1996), the addition of mineral soil affected the amounts of extractable nutrients in the soil only slightly. Mineral soil increased soil extractable potassium amounts slightly, as in the study of Wall & Hytönen (1996). In agricultural experiments, the addition of mineral soil has not increased extractable potassium amount in the soil (Anttinen 1957a, 1957b). Also, in agreement with the study of Wall and Hytönen (1996), mineral soil addition decreased extractable phosphorus amounts slightly in the top peat layer. In agricultural peat fields, the addition of mineral soil has not increased (Anttinen 1957a) or has increased only slightly (Anttinen 1957b) the extractable phosphorus amount in the peat. Contrary to earlier studies on afforested peat fields (Wall & Hytönen 1996), mineral soil addition increased also soil boron amounts slightly.

Besides the amount applied, the original quality and texture of the mineral soil can affect the results (e.g. Wall & Hytönen 1996, Aro et al. 1997). At Tohmajärvi II, the application amounts of different textured soil varied from 570–740 m^3 ha^{-1}, so that the soil which had lowest fine fraction was spread 740 m^3 ha^{-1}. The results showed clearly that fine textured soil increased the amounts of total phosphorus, potassium, calcium and magnesium in the soil the most. In agriculture, clay has increased agricultural yields more than fine sand or gravelly till (Takala 1961) or sand (Pessi 1961b, 1961c). In all of the present data, excluding Sippola, the fine fraction was higher than 15–20%, which was recommended by Aro et al. (1997) as suitable for supplying mineral nutrients for cutaway peatlands from subsoil.

During the 70 years after the application, the mineral soil had not penetrated to great extent into deeper soil layers, as was noted also in studies made of afforested peat fields (Wall & Hytönen 1996, Kaunisto 1991). However, mineral soil addition increased the soil ash content

Table 7. Stand characteristics at Muhos in 1994. Treatments: Control = no mineral soil application, Min1 = mineral soil 2530 m^3 ha^{-1}, Min2 = mineral soil 1100 m^{3}ha^{-1}, see Fig. 7.

Taulukko 7. Puustotunnukset Muhoksen kokeella vuonna 1994. Käsittelyt: Kontrolli = ei kivennäismaalisäystä, Min1= kivennäsimaata 2530 m^{3}ha^{-1}, Min2 = kivennäismaata 1100 m^{3}ha^{-1}, ks. kuva 7.

	Treatment		
Stand characteristic	Control	Min1	Min2
Stems/ha	1169	1100	1276
Diameter ($D_{1.3}$), cm	14.6	17.7	17.3
Dominant height, m	13.9	17.3	17.1
Growing stock, m^{3}ha^{-1}	102	149	187
Saw logs, % of stem volume	13	38	35

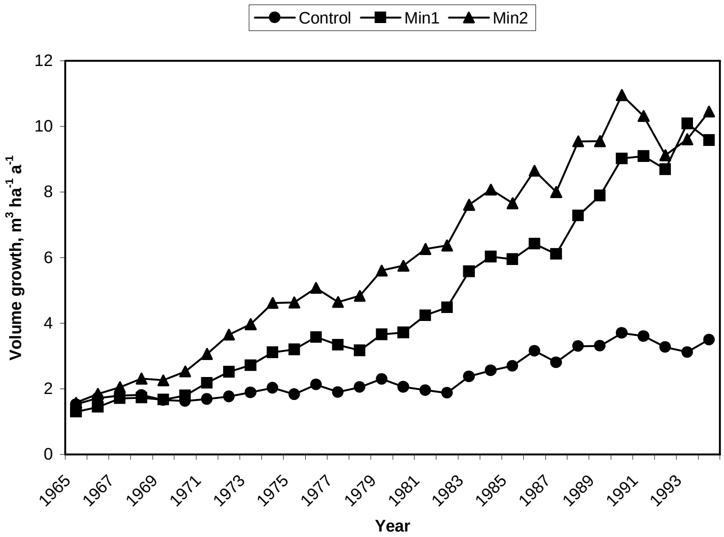

Fig. 7. Volume growth of pine stand at Muhos in 1965–1994. Control = no mineral soil application, Min1 = mineral soil 2530 m^3 ha^{-1}, Min2 = mineral soil 1100 m^3 ha^{-1}.

Kuva 7. Männyn runkopuuston tuotos Muhoksen kokeella vuosina 1965 – 1994. Control = vertailu, Min 1 = kivennäismaalisäys 2530 m^3 ha^{-1}, Min2 = kivennäismaalisäys 1100 m^3 ha^{-1}.

in the 30–40 cm layer by 0.4% of every 100 m^3 ha^{-1} of mineral soil added. Similarly, the soil total and extractable potassium contents increased also in the deeper layers. Significant increases, in all studied peat layers, were noted also in the soil total magnesium, iron and boron amounts.

For the nutrition of trees growing on peatlands, high increases in soil total phosphorus and especially in potassium amounts are probably the most important nutritional effects of mineral soil application. In agriculture, especially the effect of mineral soil addition on the soil potassium nutrition has been long standing, and the need for potassium fertilisation in agriculture was either clearly reduced (Isotalo 1952, Anttinen 1957a, 1957b, Pessi 1960, 1961b, 1961c) or even replaced by mineral soil addition (Anttinen 1957a, 1957b). In this study, addition of mineral soil on top of the peat has increased total phosphorus and potassium amounts many-fold for 50–70 years, and it is quite probable that the effect will be very long lasting.

Lukkala (1955) suggested that an approximately 5 cm thick mineral soil layer (500 m^3 ha^{-1}) from rich mineral soil forest could considerably raise the production capability of peatland forest. The present results from old experiments support these views. However, according to Silfverberg (1984), at Vilppula, mineral soil addition has increased stand growth only slightly. This was probably due to small spreading amounts (100–290 m^3 ha^{-1}; 25–39% of those intended), which were the lowest of all experiments studied here. At Vilppula, mineral soil addition increasing the soil total potassium amount in the 40 cm layer by only 140–220 kg ha^{-1} had no effect on Scots pine foliar potassium concentration. At Muhos, the corresponding increase in potassium stores was much higher (4470–7390 kg ha^{-1}) and this was reflected clearly both in stand growth and in the foliar potassium concentrations. Similarly, fine textured mineral soil from subsoil has increased Scots pine foliar potassium concentrations on cutaway peatland (Aro 1996). At Muhos, also the foliar phosphorus status and stand growth improved at least for 60–70 years. Thus, it is evident that the effect of mineral soil on the stand nutrition on drained mires is longer-lasting than that of commercial fertilisers or wood ash (Kaunisto 1992, Silfverberg & Hartman 1999, Kaunisto et al. 1999, Moilanen et al. 2005).

Despite increased boron amounts, mineral soil addition seemed to decrease foliar boron concentrations. The boron uptake of plants is affected by parameters such as soil pH, and the amounts of calcium and magnesium. Thus, increases in soil calcium amounts could have negatively affected the boron uptake of trees (Lehto & Mälkönen 1994). Decrease of foliar boron concentrations could also be due to dilution effect (see Paarlahti et al. 1971).

Mineral soil addition could ameliorate peat soil especially in nitrogen rich peatlands, which in their original state have been treeless or very wet. On such peatlands especially potassium deficiencies have been common (Kaunisto & Tukeva 1984, Moilanen 1993, Rautjärvi et al. 2004). Application of mineral soil as soil ameliorant is, however, probably not economically feasible even when considering the very long effect of the operation. However, in some cases in peatland forestry, mineral soil can be mixed with the peat. When afforesting cut-away peatlands, trees can be supplied with mineral nutrients by lifting subsoil from ditch spoil, to such an extent that fertilisation is unnecessary (Kaunisto 1987, Aro et al. 1997, Aro & Kaunisto 2003). In the future, forest regeneration in old drainage areas is increasing considerably (Saarinen 2005). The choice of the soil preparation method can in these cases thus affect the nutritional status of the peat for the new tree generation considerably. When the peat layer is not too deep, mounding instead of shallow scarification could be used to mix mineral soil with the peat, especially in cases where potassium nutrition can be questionable in the long run.

Acknowledgements

The soil and needle sampling was carried out by Mr. Timo Haikarainen, Olavi Kohal, Ismo Kyngäs, Seppo Vihanta, and Heikki Vesala. Nutrient and soil texture analysis in the laboratories of Forest Research Institute’s Kannus and Muhos Research Units were carried out by Kaisa Jaakola and Reetta Kolppanen. Mr. Aki Moilanen revised the English text. We express our sincere thanks to all these persons and others who contributed to the completion of this work.

References

Anttinen, O. 1957a. Rahkasuon lannoitus- ja maanparannuskokeen tuloksia (Referat: Ergebnissen eines Düngungs- und Bodenverbesserungsversuches auf Sphagnum-Moor). Valtion maatalouskoetoiminnan julkaisuja 155:1–30.

Anttinen, O.1957b. Saraturvesuon saveus- ja lannoituskokeen tuloksia (Referat: Ergebnisse eines Lehmzufuhr- und Düngungsversuchs auf Seggentorfmoor). Valtion maatalouskoetoiminnan julkaisuja 163:1–20.

Aro, L. 1996. Suonpohjien metsityksen ravinnetaloudellisia näkökohtia. Metsäntutkimuslaitoksen tiedonantoja 674: 71–77.

Aro, L. & Kaunisto, S. 2003. Jatkolannoituksen ja kasvatustiheyden vaikutus nuorten mäntymetsiköiden ravinnetilaan sekä puuston ja juuriston kehitykseen paksuturpeisella suonpohjalla (Summary: Effect of refertilisation and growing density on the nutrition, growth and root development of young Scots pine stands in a peat cutaway area with deep peat layers). Suo – Mires and Peat 54(2): 49–68.

Aro, L., Kaunisto, S. & Saarinen, M. 1997. Suopohjien metsitys. Hankeraportti 1986–1995 (Summary: Afforestation of peat cutaway areas. Project report 1986–1995). Metsäntutkimuslaitoksen tiedonantoja 634. 51 p.

Elonen, P. 1971. Particle-size analysis of soil. Acta Agralia Fennica 122. 122 p.

Erviö, R. 1970. The importance of soil bulk density in soil testing. Annales Agriculturae Fenniae 9: 278–286.

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

Huikari, O. 1961. Koetuloksia metsäojitettujen soiden ravinnetalouden keinollisesta parantamisesta. Metsätaloudellinen aikakauslehti 1961(5): 212–214.

Hytönen, J. & Ekola, E. 1993. Maan ja puuston ravinnetila Keski-Pohjanmaan metsitetyillä pelloilla. (Summary: Soil and nutrient regime and tree nutrition on afforested fields in central Ostrobotnia, western Finland). Folia Forestalia 822. 32p.

Hytönen, J. & Wall, A. 1997. Metsitetyjen turvepeltojen ja viereisten suometsien ravinnemäärät (Summary: Nutrient amounts of afforested peat fields and neighbouring peatland forests). Suo 48(2): 33–42.

Isotalo, A. 1952. Rahkasoiden viljelystä (Summary: Cultivation of Sphagnum peat). Suo 2(1): 3–16.

Kaunisto, S. 1987 Lannoituksen ja muokkauksen vaikutus männyn ja rauduskoivun istutustaimien kasvuun suonpohjilla (Summary: Effect of fertilization and soil preparation on the development of Scots pine and silver birch plantation on peat cutover areas). Folia Forestalia 681. 23 p.

Kaunisto, S. 1989. Jatkolannoituksen vaikutus puuston kasvuun vanhalla ojitusalueella (Summary: Effect of refertilization on tree growth in an old drainage area). Folia Forestalia 724. 15 p.

Kaunisto, S. 1991. Maa-analyysin käyttö kasvupaikan ravinnetilan arvioimiseksi eräillä Alkkian metsitetyillä suopelloilla (Summary: Soil analysis as a means of determining the nutrient regime on some afforested peatland fields of Alkkia). Folia Forestalia 778. 32 p.

Kaunisto, S. 1992. Effect of potassium fertilization on the growth and nutrition of Scots pine. Suo 43: 45–62.

Kaunisto, S. & Moilanen, M. 1998. Kasvualustan, puuston ja harvennuspoistuman sisältämät ravinnemäärät neljällä vanhalla ojitusalueella. Metsätieteen aikakauskirja - Folia Forestalia 3/1998: 393–410.

Kaunisto, S. & Paavilainen, E. 1988. Nutrient stores in old drainage areas and growth of stands. Communicationes Instituti Forestalis Fenniae 145. 39 p.

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. 1999. Effect of apatite and phlogopite application on the needle nutrient concentrations of Pinus sylvestris (L.) on drained pine mires. Suo 50(1): 1 – 15.

Korhonen, K-H., Gardemeister, R. & Tammirinne, M. 1974. Geotekninen maaluokitus. Geotekniikan laboratorio, Valtion teknillinen tutkimuskeskus. Tiedonanto 14. 20 p.

Laasasenaho, J. 1982. Taper curve and volume functions for pine, spruce and birch. Communicationes Instituti Forestalis Fenniae 108. 74 p.

Laiho, R. & Laine, J. 1994. Changes in mineral nutrient concentrations in peat soils drained for forestry in Finland. Scandinavian Journal of Forest Research 9: 251–260.

Laine, J. & Vasander, H. 1996. Ecology and vegetation gradients of peatlands. In: Vasander, H. (ed.). Peatlands in Finland: 10 – 20. Finnish Peatland Society. ISBN 952-90-7971-0. Helsinki.

Lehto, T. & Mälkönen, E. 1994. Effect of liming and boron fertilization on boron uptake of *Picea abies*. Plant Soil 163: 55–64.

Lukkala, O.J. 1951. Kokemuksia Jaakkoinsuon koeojitusalueelta (Summary: Experiences from Jaakkoinsuo experimental drainage area). Communicationes Instituti Forestalis Fenniae 39(6). 53 p.

Lukkala, O.J. 1955. Maanparannusaineet ja väkilannoitteet metsäojituksen tukena. Metsätaloudellinen aikakauslehti 6–7:189–191.

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., 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.

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

Pessi, Y. 1953. Kivennäismaan vaikutuksesta suoviljelyksen lämpöoloihin (Summary: On the influence of mineral soil upon the temperature on the cultivated peat area). Suo 4(6):67–60.

Pessi, Y. 1956. Studies on the effect of the admixture of mineral soil upon the thermal conditions of cultivated peat. State Agricultural Research Publications of Finland 147: 89 p.

Pessi, Y. 1960. Kivennäismaan merkityksestä mutasuon maanparannusaineena Leteensuon koeaseman pitkäaikaisten kenttäkokeiden perusteella (Summary: On the significance of mineral soil as a soil improving agent on fens on the basis of prolonged field tests at Leteensuo Experimental Station). Suomen maataloustieteellisen seuran julkaisuja 95(3): 1–26.

Pessi, Y.1961a. The ash content of the plough layer of peat lands cultivated by different methods. Maataloustieteellinen aikakauskirja 33: 215–222.

Pessi, Y. 1961b. Results from a soil improvement and fertilizing test on fen land at Leteensuo Maataloustieteellinen aikakauskirja 33: 223–228.

Pessi, Y.1961c. Suoviljelyksen niittonurmen perustamisesta ja hoidosta (Summary: Observations at Leteensuo on the laying down to grass of peat lands and on the tending of the grass leys). Suomen maataloustieteellisen seuran julkaisuja 97(2): 1–28.

Pessi, Y.1962. Rahkasoiden viljelystä (Summary: On plant cultivation on Sphagnum bog). Suoviljely-yhdistyksen vuosikirja 67: 21–26.

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

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., Veijalainen, H. & Nousiainen, H. 1998. Puiden ravinnepuutokset – metsänkasvattajan ravinneopas. Metsäntutkimuslaitoksen tiedonantoja 688. 44 p.

Saarinen, M. 2005. Metsänuudistaminen turvemailla. In: Ahti, E., Kaunisto, S., Moilanen, M. & Murtovaara, I. (eds). Suosta metsäksi. Suometsien ekologisesti ja taloudellisesti kestävä käyttö. Tutkimusohjelman loppuraportti. Metsäntutkimuslaitoksen tiedonantoja 947: 177–193.

Silfverberg, K. 1984. Hiekoitus-, kalkitus- ja lannoituskokeet. In: Jaakkoinsuon koeojitusalue 75 vuotta. Metsäntutkimuslaitoksen tiedonantoja 156: 47–51.

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

Takala, M. 1961. Erilaisten maanparannusaineiden vaikutuksesta mutasuolla (Summary: On the effects of the various kinds of soil improving agents of fen). Suoviljely-yhdistyksen vuosikirja 65: 23–27.

Tiainen, M. 1992. Retkeilyreitti Maatalouden tutkimuskeskuksen Karjalan koeaseman suometsäkokeille. Metla, Joensuun tutkimuskeskus. 23 p.

Valmari, A. 1983. Suon viljely. Suomen suot ja niiden käyttö. Suoseura ry. IPS:n Suomen kansallinen komitea. Helsinki. pp. 42–48.

Vesikivi, A. 1933. Suomaan lämpötilamittausten tuloksia

(Referat: Ergebnisse von Temperaturbeobachtungen im Moorboden). Suomen Suoviljelysyhdistys. Tieteellisiä julkaisuja 15. 19 p.

Wall, A. & Hytönen, J. 1996. Painomaan vaikutus metsitetyn turvepellon ravinnemääriin (Summary: Effect of mineral soil admixture on the nutrient amounts of afforested peatland fields). Suo 47(3): 78–83.

Westman, C.J. & Laiho, R. 2003. Nutrient dynamics of drained peatland forests. Biogeochemistry 63: 269–298.

Tiivistelmä:

Kivennäismaalisäyksen vaikutus turpeen ravinnemääriin ja männyn ravinnetalouteen metsäojitetuilla soilla

Maataloudesta saatujen hyvien kokemusten innoittamana kivennäismaan lisäystä tehtiin metsäojitetuille soille koeluontoisesti jo 1920- ja 1930-luvuilla. Kivennäismaan maanparannus- tai puustovaikutuksista ei kuitenkaan ole julkaistu tähän mennessä tutkimuksia. Lukkalan (1955) mukaan turvemaiden hiekoituskokeet osoittavat, että runsasravinteisesta metsämaasta peräisin oleva 5 cm:n paksuinen hiekkakerros (500 m^3 ha^{-1}) tai savimaa kohottaa tuntuvasti ojitetun suon puuntuotoskykyä.

Painomaaksi kutsuttua kivennäismaata suositeltiin turvepeltojen maanparannusaineeksi aiemmin yleisesti ja sen käyttö oli varsin tavallista turvemaiden viljelyssä Suomessa. Painomaan tarkoituksena oli parantaa peltojen ravinnetilaa, lämpöoloja ja lujittaa muutoin liian löyhää maata. Painomaa kohotti heinä- ja viljasatoja turvepelloilla sitä enemmän, mitä enemmän sitä käytettiin. Positiivisen vaikutuksen on arveltu johtuvan kivennäismaan sisältämästä kaliumista sekä painomaan vaikutuksista maan fysikaalisiin ominaisuuksiin, kuten pH:n, lämpö- ja luultavasti myös vesioloihin. Painomaan on havaittu vaikuttavan ravinnetilaan vielä suopellon tultua metsitetyksi.

Tämän tutkimuksen tavoitteena oli selvittää vanhojen hiekoituskokeiden avulla kivennäismaan määrän ja laadun pitkäaikaisia vaikutuksia turpeen ravinteisuuteen ja puuston ravinnetilaan kuudella metsäojitusalueella.

Tutkimuksessa käytetyt kenttäkokeet oli perustettu 1920 ja 1930–luvulla ja ne sijaitsivat Muhoksella, Tohmajärvellä, Vilppulassa, Sippolassa ja Tuusulassa alun perin karuilla ja usein vähäpuustoisilla tai puuttomilla soilla. Vaihtelevia määriä kivennäismaata oli levitetty suon pintaan. Kokeissa ei ollut toistoja eikä käsittelemättömiä vertailukoealoja. Tutkimusta varten vertailukoeala valittiin mahdollisimman läheltä käsiteltyjä koealoja samalta suotyypiltä. Koealojen pienen koon vuoksi puuntuotoksen tarkastelu rajoittui vain yhteen kokeeseen.

1990-luvulla puustot edustivat kehitysluokaltaan nuorta tai varttunutta kasvatusmetsikköä. Vallitseva puulaji oli kaikissa kokeissa mänty, sekapuuna esiintyi vaihtelevasti hieskoivua. Aineiston keruuhetkellä kivennäismaalisäyksestä oli kulunut kokeesta riippuen 52 – 74 vuotta. Kokeilta otettiin kaikilta koeruuduilta ja koealueen ulkopuolelta vertailualueelta tilavuustarkat maanäytteet eri turvesyvyyksiltä (kerrokset 0–10, 10–20, 20–30 ja 30–40 cm sekä Tohmajärveltä ja Vilppulasta lisäksi 40–50 cm:n kerros) koostaen ne 9:stä tai 12:sta osanäytteestä. Ravinnemäärityksiä varten otettiin neulasnäytteet Muhokselta ja Vilppulasta. Muhoksen kokeelta mitattiin myös puuston määrän ja kasvun kehitys jaksolta 1965 – 1994 (kivennäismaan lisäyksestä 31 – 60 vuotta).

Kivennäismaiden raekoostumus määritettiin sedimentointimenetelmällä (Elonen 1971) ja maalaji nimettiin d_{50} -menetelmällä (Korhonen ym. 1974). Maanäytteistä määritettiin pH, tuhkapitoisuus, kokonaistyppi sekä maan ns. kokonaisravinnepitoisuudet (P, K, Ca, Mg, Fe, Zn, B) ja happamaan ammoniumasetaattiin uuttuvat ravinnepitoisuudet (P, K, Ca, Mg). Maanäytteen sisältämän kivennäisaineen ja orgaanisen aineen määrä laskettiin maan tiheyden ja tuhkapitoisuuden perusteella. Kivennäismaan määrä arvioitiin käyttämällä vertailuperusteena niiden soiden kivennäisaineen määrän keskiarvoa, joilla kivennäismaata ei ole lisätty (vertailukoealat). Kivennäismaan massa muunnettiin tilavuudeksi käyttäen maan tiheyden arvona 1,1 kg dm^{-3} (Erviö 1970). Ravinteiden määrät esitetään kokonaismäärinä (kg ha^{-1}) 10 cm paksuisissa maakerroksissa. Alkuperäisissä koesuunnitelmissa esitetyt kivennäismaa-annostukset poikkesivat huomattavasti laskennallisista määristä. Tutkimuksessa käytettiin laskennallisia arvoja.

Korrelaatio- ja regressioanalyysillä tutkittiin kivennäismaalisäyksen vaikutuksia maan tiheyteen, tuhkapitoisuuteen, pH:n ja ravinnepitoisuuksiin eri turvekerroksissa kaikkien kokeiden yhdistetyssä aineistossa. Tohmajärven kokeessa II tarkasteltiin eri raekoostumusta olevien kivennäismaalajien vaikutusta.

Kivennäismaan lisäyksellä oli pitkäaikainen vaikutus maan fysikaalisiin ja kemiallisiin ominaisuuksiin. Turpeen tuhkapitoisuus ja kuivatuoretiheys kasvoivat kivennäismaalisäyksen määrän kasvaessa. Samalla lisääntyivät maan fosforin, kaliumin, kalsiumin, magnesiumin, sinkin, raudan ja boorin kokonaismäärät. Kivennäismaalisäys vaikutti kuitenkin vain vähän turpeen happamaan ammoniumasetaattiin uuttuvien ravinteiden määriin. Turpeen pinnalle levitetyn kivennäismaan vaikutukset rajoittuivat pääasiassa turpeen ylimpään 30 cm kerrokseen. Kuitenkin turpeen tuhkapitoisuus sekä kaliumin ja boorin määrät olivat lisääntyneet syvemmälläkin. Mitä korkeampi maan hienoainesosuus oli, sitä enemmän turpeen fosforin, kaliumin, kalsiumin ja magnesiumin kokonaismäärät lisääntyivät. Kivennäismaan lisäys nopeutti puuston kasvua ja paransi männyn neulasten fosfori- ja kaliumtaloutta, mutta laski neulasten booripitoisuutta Muhoksen kokeella. Tuloksista voidaan päätellä, että suometsien uudistamisen yhteydessä kivennäismaan saaminen turvekerroksen pintaosiin muokkauksen yhteydessä turvaisi uuden puusukupolven käytettävissä olevien kivennäisravinnevarojen säilymistä, mikäli pohjamaa ei ole kovin karkealajitteista.

Received 20.3.2008, Accepted 15.5.2008