Effects of Wood, Peat and Coal Ash Fertilization on Scots Pine Foliar Nutrient Concentrations and Growth on Afforested Former Agricultural Peat Soils

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The effects of ash and commercial fertilizers on the foliar nutrient concentrations and stand growth of Scots pine were studied in four field experiments established on former cultivated peat soils. The aims were to compare ash types (wood, peat and coal ash), study the effects of ash treatment (pelletization), compare ash fertilization with commercial fertilizers, and to study the interaction between ash fertilization and weed control. Foliar samples were collected 1–3 years and 7–8 years after fertilization.

In the unfertilized plots, the foliar nitrogen and phosphorus concentrations were fairly high, while those of potassium were low in all the experiments. The boron levels were low in three out of the four experiments. Application of either loose or pelletized wood ash, as well as of commercial fertilizers, increased foliar potassium and boron concentrations, and thus successfully remedied the existing nutrient imbalances and deficiencies. Since phosphorus deficiencies are rarely encountered on field afforestation sites, poor-quality wood ash with low phosphorus concentration could be used. Peat ash containing phosphorus, but only small amounts of potassium and boron, was not found to be very suitable for soil amelioration in connection with field afforestation. Coal ash, containing only small amounts of potassium, was a good source of boron for pine even when used in small amounts, and thus it can be used in cases where boron deficiencies alone are encountered. Wood ash significantly increased the height growth of Scots pines in two of the experiments, but peat ash and coal ash had no statistically significant effect. Wood ash increased the number of healthy seedlings. Vegetation control decreased seedling mortality by 24%, increased the growth of pine and decreased the proportion of trees damaged by elk and by deciduous trees.

Keywords wood ash, coal ash, peat ash, afforestation, peat soils, vegetation control, herbicides, Scots pine
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1 Introduction

Large-scale afforestation of agricultural land in Finland, aimed at reducing the area under cultivation in the country, began in the late 1960s. Over 220 000 ha of agricultural fields have been afforested since 1969 (Finnish statistical … 2000). Mull and peat soils, containing high amounts of organic matter, account for 20% of the total field area (Kähäri et al. 1987). However, their proportion of the total afforested field area is substantially larger (Hytönen 1999a). The afforestation of fields, especially on mull and peat soils, has often faced problems connected to the nutritional status of the soil. The development of the ground vegetation on afforested former agricultural land is usually fast and vigorous, and this constitutes one of the foremost causes of seedling damage (Hynönen 1997, Hynönen and Saksa 1997, Hytönen 1999a). Moreover, fertilization in conjunction with afforestation can also further promote the growth of weeds.

The nutrient amounts in the soil of afforested former agricultural peatlands are often quite high compared with the soils of peatland forests (Kaunisto and Paavilainen 1988, Hytönen and Ekola 1993, Wall and Hytönen 1996, Hytönen and Wall 1997, Hynönen and Makkonen 1999). Agricultural cultivation has been found to increase the soil's bulk density, ash concentration, pH, and the total amounts of phosphorus, calcium and iron in the cultivation layer, but it has had only a minor effect on the amounts of potassium, magnesium and boron (Hytönen and Wall 1997). However, nutritional variation between fields, due to factors such as cultivation history, original peatland type and peat depth, can be quite considerable. The use of mineral soil as a soil improvement agent was common practice when these fields were under cultivation. Mineral soil has a long-term positive effect on the thermal conditions and fertility of peat, especially on the potassium status of soils (Wall and Hytönen 1996, Hytönen and Wall 1997).

Deficiencies of potassium and boron, indicated by foliar analyses, are particularly common in trees growing on afforested former agricultural peat soils (Hytönen and Ekola 1993, Hytönen and Wall 1997). Such trees also commonly manifest nutrient-based growth disturbances (Raitio 1979, Veijalainen 1983, Valtanen 1991, Hytönen and Ekola 1993, Hytönen 1999a), which are often connected to high foliar nitrogen and phosphorus concentrations and low boron, copper and zinc concentrations (Reinikainen and Veijalainen 1983). Common symptoms associated with growth disturbances are dense crowns, crowns with multi-leaders and bushy crowns, heavy branching, leader dieback, and possible reduced frost hardiness (Raitio and Rantala 1977, Raitio 1979, Veijalainen et al. 1984). Such disturbances can weaken and injure trees to such an extent that afforestation fails. Liming of fields during cultivation can also contribute to an increased risk of boron deficiency (Kaunisto 1982, 1987, Lehto and Mälkönen 1994). Scots pine, which is particularly adapted to nitrogen-poor sites can incur metabolic problems on nitrogen-rich sites (Kontunen-Soppela et al. 1997). Basic improvement of the nutritional status appears to be essential on some peat-based sites for successful afforestation to take place.

Ash has long been used to improve soil fertility. The total amount of bark and wood ash produced annually in Finland is estimated to amount to 300 000 tonnes (Silfverberg 1996). Peat ash and coal ash are formed in large quantities in power plants. Recycling of the nutrients contained in ash, now mostly disposed of as waste, could be an interesting alternative for improving the nutritional status of former agricultural peat soils. Ash contains plant nutrients in the form of basic compounds. Thus, it acts both as a liming agent, reducing soil acidity, and as a fertilizer, supplying nutrients to plants (Saarela 1991). Nitrogen is normally lost during combustion and so is almost completely absent from well-burned ash. Ash is commonly classified according to its parent material, which also describe the basic differences in nutrient contents. Variation in the nutrient concentrations of ash of different kinds can be quite high. Wood ash is especially rich in phosphorus and potassium (Silfverberg 1996), which are the foremost growth-limiting mineral nutrients in peatland forests. Peat ash generally contains only small amounts of potassium, but it is rich in phosphorus. The nutrient content of coal ash is generally very low (Saarela 1989, 1991, Veijalainen et al. 1993).

Numerous fertilization experiments using wood ash, especially on nitrogen-rich peatlands, have shown that high-quality ash can produce long-term increases in stand growth (Silfverberg 1996). Also, peat ash can serve as a slowly-soluble phosphorus fertilizer in peatland forests (Silfverberg and Issakainen 1987a, Issakainen et al. 1994) and in agriculture (Hartikainen 1984). High applications of peat ash have increased tree growth on peatlands (Silfverbeg and Issakainen 1987a). Research results on the effects of coal ash on peatlands are scarce, being limited to greenhouse studies (Veijalainen et. al. 1993).

The results obtained in peatland forests are not directly applicable to afforested former arable peat soils. These differ considerably from peatland forests in regard to their physical and nutritional properties (Hytönen and Wall 1997), and field-to-field variation in nutrient status can be high. Therefore, the suitability of different kinds of ash and application rates may depend on the nutritional characteristics of the field soils in question.

Recycling of ash is partly hindered by technical problems related to the handling and spreading technology (Hakkila 1986). Pelletizing could significantly reduce these problems; e.g. storage of ash would be easier, dust problems would be reduced, spreading outcome would be more uniform, and there would be fewer problems with clogging up of the spreading machines. Pelletized wood ash has produced promising results in a greenhouse study (Hytönen 1998), but results from field experiments are lacking.

The possibilities of remedying nutritional imbalances of Scots pine (*Pinus sylvestris* L.) stands on afforested peat soil fields by means of ash fertilization was investigated in four field experiments set up in stands suspected of being afflicted by nutritional imbalance. The aims were: 1) to compare different kinds of ash (wood, peat and coal), 2) to study the effects of pre-treatment of ash (pelletization), 3) to compare ash fertilization with commercial fertilizers, and 4) to study the interactions between ash fertilization and weed control. The effect of fertilization on nutritional status was studied by means of foliar and soil analyses and stand measurements.

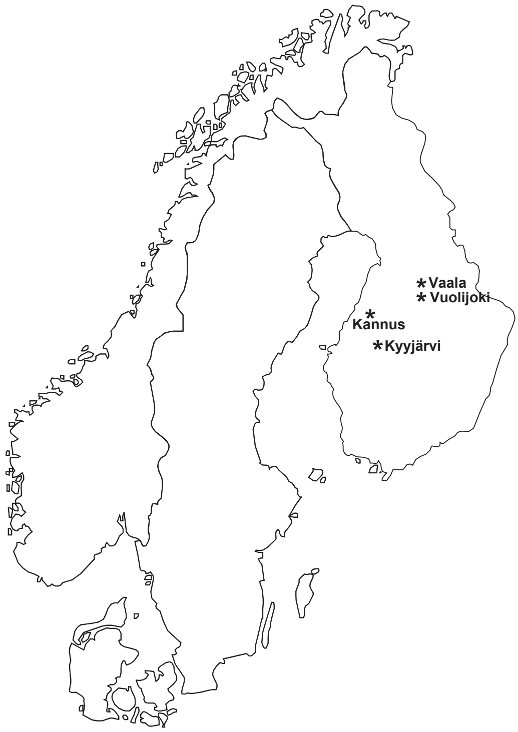

Fig. 1. The location of the experimental fields.

2 Material and Methods

2.1 Experiments

Ash fertilization experiments were established on four former agricultural peat soil fields afforested with Scots pine in Central Finland (Fig. 1). General information on the experiments is provided in Table 1 and information on the treatments and ash used in Tables 2 and 3. The mean depth of the organic layer in the various experimental areas varied from 30 cm to 70 cm. Fertilization of Scots pine plantations was done one, six or twenty-four growing seasons after planting (Table 1). The moisture content of the ash applied was determined prior to application and the amounts applied were calculated on the basis of dry ash. Randomized block design using three or four replicates was applied in all the experiments (Table 1).

Oats and hay had been cultivated on the field in Kannus prior to planting Scots pine in 1974.

Table 1. General information on the experiments.

	Experiment			
	Kannus	Kyyjärvi	Vaala	Vuolijoki
Planting year	1974	1986	1991	1991
Fertilization, month/year	Feb 1998	March–May 91[1)]	Spring 1992	Spring 1992
Height of trees at	fertilization, m	6.9	0.7	0.2 0.2
Foliar samples, growing seasons after fertilization	1 & 2	2 & 8	3 & 7	3 & 7
Soil samples, month/year	Sep 2000	Nov 1994	Oct 1992	Oct 1992
Peat depth, m	0.5	0.5	0.3	0.7
Stand measurements, growing seasons after fertilization	3	5 & 10	9	1 & 2 & 9
Size of sample plots, m^2	1008–1575	900	300	450
Number of replications	3	3	4	4
Number of sample plots	9	24	16	16

[1)] = Wood bark ash applied in March 1992.

Mineral soil had been added to the topsoil as a soil ameliorant during the agricultural use of the field. The fertilization treatments were a) unfertilized control, and application of equal amounts of b) loose wood ash and c) pelletized wood ash (Tables 1–3). The ash pellets (diameter 8 mm, length 5–15 mm) were made using a machine developed at Kannus Research Station (Takalo 1997). Foliar samples (March 1997) were taken prior to the establishment of the experiment. The mean nitrogen, phosphorus and potassium concentrations were 18 mg/g, 1.9 mg/g and 4.8 mg/g, respectively. Even though the nutrient concentrations were satisfactory, visual observation showed signs of growth disturbance in the stand.

Cereals and hay had been cultivated in the field in Kyyjärvi, which had been left uncultivated for some years before planting with Scots pine in 1986. In the fertilization experiment established in 1991, varying doses of wood ash, peat ash and coal ash were compared with each other and one commercial fertilizer (PK with micronutrients) (Tables 1–3). According to the results of analysis of the foliar samples (n = 6) taken prior to the establishment of experiment (March 1991), potassium deficiency or growth disturbances were considered to be likely at some stage of stand development. In particular, the foliar potassium concentrations were low (range 2.9–3.6 mg/g) and in many cases below the deficiency limit. Also, the boron concentrations were in some cases low (range 6.6–13.1 mg/kg). Nitrogen (15 mg/g) and phosphorus (1.7 mg/g) concentrations were quite good.

The Vaala experimental area was set up to compare wood ash with two commercial fertilizers (Tables 1–3). Barley had been cultivated in the field in 1966–1967 and thereafter hay. The field had been limed in 1966 and fertilized annually with NPK fertilizer. The site was mounded in the autumn of 1990 and three-year-old bare-rooted Scots pine seedlings were planted in the spring of 1991. Post-planting weed control was done (mixture of terbuthylzine and glyphosate) in 1991 and 1992, and fertilizers were applied in the spring of 1992.

The Vuolijoki experimental area was set up to study the effect of wood ash, weed control and their interaction. Oats and hay had been cultivated there until 1971. In 1990, the peat field was mounded and planted in spring 1991 with three-year-old bare rooted Scots pine seedlings. According to visual observations and the results of soil analyses, mineral soil had been added to the top peat layer. Before planting, two blocks were treated with glyphosate (Roundup, active ingredient 360 g/l, application rate 6 l/ha) and two were left untreated. After planting, a factorial ash application and weed control trial was set up. Post-planting weed control was done in appropriate plots over the entire plot in July 1991 and repeated in July 1992 (Table 2). Ash was applied in 1992.

Table 2. Fertilization treatments and nutrient amounts applied. All experiments also included an unfertilized control treatment. Fertilizer and ash amounts shown as per dry mass.

Experiment	Ash/fertilizer, kg/ha (abbreviation)	P	K	Ca	Mg	Mn	Fe	Zn	B
					kg/ha				
Kannus	Wood ash, 5000[1)] (WA L)	83	193	980	95	45	20	8.5	1.3
	Wood ash, pelletized (WA P)	83	193	980	95	45	20	8.5	1.3
Kyyjärvi	Wood ash 4300 (WA4)	40	119	602	39	24	75	8.6	0.9
	Wood ash 8600 (WA9)	80	237	1204	78	47	150	17.2	1.7
	Coal ash 400 (CA0.4)	0.5	1.3	6	2	0.1	12	0.1	0.1
	Coal ash 4000 (CA4)	5	13	60	10	1	118	1.2	0.9
	Coal ash 20000 (CA20)	24	64	300	50	6	590	6.0	4.3
	Peat ash 10000 (PA10)	127	37	670	90	13	470	1.0	0.2
	Peat ash 20000 (PA20)	254	74	1340	180	26	940	2.0	0.4
	PKM 1125 [2)]	45	84	146	90	–	–	0.9	2.3
Vaala	Wood ash 5000 (WA5)	48	124	1010	75	0	88	1.2	1.5
	PK 625 [3)]	56	100	138	3.1	–	–	–	1.9
	KM 333 [4)]	0	100	5	23	–	–	1.3	1.3
Vuolijoki	Wood ash 5000 [5)] (WA5)	48	124	1010	75	0	88	1.2	1.5

1) Kannus experiment was given ash both in pelletized (P) and loose (L) form.
2) PKM = PK fertilizer with micronutrients (Kunnostuslannos 2): P 4%, K 7.5%, Mg 8%, Ca 13%, Zn 0.08%, Cu 0.08%, B 0.2%, S 5%.
3) PK = PK-fertilizer (Metsän PK-lannos): P 9%, K 16%, Ca 22%, Mg 0.5%, S 1.5%, B 0.3%, Cu 0.2%.
4) KM = K fertilizer with micronutrients (Metsän kali-hivenlannos): K 30%, Ca 1.5%, Mg 7.0%, S 6.0%, B 0.4%, Zn 0.4%.
5) The treatments were: a) control, b) wood ash (WA5), c) weed control with herbicide (WC) and d) ash+weed control with herbicide (WA5+WC). Weed control was done using glyphosate (Roundup, application rate 7 l/ha) and terbuthylzine (Gardoprim, active ingredient 500 g/l, application rate 3 l/ha) in July 1991 and repeated in July 1992.

Table 3. Nutrient concentrations of the various kinds of ash.

Experiment	Ash	P	K	Ca	Mg	Mn	Fe	Zn	B
					mg/g				
Kannus	Wood	16.6	38.6	196	19	9.1	4.1	1.7	0.2
Kyyjärvi	Wood	9.3	27.6	140	91	5.5	17.4	2.0	0.2
	Peat	12.7	3.7	67	9	1.3	47.0	0.1	0.02
	Coal	1.2	3.2	15	5	0.3	29.5	0.3	0.2
Vaala and Vuolijoki	Wood	9.6	24.7	202	15	0.01	17.5	2.3	0.3

Kannus: Ash from Haapajärvi power plant
Kyyjärvi Vaala and Vuolijoki: Wood bark ash from Wisaforest Oy power plant at Pietarsaari
Kyyjärvi: Peat ash from Saarijärven Kaukolämpö Oy, Saarijärvi, coal ash from Outokumpu Kokkola Zinc Oy, Kokkola

2.2 Foliar and Soil Analyses

To facilitate the study of the initial response to ash fertilization treatments, the first foliar samples were taken one to three growing seasons after fertilization (Table 1). The second sampling was done 7–8 growing seasons after ash application. Each foliar sample was composed of Scots pine needles collected during the dormant season from at least five trees from the south-facing side on the top whorl. The samples were dried to constant weight at 70ºC, ground and then ashed at 550ºC. The total concentrations of N, P, K, Ca, Mg, Fe, Mn, Zn, Cu and B were analyzed using standard methods (Halonen et al. 1983).

Volumetric soil samples composed of three sub samples (0–10 cm and 30–40 cm layers) were taken from unfertilized plots except in Kyyjärvi where samples (0–10 cm layer) were taken from all the sample plots (Table 1). The soil samples were dried at 60ºC and ground to pass through a 2 mm sieve. The ash content was determined as loss on ignition (550ºC, 8 h). The soil samples were analyzed for their total and acid ammonium

Table 4. Soil pH, ash content, bulk density and total and acid ammonium acetate (AAs) extractable nutrient amounts in the unfertilized sample plots (layers 0–10 cm and 30–40 cm).

Experiment	Layer cm	pH water	Ash content %	Density g/dm^3 tot.	Nutrient amounts, kg/ha N tot.	P AAs	P tot.	K AAs	K tot.	Ca AAs	Ca tot.	Mg AAs	Mg tot	B
Kannus	0–10	4.3	52.7	263	3628	370	4.4	310	60	1235	308	566	67	0.9
	30–40	4.4	14.0	226	5464	416	2.3	75	14	860	451	142	49	0.3
Kyyjärvi	0–10	4.4	10.1	130	2391	196	11.6	72	48	2372	599	122	95	0.4
	30–40	4.5	29.3	254	2578	176	9.0	163	3	1466	274	325	36	0.7
Vaala	0–10	4.6	37.9	434	6640	550	14.4	191	119	783	454	174	221	0.6
	30–40	4.8	97.1	1235	741	722	2.3	679	24	762	41	690	8	2.7
Vuolijoki	0–10	4.5	46.5	292	5129	983	5.0	136	35	1032	582	181	113	1.0
	30–40	4.5	46.3	268	3740	241	1.5	185	9	655	345	481	73	0.9

acetate (pH 4.65) extractable (P, K, Ca, Mg, Mn, Fe, Zn) nutrient concentrations. Kjeldahl nitrogen and boron in H_3PO_4–H_2SO_4 were also analyzed (Table 4). Soil acidity was measured from a soil water 1:2.5 (v/v) suspension. The particle size distribution of the mineral soil added in Kannus, Vaala and Vuolijoki was determined using the sedimentation method (Elonen 1971). The mineral soil was classified according to the median particle size.

2.3 Stand Measurements

Seedling measurements were made within two permanent circular (100 m^2) sub-sample plots established within each experimental plot. The seedlings were mapped and their height, annual height growth and diameter were measured. Also, seedling vitality and seedling injuries were estimated (Table 1). The first year's growth after fertilization was not measured in Vaala.

In the case of Vuolijoki also the vegetation cover and mean height of the vegetation were estimated on each plot in early September 1992, late August 1993, and in August–September 1994. The three main weed species from each plot were identified. The most common species were *Deschampsia caespitosa*, *Agrostis* spp., *Epilobium* spp., *Rumex* spp, *Ranunculus* spp., and *Juncus* spp. In 1992 and 1993 observations were also made of the shading caused by weeds on the seedlings (1 = Weeds do not shade seedling, 2 = 1/4 of seedling shaded, 3 = 1/2 of seedling shaded, 4 = 3/4 of seedling shaded, 5 = Entire seedling in shade).

2.4 Statistical Analyses

Analysis of variance (Kannus, Kyyjärvi: ash type, block, Vaala: fertilization, block; Vuolijoki: ash, weed control, ash*weed control interaction, block) was used to test the effects of treatments on the measured variables. Seedling height at the time of fertilization (Kyyjärvi), annual height increment before fertilization (Kannus), and peat depth (Vuolijoki, Kyyjärvi) were used as the covariates. The covariates were used also when testing the effects of fertilization on the number of seedlings exhibiting nutrient deficiency symptoms or other tree damage. In the case of Vuolijoki, the pre-planting weed control made before soil preparation did not significantly affect the foliar nutrient concentrations or any of the other parameters studied, and these results are not shown. Transformations were used when testing the variables expressed as percentages. After analysis of variance, Dunnett's test was used to find the means differing from the unfertilized control treatment.

3 Results

3.1 Soil Nutrient Amounts

The effects of different ash types on soil properties (0–10 cm soil layer) were studied in the Kyyjärvi experiment. All ash fertilizers (except the smallest coal ash application rate) significantly increased soil pH from 4.4 in control to 4.7–5.9 ($F = 11.5$, $p < 0.001$). Wood ash and its highest application amount increased soil pH and nutrient amounts more than did the other ash types. Peat ash, richest in phosphorus (Table 2), and the greatest wood ash application significantly ($F = 3.6$, $p < 0.05$) increased soil total phosphorus amounts (control: 196 kg/ha, peat ash: 363–391 kg/ha, wood ash 9 t/ha: 372 kg/ha). Wood ash also significantly increased both total (control: 72 kg/ha, wood ash 4 t/ha: 145 kg/ha, wood ash 9 t/ha: 490 kg/ha; $F = 8.8$, $p < 0.001$) and acid ammonium acetate extractable (control: 48 kg/ha, wood ash 4 t/ha: 114 kg/ha, wood ash 9 t/ha: 156 kg/ha; $F = 14.7$, $p < 0.001$) potassium amounts and total zinc amounts ($F = 19.4$, $p < 0.001$). Ash also increased the total and extractable calcium and magnesium amounts, but these were statistically significant only for the highest wood ash application amount. The highest application rates of wood and coal ash – containing the most boron – significantly increased boron amounts (control: 0.3 kg/ha, wood ash 9 t/ha: 2.3 kg/ha, coal ash 20 t/ha: 1.6 kg/ha; $F = 19.4$, $p < 0.001$). Also, coal and peat ash, as well as PK fertilizer, more than doubled the boron amounts in the soil, but not significantly.

3.2 Foliar Nutrient Concentrations

The fertilization treatments did not include nitrogen, but all treatments (except potassium and micronutrients fertilizer applied in Vaala) contained variable amounts of phosphorus. The maximum amount of phosphorus applied in Kyyjärvi was 254 kg/ha (peat ash 20 t/ha). Neither ash nor commercial fertilizers affected the foliar nitrogen, phosphorus or calcium concentrations in any of the experiments.

Of the ash types studied in the Kyyjärvi experiment, only wood ash at its greatest application rate, containing the most potassium, significantly increased foliar potassium concentrations seven years after application (App. 1). Wood ash (9 t/ha) increased foliar potassium concentration by 1.3 mg/kg already one growing season from application, but not significantly. All ash types increased foliar boron concentrations seven (wood ash) or eight years after application. The greatest application rate of wood ash (Kyyjärvi) increased foliar boron concentrations during the year of application. Coal ash, even when applied in small amounts (0.4 t/ha), significantly increased foliar boron concentrations of Scots pine two and eight growing seasons after application. Peat ash resulted in the slowest initial response to boron concentrations and did not significantly increase foliar boron concentration after two growing seasons.

Pelletized wood ash gave responses similar to those produced by loose wood ash. Pelletized ash had an even slightly better initial response than loose ash in that it significantly increased foliar potassium concentrations one and two growing season after the application (App. 1, Kannus). Although both loose and pelletized ash considerably increased foliar boron concentrations during the application year this was not significant until the second year. Then both ash treatments more than doubled foliar boron concentrations (App. 1).

Commercial fertilizers as well as wood ash significantly increased foliar potassium concentrations three and seven years from fertilization in Vaala (App. 1). Commercial fertilizers had a faster initial effect on foliar boron concentrations, but seven years from application foliar boron concentrations in the ash treatment were also significantly greater than in the control treatment.

Weed control (Vuolijoki experiment) did not significantly affect foliar nutrient concentrations nor were there statistically significant interactions between ash application and weed control, except for zinc in the third year and phosphorus in the seventh year (App. 1). However, ash did increase foliar potassium and boron concentrations three and seven years from application.

The effect of fertilization on other nutrient concentrations was minor. Foliar zinc concentrations were low in all the experiments compared to the deficiency limit of 40 mg/kg for Scots pine growing on peatlands (Reinikainen et al. 1998). However, fertilization significantly increased foliar Zn concentrations only in the Vaala (potassium micronutrient fertilizer) and Vuolijoki (wood ash) experiments.

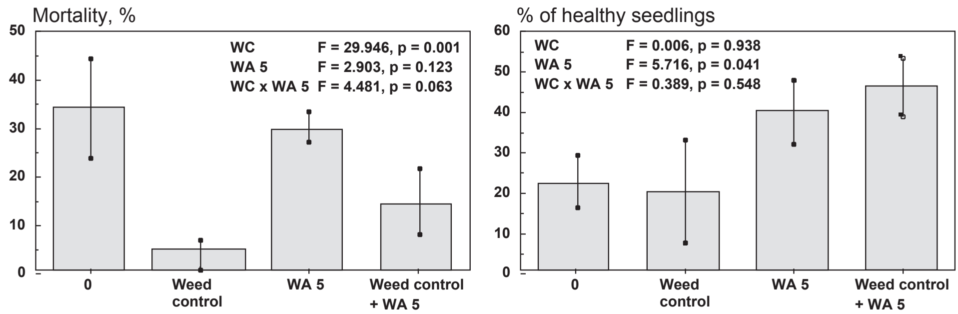

Fig. 2. Effect of ash fertilization and weed control on seedling mortality and share of healthy seedlings in the Vuolijoki experiment nine years after fertilization. Post-planting weed control was made for the first time in the summer of 1991 and then repeated the following summer. Ash was applied in the spring of 1992. Standar errord of the mean is indicated inside the bars.

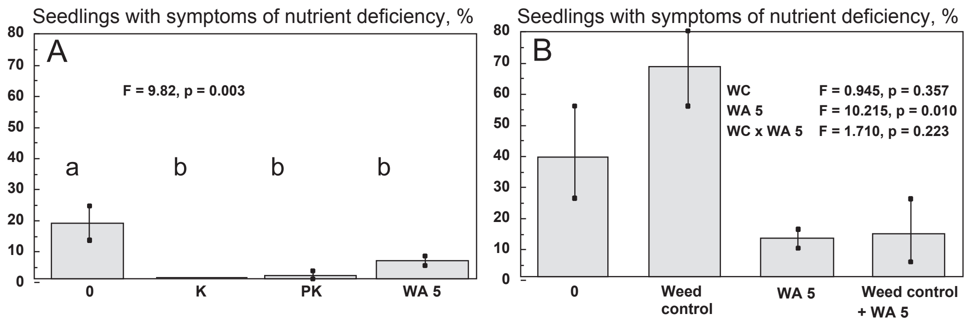

Fig. 3. Effect of fertilization on the percentage of seedlings showing nutrient deficiency symptoms in the Vaala (A) and Vuolijoki (B) experiments nine years after fertilization. Standard error of the mean is indicated inside the bars.

3.3 Condition of Seedlings

Seedlings in the Kyyjärvi experiment, where different kinds of ash were compared, were damaged by a fungal disease (*Melampsora pinitorqua*), making it difficult to assess with certainty whether their leader damage was due to the disease or to nutrient deficiency. Neither loose wood ash nor pelletized wood ash significantly affected the vitality or condition of the seedlings after three years (Kannus experiment). In the Vaala experiment, both commercial fertilizers and wood ash significantly reduced the percentage of seedlings with symptoms of nutrient deficiency (Fig 3A), but they did not affect the percentage of dead or healthy seedlings.

In Vuolijoki, the total vegetation cover percentage was 47%, 56% and 36% points lower in the weed-control plots than in the control plots one ($F = 4.36$, $p = 0.067$), two ($F = 12.10$, $p = 0.007$) and three ($F = 2.36$, $p = 0.159$) growing seasons from the reapplication of herbicide (Fig. 4). Ash application did not significantly affect vegetation cover, nor was there any significant interaction between weed control and ash treatment. Moreover, weed control significantly reduced the mean height of the vegetation one growing season after herbicide application by 26 cm ($F = 9.00$, $p = 0.015$). Two and three growing seasons after application, the mean length of the vegetation was 24 cm and 4 cm lower in the weed-control plots, but not significantly so. Weed control significantly ($\chi^2_{92} = 216.1$, $p = 0.000$, $\chi^2_{93} = 178.3$, $p = 0.000$) affected the proportion of seedlings (1992, n = 458, 1993, n = 441) classified as being shaded by 0%, 25%, 50%, 75% or 100% by the ground vegetation (Fig. 4).

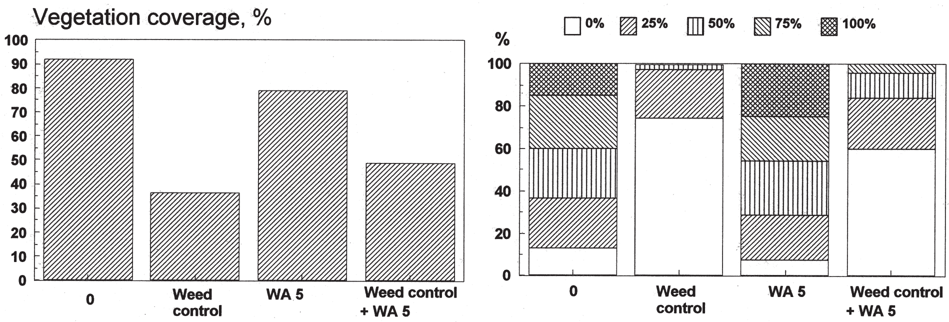

Fig 4. Effect of ash fertilization and weed control on the vegetation cover (1993) and shading (1992) caused by vegetation in the Vuolijoki experiment. Seedlings (1992, n = 458) classified as shaded by 0%, 25%, 50%, 75% or 100% by ground vegetation.

During the first couple of years, seedling mortality was very low in the Vuolijoki experiment (average in 1991: 0.2%, 1992: 1.4%, 1993: 5.0%). After nine years, post-planting weed control had significantly decreased seedling mortality (by 23.5%), but ash had no effect (Fig 2). However, ash fertilization did significantly increase the share of seedlings estimated to be healthy (by 21.7%) whereas weed control had no effect (Fig 2). Ash fertilization also significantly decreased the share of seedlings with visible nutrient deficiency symptoms (by 39.5%, Fig 3B.). Weed control significantly (F_{WC} = 9.01, p = 0.015) reduced the share of Scots pine seedlings damaged by deciduous trees; the reduction was 26% (from 32% to 6%). Weed control with herbicides reduced the share of trees damaged by elk by 14% down to 5% (F_{WC} = 5.54, p = 0.046), but ash fertilization had no effect on elk damage. Elk damage was closely linked to the number of decidious seedlings on the sample plots such that the positive correlation between elk damage and number of decidious seedlings was highly significant (r = 0.820, p = 0.000).

3.4 Height Growth

Both wood and peat ash application and fertilization with PK fertilizer increased the 10-year height increment of the seedlings (Fig. 5, Kyyjärvi). Coal ash did not significantly affect the growth of the seedlings. The 10-year height increment (68 cm) produced by the greatest wood ash application amount corresponded to two years' average increment of the Scots pine seedlings in the control treatment. The height growth achieved by seedlings fertilized with peat ash (10 and 20 t/ha) was 41 cm and 49 cm greater than that of the control seedlings. PK fertilizer increased the height growth of seedlings during the 10-year period by 55 cm. Increase in ash application amount did not result in a significant increase in seedling height growth.

The effects of pelletized and loose ash on the height growth of seedlings was monitored in Kannus for three years. Neither loose nor pelletized wood ash significantly increased the three-year height growth (average 1.4 m) of Scots pine following application (Fig. 5, Kannus).

In the Vaala experiment fertilization, neither with ash nor commercial fertilizers significantly (Fig. 5, Vaala) increased annual height increment over the period as a whole.

In Vuolijoki, both ash fertilization and post-planting weed control significantly increased 9-year height growth by 40 cm and 50 cm respectively (Fig. 5, Vuolijoki). The effect of ash fertilization increased up to the ninth growing season. The effect of post-planting weed control reached its maximum during the fourth growing season and then its effect started to decline. Ash fertilization and weed control did not have a significant interaction. Thus, ash and weed control, when combined, increased Scots pine growth by 90 cm in nine years. Since the average annual height increment of the control seedlings was 16.6 cm, the increment gained through ash application and

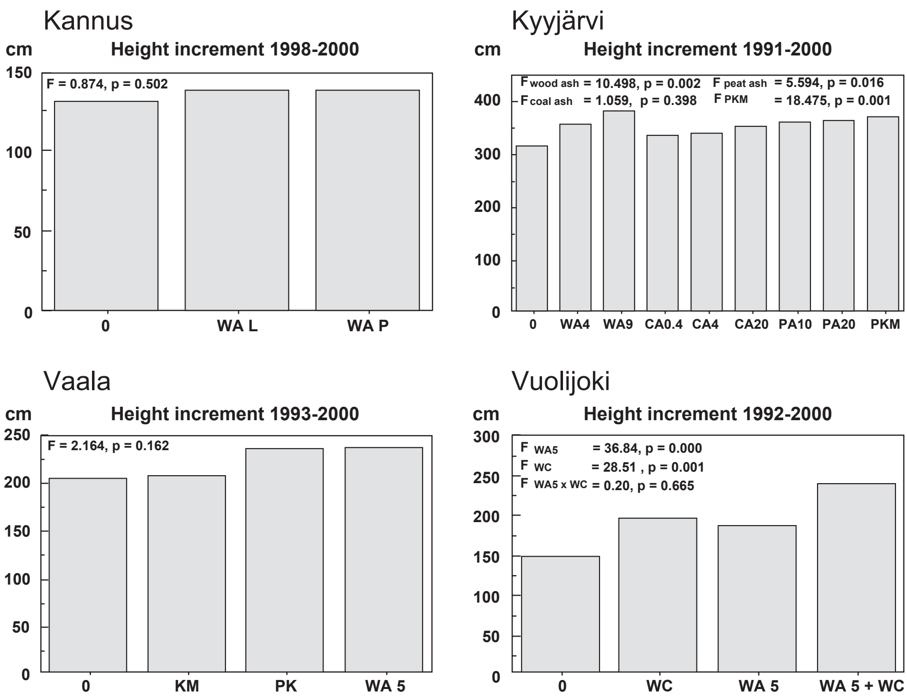

Fig. 5. Height increment after fertilization. For legend to the treatments, see Table 2.

weed control corresponded to five years' average growth as shown by the control seedlings. Ash fertilization (F_{ASH} = 37.03***) and weed control (F_{WC} = 26.58**) also increased the mean diameter ($d_{1.3}$) of Scots pine.

4 Discussion

Agricultural cultivation of the studied former peat fields had increased their soil pH, ash content, bulk density and the amounts of most nutrients to above-average levels for peatlands drained for forestry (Kaunisto and Paavilainen 1988, Laiho and Laine 1994). Especially mineral soil application, which was clearly to be seen by observing the tilled layer (0–20 cm) and in soil analysis (high bulk density and ash content), had changed the soil properties on two fields (Kannus and Vuolijoki; silt). Also, the mineral soil under the thin peat layer in one of the fields (Vaala; fine sand) was mixed with the peat during cultivation. Mineral soil addition has been shown to increase the topsoil bulk density, ash content and the amounts of several nutrients, but not of nitrogen, calcium or boron (Wall and Hytönen 1996, Hytönen and Wall 1997). In the Kannus experimental area, there was a sharp decrease both in the potassium amounts and ash content of the soil when going deeper down (to 30–40 cm), which indicated that the mineral soil was mainly mixed in with the cultivated layer. The potassium amounts were lowest in the Kyyjärvi experimental area where mineral soil had not been added. Boron amounts in the unfertilized plots were small (less than 1 kg/ha in the 10 cm layer) and similar to those reported in other studies (Kaunisto 1991, Hytönen and Ekola 1993, Wall and Hytönen 1996, Hytönen and Wall 1997, Hynönen and Makkonen 1999). Field-to-field variation in the nutrient amounts was high, especially in the case of potassium.

Ash application was shown to increase soil nutrient amounts, the increase depending of application rate and ash type. In Kyyjärvi, wood ash application was found to increase the topsoil potassium amounts, but coal or peat ash, containing smaller amounts of potassium, had no effect. Wood ash has been shown to have long-term impacts on the soil potassium amounts (Silfverberg and Hotanen 1989).

In all the unfertilized plots, the foliar nitrogen and phosphorus concentrations of the pine seedlings were above deficiency limits, and in most cases within the optimum range (N 15–16 mg/g, P 1.6–2.0 mg/g) as proposed by Kaunisto (1982) and Paarlahti et al. (1971) for Scots pine stands growing on peatlands. The high foliar nitrogen concentrations found in the present study could contribute to the occurrence of nutritional imbalances, increased risk of nutritional growth disorders, and growth damage (Aronsson 1980, Reinikainen and Veijalainen 1983, Veijalainen et al. 1984, Pietilä et al. 1991, Hytönen and Ekola 1993, Kontunen-Soppela et al. 1997)).

In all the study sites, the fertilizers applied (wood ash, peat ash, coal ash, commercial fertilizers) failed to increase foliar phosphorus concentrations. This was probably due to foliar phosphorus concentrations having been within the optimum range even without fertilization. Phosphorus deficiencies have not been reported on afforested peat fields (Ferm et al. 1992, Hytönen and Ekola 1993), probably due to the applications of phosphorus fertilizers during the agricultural use. Thus, it would appear that on afforested former fields neither nitrogen nor phosphorus – contrary to peatland forests – limit tree growth. The use of only phosphorus fertilizers or peat ash (rich in phosphorus but poor in other elements) is not a good choice in soil amelioration on afforested fields.

Potassium deficiencies are quite common on afforested peat fields (Hytönen and Ekola 1993). In the present study, foliar potassium concentrations on unfertilized plots were also found to be below or only slightly above the deficiency limit (4.0 mg/g, Paarlahti et al. 1971). In the present study, and in an earlier study by Ferm et al. (1992), wood ash consistently increased the foliar potassium concentrations of Scots pine. Pelletized ash gave good initial responses one and two growing seasons from application, thereby confirming earlier results obtained in a greenhouse study (Hytönen 1998) and agreeing with the results of a study showing that potassium could be easily leached from pellets (Hytönen 1999b). Besides wood ash, commercial fertilizers were also found to be good sources of potassium for Scots pine. However, coal and peat ash proved to be fairly poor sources of potassium and did not significantly increase foliar potassium concentrations two or eight years from application. In agreement with the results of the present study, wood ash has also been shown to be a good source and peat ash a poor source of potassium for pine on mires (Silfverberg and Issakainen 1987a, b, Silfverberg and Hotanen 1989, Issakainen et al. 1994).

Even though mineral soil had been used for soil amelioration (Kannus and Vuolijoki), there were visible potassium-deficiency symptoms in the seedlings on unfertilized plots and these were verified by foliar analysis. In Vuolijoki, the foliar potassium concentrations remained below the deficiency limit (Paarlahti et al. 1971) even after wood ash application. Thus, the addition of mineral soil in peat fields is not always enough to ensure good potassium nutrition for Scots pine. Thus, earlier recommendations on potassium fertilization needs based on the results of studies looking into the use of mineral soil in the cultivated layer are not always valid (Hytönen and Wall 1997, Wall and Hytönen 1996). In Vuolijoki, mounding may have reduced the amount of mineral soil in the mounds. As tree roots develop, the mineral soil could subsequently affect potassium nutrition.

Trees growing on afforested fields have been shown to be susceptible to nutritional growth disturbances and boron deficiencies (Veijalainen 1983, Ferm et al. 1992, Hytönen and Ekola 1993, Hytönen 1999b). Boron deficiencies were common in Finnish agriculture until boron was added into all combination fertilizers in 1972 (Simojoki 1972, 1991, Saarela 1985). The boron uptake of plants is affected by parameters such as soil pH, and the amounts of calcium and magnesium. Elevation in pH caused by liming can negatively affect the boron uptake of trees (Lehto and Mälkönen 1994) and increase boron fixation in soils (Saarela 1985) and absorption to the forest mor layer (Lehto 1995). Liming has been found to aggravate boron deficiencies in agriculture (Simojoki 1972) and to decrease foliar boron concentrations of Scots pine both on peat and mineral soils forests (Kaunisto 1982, 1987, Lehto and Mälkönen 1994). It is probable that liming of the agricultural soils examined in this study has also increased the risk of nutritional growth disturbances in trees.

When Scots pine foliar boron concentrations are lower than 6–7 mg/kg, the proportion of trees with visible growth disturbance symptoms, often occurring in patches, sharply increases (Reinikainen and Veijalainen 1983, Hytönen and Ekola 1993). In all of the present experiments, the application of wood (both pelletized and loose), coal ash, peat ash and commercial fertilizers containing boron considerably increased foliar boron concentrations. Wood ash has also been shown to be a good source of boron for Scots pine in peatland forests (Silfverberg and Issakainen 1987b, 2001) and on afforested former peat fields (Ferm et al. 1992). The impact of wood ash fertilization on foliar boron concentration was quite rapid. Peat ash, even when applied in high doses (10 and 20 t/ha), produced the slowest initial response. In stands growing in pine mires, peat ash has failed to increase foliar boron concentrations (Silfverberg and Issakainen 1987a,b, Issakainen et al. 1994). Coal ash applied in small amounts (400 kg/ha) proved to be a good source of boron for Scots pine seedlings; this has been demonstrated earlier in a greenhouse experiment (Veijalainen et al. 1993). High amounts of coal ash can even increase the risk of boron toxicity (Saarela 1989). Remedying boron deficiency by means of coal ash fertilization could be a feasible option as in many cases the growth of boron-deficient trees has increased after the application of boron fertilizers or wood ash (e.g. Brakke 1979, Ferm et al. 1992).

Ash fertilization affected the vitality of the tree seedlings and thereby increased the proportion of healthy seedlings (Vuolijoki) and decreased the proportion of seedlings having visible nutrient deficiency symptoms (Vuolijoki and Vaala). Ash has earlier been demonstrated to decrease the share of trees exhibiting growth disturbances (Ferm et al. 1992).

Wood ash or PK fertilization significantly increased the growth of seedlings in Kyyjärvi and Vuolijoki. In Kannus, a period longer than the three-year observation period would have been needed to detect growth responses. In greenhouse experiments, both tree seedlings (Hytönen 1998) and agricultural crops (Saarela 1989) fertilized with pelletized ash have initially grown less compared with crops fertilized with the same amount of loose ash. The Vuolijoki experiment showed that combining fertilization and weed control could be an interesting treatment since it produced a growth advantage of five years over the control seedlings. The experiment conducted by the Paavilainen (1970, 1977) using commercial fertilizers on Scots pine failed to show any growth response. Fertilizers used at that time did not contain any micronutrients. Consequently the seedlings in his study showed clear growth disturbance symptoms at the age of 10 years.

One of the major problems in the afforestation of fields is the heavy competition from weeds (Leikola 1976, Ferm et al. 1994). The pre-planting weed control treatment did not have any effect on the vegetation cover in the vicinity of seedlings in Vuolijoki; this was probably due to wrong timing of the application (herbicide application before soil treatment). Due to the high organic matter content, soil-active herbicides can become bound into the soil and thereby loose their effectiveness.

Successful post-planting weed control significantly affected the early development of seedlings. This was linked to considerable reduction of the weed cover and the mean height of the vegetation around the seedlings, and the reduction of the shading of seedlings by vegetation. Weed control significantly increased the height growth of seedlings, reduced the number of dead seedlings (by almost 24%), and decreased the proportion of seedlings suffering damage caused by elk and competition from the ground vegetation and deciduous trees. The effect of herbicide on elk damage was most probably linked to the outcome that weed control reduced the number of decidious seedlings and perhaps also affected the vegetation cover in such a way that elk preferred the control and ash-fertilized plots. These results emphasize the importance of vegetation control in the afforestation of abandoned fields. Even though this experiment did not show wood ash as having significantly increased the vegetation cover, ash application has been found to increase the frequency of herbs and grasses on nitrogen rich peatlands (Silfverberg and Huikari 1985, Silfveberg and Hotanen 1989) emphasizing the need for proper vegetation control.

5 Conclusions

According to the results of the present study and other investigations, Scots pine growing on former peat fields often faces problems regarding potassium, boron and possibly also other micronutrient nutrition. The need for phosphorus fertilization on afforested fields is probably quite rare and nitrogen is not needed.

Good potassium and boron nutrition of trees can be ensured at least for the first 8–9 years either by applying wood ash or commercial fertilizers containing potassium and boron. If the wood ash has as lasting an effect as it does on peatland forests, wood ash application even at the phase of establishing stands could be feasible. Spreading of dusty loose ash is technically possible before afforestation, but granulation or pellitizing of the ash would enhance its spreadability. Since pelletized and loose wood ash produced similar nutritional responses, it seems that the use of either one is biologically viable. The amounts of wood ash applied in forested peatlands should be based on the phosphorus concentration of the ash to ensure adequate phosphorus supply. Since phosphorus is not limiting factor on afforested former agricultural sites with peat soils, one could use fairly poor-quality wood or bark ash with low phosphorus concentrations and place more emphasis on its potassium content.

High amounts of peat ash (10 t/ha) increased foliar boron concentrations, but the low potassium concentrations of peat ash restrict its usability on afforested peat fields. Peat ash also contains considerable amounts of phosphorus, which is usually not needed in the fertilization of afforested peat fields. Coal ash, even when used in small amounts, proved to be a good source of boron for pine seedlings, and thus it could be used to alleviate boron deficiencies. However, since both coal ash and peat ash contain only minor amounts of potassium, addition of potassium may be required. Prior to ash application, the nutrient contents of the ash, as well as the nutritional status of the stand should be determined, either through foliar analyses (if the trees have already been planted), or through soil analyses (if afforestation is still at the planning stage). The results of the present study also emphasize the importance of proper weed control in the afforestation of peat fields.

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Appendix 1. Effect of fertilization on foliar nutrient concentrations. F-values and significance (*=p<0.05, **=p<0.01, ***=p<0.001). Treatments differing significantly (p < 0.05, Dunnett's test) from unfertilized control treatments are underlined. For legend to treatments, see Table 2

Treatment	Years from fertilisation	Nutrient N mg/g	P mg/kg	K	Ca	Mg	B	Fe	Mn	Zn	Cu
KANNUS											
Control	1	17.5	1.70	3.41	1.72	1.20	4.89	31	306	30.0	2.0
Ash, loose	1	15.0	1.64	3.74	1.99	1.19	8.21	28	368	39.3	2.1
Ash pelletized	1	16.3	1.65	4.18	2.03	1.24	7.37	29	298	37.9	2.2
F-value		1.61	0.49	**13.74***	2.99	0.56	2.62	0.85	0.42	3.78	0.02
Control	2	17.7	1.66	4.22	1.80	1.26	5.06	31	na	34..7	2.8
Ash, loose	2	16.0	1.55	5.02	1.97	1.18	13.11	31	na	40.5	2.6
Ash pelletized	2	16.3	1.49	5.28	1.80	1.24	13.72	31	na	38.2	2.6
F-value		6.07	1.27	**13.95***	4.32	0.61	**14.68***	0.00	0.71	0.45	
KYYJÄRVI											
Control	2	13.3	1.79	4.35	1.90	1.07	6.6	32	218	43	3.6
WA4	1	13.6	1.76	4.68	1.68	0.87	11.6	30	204	35	3.5
WA9	1	12.6	1.70	5.58	1.79	0.81	14.0	32	167	32	3.5
CA0.4	2	13.3	1.80	4.53	1.82	1.01	19.4	30	236	42	3.3
CA4	2	13.2	1.70	4.81	1.86	1.03	16.9	29	245	43	3.3
CA20	2	13.3	1.80	4.74	1.83	1.01	24.2	30	199	32	3.5
PA10	2	13.8	1.88	4.91	1.71	0.96	10.6	31	251	37	3.7
PA20	2	12.8	1.83	4.75	1.73	0.94	5.9	36	240	41	4.1
PKM	2	13.7	1.79	5.38	1.62	0.92	15.7	34	266	42	3.4
F-value		1.01	1.64	0.92	0.82	**3.56***	**6.73****	2.11	0.92	1.30	1.34
Control	8	15.7	2.00	4.01	1.61	1.00	5.24	29.73	179	32	2.6
WA4	7	15.6	1.88	4.97	1.68	0.88	16.42	33.20	131	41	2.4
WA9	7	15.1	1.86	5.04	1.92	0.88	16.18	34.09	90	37	2.1
CA0.4	8	16.2	2.02	4.12	1.66	1.02	10.19	30.01	220	37	2.5
CA4	8	16.3	2.04	4.32	1.57	1.03	17.33	32.07	218	39	3.0
CA20	8	15.3	1.81	4.10	1.39	0.90	20.53	28.71	112	35	2.2
PA10	8	16.0	2.03	4.43	1.55	0.96	8.89	31.05	139	37	2.7
PA20	8	16.4	2.09	4.64	1.98	0.92	10.84	33.22	121	36	2.9
PKM	8	15.3	2.03	4.72	1.59	0.79	10.58	31.07	159	37	2.3
F-value		1.01	1.32	**2.75***	253	1.68	**82.58*****	0.86	**7.08***	0.91	1.26
VAALA											
Control	3	14.6	1.64	3.72	1.40	1.06	8.90	26.1	217	26	na
WA5	3	14.6	1.55	4.62	1.67	1.14	12.01	26.3	158	27	na
PK	3	14.2	1.57	6.06	1.73	0.98	22.78	29.9	215	29	na
KM	3	13.6	1.49	5.94	1.55	0.99	21.36	31.7	222	35	na
F-value		1.88	1.65	**25.00*****	0.95	1.61	**7.42****	**3.85***	1.45	1.92	
Control	7	17.2	1.95	3.49	1.44	1.07	7.97	25.4	205	27	1.8
WA5	7	1.53	1.81	4.47	1.63	1.04	14.63	27.9	151	32	2.0
PK	7	15.3	1.85	5.15	1.71	0.94	15.45	29.2	211	30	2.1
KM	7	1.60	1.89	5.05	1.72	0.94	12.40	31.3	199	35	2.4
F-value		**6.27***	1.71	**37.15*****	3.77	2.62	**8.60****	**5.61***	**4.14***	**3.86***	1.83
VUOLIJOKI											
Control	3	15.6	1.62	3.19	1.74	0.91	13.28	15.23	324	26.9	4.2
WA5	3	15.7	1.52	3.83	1.88	0.88	19.58	16.00	418	35.3	5.2
Weed c. (WC)	3	15.2	1.62	3.14	1.66	0.83	11.88	16.75	419	33.4	4.1
WA+WC	3	15.7	1.67	3.93	1.89	0.98	18.43	17.03	384	30.2	3.6
F_{WA5}		0.21	0.38	**5.59***	1.75	1.78	**59.64*****	0.47	0.51	1.50	0.14
F_{WC}		0.06	3.38	0.01	0.07	0.09	2.35	2.76	0.56	0.12	1.13
$F_{WA5 \times WC}$		0.10	2.95	0.06	0.09	3.94	0.02	0.11	2.48	**7.53***	0.91
Control	7	16.1	1.99	3.28	1.49	0.96	11.42	23.41	372	32.8	2.8
WA5	7	16.9	1.93	3.74	1.50	0.94	15.22	23.84	410	43.5	2.9
Weed c. (WC)	7	15.7	1.78	2.77	1.52	0.99	13.68	23.84	467	32.2	3.0
WA+WC	7	16.1	1.98	3.45	1.52	0.93	15.48	24.42	317	37.0	2.7
F_{WA5}		2.26	2.23	**6.25***	0.20	0.81	**9.14***	0.30	1.67	**10.34***	0.37
F_{WC}		1.96	1.68	3.02	0.00	0.16	1.85	0.31	0.00	2.14	0.02
$F_{WA5 \times WC}$		0.19	**5.55***	0.23	0.01	0.30	1.16	0.01	4.67	1.43	0.86

na = not analyzed