Effect of wood ash fertilisation on stand growth, soil, water and needle chemistry, and berry yields of lingonberry (*Vaccinium vitis-idaea* L.) in a Scots pine stand in Finland

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Abstract. Soil chemical properties, needle nutrient concentrations and tree growth were investigated 12 years after the application of 1.0, 2.5 and 5.0 t ha^{-1} of loose wood ash in a 100-year-old Scots pine (*Pinus sylvestris* L.) stand. In addition, the effects of wood ash on acidity and element mobility in the soil solution were studied during the 2- to 10-year period, and the yields of *Vaccinium vitis-idaea* L. (lingonberry) berries were studied during the 11- to 14-year period after wood ash application. In the humus layer, wood ash decreased soil acidity by 1.3 to 2.5 pH units, and significantly increased the concentrations of extractable Ca and Mg with the two highest doses of ash. Compared to the controls, the increase in both the total and extractable Ca concentrations was 4-fold and 9-fold after the treatments with 2.5 and 5.0 t ha^{-1} of wood ash, respectively. The neutralisation effects of wood ash were seen also in the uppermost mineral soil layer, but only with the highest dose of ash. Wood ash had an increasing effect on Ca, K and Mg concentrations in the soil solution at 20 cm depth, but had no appreciable effect either on the NO_3 concentration or pH in the soil solution. The concentrations of Cd, Cr, Cu and Pb in the soil solution were not increased by the application of wood ash. Wood ash with the dose of 5.0 t ha^{-1} had a decreasing effect on the yields of *V. vitis-idaea* berries. Wood ash had no significant effect on volume growth. The two highest doses of wood ash had an increasing effect on B concentrations in the needles.

Key words: acidity, effective cation exchange capacity, base saturation, *Pinus sylvestris*.

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Introduction

Due to the increased use of energy wood fuels the amounts of wood ash originating from the forest are continuously increasing. At the present time much of this ash is considered to be a waste and is primarily dumped at landfills. An increase in the use of wood, and especially the harvesting of felling residues, will result in an increase in the export of nutrients from the forest, with resulting soil acidification, compared with traditional stem-wood harvesting (Nykvist and Rosén, 1985; Olsson *et al*., 1996). Wood ash recycling has been suggested as one means of counteracting the depletion of base cations from forest soils.

The neutralisation capacity of the oxides, hydroxides and carbonates of Ca, Mg and of K in wood ash is probably its most important characteristic as far as soil amendment is concerned (Vance, 1996). In fact, a decrease in soil acidity and an increase in base saturation following the application of loose wood ash to forested mineral soils have been widely reported (Khanna *et al*., 1994; Bramryd and Fransman, 1995; Kahl *et al*., 1996; Eriksson, H.M., 1998; Saarsalmi *et al*., 2001, 2004; Ludwig *et al*., 2002).

Since nitrification is, to some degree at least, controlled by soil pH, the application of wood ash may accelerate the formation and leaching of NO_3^- in the soil as detected by Kahl *et al*. (1996) and Högbom *et al*. (2001). However, this has not always been found to be the case (Ring *et al*., 1999; Lundell *et al*., 2001; Arvidsson and Lundkvist, 2003). In some cases the application of wood ash has been reported to cause a slight decrease in the coverage of dwarf shrubs (Levula *et al*., 2000; Jacobson and Gustafsson, 2001). Hence it has been suspected that wood ash application may be harmful for berry yields.

Scots pine growing on relatively infertile sites (C/N ratio > 30) in Fennoscandinavia usually shows either no response or a slight growth decrease following wood ash application (Sikström, 1992; Jacobson, 2003; Saarsalmi *et al*., 2004). The slightly negative response may be caused by a decrease in N mineralisation or an increase in N immobilisation by microorganisms due to the high C/N ratio of the soil (e.g. Bramryd and Fransman, 1995). So far, however, the effects of wood ash on forest growth on mineral soil sites have not been well documented.

The effects of different doses of loose wood ash on soil chemical properties, needle nutrient concentrations, tree growth and element leaching from the soil in a Scots pine (*Pinus sylvestris* L.) stand were investigated in this study. The effects of wood ash application on the yields of *Vaccinium vitis-idaea* L. (lingonberry) berries were also determined.

Material and methods

Establishment of the experiments

A wood ash field experiment was established in a 100-year-old Scots pine (*Pinus sylvestris* L.) stand at Kuorevesi (62°2′ N, 24°50′ E, 130 m a.s.l.), central Finland, in spring 1990. At the time of the establishment the stem number of the stand was 300 stems ha^{-1}, mean height 21 m, and the volume including bark 180 m^3 ha^{-1}. The stand was growing on a relatively infertile site of the *Calluna vulgaris* forest site type (Cajander, 1949). The 2.5 cm thick humus layer was mor, the soil texture sorted sand, and the soil type haplic podzol (FAO-UNESCO, 1988). The organic matter content of the humus layer was 74%.

The experiment was laid out in a random block design, with four treatments in four blocks. The treatments within each block were a control and three levels of ash fertilisation (1.0, 2.5 and 5.0 t ha^{-1}) on 30 × 30 m plots. The ash was derived from bark, mechanically stripped from the stems of Scots pine and Norway spruce (*Picea abies* (L.) Karsten) during processing for saw timber that was burnt at a temperature of 850–1000 °C for about 30 minutes. The composition of the bark ash was: Al 9.4, Fe 4.3, Ca 280, K 36, Mg 21, Mn 16, P 13, Zn 0.63 g kg^{-1} dry weight, and Cd 1.4, Cu 90, Pb 19 mg kg^{-1} dry weight. The ash was spread on the plots on 21–22.05.1990.

Soil and needle sampling

Soil samples were taken from the humus layer and the mineral soil at a depth of 0–10 cm in May 1990. Sampling was repeated in September 2001, i.e. 12 growing seasons after the treatments. Soil samples were taken systematically at 15 sampling points from each plot, and the samples from the same plot were bulked by layer. The humus samples were taken using a cylinder (d = 58 mm) and the mineral soil samples using an auger (d = 21 mm). The thickness of the humus layer was measured in conjunction with sampling. The humus samples did not include visible plant material.

Needle samples were collected during the winter before fertilisation. The needle samples were taken from 5 sample trees, randomly selected from the dominant crown layer. The needles were collected from the current needles (C) growing on the third to fifth branch whorl, counting from the top, on the southern side of the crown. Needle sampling was repeated in March 1992 and in December 2001, i.e. after 2 and 12 years, in the same way as before fertilisation.

Percolation water sampling

Percolation water was collected at 2-week intervals during the snowfree period in the years 1990–1999 using zero-tension lysimeters installed at a depth of 20 cm below the ground surface. The construction and installation of the lysimeters are described in detail in Derome *et al*. (1991). There were three replicate lysimeters on each plot, and two replicate plots for each of the treatments (control, 1.0, 2.5 and 5.0 t ash ha^{-1}). The samples from the individual lysimeters were analysed separately. The collection bottles in the lysimeters installed in 1990 were made of glass and they broke at the end of 1991 during a period of severe ground frost prior to the formation of the permanent snow cover. New lysimeters, with plastic collection bottles, were installed at points close to the original lysimeters in spring 1992. As there is very high spatial variation in percolation water collected from lysimeters located even very close to each other, it was decided to exclude the results for 1990–1991. The results presented in this paper therefore cover the period 1992–1999.

Tree stand measurements

The tree stand was measured at the time the experiment was established, and 7 and 12 growing seasons after the treatments. The breast height diameter of all the trees was measured with an accuracy of 1 mm from two directions. Tree height was measured on all the trees using a hypsometer with an accuracy of 1 dm. Increment cores were taken with a borer at breast height from every second tree 12 growing seasons after the treatments. The annual growth ring widths were measured under a microscope with an accuracy of 0.01 mm.

Lingonberry sampling

Lingonberries were collected from five 2 m^2 subplots on each plot in autumns 2000–2003, i.e. between 11 to 14 years following wood ash application. The same subplots were used in all sampling years. The berries were collected when ripe and weighed as fresh.

Soil, needle and percolation water analyses

The soil samples were dried in a ventilated chamber at a temperature of 30–40 °C. The humus samples were ground in a mill with a 2 mm bottom sieve, and the mineral soil samples were passed through a 2 mm sieve to remove stones and larger roots. Total element concentrations (P, K, Ca, Mg, B, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn) were determined on the humus samples by dry ashing (550 °C for 2 h), extraction of the ash with HCl, and analysis by inductively coupled plasma-atomic emission spectrometry (ICP-AES) (TJA, Iris Advantage, Franklin, Mass.). Total N and C were determined on the humus samples on a CHN analyser (Leco) and on the mineral soil samples by the Kjeldahl method. Extractable nutrients (P, K, Ca, Mg, Na) were determined on both the humus and mineral soil samples by extraction with acid ammonium acetate (pH 4.65) using a ratio of 15 ml of sample and 150 ml of extractant. The suspensions were left to stand overnight before being shaken for 1 h and then filtered. The concentrations of the individual nutrients were determined by ICP-AES (ARL 3580). The analytical methods are described in Halonen *et al.* (1983). Soil pH was determined in a water suspension with a ratio of 15 ml of sample and 25 ml of distilled water. Exchangeable acidity (EA) was determined on a KCl extract with a ratio of 15 ml of sample and 150 ml 1.0 M KCl by titration with 0.05 M NaOH to an endpoint of pH 7.0.

The needle samples were dried (40 °C, 48 h) and analysed separately for each tree. Needle unit mass (mg/needle) was also determined separately for each tree. The concentrations of P, K, Ca, Mg, Mn, Cu, Zn, Fe and B were determined on finely ground needles by dry ashing (550 °C for 2 h), followed by extraction with HCl (Halonen *et al.*, 1983) and analysis by ICP-AES (TJA, Iris, Advantage). The N concentration was determined on a CHN analyser.

On arrival at the laboratory, the pH of the percolation water samples was measured and the samples were then filtered through a 0.45 µm membrane filter using positive pressure. The samples were divided into subsamples for the following determinations: Ca, Mg, K, NO_3 and SO_4 by ion chromatography (IC), and Al, Mn, Cr, Cu, Cd, Pb and Zn by ICP-AES. In the calculations, values below the Limit of Quantification (LOQ) of the analytical instruments have been substituted by a value equivalent to 2/LOQ.

Calculation of the results

The cation exchange capacity (CEC_e) was calculated as the sum of equivalent values of extractable Ca, Mg, K and Na and EA. Base saturation (BS) was obtained from the proportion of the sum of the equivalent Ca, Mg, K and Na concentrations out of CEC_e.

Statistical significance of the difference in soil parameters, needle nutrient concentrations and yields of lingonberries between the treatments was tested using analysis of variance. Bonferroni's test was used to test the equality of the treatment means.

The stand characteristics at the start and 7 and 12 years after the treatments were calculated using the KPL calculation programme for sample plots (Heinonen, 1994). A function based on breast height diameter and height was used for calculating the volume of the trees (Laasasenaho, 1982). The growth for the consecutive 7- and 5-year periods was calculated as the difference between consecutive measurements (the same trees at the start and at the end of each period). Statistical significance of the differences in volume growth between the treatments was tested using analysis of variance. Bonferroni's test was used to test the equality of the treatment means. The following model was used for the individual experiments: $y_{ij} = \mu + t_j + e_{ij}$, where y_{ij} is the growth for block i (i = 1,2,3,4) and treatment j (j = 1,2,3,4), μ is the total mean, t is the fixed effect of treatment j, and e_{ij} is the residual effect for observation ij.

Results

Soil chemistry

The nutrient concentrations (Table 1) in the soil before wood ash application were within the range of values published by Tamminen (1991) for the *Calluna* forest site type in southern Finland. The thickness of the humus layer was 2.5 cm.

Application of 2.5 t ha^{-1} of wood ash resulted in a significant increase of 1.3 pH units in the humus layer after 12 years, and application of 5 t ha^{-1} of ash in an increase of 2.5 pH units (Table 2). There was also an increase in the pH in the mineral soil, but the response was significant only with the highest ash dose (5.0 t ha^{-1}) (Table 2). There was a significant positive correlation between the pH and the size of the ash dose in both the humus layer and in the mineral soil (Table 3).

Exchangeable acidity (EA) showed a dose-dependent decrease both in the humus layer and in the mineral soil (Table 2). In the humus layer EA was 50–92% lower on the ash-treated plots than on the control plots. In the mineral soil the decrease in the EA was significant only with the highest dose of ash.

Table 1. Average total and extractable element concentrations in mg kg^{-1} (N, g kg^{-1}) and the pH in the soil before wood ash application. SEM = standard error of the mean. *n* = 16. Element concentrations are expressed on dry matter basis, except N in the humus layer expressed on organic matter basis

			Mean	SEM
Humus layer				
	Total			
		Ca	3225	163
		K	848	37
		Mg	389	13
		P	864	38
		N	12.4	0.1
		C/N	47	0.5
		B	2.2	0.5
		Cu	7.4	0.4
		Fe	2100	107
		Mn	227	21
		Pb	59.6	3.5
		Zn	58.4	2.6
	Extractable			
		Ca	1910	88
		K	860	40
		Mg	217	9
		P	291	16
		pH	3.60	0.01
Mineral soil, 0–10 cm				
	Total			
		N	0.51	0.02
		C/N	25	0.1
	Extractable			
		Ca	24.6	1.6
		K	18.2	0.7
		Mg	4.2	0.3
		P	6.3	0.2
		pH	4.56	0.03

The two highest ash doses significantly increased both the total and extractable Ca and Mg concentrations in the humus layer (Fig. 1). Compared to the controls, the increase in both the total and extractable Ca concentrations following application of 2.5 and 5.0 t ha^{-1} of wood ash was 4- and 9-fold, respectively. There was also a significant increase in the total P concentrations with the two highest ash doses, and in the extractable P concentrations with the highest ash dose.

In the mineral soil layer, the application of wood ash increased the concentrations of extractable Ca, K and Mg. However, the increases were significant only in the case of the highest dose (Fig. 1). Wood ash had no effect on the concentrations of extractable P in the mineral soil.

The two highest ash doses significantly increased the concentrations of total Cu, Mn and Zn in the humus layer (Table 4). There were also significant increases in the total B concentrations, but only with the highest ash dose. The increase in the concentrations of B, Cu, Fe, Mn and Zn ($p < 0.001$) and of Cd, Cr and Ni ($p < 0.05$) were positively correlated with the size of the ash dose.

Wood ash increased the CEC$_e$ in the humus layer (Table 2). Compared to the control, the increase in CEC$_e$ with a dose of 2.5 and 5.0 t ha^{-1} was 2- and 3-fold, respectively. However, the application of wood ash had no effect on CEC$_e$ in the mineral soil. Ash application increased the BS both in the humus layer and the mineral soil, the increases with the two highest ash doses being significant.

Table 2. Mean pH, exchangeable acidity (EA), effective cation exchange capacity (CEC$_e$), and base saturation (BS) in the humus layer and mineral soil (0–10 cm) 12 years after wood ash application. Standard error of the mean given in parentheses. Mean values with the same letter within the soil layer do not differ significantly from each other ($p < 0.05$)

	Soil layer	Control	Wood ash, t ha^{-1}		
			1.0	2.5	5.0
pH	Humus layer	3.43 (0.01) a	3.90 (0.01) a	4.68 (0.15) b	5.88 (0.18) c
	Mineral soil	4.62 (0.07) a	4.76 (0.04) a	4.91 (0.09) a	5.30 (0.12) b
EA, mmol kg^{-1}	Humus layer	103 (11) a	51 (5) ab	21(6) c	8 (6) c
	Mineral soil	19 (4) a	17 (2) a	13 (3) ab	7 (4) b
CEC$_e$, mmol kg^{-1}	Humus layer	230 (8) a	267 (9) a	433 (31) b	695 (7) c
	Mineral soil	20 (2)	22 (1)	22 (1)	23 (3)
BS, %	Humus layer	55 (1) a	81 (2) b	95 (1) c	98 (0) c
	Mineral soil	9 (1) a	24 (2) ab	40 (7) bc	66 (12) c

Table 3. Spearman's correlation coefficients between the ash dose and the parameters listed both in the humus layer and in the mineral soil (0–10 cm) 12 years after the treatments. Critical concentrations, $n = 16$: $r_{0.05} = 0.47$, $r_{0.01} = 0.59$

Variable	Humus layer	Mineral soil
Ca	0.97	0.87
K	0.17	0.65
Mg	0.97	0.92
P	0.82	−0.07
pH	0.97	0.88
EA	−0.97	−0.81
CEC$_e$	0.95	0.16
BS	0.97	0.95

In this study, the application of wood ash had no effect on either the total N concentration or the C/N ratio (Table 5), or on the amount of organic matter in the humus layer.

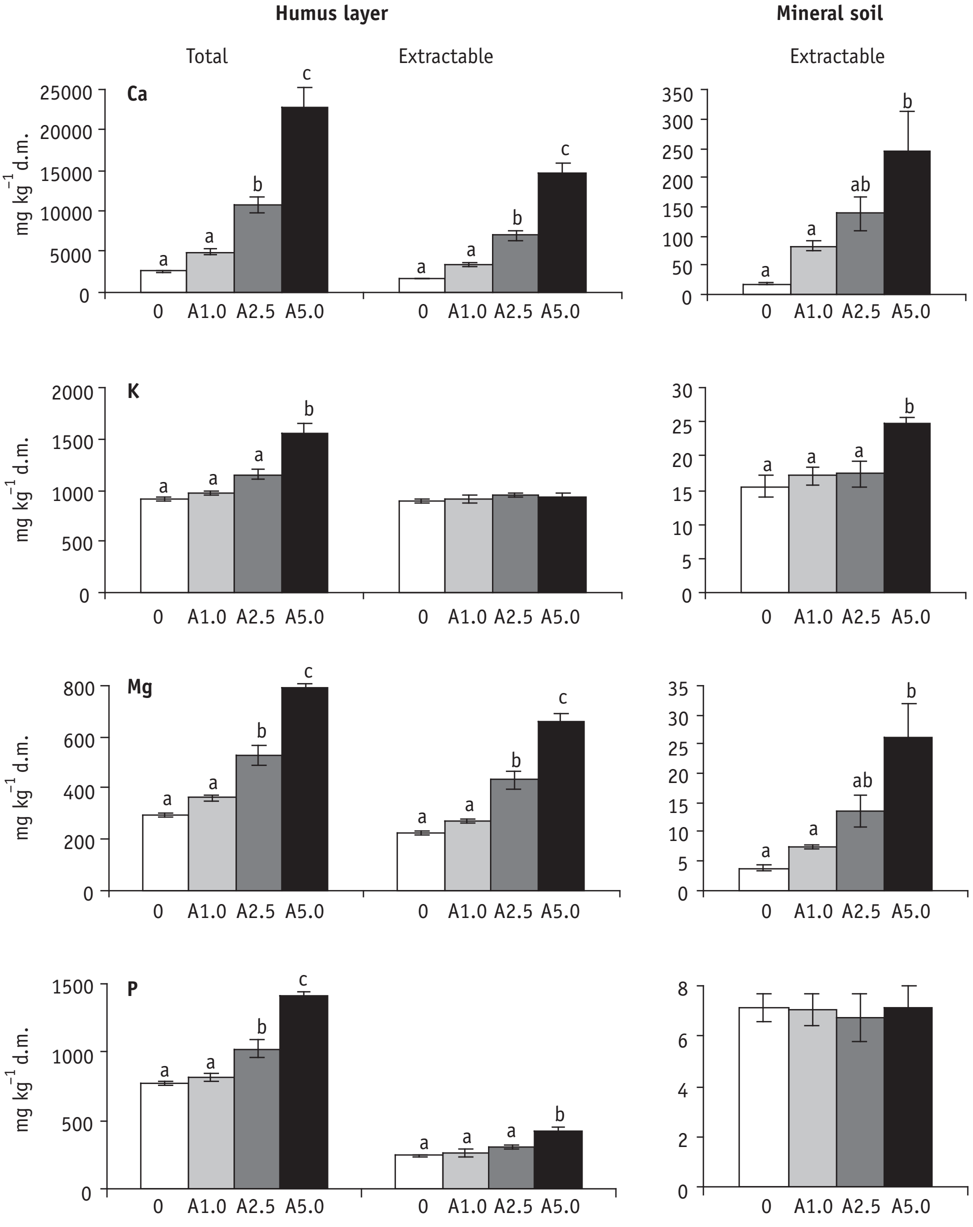

Figure 1. Average total nutrient concentrations in the humus layer, and extractable nutrient concentrations in the humus layer and mineral soil layer 12 years after wood ash application. Standard error of the mean is marked on the columns by bars. Wood ash (A) applied in the different treatments: 1.0, 2.5 or 5.0 t ha^{-1}. d.m. = dry matter.

Table 4. Average total element concentrations (mg kg^{-1} on dry matter basis) in the humus layer 12 years after wood ash application. Mean values with the same letter do not differ significantly from each other ($p < 0.05$). A = wood ash: 1.0, 2.5 and 5.0 t ha^{-1}. SEM = standard error of the mean

	Treatment	Mean		SEM
B	Control	1.6	a	0.02
	A1.0	2.1	a	0.19
	A2.5	4.2	a	0.49
	A5.0	12.8	b	2.40
Cd	Control	0.35		0.02
	A1.0	0.34		0.02
	A2.5	0.44		0.05
	A5.0	0.46		0.03
Cr	Control	10.1		2.4
	A1.0	19.8		4.0
	A2.5	26.0		4.0
	A5.0	28.0		5.8
Cu	Control	6.4	a	0.1
	A1.0	8.5	a	0.2
	A2.5	15.2	b	2.3
	A5.0	18.3	b	1.6
Fe	Control	1518		68
	A1.0	1715		121
	A2.5	2618		760
	A5.0	2278		163
Mn	Control	140	a	19
	A1.0	418	a	58
	A2.5	1156	b	183
	A5.0	1928	c	56
Ni	Control	10.7		2.1
	A1.0	17.9		3.7
	A2.5	19.4		2.5
	A5.0	21.3		3.8
Pb	Control	41.5		1.9
	A1.0	38.2		1.3
	A2.5	39.6		1.4
	A5.0	37.4		1.8
Zn	Control	45.4	a	1.1
	A1.0	46.3	a	1.8
	A2.5	66.1	b	5.6
	A5.0	83.7	b	2.1

Table 5. Total N concentration and C/N ratio in different soil layers, and organic matter content in the humus layer 12 years after wood ash application. OM = organic matter, DM = dry matter, SEM = standard error of the mean. A = wood ash: 1.0, 2.5 and 5.0 t ha^{-1}

Treatment	Humus layer						Mineral soil, 0–10 cm			
	N, g kg^{-1} OM		C/N		OM, t ha^{-1}		N, g kg^{-1} DM		C/N	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Control	13.4	0.1	43	0	33.5	2.8	0.41	0.05	49	4
A1.0	13.1	0.3	44	1	33.3	1.8	0.38	0.03	47	1
A2.5	13.6	0.1	43	0	33.1	2.8	0.37	0.08	48	3
A5.0	14.1	0.2	41	0	30.2	1.8	0.40	0.04	48	2

Soil solution composition

The effects of wood ash application on pH, Al, Ca, Mg, K and SO_4 are presented in Fig. 2 as the change compared to the situation on the control plots. The absolute values of these parameters for the individual treatments are given in Appendix 1. The pH of percolation water at a depth of 20 cm on the ash-treated plots was clearly higher in

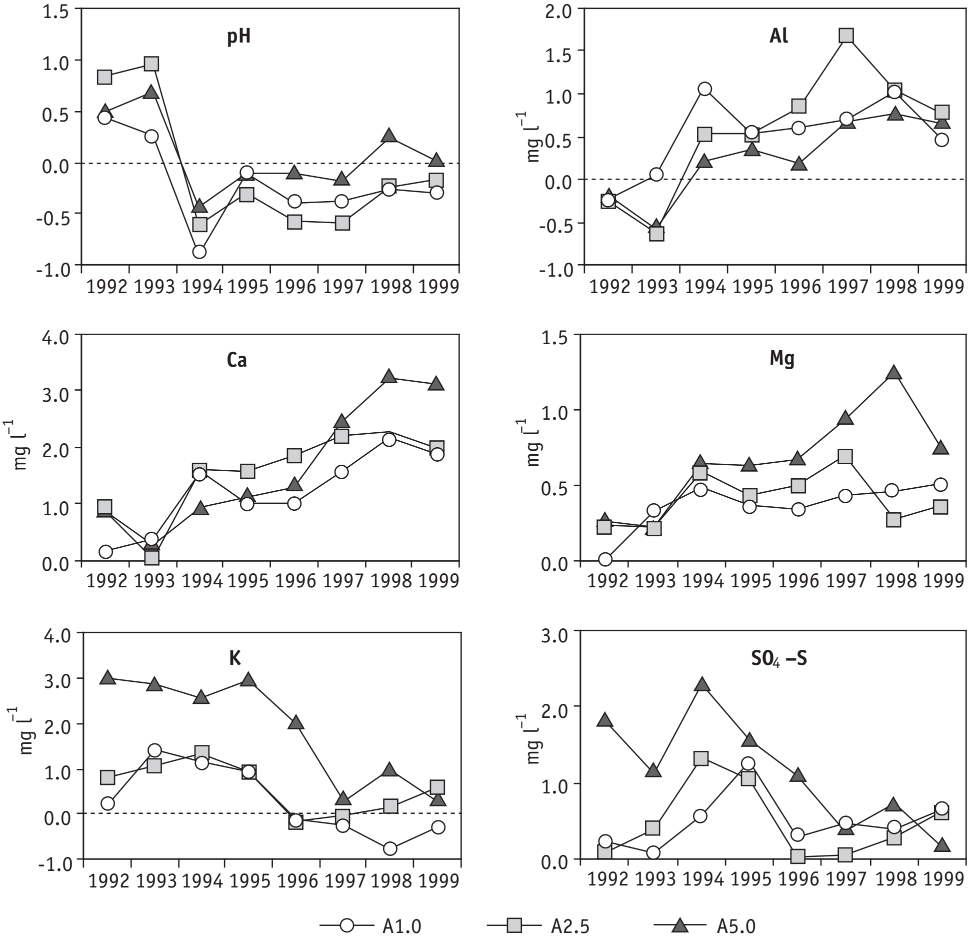

Figure 2. Difference between the annual mean pH and mean Al, Ca, Mg, K and SO_4–S concentrations in percolation water at 20 cm depth in the individual treatments compared to the control during 1992–1999. See Fig. 1 for explanations.

1992 and 1993 (Fig. 2), but fell to approximately the same level (or slightly below) as on the control plots during the period 1994–1999. The exchangeable Al concentrations followed an inverse pattern to that for pH, i.e. increased with all ash dosages after 1994. Both the Ca and Mg concentrations showed a clearly increasing trend during the period 1993/94–1999, and remained at a relatively high level compared to that on the control plots. The Ca and Mg concentrations in the highest ash dosage were clearly higher than those of the other two dosages towards the end of the monitoring period. The K concentrations during the period 1992–1995/96 were higher with all three ash dosages, but fell to approximately the same level as the control from 1997 onwards. The SO_4 concentrations on the plots with the highest ash dose remained high almost throughout the monitoring period, but with the two smaller ash doses they were elevated only during 1994 and 1995. None of the ash doses had any effect on the NO_3, Cd, Cr, Cu or Pb concentrations in percolation water, and only a slight increasing effect on the Mn and Zn concentrations occurred (Appendix 2).

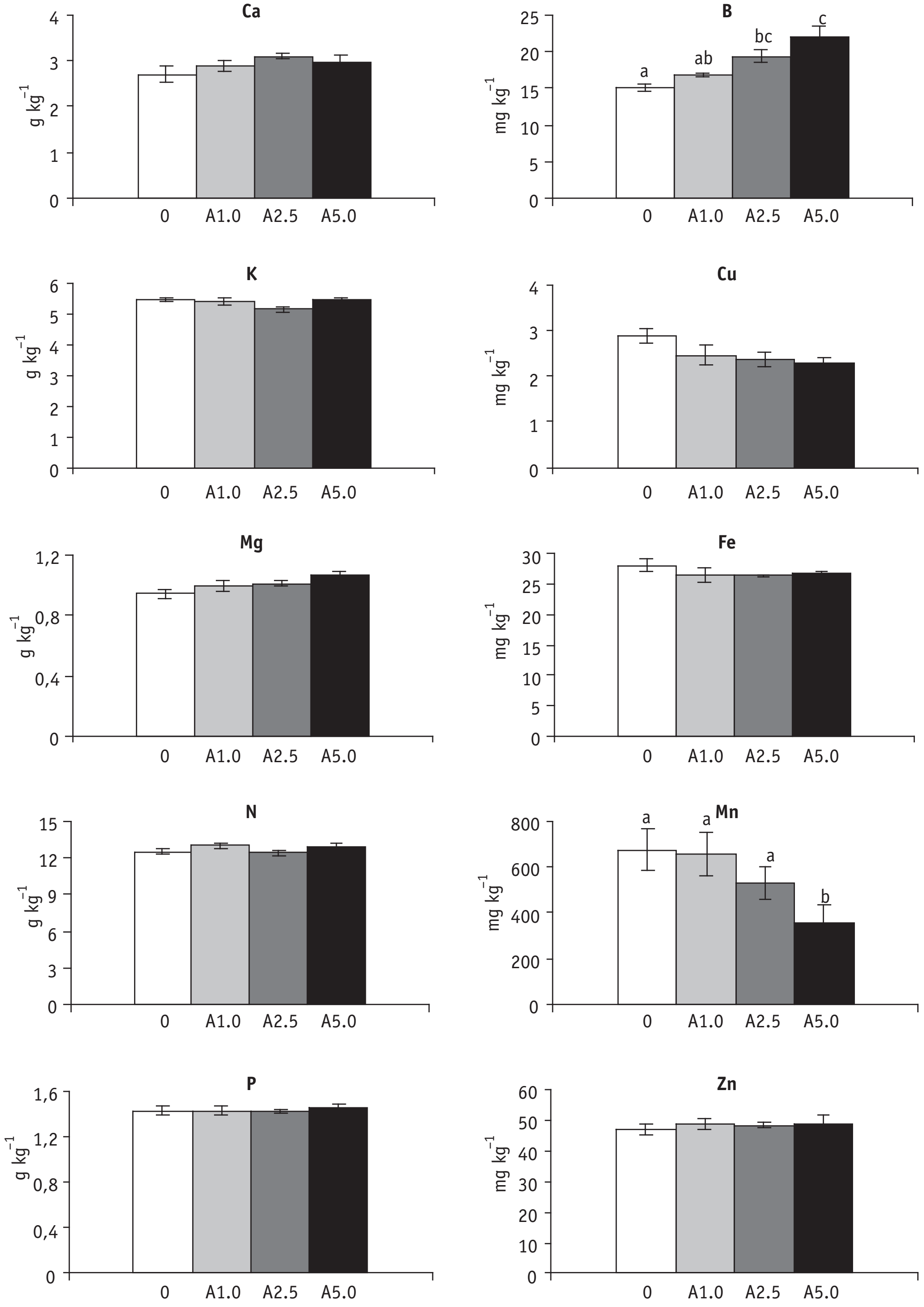

Figure 3. Average needle nutrient concentrations 12 years after wood ash application. See Fig. 1 for explanations.

Needle nutrients

Before the application of wood ash, the needle N, P and Mg concentrations (Table 6) were lower and the concentrations of the other nutrients approximately the same as the mean concentrations of corresponding nutrients in current-year needles in 98 Scots pine stands (years 1987–1989) growing in different parts of southern Finland (Raitio *et al.*, 2000). The concentrations of N, P and Mg were close to the deficiency level of 10.9, 1.3 and 0.9, respectively, for Scots pine stands growing on this site type (Jukka, 1988).

Two years after application the wood ash had no effect on needle nutrient concentrations (data not shown). After 12 years, however, the needle B concentrations on the plots treated with doses of 2.5 and of 5.0 t ha^{-1} were significantly higher (Fig. 3). Furthermore, the needle Mn concentrations were significantly the lowest on the plots treated with 5.0 t ha^{-1} of ash. The concentrations of B ($p < 0.001$) and Mg ($p < 0.05$) were positively correlated, and those of Mn ($p < 0.01$) and Cu ($p < 0.05$) negatively correlated with the ash dose.

Table 6. Average needle nutrient concentrations (on dry matter basis) and average needle dry mass before fertilisation. *n* = 16. SEM = standard error of the mean

Nutrient	Mean	SEM
	g kg^{-1}	
Ca	2.53	0.07
K	4.58	0.07
Mg	0.83	0.01
P	1.20	0.01
N	10.2	0.1
	mg kg^{-1}	
B	14.5	0.4
Cu	3.69	0.06
Fe	53.2	1.5
Mn	584	39
Zn	46.2	0.9
	mg/needle	
Needle mass	9.4	0.3

Tree growth

Wood ash had no significant effect on volume growth during the first 7-year period or the second 5-year period (Fig. 4). There was a slight reduction in the mean annual radial growth after all the ash treatments, but this had almost levelled off after 7 years, apart from on the plots that received 2.5 t ha^{-1} of wood ash (Fig. 5).

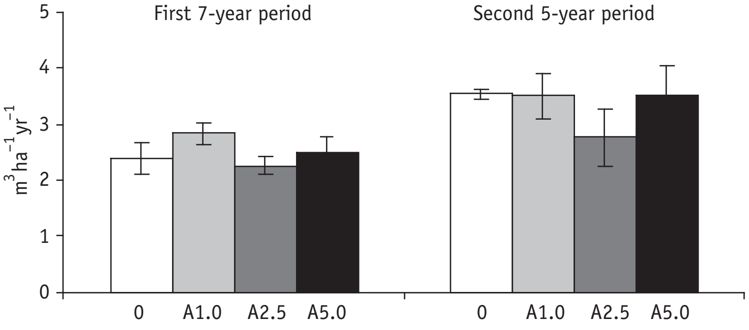

Figure 4. Mean annual volume growth of the stand during the first 7-year (1990–1996) and second 5-year (1997–2001) period after wood ash application. See Fig. 1 for explanations.

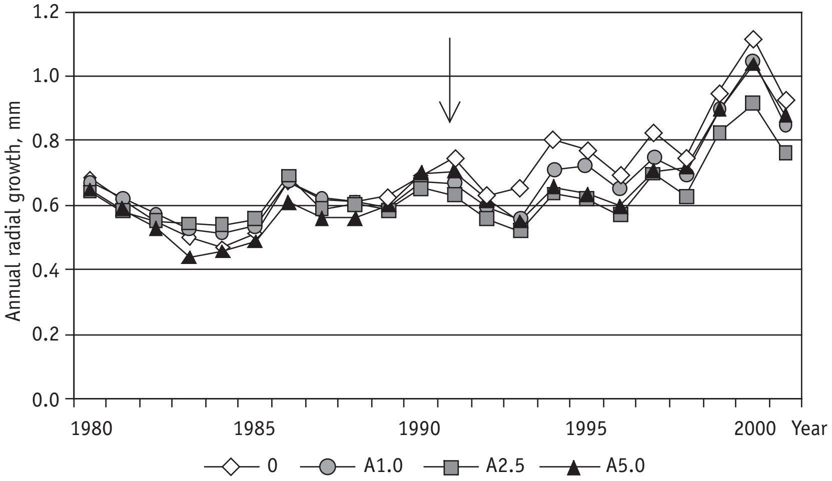

Figure 5. Mean annual radial growth at breast height of the sample trees 12 years after wood ash application. Arrow indicates the time of ash application. See Fig. 1 for explanations.

Berry yields

The mean annual yields of lingonberries on the control plots were 149, 190, 95 and 130 kg ha^{-1} in 2000, 2001, 2002 and 2003, respectively. The highest dose of wood ash had a decreasing effect on the mean annual berry yield for the period 2000–2003 (Fig. 6), as well as on the yields in individual years. However, due to the high variation in the berry yields between the replications within the treatments, no significant differences were found between the treatments in either the mean annual berry yield (2000–2003) or in the individual years. The mean annual berry yield was negatively correlated with the size of the ash dose ($p < 0.01$). Negative correlation was also found between the ash dose and berry yields in the individual years ($p < 0.01$ in 2000, and $p < 0.05$ in 2001, 2002 and 2003).

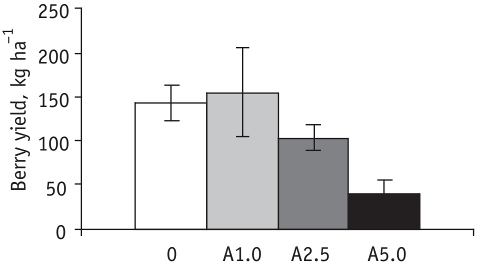

Figure 6. Mean annual berry yields 11–14 years after wood ash application. See Fig. 1 for explanations.

Discussion

Soil

In the same experiment, Levula *et al*. (2000) reported a decrease of 1.0 to 2.0 pH units already one growing season following wood ash application with doses of 2.5 and 5.0 t ha^{-1}, respectively. Loose ash is usually highly alkaline, and the sharp increase in soil pH after wood ash application can have negative effects on the ground vegetation (Kellner and Weibull, 1998; Jacobson and Gustafsson, 2001) and microfauna (Huhta, 1984). Hence, doses of loose wood ash exceeding 2.5–3.0 t ha^{-1} are not recommended for use on mineral soils (Mälkönen *et al*., 2001).

The decrease in soil acidity obtained with a dose of 2.5 t ha^{-1} of wood ash in our study was 1.3 pH units in the humus layer after 12 years. A similar wood-ash induced, long-term decrease in the acidity of the humus layer has also been reported in other studies (Bramryd and Fransman, 1995; Saarsalmi *et al*., 2001, 2004). The largest dose of wood ash (5 t ha^{-1}) gave a 2-fold increase in humus layer pH. Bramryd and Fransman (1985) reported a similar dose–response relationship in soil acidity of about 1.0 and 2.6 pH units in the humus layer 10 years after the application of 2 and 7 t ha^{-1} of wood ash, respectively, to a forest soil in Sweden.

There is usually a time lag before wood ash starts to have neutralising effects in the mineral soil, and the magnitude of the effect is almost always much smaller than that in the humus layer. For instance, in Scots pine stands of different site fertility no decrease in acidity was found in the 0–10 cm mineral soil layer 7 years after the application of 3 t ha^{-1} of wood ash, but an increase of 0.2–0.3 pH units was detected after 16 years (Saarsalmi *et al*., 2001). In our study a significant response in soil acidity in the mineral soil was seen after 12 years, but in this case only with the highest dose (5.0 t ha^{-1}) of ash. In a study carried out by Saarsalmi *et al*. (2004), an increase of 0.3–0.4 pH units was detected in the 0–5 cm mineral soil layer 10 years after the application of 3 t ha^{-1} wood ash in three Scots pine stands.

Wood ash recycling offers an opportunity to compensate for the extra losses of base cations and acid neutralisation capacity that can result from whole-tree harvesting compared with conventional harvesting techniques. In this study, a dose of 2.5 t ha^{-1} of wood ash was sufficient to significantly increase the exchangeable Ca and Mg concentrations in the humus layer. Similar long-term increases in exchangeable Ca and Mg concentrations, and in some cases also in P and K concentrations, in the humus layer following wood ash application have been reported in other studies (Bramryd and Fransman, 1995; Saarsalmi *et al*., 2001, 2004). Only the largest dose of wood ash increased the total K concentrations in the humus layer, and none of the doses had an effect on exchangeable K concentrations. Potassium has been shown to be released very rapidly from the ash (Eriksson, J., 1998; Holmberg *et al*., 2000). Since exchange sites on the soil particles attract Ca more strongly than they attract K, the low recovery of K on the exchange sites could be due to greater leaching of K (Arvidsson and Lundkvist, 2003). In our study, this assumption is supported by the fact that exchangeable K concentrations in the mineral soil were significantly elevated only on the plots receiving the highest dose of wood ash. However, these results should not be interpreted to mean that there will be high losses of K from the soil, since, although K is highly mobile, excess K given with wood ash is rapidly taken up by trees (cf. Arvidsson and Lundkvist, 2002; Jacobson, 2003). Similar wood ash induced increases in total B and Mn concentrations in the humus layer following wood ash application have also been reported in other studies (Tamminen, 1998; Saarsalmi *et al*., 2004).

The CEC_e in the humus layer, i.e. the number of dissociated, negatively charged cation exchange sites, is pH dependent (Pratt and Bair, 1962). In this study there was a 2- and 4-fold increase in the CEC_e in the humus layer 12 years after the application of 2.5 and 5.0 t ha^{-1} of wood ash, respectively. The increase was obviously caused by the marked increase in the pH of this layer, and is not likely to be due to a change in the chemical composition of the organic matter in the humus layer. Base saturation, which is the proportion of cation exchange sites occupied by base cations (Ca, Mg, K, Na), was strongly increased by wood ash application in both the humus layer and mineral soil. However, as the exchangeable K concentrations were not affected by wood ash application, except the response to the highest ash dose in the mineral soil, it is clear that the increase in BS is almost solely attributable to the large input of exchangeable Ca and Mg from the wood ash. This means that wood ash, as well as reducing acidity, has also considerably increased the soil's capacity to counteract increased soil acidity in the future, as well as to provide a considerable reserve of Ca and Mg for future stand growth. Wood ash-induced increases in the CEC_e and BS in the humus layer have also been reported in several other studies (Unger and Fernandez, 1990; Khanna *et al*., 1994; Eriksson, H.M., 1998; Saarsalmi *et al*., 2001, 2004).

One of the major concerns regarding the negative effects of wood ash application is that it might lead to increased Cd concentrations in soil. However, the Cd in ash can remain in an insoluble form (immobilised) for a long time owing to the pH-increasing effect of the ash (Eriksson, J., 1998). The Cd concentrations in wood ash normally vary from 4 to 20 mg kg^{-1} (cf. Jönsson and Nilsson, 1996). The Cd concentration in the wood ash used in this study was relatively low (1.4 mg kg^{-1}), and not even the highest amounts of Cd applied in the ash (totalling 2–7 g ha^{-1}) had any significant effect on the Cd concentrations in the humus layer. Although significantly elevated Cd concentrations in the humus layer in Finnish coniferous stands have in some cases been reported following wood ash application (Tamminen, 1998; Saarsalmi *et al*., 2004), the elevated concentrations presented in these studies have in all cases fallen within the normal variation range of Cd concentrations in Finnish soils (Tamminen, 2000).

Soil solution

There has been concern that the application of wood ash to forest soils may represent a potential threat to watercourses. Högbom *et al*. (2001) stated that, at sites characterised by a relatively low C/N ratio (< 25), there is an increased risk of N leaching into the watercourses in the form of nitrate. According to Högbom *et al*. (2001), the application of 4.2 t of wood ash ha^{-1} to a Norway spruce dominated site on an acidic till soil, with relatively high N deposition, in SW Sweden tended to decrease pH and increase NO_3 concentrations in soil solution at 50 cm depth 6–7 years after the treatment. Högbom *et al*. (2001) concluded that the slow release of cations from the wood ash results in the displacement of protons from cation exchange sites on the soil particles. The subsequent increase in protons in the soil solution promotes the transport of NO_3 anions down the soil profile. In our study, the C/N ratio in the humus layer was relatively high (47), and we can therefore assume that there was a severe shortage of plant-available N (NH_4 and NO_3) in both the soil and the soil solution. The pH increase resulting from wood ash application will undoubtedly increase N mineralisation in the humus layer to some extent, but we cannot expect a marked increase in the NH_4, and subsequently NO_3 via nitrification, in the soil of a site with low N reserves. The soil solution results from our experiment cover the period 1992–1999, but unfortunately not the first 2-year period immediately following wood ash application. As the NO_3

concentrations in the soil solution measured at a depth of 20 cm were, throughout the 8-year period, extremely low, it seems probable that the risks of nitrate leaching on a site of relatively low fertility are negligible.

Arvidsson and Lundkvist (2003) found no effects of wood ash application on the pH or NO_3 and Al concentrations in the soil water at 50 cm depth during the 6-year period following the application of hardened and crushed wood ash (3 t ha^{-1}) in four Norway spruce stands along a fertility and climate gradient in Sweden. Neither did Ring *et al*. (1999) detect any changes in the pH or the NO_3, SO_4 and Al concentrations in soil solution at 50 cm depth in two experiments, one in the north and one in the south of Sweden, during the 3-year period after addition of 1.0, 3.0 and 6 t ha^{-1} wood ash. Similarly, Fransman and Nihlgårdh (1995) detected no response to granulated wood ash in soil solution acidity sampled at 30 cm depth during a 5 year study period in central Sweden. In our study, wood ash application initially increased the soil solution pH, but decreased the pH over the long term. This was associated with an overall increase in the Al concentrations. Despite the fact that there is normally a relatively strong positive relationship between the pH and Al concentrations, wood ash application results in the releases of large amounts of Ca and Mg into the soil solution and the increase in Al concentrations is most likely due to the displacement of Al from cation exchange sites. This assumption is supported by the elevated, long-term increase in Ca and Mg concentrations in the soil solution.

While the effect of wood ash application on the pH in soil solution is rather weak there are consistent observations of increased downward transport of base cations. Arvidsson and Lundkvist (2003) found higher concentrations of Ca, Mg and K in the soil solution at all 4 different field experiments using two different crushed ash types. The Ca concentration, however, gradually decreased during 5 years after ash addition and after 6 years the concentration was at the same level as in the control plots. Increased leaching of Ca and Mg has also been shown 5 years after the application of granulated wood ash (3.2 t ha^{-1}) to a 30 year old Norway spruce stand in southern Sweden (Lundell *et al*., 2001).

In our study, the elevated concentrations of SO_4^{2-} in the soil solution, derived either from the ash or from SO_4 already present in the overlying humus and mineral soil layers, obviously provide an accompanying anion for the increased concentrations of Al^{3+}, Ca^{2+} and Mg^{2+} in the soil solution. Our results showing a relatively early increase in K concentrations in the soil solution, followed by a gradual return to the control level, are in good agreement with the results for exchangeable K concentrations in the humus and mineral soil.

Our results for heavy metal (Cd, Cr, Cu, Pb, Zn) concentrations in the soil solution at a depth of 20 cm following the addition of various doses of wood ash are rather encouraging. The concentrations of Cd, Cr, Cu and Pb were repeatedly below the LOQ of the analytical equipment, even in the case of the 5.0 t wood ash ha^{-1} treatment. Even though the wood ash did contain appreciable amounts of these metals, the relatively strong increase in the pH has ensured that they have remained on/in the humus layer in an immobilised form and are unlikely in the near future to be released for uptake into the vegetation or leach into the watercourses. The situation as regards Zn is somewhat different. Zinc is known to be relatively mobile in forest soils (Derome and Nieminen, 1998): it does not readily form complexes with organic matter (Alloway, 1995), and has a lower affinity for cation exchange sites than most other heavy metals (Bohn *et al*., 1985). Even though the two higher doses of wood ash (2.5 and 5.0 t ha^{-1}) almost doubled the Zn concentrations in the soil solution compared to the situation on the control plots, the levels are far from the toxic limits and in fact will ensure that the vegetation receives a satisfactory supply of Zn, which is an important micronutrient.

Tree growth

Wood ash application had no significant effect on volume growth. This result is in agreement with the experience usually gained in wood ash experiments in Scots pine stands on mineral soil (Sikström, 1992; Moilanen and Issakainen, 2000; Jacobson, 2003; Saarsalmi *et al*., 2004). According to Jacobson (2003), however, the growth response to wood ash may be dependent on soil fertility. Jacobson (2003) reported a decrease in wood production, although not significant, following wood ash application at doses of 1 to 9 t ha^{-1} on sites with relatively high C/N ratios during a 5- to 11-year study period, but an opposite result on sites with low C/N ratios (< 25). On the other hand, Perkiömäki *et al*. (2004) found an increase in stem volume growth in a relatively infertile (C/N ratio, 34) Scots pine stand 16 years after the application of 3 t ha^{-1} wood ash. However, Perkiömäki *et al*. (2004) did not report whether the volume increase was significant or not.

Needles

The significant increase in needle B concentrations after wood ash application found in this study is in agreement with the results reported by Jacobson (2003) and Saarsalmi *et al*. (2004). In fact, wood ash is a good source of available B, which makes amendment with wood ash particularly suited for rectifying the B deficiencies that occur in coniferous forests in Fennoscandia, where the bedrock and soil have relatively low B concentrations. A similar decrease in needle Mn concentrations following wood ash application was reported by Saarsalmi *et al*. (2004). Liming is also known to decrease needle Mn concentrations in Scots pine as a result of the increase in the soil pH and subsequent immobilisation of soil Mn (Derome *et al*., 1986).

Berry yields

The berry yields of *V. vitis-idaea* on the control plots during the years 2000–2003 (95–190 kg ha^{-1}) fell within the normal range of variation represented for the berry yields of *V. vitis-idaea* (from 80 to 300 kg ha^{-1}) in Finland (Issakainen and Moilanen, 1998). The sharp increase in the pH of the substrate caused by ash fertilisation may have a detrimental effect on the functioning of the mycorrhizas of forest berry species (Moberg and Tideström, 1985). In fact, there was a slight significant decrease in the coverage of *V. vitis-idaea* in our experiment 6 years after the application of 5.0 t ha^{-1} of wood ash (Levula *et al*., 2000). Similarly, Jacobson and Gustafsson (2001) reported that wood ash at doses of 3 to 6 t ha^{-1} tended to lead to a decrease in the coverage of *V. vitis-idaea* during a 5-year study period. However, the effects of wood ash on berry yields may be different immediately after the treatment. For instance, Silfverberg and Issakainen (1991) reported an increase in the berry yields of *V. vitis-idaea* 3 months after the application of 10 t ha^{-1} of wood ash.

Conclusions

The application of wood ash had a relatively long-term increasing effect on the pH, the concentrations of exchangeable base cations (Ca and Mg), CEC_e and BS in the humus layer. The effects were dose-dependent, and it seems that a dose of 2.5 t ha^{-1} of loose wood ash is sufficient to decrease soil acidity and to compensate for the loss of base cations resulting from tree harvesting in a Scots pine stand growing on a relatively infertile site. A dose of 5 t ha^{-1} of loose wood ash may result in a too sharp increase in the soil pH, and have a detrimental effect on the ground vegetation, as shown by the reduction in the yield of *V. vitis-idaea* berries in this study. Wood ash application with a dose of 5 t ha^{-1} even did not result in a significant increase in the concentrations of heavy metals (Cd, Pb, Cr, Cu) and NO_3 or pH in the percolation water collected at a depth of 20 cm in the soil. The application of wood ash had no significant effect on the volume growth of the tree stand. As the B in wood ash is in a form readily utilisable by trees, wood ash could be used as a boron fertiliser in stands suffering from its deficiency.

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Appendix 1. Mean pH and the Al, Ca, Mg, K and sulphate (SO_4-S) concentrations in percolation water (mg l^{-1}) collected at a depth of 20 cm on the control and ash-treated (A = wood ash: 1.0, 2.5 and 5.0 t ha^{-1}) plots during 1992–1999

Year	pH	Al	Ca	Mg	K	SO_4-S
Control						
1992	5.02	0.41	1.04	0.230	2.01	1.72
1993	5.13	0.74	1.37	0.232	1.20	0.85
1994	5.79	0.07	1.41	0.275	1.62	1.95
1995	5.76	0.06	1.06	0.257	2.21	1.62
1996	5.84	0.10	1.31	0.335	2.95	2.19
1997	5.84	0.12	1.13	0.321	2.25	2.16
1998	5.63	0.08	1.24	0.343	1.83	1.85
1999	5.29	0.14	1.82	0.351	1.30	1.34
A1.0						
1992	5.46	0.17	1.21	0.234	2.22	1.95
1993	5.40	0.77	1.74	0.558	2.61	0.92
1994	4.90	1.12	2.98	0.758	2.78	2.52
1995	5.66	0.58	2.07	0.624	3.13	2.89
1996	5.44	0.71	2.31	0.675	2.82	2.48
1997	5.45	0.81	2.71	0.750	1.99	2.62
1998	5.37	1.10	3.40	0.802	1.04	2.24
1999	5.00	0.61	3.70	0.858	1.01	1.99
A2.5						
1992	5.86	0.16	1.92	0.459	2.81	1.81
1993	6.09	0.11	1.40	0.449	2.26	1.26
1994	5.18	0.60	3.00	0.864	2.97	3.28
1995	5.47	0.59	2.64	0.687	3.13	2.67
1996	5.26	0.94	3.16	0.834	2.77	2.22
1997	5.24	1.80	3.34	1.011	2.22	2.03
1998	5.40	1.12	3.52	0.614	1.98	2.14
1999	5.12	0.91	3.81	0.714	1.88	1.97
A5.0						
1992	5.51	0.22	1.92	0.490	5.01	3.56
1993	5.82	0.16	1.64	0.450	4.05	1.98
1994	5.36	0.28	2.33	0.918	4.18	4.25
1995	5.66	0.41	2.18	0.881	5.17	3.18
1996	5.73	0.29	2.61	1.002	4.95	3.29
1997	5.66	0.80	3.58	1.252	2.54	2.54
1998	5.87	0.84	4.47	1.587	2.81	2.58
1999	5.30	0.81	4.92	1.088	1.59	1.51

Appendix 2. Average nitrate (NO_3-N), Mn, Cr, Cu, Cd, Pb and Zn concentrations in percolation water (mg l^{-1}) collected at a depth of 20 cm on the control and ash-treated (A = wood ash: 1.0, 2.5 and 5.0 t ha^{-1}) plots during 1992–1999. n.d. = not determined owing to insufficient sample volumes. The "<" sign indicates that the concentrations were below the limit of quantification (LOQ) of the analytical equipment. In such cases, the LOQ value for the ion/element in question is given

Year	NO_3-N	Mn	Cr	Cu	Cd	Pb	Zn
Control							
1992	0.043	0.081	<0.037	<0.032	<0.024	<0.319	0.014
1993	0.006	0.146	<0.037	<0.032	<0.024	<0.319	0.016
1994	0.019	0.289	<0.037	<0.032	<0.024	<0.319	<0.005
1995	0.013	0.129	<0.037	<0.032	<0.024	<0.319	<0.005
1996	<0.012	0.062	<0.037	<0.032	<0.024	<0.319	0.015
1997	n.d.	0.061	<0.037	<0.032	<0.024	<0.319	0.017
1998	n.d.	<0.005	<0.037	<0.032	<0.024	<0.319	0.019
1999	0.023	<0.005	<0.037	<0.032	<0.024	<0.319	0.010
A1.0							
1992	0.032	0.098	<0.037	<0.032	<0.024	<0.319	0.017
1993	0.012	0.111	<0.037	<0.032	<0.024	<0.319	0.021
1994	0.023	0.286	<0.037	<0.032	<0.024	<0.319	0.014
1995	0.018	0.279	<0.037	<0.032	<0.024	<0.319	0.011
1996	0.012	0.110	<0.037	<0.032	<0.024	<0.319	0.023
1997	n.d.	0.077	<0.037	<0.032	<0.024	<0.319	0.027
1998	n.d.	0.046	<0.037	<0.032	<0.024	<0.319	0.041
1999	0.012	0.049	<0.037	<0.032	<0.024	<0.319	0.015
A2.5							
1992	0.033	0.059	<0.037	<0.032	<0.024	<0.319	0.019
1993	0.012	0.031	<0.037	<0.032	<0.024	<0.319	0.012
1994	0.012	0.289	<0.037	<0.032	<0.024	<0.319	0.022
1995	0.012	0.171	<0.037	<0.032	<0.024	<0.319	0.020
1996	0.028	0.097	<0.037	<0.032	<0.024	<0.319	0.030
1997	n.d.	0.130	<0.037	<0.032	<0.024	<0.319	0.040
1998	n.d.	0.069	<0.037	<0.032	<0.024	<0.319	0.034
1999	0.032	0.047	<0.037	<0.032	<0.024	<0.319	0.022
A5.0							
1992	<0.012	0.420	<0.037	<0.032	<0.024	<0.319	0.013
1993	<0.012	0.058	<0.037	<0.032	<0.024	<0.319	0.016
1994	<0.012	0.166	<0.037	<0.032	<0.024	<0.319	0.014
1995	<0.012	0.155	<0.037	<0.032	<0.024	<0.319	0.012
1996	0.023	0.090	<0.037	<0.032	<0.024	<0.319	0.017
1997	n.d.	0.046	<0.037	<0.032	<0.024	<0.319	0.022
1998	n.d.	0.016	<0.037	<0.032	<0.024	<0.319	0.029
1999	0.028	0.046	<0.037	<0.032	<0.024	<0.319	0.016

Puutuhaga väetamise mõju puistu kasvule, mullale, mullaveele ja okaste keemilisele koostisele ning pohla (*Vaccinium vitis-idaea* L.) saagikusele hariliku männi puistutes Soomes

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Kokkuvõte

Artiklis esitatakse andmed puutuha erinevate kogustega (1,0, 2,5 ja 5,0 t/ha) väetamise tagajärjel toimunud muutustest okaste toitainete kontsentratsioonis ja puu kasvus 100-aastases männipuistus. Puutuha mõju mulla happesusele ja elementide liikuvusele uuriti ajavahemikus 2–10 aastat, mõju pohla saagikusele ajavahemikus 10–14 aastat pärast töötlemist. Selgus, et mulla huumushorisondi pH langes 1,2 kuni 2,6 ühiku võrra ja oluliselt suurenes Ca- ja Mg-sisaldus suuremate puutuhakoguste korral. Puutuha neutraliseerivat mõju mullale oli märgata ka ülemistes mineraalhorisontides, kus täheldati Ca, K ja Mg kontsentratsiooni tõusu. Seejuures ei avaldanud puutuhk mõju raskmetallide Cd, Cr, Cu ja Pb sisaldusele mullas. Küll aga vähendas puutuha kogus 5,0 t/ha pohla saagikust. Ei täheldatud mõju puistu tagavarale.