Effects of Wood Ash Fertilization on Forest Soil Chemical Properties

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The effects of wood ash fertilization on soil chemical properties were studied in three young Scots pine (*Pinus sylvestris* L.) plantations and a Norway spruce (*Picea abies* (L.) Karst.) plantation with different site fertility in southern Finland. The dose of 3 t ha^{-1} of loose wood ash was applied to 4 replicate plots (25×25 m) at each experiment. Humus layer and mineral soil samples were taken before the treatment and 7 and 16 years after wood ash application. Results showed that neutralization as well as fertilization effects of wood ash on forest soil were of long duration. An ash-induced pH increase of 0.6–1.0 pH units and exchangeable acidity (EA) decrease of 58–83% were detected in the humus layer 16 years after wood ash application. The decrease in acidity was most pronounced on the *Calluna* site with initially the lowest pH and highest EA. In the mineral soil the increase in pH was observed later than in the humus layer. After 16 years, the mineral soil pH was increased (0.2–0.3 pH units) on the *Vaccinium* and *Myrtillus* sites. A corresponding and in most cases a significant increase in the extractable Ca and Mg concentrations was detected in both the humus layer and in the mineral soil. Wood ash significantly increased the effective cation exchange capacity (CEC_e) and base saturation (BS) but decreased the concentration of exchangeable Al in both soil layers on all the sites. No response of N availability to wood ash application could be found.

Key words wood ash, acidity, neutralization, nutrients, pH, *Pinus sylvestris*, *Picea abies*
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1 Introduction

It has been stated that wood ash can be used to counteract natural and anthropogenic acidification of forest soil and loss of nutrients resulting from tree harvesting (Åbyhammar et al. 1994, Mälkönen 1996), i.e. nutrients could be returned to the forest soil by wood ash fertilization. Recycling of nutrients should be a fundamental principle in sustainable forestry.

When loose wood ash is dissolved in water, a highly alkaline solution (pH 11–13) is produced. Wood ash generally has a good acid-neutralizing capacity and ability to supply the soil with base cations (Ca^{2+}, K^+, Mg^{2+}, Na^+). The acid-neutralizing capacity of a wood ash mainly depends on the content of oxides, hydroxides and carbonates of Ca, Mg and K. Wood ash also contains various concentrations of readily soluble neutral salts, such as sulphates and chlorides of K and Na (Eriksson 1998).

Decreased acidity and increased base saturation following application of loose (non-hardened) wood ash have been frequently reported (Åbyhammar et al. 1994, Khanna et al. 1994, Bramryd and Fransman 1995, Kahl et al. 1996, Rühling 1996, Eriksson 1998). Wood ash has also been found to increase the microbial activity in soil (Martikainen et al. 1994, Fritze et al. 1994, 1995).

In addition to base cations, wood ash also contains harmful heavy metals, i.e. Cd, Hg and Pb, of which Cd is probably of most concern. Normally the Cd concentrations in wood ash vary from 4 to 20 mg kg^{-1} and therefore a maximum of 4 t ha^{-1} of wood ash is considered to be an appropriate dose in Finnish upland forests (Työryhmämuistio 1993). This dose is expected to have an effect on soil chemical properties for some decades. The heavy metal content included in this dose has not been found to retard the decomposition of organic matter (Fritze et al. 1994) or accumulate significantly in berries (Silfverberg and Issakainen 1991, Levula et al. 2000).

Granulation can be used as a means of reducing the reactivity of wood ash and consequently, avoid possible shock effects to flora and fauna. However, there is a scarcity of knowledge on how the early effects of wood ash additions correlate with the solubility properties of hardened and non-hardened ashes (e.g. Eriksson et al. 1998).

The aim of this study is to determine the long-term effects of loose wood ash fertilization on chemical properties of the humus layer and mineral soil in coniferous sapling stands with different site fertility.

2 Material and Methods

2.1 Experiments

Four field experiments were established in young Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) plantations representing site types of increasing fertility: *Calluna* (CT), *Vaccinium* (VT) and *Myrtillus* (MT) site types in southern Finland (Table 1). The soil at each experiment was podzolic and developed on glacial till.

At the experiments 3 t ha^{-1} of loose wood ash, containing P 13, K 42, Ca 250, Mg 23, Mn 16, Cu 0.023 and Zn 0.38 g kg^{-1} on a dry mass basis, was applied in July–August 1982. The size of the plots was 25 × 25 m and there were 4 replications at each experiment.

Table 1. Information about the experimental stands at the beginning of the study period. Site types according to the classification of Cajander (1949).

Location	Site type [1)]	Humus-layer, cm	Soil texture class	Tree species	Age, a
Keuruu, Vuorisjärvi 62°03'N 24°51'E	CT	1.8	Gravelly loamy sand	Scots pine	5
Keuruu, Yltiä 62°16'N 24°20'E	VT	2.5	Loamy sand	Scots pine	6
Janakkala, Harviala 61°00'N 24°45'E	MT	2.3	Loamy sand	Scots pine	6
Janakkala, Harviala 61°02'N 24°39'E	MT	1.6	Loamy sand	Norway spruce	5

[1)] *Calluna vulgaris* (CT), *Vaccinium vitis-idaea* (VT), *Vaccinium myrtillus* (MT) site types

2.2 Soil Sampling

The first round of soil sampling was carried out prior to wood ash application in 1982 and the sampling was repeated 7 and 16 years after the treatment, i.e. in 1989 and 1998. A distinct raw humus layer could not be found on the MT sites in 1998. Therefore the humus layer samples were taken either from the uppermost 0–3 cm (the MT pine site) or 0–2 cm layer (the MT spruce site), i.e. the depths corresponding the average thickness of the humus layer 9 years earlier. Mineral soil samples were taken at a depth of 0–30 cm below the humus layer in 1982 and that of 0–10 cm in 1989 and 1998.

Humus layer and mineral soil samples were taken systematically from 20 points on each plot, and samples from the same plot were bulked by layer. The humus layer samples were taken using a cylinder (d = 58 mm) and mineral soil samples using an auger (d = 25 mm) except in 1982, when the mineral soil samples were taken from 5 sampling points with a spade. The thickness of the humus layer was measured in connection with the sampling.

2.3 Soil Analyses

The samples were air-dried (40–60 °C) and milled to pass through a 2 mm sieve. The total concentrations of P, K, Ca and Mg were determined from the humus samples by dry ashing and extraction with HCl. Extractable nutrients (P, K, Ca, Mg, Na) were determined by extraction with 1 M ammonium acetate (pH 4.65). The filtered solutions were analyzed by the flame atomic absorption spectrophotometry, except for P, which was determined colorimetrically. Total N was determined by the Kjeldahl method from the samples taken in 1982 and 1989 and on a CHN analyser (LECO) from the samples taken in 1998. The methods used are described by Halonen et al. (1983).

pH was determined from a soil-water suspension (15 ml sample/25 ml water). Exchangeable acidity (EA) ($H^+ + Al^{3+}$), was determined in 1998 by titrating the extract (1.0 M KCl) to pH 7.0, and exchangeable Al by back titration to pH 7.0 following addition of NaF (Halonen et al. 1983).

The organic matter content of the humus layer was determined as percent of loss-of-ignition from the samples taken in 1982 and 1989 and calculated from the C content from the samples taken in 1998.

2.4 Calculation of the Results

The effective 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 Ca, Mg, K and Na concentrations of the CEC_e.

Statistical significance of the difference between soil parameters on the control and wood ash fertilized plots for each experiment was tested using t test. Analysis of variance was used to test the effect of wood ash application on various soil parameters together for all experiments.

3 Results

3.1 Soil Organic Matter

At the beginning of the study the organic matter content of the humus layer was higher on the CT and VT sites than on the MT sites (Table 2). A clear decrease in the organic matter content of the humus layer was found on all the sites both on the control and wood ash treated plots during the course of the study. On the MT sites, a distinct raw humus layer could no longer be found after 16 years. On fertile sites, a raw humus layer can disappear after clear cutting, this was carried out on all the sites 6 to 7 years before wood ash application. Wood ash had no significant effect on the soil organic matter content either in the humus layer or in the mineral soil during the study (Table 2).

3.2 Soil Acidity

The sites differ from each other with regard to humus layer acidity (Fig. 1, Table 3). Thus, on the MT sites the pH was significantly higher than on

Table 2. Organic matter content in the humus layer and mineral soil on different sites before (1982), 7 years (1989) and 16 years (1998) after wood ash application. Range given in parentheses. n.d. = not determined.

Soil layer and site type	Organic matter, % 1982 Control	1982 Ash	1989 Control	1989 Ash	1998 Control	1998 Ash
Humus layer						
CT_{pine}	75 (71–78)	72 (65–79)	53 (48–61)	53 (49–58)	32 (24–36)	32 (22–43)
VT_{pine}	73 (70–77)	74 (64–79)	58 (51–60)	51 (42–65)	36 (26–47)	37 (29–48)
MT_{pine}	54 (48–63)	59 (47–72)	40 (34–43)	42 (32–58)	23 (19–27)	28 (22–33)
MT_{spruce}	38 (29–42)	37 (35–41)	33 (23–40)	25 (21–32)	19 (16–25)	20 (17–23)
Mineral soil						
CT_{pine}	n.d.	n.d.	4.9 (3.2–6.7)	5.9 (5.4–6.3)	5.3 (3.1–6.4)	6.5 (5.4–7.5)
VT_{pine}	n.d.	n.d.	4.3 (3.5–4.7)	4.3 (3.2–5.8)	4.3 (3.1–5.3)	4.2 (4.0–4.5)
MT_{pine}	n.d.	n.d.	5.6 (5.0–6.7)	5.3 (4.8–5.8)	6.1 (5.6–6.5)	7.1 (6.4–9.0)
MT_{spruce}	n.d.	n.d.	6.0 (5.0–7.5)	6.8 (5.3–8.0)	5.7 (5.3–6.2)	6.6 (4.8–7.8)

Table 3. The p values according to the two-way ANOVA table for the nutrient concentrations and pH in the humus layer and mineral soil 7 (1989) and 16 years (1998) after wood ash application. In all cases $df_{treatment} = 1$, $df_{sites} = 3$ and $df_{S \times T} = 3$.

	p value 1989 Site (S)	1989 Treatment (T)	1989 S×T	1998 Site (S)	1998 Treatment (T)	1998 S×T
Humus layer: total nutrients						
N	0.000	0.821	0.550	0.000	0.143	0.085
P	0.821	0.000	0.403	0.273	0.008	0.646
K	0.000	0.006	0.078	0.000	0.763	0.995
Ca	0.075	0.000	0.004	0.001	0.000	0.024
Mg	0.000	0.001	0.668	0.000	0.665	0.992
Humus layer: extractable nutrients						
P	0.000	0.000	0.000	0.000	0.023	0.906
K	0.000	0.283	0.471	0.003	0.012	0.542
Ca	0.076	0.000	0.003	0.000	0.000	0.055
Mg	0.012	0.000	0.019	0.000	0.000	0.001
pH	0.000	0.000	0.227	0.000	0.000	0.276
Mineral soil: total N, extractable P, K, Ca and Mg						
N	0.000	0.438	0.808	0.000	0.055	0.367
P	0.010	0.820	0.911	0.028	0.612	0.980
K	0.000	0.111	0.956	0.000	0.008	0.526
Ca	0.001	0.022	0.827	0.002	0.000	0.701
Mg	0.039	0.000	0.964	0.000	0.000	0.206
pH	0.160	0.003	0.778	0.140	0.000	0.788

the VT and CT sites at the beginning of the study. Wood ash application resulted in a significantly elevated pH in the humus layer on all the sites, except on VT site in 1998 (Fig. 1). The difference in acidity between treatments was 1.1–1.5 pH units after 7 years and 0.6–1.0 pH units 16 years after wood ash application. The increase was most pronounced on the CT site with initially the lowest pH.

In the mineral soil no significant increase in the pH was seen 7 years after wood ash application, however, after 16 years the mineral soil pH did increase by 0.2–0.3 pH units on the VT and MT sites as the result of the ash treatment (Fig. 1).

Wood ash application significantly decreased the EA and exchangeable Al concentration both in the humus layer and the mineral soil (Table 4). In the humus layer, the decrease in EA was most

Table 4. Mean pH, exchangeable acidity (EA), exchangeable Al concentration, effective cation exchange capacity (CEC_e) and base saturation (BS), in the humus layer and mineral soil in the experiments 16 years after wood ash fertilization. Range given in parentheses. Statistical significance of difference in acidity parameters between treatments is indicated by asterisks. * 5%, ** 1% and *** 0.1% risk level.

Site type and soil layer	pH Control	pH Ash	EA Control	EA Ash	Al mmol kg^{-1} Control	Al mmol kg^{-1} Ash	CEC_e Control	CEC_e Ash	BS % Control	BS % Ash
CT_{pine}										
Humus layer	3.9	4.9**	53.2	8.8***	32.4	2.5***	101	174**	47	95***
	(3.7–4.2)	(4.7–5.2)	(43.8–65.3)	(5.6–13.9)	(23.8–38.5)	(1.5–3.4)	(79–118)	(147–212)	(45–56)	(92–97)
0–10 cm	4.7	4.9	17.7	8.0*	16.3	7.2*	23	45*	23	81***
	(4.4–5.0)	(4.8–5.1)	(9.4–22)	(5.3–10.4)	(8.8–20.5)	(4.6–9.4)	(12–30)	(36–57)	(22–25)	(76–91)
VT_{pine}										
Humus layer	4.2	4.8	30.0	11.7**	11.1	1.4*	110	232***	73	95**
	(3.9–4.4)	(4.6–5.3)	(20.6–41–9)	(7.8–15.4)	(4.2–18.5)	(0.4–3.3)	(84–131)	(200–265)	(65–80)	(93–97)
0–10 cm	4.6	4.9*	18	7.1**	16.6	6.3**	28	42*	35	82***
	(4.5–4.7)	(4.8–5.0)	(13.3–22.5)	(4.4–9.9)	(12.9–20.1)	(3.3–9.1)	(23–32)	(35–50)	(29–42)	(78–91)
MT_{pine}										
Humus layer	4.7	5.6***	13.9	5.0**	5.9	0.03*	119	287***	87	98*
	(4.6–5.0)	(5.4–5.9)	(8.4–18.5)	(4.4–5.7)	(1.9–11.8)	(0–0.1)	(82–145)	(222–331)	(78–94)	(98–99)
0–10 cm	4.7	4.9*	18.3	7.0***	15.7	5.2***	43	71*	57	90***
	(4.7–4.8)	(4.8–5.1)	(14.0–21.3)	(5.0–8.7)	(11.8–17.6)	(3.3–6.7)	(34–51)	(60–91)	(46–67)	(86–93)
MT_{spruce}										
Humus layer	4.9	5.5***	11.0	4.6 **	4.4	0.2*	114	198**	90	98**
	(4.8–5.1)	(5.4–5.7)	(9.2–14.8)	(4.0–5.5)	(2.0–8.1)	(0–0.5)	(94–146)	(164–232)	(84–94)	(97–98)
0–10 cm	4.7	5.0**	15.2	6.2*	12.6	4.8*	41	59	61	86*
	(4.6–4.9)	(5.0–5.1)	(11.6–17.9)	(2.6–12.2)	(9.6–15.7)	(1.1–11.0)	(32–51)	(34–82)	(44–72)	(64–97)

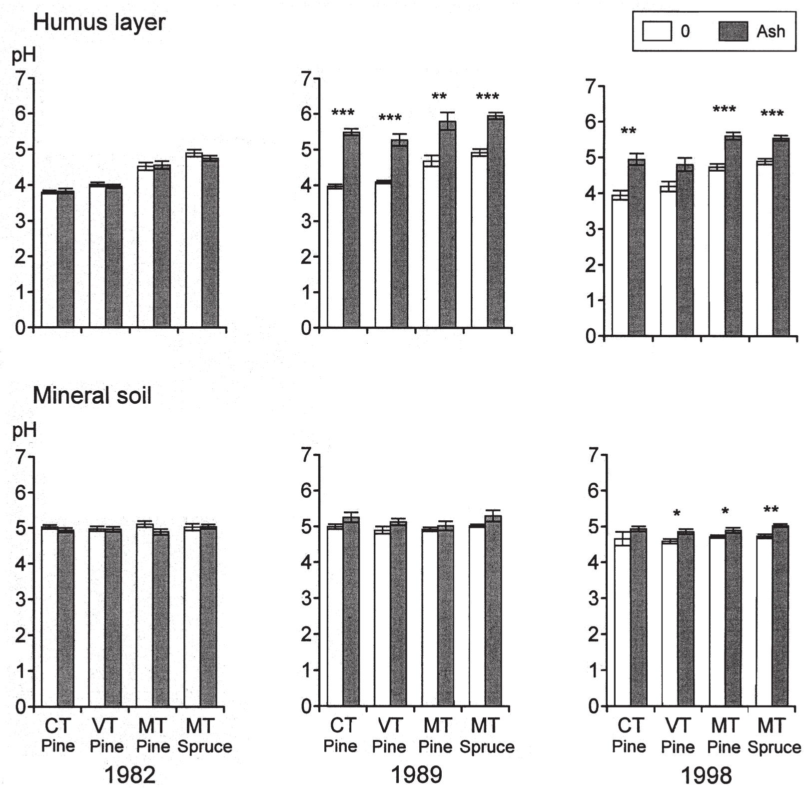

Fig. 1. Effect of wood ash fertilization on acidity ($pH_{(water)}$) in the humus layer and mineral soil on different sites. Sampling before (1982), 7 years (1989) and 16 years (1998) after wood ash application. Standard error of the mean is marked on the columns by bars.

apparent on the CT site with initially highest EA. On all sites the concentration of exchangeable Al was low after the ash treatment.

When handling the sites and treatments together significant differences in the EA were found both between sites and between treatments ($p<0.001$) in the humus layer and between treatments ($p<0.001$) in the mineral soil. An interaction between site and treatment in the EA was found in the humus layer ($p<0.001$) but not in the mineral soil.

3.3 Total Nutrients in the Humus Layer

At the beginning of the study, the total N concentration in the humus layer was on the CT site practically the same and on the other sites somewhat higher than the mean values presented for corresponding site types in southern Finland (Tamminen 1991). No response to wood ash fertilization was seen in the total N concentrations 7 years after wood ash application (Fig. 2). On the MT pine site, a significant increase in the total N concentration was found 16 years after wood ash application. The C/N ratio of the humus layer on the CT and VT sites exceeded that on the MT sites (Table 5). Wood ash had no effect on the C/N ratio in the humus layer during the study.

The control plots did not differ significantly from each other with respect to P concentrations during the course of this study. Wood ash somewhat increased the P concentration, however, the difference between treatments was significant only on the CT site (Fig. 2)

On the CT and VT sites, the concentration

Table 5. C/N ratio in the humus layer and mineral soil on different sites before (1982), 7 years (1989) and 16 years (1998) after wood ash application. Range given in parentheses. n.d. = not determined.

Soil layer and site type	C/N ratio 1982 Control	1982 Ash	1989 Control	1989 Ash	1998 Control	1998 Ash
Humus						
CT_{pine}	41 (37–45)	39 (35–40)	42 (37–45)	42 (35–45)	34 (31–37)	34 (32–35)
VT_{pine}	32 (29–35)	33 (31–36)	33 (30–37)	35 (32–37)	28 (25–33)	29 (25–33)
MT_{pine}	28 (27–28)	27 (26–29)	28 (24–33)	27 (26–28)	22 (21–23)	20 (19–21)
MT_{spruce}	30 (28–31)	29 (28–31)	28 (24–33)	26 (24–27)	21 (19–23)	20 (19–22)
Mineral soil						
CT_{pine}	n.d.	n.d.	39 (36–45)	39 (36–41)	28 (24–30)	29 (27–30)
VT_{pine}	n.d.	n.d.	29 (24–34)	28 (18–35)	22 (19–26)	23 (21–26)
MT_{pine}	n.d.	n.d.	27 (24–31)	29 (27–33)	22 (22–23)	21 (20–23)
MT_{spruce}	n.d.	n.d.	26 (24–29)	27 (25–28)	20 (18–23)	21 (18–23)

of K was significantly lower than on the MT sites. Wood ash fertilization did not level out this difference between sites. Some increase in the K concentration was found on the VT and MT spruce sites 7 years after wood ash application but this had disappeared later.

Wood ash significantly increased the concentration of Ca on all the sites. The greatest increase appeared on the CT site with initially the lowest Ca concentration. Here the Ca concentration was almost fivefold after 7 years and still fourfold compared to the control after 16 years on the wood ash treated plots. The smallest increase in Ca concentration was detected on the MT spruce site.

On the CT and VT sites, a significant increase in the Mg concentration was found 7 years after wood ash application. Nine years later no response was detected.

When handling the sites and treatments together, significant differences between treatments were found in the total P, K, Ca and Mg concentrations 7 years after wood ash application, but only in those of P and Ca after 16 years (Table 3). On both sampling occasions, an interaction in the Ca concentration between site and treatment was evident.

3.4 Total N in the Mineral Soil

In the mineral soil, the total N concentrations were at the beginning of the study on all the sites relatively typical for these site types (cf. Tamminen 1991). No response to wood ash was seen in the total N concentration 7 years after application (Fig. 3). However, 9 years later a significant increase in the mineral soil N concentration was found in the wood ash treatment on the MT pine site. Wood ash had no effect on the C/N ratio of the mineral soil in any of the sites (Table 5).

3.5 Extractable Nutrients in the Humus Layer

At the beginning of the study, the concentrations of P and K in the humus layer (Fig. 4) were on all the sites lower than the mean values presented for corresponding site types in southern Finland (cf. Tamminen 1991). The concentrations of Ca and Mg, excluding Mg on the MT spruce site, were practically the same or somewhat higher.

At the beginning of the study the significantly highest Ca and Mg concentrations were observed on the MT pine site (Fig. 4). The P concentration was lowest on the MT spruce site. This difference was significant compared to that on the CT and VT sites. There were no significant differences in the K concentrations between sites at the beginning of the study.

Wood ash fertilization strongly increased the Ca concentration on all the sites. The most pronounced increase was on the CT site, where the Ca concentration was fivefold after 7 years and still fourfold compared to the control 16 years

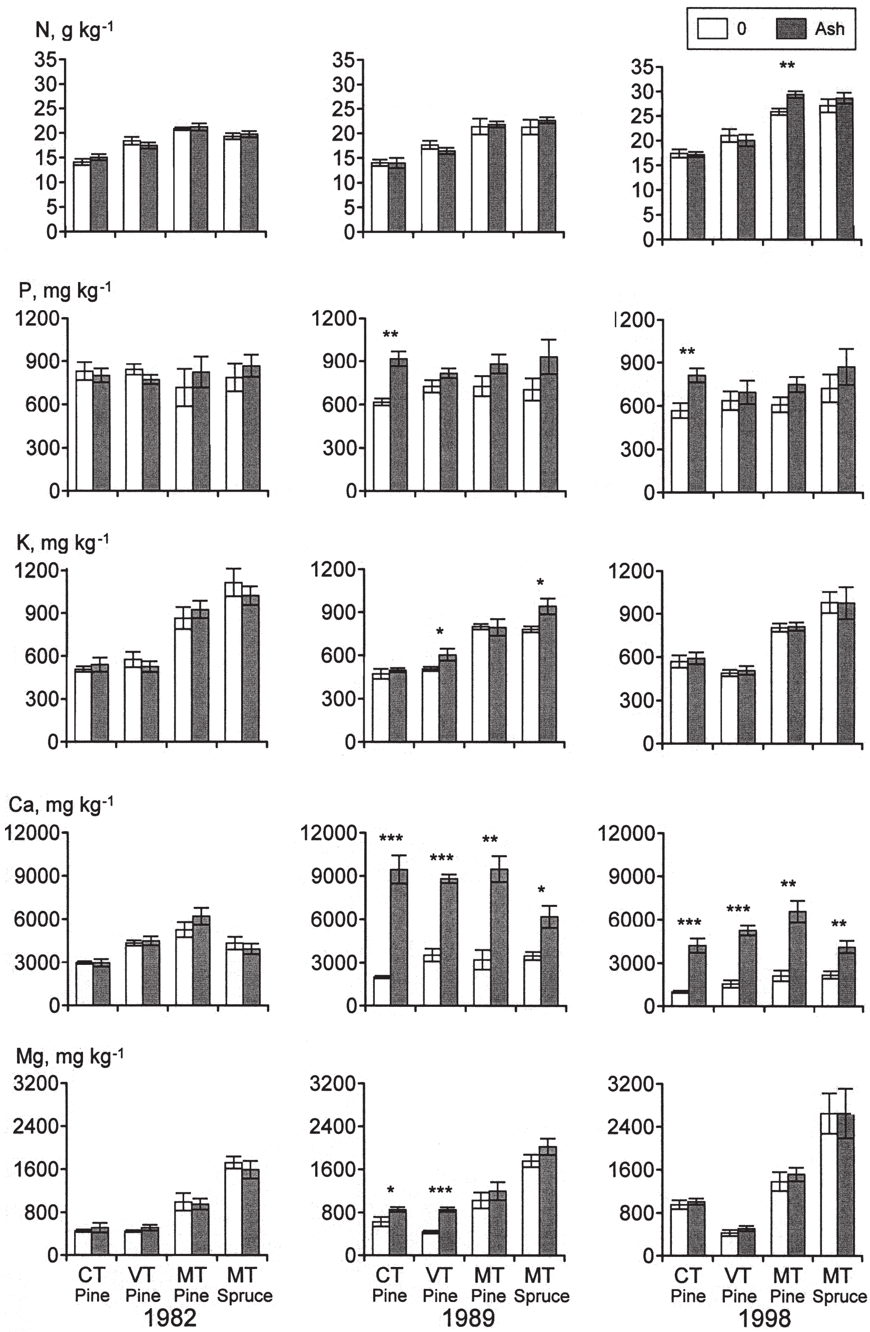

Fig. 2. Effect of wood ash fertilization on concentrations of total N (organic matter basis), P, K, Ca and Mg (dry matter basis) in the humus layer on different sites. Sampling before (1982), 7 years (1989) and 16 years (1998) after wood ash application. Standard error of the mean is marked on the columns by bars.

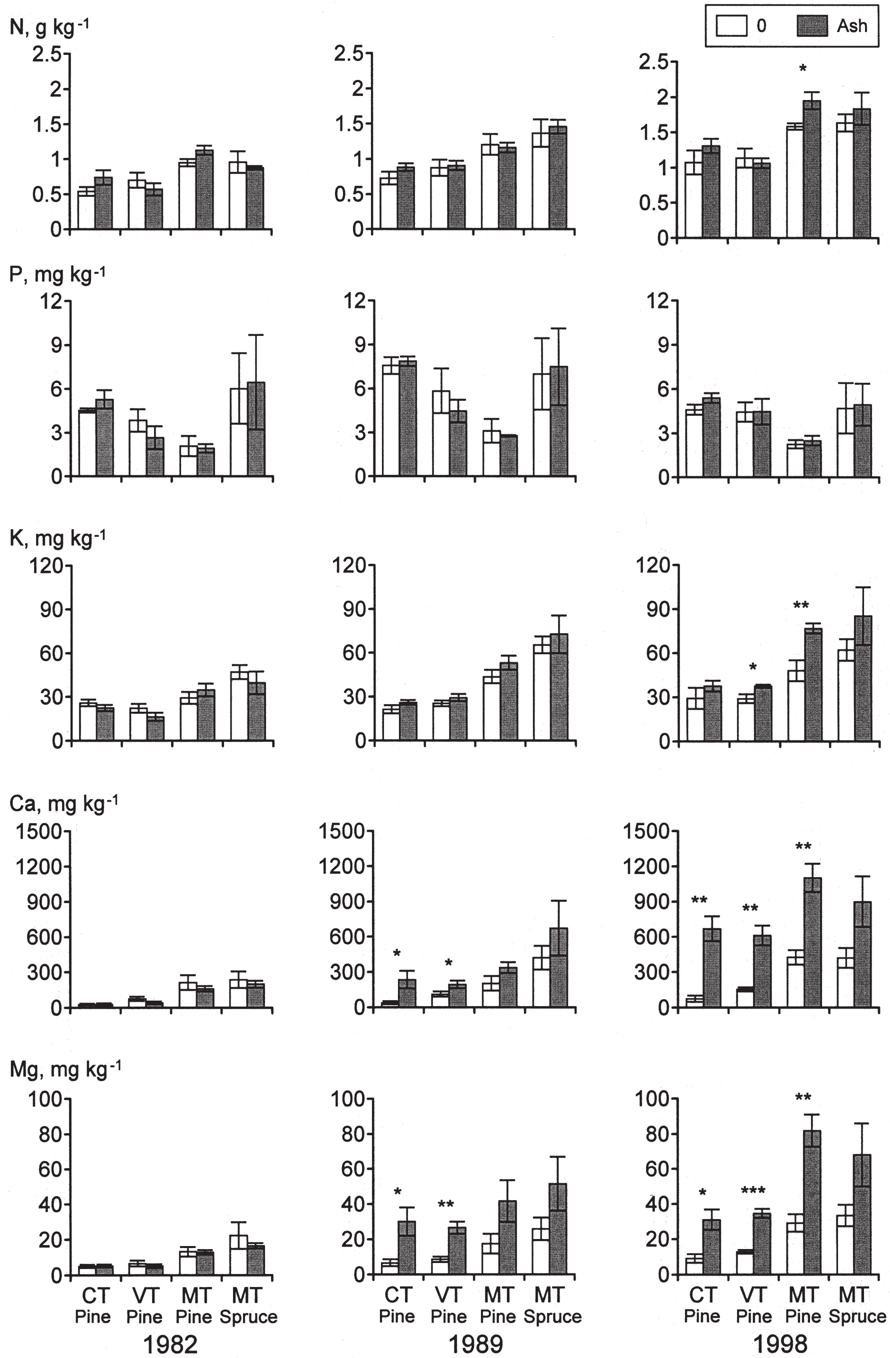

Fig. 3. Effect of wood ash fertilization on concentrations of total N (dry matter basis) and extractable P, K, Ca and Mg (dry matter basis) in the mineral soil (0–30 cm in 1982 and 0–10 cm in 1989 and 1998) on different sites. Sampling before (1982), 7 years (1989) and 16 years (1998) after wood ash application. Standard error of the mean is marked on the columns by bars.

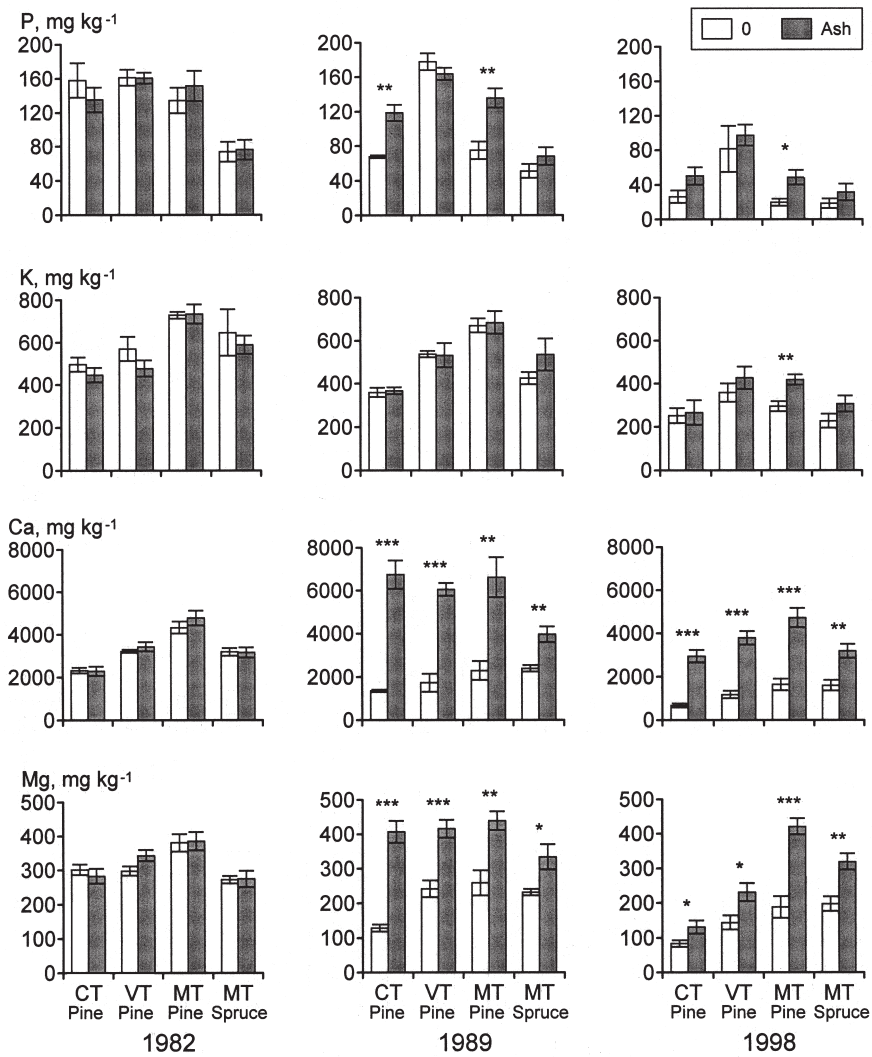

Fig. 4. Effect of wood ash fertilization on concentrations of extractable P, K, Ca and Mg (dry matter basis) in the humus layer on different sites. Sampling before (1982), 7 years (1989) and 16 years (1998) after wood ash application. Standard error of the mean is marked on the columns by bars.

after wood ash application. Even on the MT spruce site, where the response was weakest, the Ca concentration was twofold compared to the control 16 years after wood ash application.

Wood ash fertilization resulted in an elevated Mg concentration on all the sites. Seven years after wood ash application the increase was most pronounced on the CT site and 9 years later on the MT sites.

Wood ash had an increasing effect on the P concentration on the MT pine site during the study period. A significant increase in the P concentration was also found on the CT site 7 years after wood ash application.

No significant differences in the K concentration between treatments were found 7 years after wood ash application. On the MT pine site, a significant increase in the K concentration appeared

16 years after wood ash fertilization.

Significant differences both between sites and between treatments in concentrations of all the extractable nutrients could be found still 16 years after wood ash application when handling the sites and the treatments together (Table 3). There was also some interaction between the site and treatment in respect to Mg concentration.

At the beginning of the study the proportion of extractable P concentration of total P (P_{ext}/P_{tot}) was only 9% on the MT spruce site but 17–21% on the other sites. It should be noted that a low concentration of extractable P in a humus layer is typical for fertile sites (Viro 1969, Tamminen 1991). In addition the ratio of Mg_{ext}/Mg_{tot} was lower on the MT spruce site (17%) than on other sites (39–66%). A decrease in the ratios of P_{ext}/P_{tot}, Mg_{ext}/Mg_{tot} and K_{ext}/K_{tot} were found during the course of the study on all the sites. Wood ash increased the proportion of extractable Mg of total Mg on all the sites. No other differences in the proportion of extractable and total concentrations between treatments were found.

3.6 Extractable Nutrients in the Mineral Soil

Differently to other sampling occasions, mineral soil nutrients were determined in 1982 from the 0–30 cm soil layer instead of 0–10 cm. This partly explains some of the variation which appeared in the mineral soil nutrient concentrations on the control plots between the sampling years. Lower K, Ca and Mg concentrations were found in the CT and VT sites compared with those on the MT sites (Fig. 3). The P concentration was lowest on the MT pine site.

Wood ash fertilization resulted in significantly elevated concentrations of Ca and Mg on the CT and VT sites during the study period. This increase was also evident on the MT pine site, but only in the last sampling. Then also a significant increase in the K concentration was found on the VT and MT pine sites. No interaction between site and treatment could be found (Table 3).

3.7 Cation Exchange Capacity and Base Saturation

In the humus layer, the cation exchange capacity (CEC_e) on the control plots on the different sites did not significantly differ from each other (Table 4). In the mineral soil, the CEC_e was significantly higher on the MT sites than on CT and VT sites. Wood ash increased the CEC_e on all the sites. In the humus layer, this increase was most pronounced on the VT and MT pine sites. Here the increase resulted in a CEC_e that was more than twofold in comparison to the control.

The base saturation (BS) was significantly lower on the CT site in both soil layers (Table 4). On the MT sites, the BS in the humus layer was high even on the control plots. Wood ash fertilization significantly increased the degree of BS, being 95–98% in the humus layer and 81–90% in the mineral soil 16 years after wood ash application. The increase was most apparent on the CT site. Consequently, wood ash leveled out the differences in BS between sites with different fertility.

4 Discussion

4.1 Neutralization Effects

An ash-induced pH increase of 0.6–1.0 pH units was detected in the humus layer 16 years after wood ash application. In accordance with our results, decreased acidity and increased BS following application of wood ash have been reported in several studies. In a study by Martikainen (1984) an increase of 2 pH units was detected in the humus layer 2–3 years after the application of 6 t ha^{-1} wood ash in CT and MT pine stands in southern Finland. Similarly, Levula (1991) found a wood ash-induced pH increase of 1.0 pH unit in the humus layer 5 years after the application of 2 t ha^{-1} ash in a VT pine stand in southeastern Finland. According to Priha and Smolander (1994), an increase of 0.4 pH units in the humus layer was detected in a young CT pine plantation in southeastern Finland one year after bark ash application of 2.5 t ha^{-1}.

Levula et al. (2000) found a wood ash-induced pH increase of 0.3, 1.0 and 2.0 pH units in the humus layer in a mature CT pine stand in central Finland 5 months after wood ash application with doses of 1, 2.5 and 5 t ha^{-1} respectively. Three years after wood ash application the corresponding increase in pH at the same experiment was 0.7, 1.3 and 2.4 pH units respectively (Fritze et al. 1995). Mälkönen (1996) found a wood ash-induced pH increase of 0.5, 1.0–1.5 and 2.0 pH units in the humus layer in a young pine stand in southeastern Finland 12 years after wood ash application with the doses of 1, 2.5 and 5 t ha^{-1} respectively. Similarly, in a pine stand in southern Sweden wood ash application of the levels of 2 and 5 t ha^{-1} raised the humus layer pH by 0.9 and 2.5 pH units in 4 to 5 years (Bååth and Arnebrandt 1994). Bramryd and Fransman (1995) detected a wood ash-induced pH increase of 1.2 and 2 pH units in the humus layer in a pine stand in southern Sweden 10 years after wood ash application with the doses of 2 and 7 t ha^{-1} of respectively.

Since a sudden high increase in pH after wood ash application can have a detrimental effect on flora and fauna, some type of hardening or granulation pretreatment of the ash might be advisable (Åbyhammar et al. 1994, Eriksson 1998, Eriksson et al. 1998, Hytönen 1999). According to a study by Eriksson et al. (1998), loose wood ash significantly increased pH of the uppermost soil layers (0–5 cm) during the 11 months proceeding application, but the granules of the same ash did not significantly increase the pH in a sandy Arenosol.

Neutralizing effects of wood ash became evident in the surface layer of mineral soil at a considerably slower rate than in the humus layer. Similarly, Bramryd and Fransman (1995) detected a wood ash-induced pH increase of 0.5–1.0 pH units in mineral soil 10 years after the application of 2 and 7 t ha^{-1} of wood ash respectively in a pine stand in southern Sweden. In a study by Mälkönen (1996) an increase of 0.1–0.4 pH units in mineral soil was detected 12 years after wood ash application of 1, 2.5 and 5 t ha^{-1} in a young pine stand in southeastern Finland.

Wood ash decreased the exchangeable Al concentration in both the humus layer and mineral soil. In the humus layer the exchangeable Al concentration was very low, on MT sites even non-detectable 16 years after wood ash application. The lower exchangeable Al concentration could be either a result of cation exchange reactions or of a pH effect on Al solubility or a combination of both. Also in other studies, inversely related results between exchangeable Al concentration and wood ash application have been found (Unger and Fernandez 1990, Bramryd and Frasman 1995, Kahl et al. 1996).

4.2 Fertilization Effects

Particular attention can be paid to the long duration of increased concentrations of extractable Ca and Mg both in the humus layer and in the uppermost layer of mineral soil. Increases in Ca and Mg concentrations in the humus layer after wood ash addition have been reported also in other studies (Bramryd and Fransman 1995, Kahl et al. 1996, Rühling 1996, Eriksson 1998). Priha and Smolander (1994) found a bark wood ash-induced increase not only in extractable Ca and Mg concentrations but also in a K concentration in the humus layer in a young CT pine plantation one year after ash application. Bramryd and Fransman (1995) showed an increased concentration of extractable K in the mineral soil 10 years after wood ash application. In this study, wood ash application resulted in an elevated K concentration only on the MT pine site.

This study has detected an increase in the CEC_e and a decrease in the EA on all the sites as a result of wood ash application. This means that not only the relative proportion of cation exchange sites occupied by base cations increased, but also the concentrations of base cations. The response was strongest on the CT site with initially the lowest buffering capacity.

CEC_e in the soil organic matrix has been reported to be as pH dependent (Pratt and Bair 1962). Consequently, increases in CEC_e after wood ash addition have also been reported in other studies (e.g. Unger and Fernandez 1990, Khanna et al. 1994, Fritze et al. 1995, Eriksson 1998). The increase in CEC_e can probably be attributed mainly to the dissociation of pH dependent exchange sites within the organic matter. Eriksson (1998) found that the increase in CEC_e, was two years after applying granulated wood ash to a soil in southern Sweden, at lower doses more significant than the increase in pH.

An increase in the concentration of extractable P in the humus layer due to wood ash application was observed on the MT pine site even at the end of the study period. As also the concentration of total N increased on the MT pine site, no change in the N/P ratio appeared 16 years after wood ash application. Clarholm (1994) reported that plant available P in the humus layer was on an areal basis not significantly different from that of the control 18 months after an application of 3.2 t ha^{-1} granulated wood ash in a spruce stand in southwestern Sweden.

The hypothesis that wood ash fertilization can promote N mineralization was derived from results obtained on peat soils (Weber et al. 1985, Eriksson and Börjesson 1991). According to this study, no response in the soil C/N ratio to wood ash application was found. Obviously due to this reason, no significant increase in stand growth in upland forests after wood ash fertilization has been found (Levula 1991, Sikström 1992) as opposite to results obtained on peat soils (Silfverberg and Huikari 1985, Silfverberg and Hotanen 1989).

5 Conclusions

Acidification of forest soils can be counteracted and leaching of nutrients can be compensated by recycling of wood ash.

Neutralization as well as fertilization effects of wood ash on forest soil can be significant and of long duration. Even 16 years after wood ash application significant increases in pH, CEC_e, and BS and a corresponding decrease in EA were detected on all site types. The increase in pH came out later in the mineral soil than in the humus layer. An increase in the concentrations of extractable Ca and Mg was detected on all the sites still after 16 years.

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