THE SHORT-TERM EFFECTS OF WOOD-ASH AMENDMENT ON FOREST SOILS

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Abstract. In the heavily forested regions of the northeastern U.S. the potential for producing electricity from wood-fired boilers is also creating a growing supply of wood-ash requiring disposal. Landfill space is expensive and limited, which has resulted in an interest in spreading wood-ash on forest sites. This greenhouse study was designed to provide information on soil and seedling response to wood-ash applications. Red maple (*Acer rubrum*) seedlings were grown in either O or B horizon forest soil material and amended with six levels of ash (0, 4, 8, 12, 16, and 20 Mg ha^{-1}) and two levels of N fertilizer (0 and 224 kg ha^{-1}). Ash amendments increased pH and exchangeable base cations, and decreased extractable Al and Fe concentrations, in both soil materials. Ash treatments increased seedling foliar K and Na concentrations in O horizon soils, but had little effect on growth. No significant effects on seedling properties from ash in B horizon soils were found. Fertilizer N treatments did not improve seedling growth in either soil material. Soil and seedling response to N were notably different for the different soils used. Based on this short-term study it appears that (a) land applications of wood-ash at the rates used may be a viable approach to recycling this solid waste, and (b) long-term studies are required to evaluate this practice under field conditions.

1. Introduction

Wood-derived boiler ash is a by-product of operating wood-fired electricity generating plants. There are already a number of plants in the northeastern U.S., and the number of these facilities will increase in the future. As the number of plants increases, so will the amount of ash requiring disposal. Annually, a single plant generating 24 MW of electricity can produce 4 to 5 × 10^3 t of wood-ash.

Currently, much of this ash is landfilled; however space in landfills is becoming increasingly scarce and subject to restrictive regulations, making ash disposal costly. Furthermore, the practice of land disposal may pose a risk of ground and surface water pollution, because when mounds of ash are subjected to rain or melting snow, nutrients and heavy metals contained in the ash may be leached and can contaminate groundwater (Hakkila, 1986). One alternative to landfilling is to apply wood-ash to farm lands after site evaluation and permitting by the appropriate government agency. Amending farm fields could introduce heavy metals into the human food chain, but this risk can be minimized by applying ash to forest soils.

Wood-ash is primarily the inorganic constituents of wood left after combustion. The ash is alkaline (pH 12 to 13) and is composed predominantly of oxides of Ca, K, Mg, Na, P, Si, and small amounts of trace elements (Hakkila, 1986). When applied to soil, wood-ash can serve as a source of macro- and micronutrients for

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plants. Ash amendments on peat soils in Finland significantly improved tree growth (Malmstrom, 1952), and ameliorated micronutrient deficiencies in a Scots pine stand (Veijalaine, 1983). The beneficial effects of ash amendment have been reported to persist longer than those of commercial fertilizers (Reinikainen, 1980). The use of wood-ash to amend forest soils may also serve to lessen the effect of nutrient removals via harvesting by returning nutrients to harvested sites. Thus, ash amendments to forest soils could be a positive step in resource recovery (Hakkila, 1986).

Wood-ash also has potential as a liming material (Lerner and Utzinger, 1986; Naylor and Schmidt, 1985; Hakkila, 1986). The dominant constituent, CaO, when exposed to moisture and CO_2, first reacts to form $Ca(OH)_2$ then $CaCO_3$ (Shelton and Shapiro 1976). Naylor and Schmidt (1985) reported that wood-ash had the equivalent neutralizing value of about one-half that for agricultural limestone.

Few studies have been conducted on ash amendment to organic horizons from forested sites, and we did not find any reported for mineral forest soils. The objective of this study was to address basic information needs on the application of ash from wood-fired electric generating facilities to forest soils. More specifically, to determine the effect of wood-ash amendments on: (1) forest soil fertility, cation exchange capacity and pH; (2) seedling growth response and nutrient bioavailability; and (3) seedling growth response to N addition in ash-amended soil.

2. Materials and Methods

2.1. GREENHOUSE STUDY

The soil used in this study was a Hermon sandy loam (sandy, mixed, frigid Typic Haplorthod) collected from the Tunk Mountain area of eastern Maine. Chemical characteristics of this soil are shown in Table I. Material from the O and B horizons was collected separately, placed into plastic buckets, and transported to the greenhouse for air-drying. After drying, soils were thoroughly mixed to ensure homogeneity. Mineral soils were passed through a 0.64 cm sieve; whereas, the organic materials were passed through a 1.27 cm sieve. Forty-eight pots were filled with 213 g (air-dry) O horizon material and another 48 pots with 1325 g (air-dry) of B horizon material. The pots were 15 cm in diameter and 21 cm high with three drainage ports in the bottom.

Ash used in this study was composed of 13% Ca, 1.4% Mg, 2.8% K, 0.9% P, 5.8% Al, and 1.6% Fe. The ash also contained 9 mg kg^{-1} Cd, 41 mg kg^{-1} Cr, 74 mg kg^{-1} Cu, 29 mg kg^{-1} Pb, 156 mg kg^{-1} Ni, 834 mg kg^{-1} Zn, and 9 mg kg^{-1} Mo. If 1 T of ash were applied to 1 ha of soil it would provide 130 kg Ca, 14 kg Mg, 28 kg K, 9 kg P, 59 kg Al and 16 kg Fe. The lime equivalency as $CaCO_3$ was determined to be 21%.

Red maple (*Acer rubrum*) seeds were germinated in small plastic chambers lined with moistened blotter paper, and incubated in a germination cabinet for 5 to

TABLE I

Selected chemical properties of unamended forest soil materials used in this study ($n = 4$)

Horizon	pHw	pHs	CEC	Ca	Mg	K	Na	Al	Fe	Mn	Zn	P	N
			cmol kg^{-1}					cmol kg^{-1}					%
O	3.98	3.12	18	10.2	4.3	0.8	0.5	134	35	124	30	56	1.3
B	5.00	4.74	3	0.13	0.04	0.07	0.01	58	3.2	2.6	0.1	1.6	0.1

45 days at 22 °C. Fifteen germinated seeds were planted into each pot. Red maple was chosen because it is a common regeneration species on clearcut sites where wood-ash is typically landspread.

The potted seedlings were exposed to 14 h supplemental lighting per day from metal halide lamps within a 24 hr photoperiod. Temperature in the greenhouse ranged from 13 to 35 °C during the course of the experiment. The experimental units were brought to 75% of field capacity gravimetrically two times each week. Some leaching of the pots occurred during each watering process as a result of macropore flow, and these leachates were not recycled. Water was applied using a perforated container to simulate raindrop impacts on the soil. Seedlings were sprayed once per week for four weeks with Resmithrin^R for mite control.

The experimental design was a 6 (ash level) × 2 (N level) × 2 (soil horizon) completely randomized block design with four blocks. Each pot was treated with one of six levels of ash on a weight equivalent basis at 0, 4, 8, 12, 16, and 20 Mg ha^{-1}. Out of a total of 96 pots, half (24 each with O and B horizon material) received supplemental N added as fertilizer grade NH_4NO_3 at a rate of 224 kg N ha^{-1} on an area equivalent basis. The remaining pots received no additional N. The 96 pots were grouped into four replications with each replication containing all possible combinations of ash, N, and soil horizon. Ash and fertilizer were added to soils as surficial amendments. Germinated seedlings were planted approximately 1 wk after ash was applied to soils. Soil and seedling properties were analyzed for Analysis of Variance using the Statistical Analysis System (SAS 1982). For most parameters interactions among main effects were non-signicicant for fertilizer and wood-ash treatments. We therefore focus our discussion on the main effects.

After approximately 18 weeks seedlings were removed from the pots and root-collar diameter, stem height, and the number of seedlings per pot were recorded. Leaves, together with the petioles, and roots were clipped from the stem, placed into separate paper bags and dried at 77 °C. Weights of the stems, foliage, and roots were recorded after drying.

The top 2 cm of soil and undissolved ash from each pot was removed prior to sampling. The remaining soil material from each pot was air-dried and thoroughly homogenized. Mineral soils were passed through a 2 mm sieve and organic material through a 0.64 cm sieve. Soils were then transferred to plastic bags until analysis.

2.2. PLANTS ANALYSIS

Foliage was ground to pass through a No. 20 screen (1 mm) using a Wiley mill, Ground tissue was digested using a $HNO_3^-HClO_4$ digestion procedure (Thornton *et al.*, 1985). Digests were analyzed for Ca, Mg, Al, Fe, Mn, Zn, and P using inductively coupled plasma spectrometry. Potassium and Na were measured by atomic absorption. Digests were treated with 0.1% $LaCl_3$ to suppress anionic activity. Total N was determined by macro-Kjeldahl (Bremner and Mulvaney, 1982).

2.3. SOIL ANALYSIS

Air-dry moisture content was measured gravimetrically on a subsample of soil collected from each pot to permit expression of results on an oven-dry soil basis (Robarge and Fernandez, 1986).

Mineral soil pH was measured using a 1:1 dilution with distilled, deionized water (DDI) and a 2:1 (solution: soil) dilution when measured in 0.01 M $CaCl_2$ solution. Organic material pH was measured in DDI H_2O using a 10:1 dilution and in 0.01 M $CaCl_2$ using a 15:1 dilution.

Exchangeable cations and cation exchange capacity were measured following extraction with 1 N NH_4Cl on a mechanical extractor for 16 hr. Extract concentrations of Ca, Mg, Al, Fe, Mn, K, Na, and Zn were measured as described for the tissue digests (Robarge and Fernandez, 1986). Extracted NH_4^+ concentration was quantified

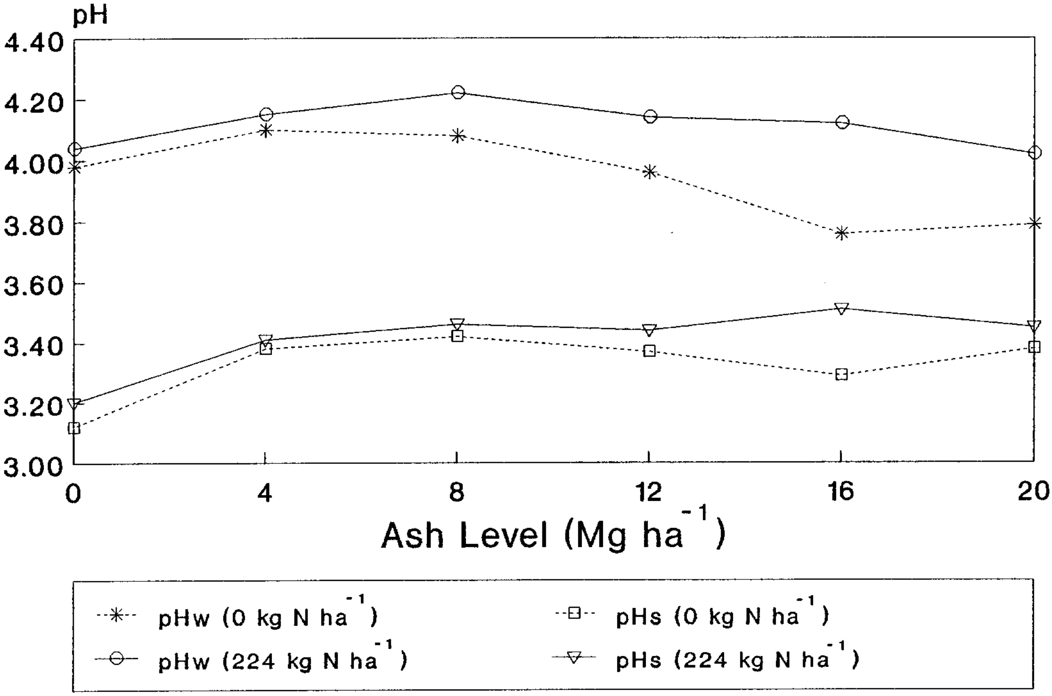

Fig. 1. Changes in pH *vs* the rate of wood-ash amendment on O horizon soils.

using a Wescan^R Ammonium analyzer for cation exchange capacity determinations.

Phosphorus was extracted using 1 N NH_4OAc pH 4.8 as described by McLean *et al.* (1959). Percent total organic matter was measured for each soil sample by loss-on-ignition (Robarge and Fernandez, 1986), a suitable method for this Hermon sandy loam with less than 8% clay. Total N was determined by macro-Kjeldahl procedures (Bremner and Mulvaney, 1982).

3. Results and Discussion

NITROGEN EFFECTS

3.1. *Soil Responses*

The positive effect of N fertilization on O horizon pH is shown in Figure 1. Fertilization with N resulted in slightly higher soil pH, particularly at the higher levels of ash amendment. This is in contrast to the small acidifying effect NH_4NO_3 fertilizer typically has on soils. When measured in water (i.e. pHw), the O horizon pH of both O and 224 kg N ha^{-1} treatments initially increased but started to decline at the 8 Mg ha^{-1} ash level. These declines in pH may reflect a 'salt effect' where soil suspension pH decreases with increasing levels of ash because of increased ionic strength and displacement of H and Al ions from exchange sites. Aluminum hydrolysis thereby increases H ion activity and decreases soil solution pH (McLean, 1984). Soil pH measured in dilute salt solution (i.e., pHs) for both the O and 224 kg N ha^{-1} treatments increased with the initial ash levels as a result of the liming effect of ash, then remained relatively constant (Figure 1). The high ionic strength of the 0.01 M $CaCl_2$ solution apparently subdued the 'salt effect' that was evident from the pHw data.

The efficacy of ash as a limiting material has been reported by several investigators (Lerner and Utzinger, 1986; Naylor and Schmidt, 1985; Hakkila, 1986; Roberts and Wright, 1981; Magdoff *et al.*, 1983). Our data show that N amended O horizon

TABLE II

Effect on N treatment on selected soil variables ($n = 24$)

Variable	N added as kg ha^{-1}			
	O	224	O	224
	O Horizon		B Horizon	
pHw	3.94b	4.12a[a]	5.19a	4.56b
pHs	3.33a	3.41b	4.78a	4.70b
N (%)	1.21a	1.33b	0.11a	0.11a
Mg (cmol kg^{-1})	4.53a	4.69a	0.07a	0.05b
Na (cmol kg^{-1})	2.74a	2.66a	0.24a	0.18b
Al (mg kg^{-1})	79.77a	86.50a	37.93b	47.73a

[a] Values followed by the same letter are not significantly different at the 0.05 level using Duncan's New Multiple Range test.

materials had a slightly higher pH than those not receiving N (Figure 1). This is contrary to other published reports on the effects of N fertilization of forested systems. Radwan *et al.* (1984) studied the effects of several N fertilizers on the pH of forest floors. They reported that the use of NH_4NO_3, $(NH_4)_2SO_4$, and $Ca(NO_3)_2$ resulted in an initial decrease in soil pH. The only other characteristic of the O horizon that differed significantly with N treatments was percent N, with greater total N in the amended soils as would be expected (Table II).

In B horizon soil materials, pH generally increased with increasing ash level due to the liming effect of ash (Figure 2). Unlike the O horizons, the pH of the 224 kg N ha^{-1} treated mineral B horizons was typically lower than the O kg N ha^{-1} soils. It appears that in the B horizon, pH was primarily controlled by cation exchange equilibria. In particular, extractable Al was significantly greater following N treatments in the mineral B horizon (Table II). The lower Al concentration in the O kg N ha^{-1} treated soils may be the result, in part, of displacement of Al ions from exchange sites by base cations derived from the ash. This contention is further supported by the significant increase in the sum of the base cations (SC) with increasing ash loadings (Figure 3), while CEC remained relatively unchanged (Table III). The 0.63 unit decline in B horizon pH_w (Table II) with the 224 kg N ha^{-1} treatment likely reflects displacement of mineral soil Al by NH_4, with the counter anion being fertilizer derived NO_3 in soil solution. The lower pH would

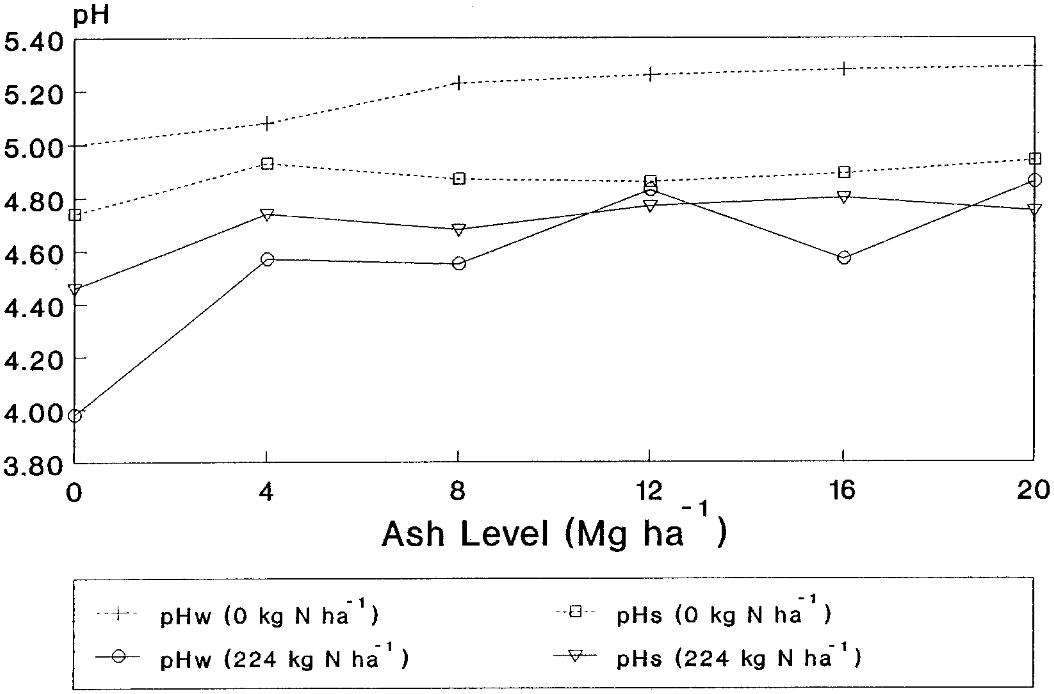

Fig. 2. Changes in pH *vs* the rate of wood-ash amendment on B horizon soils.

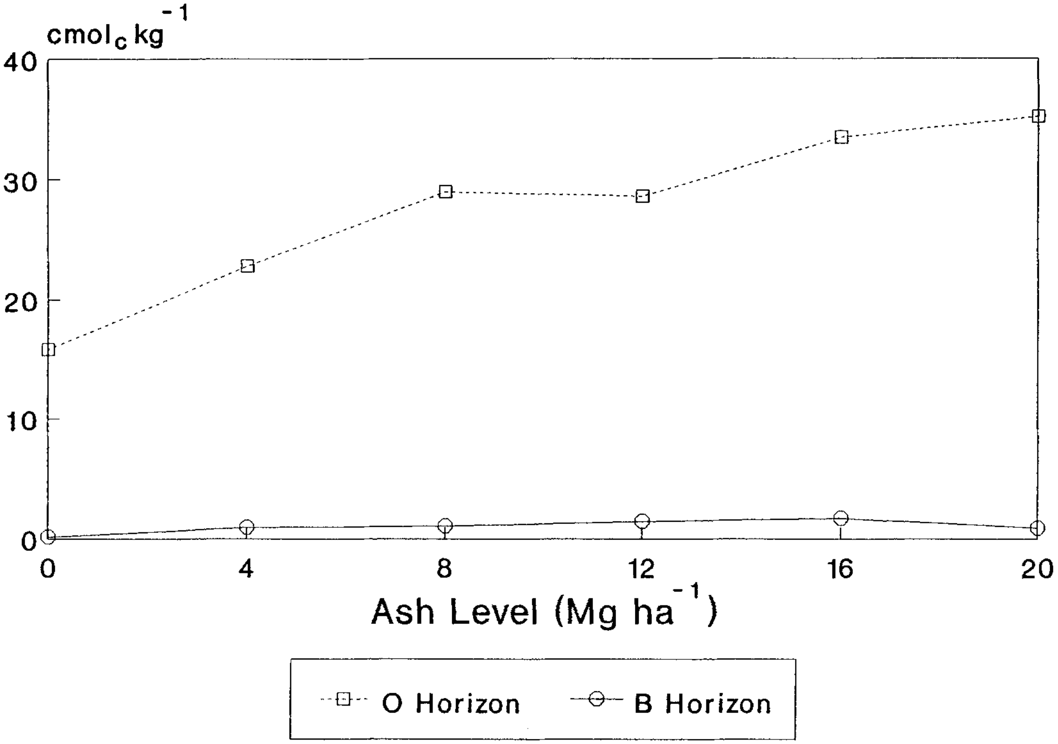

Fig. 3. Sum of exchangeable base cations (SC) *vs* wood-ash level for the O and B horizons.

TABLE III

Coefficient of determination, intercept, slope, and significance for linear regression equations of soil properties with rates of wood-ash amendment ($n = 6$)

Variable	Units	O Horizon				B Horizon			
		r^2	a	b	prob>F	r^2	a	b	prob>F
pHw		0.06	−0.03	4.15	0.08	0.17	0.10	4.54	0.003
pHs		0.21	0.04	3.24	0.001	0.16	0.04	4.64	0.005
Ca	cmol kg^{-1}	0.43	1.74	10.84	0.0001	0.46	0.07	0.14	0.0001
Mg	cmol kg^{-1}	0.17	0.14	4.12	0.003	0.34	0.02	0.001	0.0001
K	cmol kg^{-1}	0.86	1.00	−0.30	0.0001	0.82	0.14	−0.01	0.0001
Na	cmol kg^{-1}	0.90	0.80	−0.08	0.0001	0.72	0.07	−0.02	0.0001
CEC	cmol kg^{-1}	0.35	1.34	17.56	0.0001	0.001	0.02	3.00	0.81
Al	mg kg^{-1}	0.40	−15.36	136.9	0.0001	0.25	−3.78	55.0	0.0003
Fe	mg kg^{-1}	0.52	−3.90	28.20	0.0001	0.001	0.02	3.00	0.81

further promote the formation of labile Al in soil solution. Similar results were reported by Matzner *et al.* (1985) where concentrations of Fe and Al in a mineral soil were lower after receiving NH_4NO_3 fertilizer plus lime treatments. Lower amounts of Na in the N treated soil (Table II) also likely reflect displacement by fertilizer

NH_4 as a result of both mass action and a greater selectivity of soil colloids for NH_4 as compared to Na. Evidence for NH_4 displacement of existing cations is also apparent in B horizon Mg data (Table II). A decrease in available Mg in soils is a common result in agriculture when ammoniacal fertilizers are used (Tisdale *et al.*, 1985).

3.2. *Seedling Response*

Seedlings grown in the O horizon and receiving N had numerically higher average foliage, stem, and root dry weight, average seedling height and average root collar diameter when compared to O kg N ha^{-1} O horizon soils but differences were not statistically different at the 0.05 confidence level (Table IV). Foliar N was significantly higher in the 224 kg N ha^{-1} than the O kg N ha^{-1} treatment which could reflect luxury uptake or response to increased available N under N deficiency conditions (Table IV). The limited amount of B horizon grown foliar tissue prohibited analysis for N concentration. Foliar concentration of Ca was significantly different between O and 224 kg N ha^{-1} treatments in the O horizon. Higher foliar Ca concentrations in seedlings that received the 224 kg N ha^{-1} treatment (Table IV) may be the result of plant uptake of NO_3 which necessitates either the uptake of cations of release of H^+ to maintain electro-neutrality. Calcium was typically the most abundant cation in the system. Fertilization had only a small effect on increasing the N/Ca ratio, and both elements were in much higher concentrations after growing in O horizon material when compared with other reports for red maple foliar chemistry (Young and Carpenter, 1967; Kinerson and Bartholomew, 1977).

Seedling growth declines in response to N fertilization of the mineral B horizon

TABLE IV

Effects of N treatments on selected red maple seedling characteristics ($n = 24$)

Variable		O Horizon		B Horizon	
		O	224	O	224
		kg N ha^{-1}			
Foliage Dry Wt.	(g)	0.44a	0.54a[a]	0.08a	0.04b
Stem Dry Wt.	(g)	0.23a	0.24a	0.08a	0.05a
Root Dry Wt.	(g)	0.33a	0.38a	0.09a	0.05b
Seedling Height	(cm)	12.88a	12.99a	7.52a	6.38b
Root Collar Diameter	(cm)	0.24a	0.26a	0.18a	0.15b
N	(%)	2.54b	3.10a	–	–
Al	(mg kg^{-1})	35a	32a	151a	255a
Fe	(mg kg^{-1})	90a	95a	1487b	2548a
Ca	(mg kg^{-1})	6335b	7036a	6298a	6600a

[a] Values followed by the same letter are not significantly different at the 0.05 level using Duncan's New Multiple Range test.

(Table IV) may have resulted from nutrient imbalances, direct Al and/or Fe toxicity to roots, or competitive inhibition of nutrient uptake. Tissue concentrations of Fe were significantly higher in the 224 kg N ha^{-1} treated seedlings, while Al was numerically but not significantly higher (Table IV). Although the correlations were not strong, both Fe and Al tissue concentrations were significantly and negatively correlated with various growth characteristics of seedlings. Regression analysis of tissue Fe *vs* foliage dry weight yielded an r^2 value of 0.17 (Prob $> F$ 0.004), while the same analysis of Al *vs* average seedling height resulted in an r^2 value of 0.10 (Prob $> F$ 0.002). The increased availability of Fe and Al in the (224 kg N ha^{-1}) treated soil was likely attributable to the 0.63 unit decrease in soil pH (Table II) and the displacement by NH_4 as discussed earlier. The large differences in Al and Fe tissue concentrations between O and B horizon grown seedlings clearly illustrates the different chemical environment for seedling roots in these two soil materials.

ASH EFFECTS

3.3. *O Horizon*

Concentrations of exchangeable base cations increased with increasing ash level due to the dissolution of ash (Figure 4). The relative increase in concentrations of base cations between the control and 20 Mg ha^{-1} treatments was:

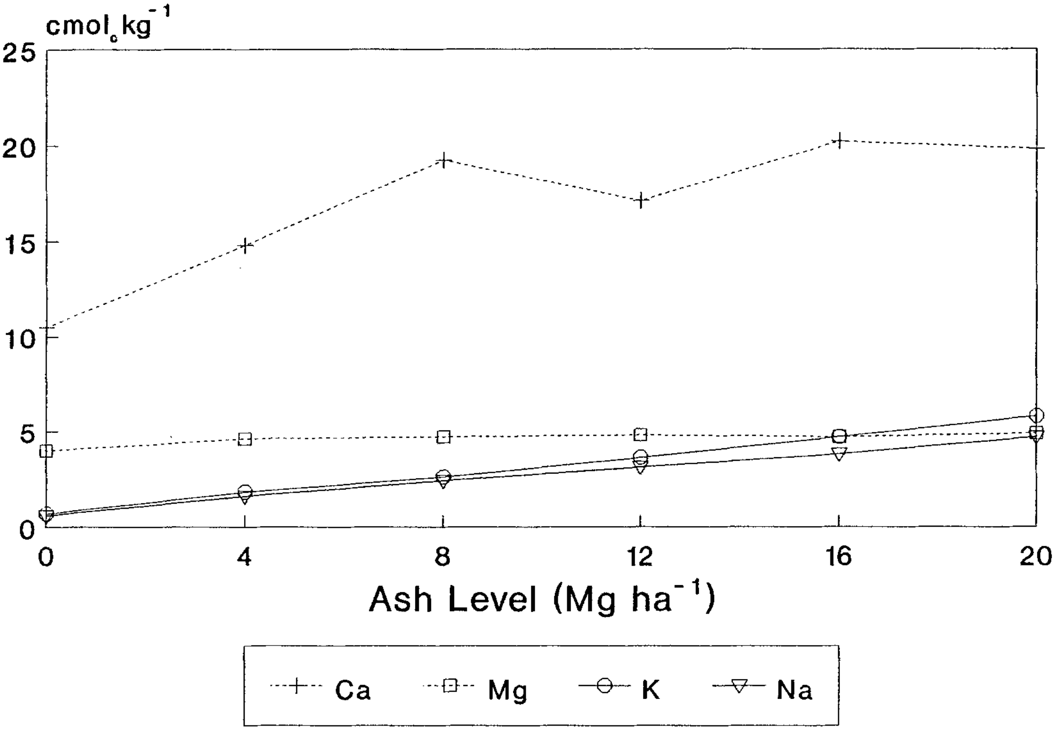

Fig. 4. Exchangeable base cations *vs* the rate of wood-ash amendment on O horizon soils.

Ca > K > Na > Mg.

When compared with conditions in the control (Ca > Mg > K > Na) the relative abundance of exchangeable soil cations was shifted to resemble the relative abundance of cations in ash (Ca > K > Mg > Na). The greater relative increase of Na over Mg reflects Na's lower initial concentrations and higher mobility. Cation exchange capacity increased significantly in the O horizon with ash amendment (Table III) because of the liming effect of ash, which increased the pH-dependent fraction of the CEC. The influx of cations resulted in significantly more exchangeable base cations (Figure 3).

Both extractable Al and Fe were significantly and inversely related to increasing ash amendments (Figure 6). The reduced availability of Al and Fe resulted from displalcement of the acid cations by base cations derived from the dissolution of ash. This is further shown by the increased SC (Figure 3), which indicates that lower soil Al and Fe was at least partly the result of cation exchange reactions rather than a simple pH effect on Al and Fe solubility. The relatively small increase in pH with ash amendment (maximum change pHw = 0.59, pHs = 0.25) would not fully account for the reduced availability of Al and Fe.

Only Mn increased significantly between the control (Table 1) and all ash amended treatments, presumably due to additions of Mn in the ash amendments. Mean Mn

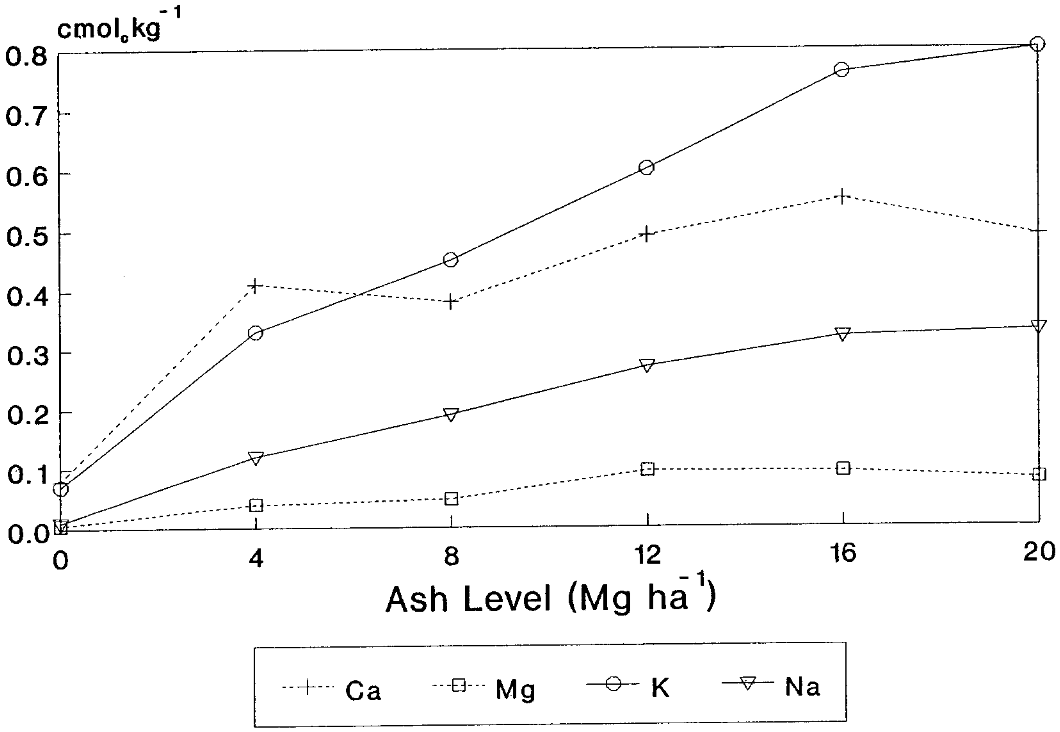

Fig. 5. Exchangeable base cations *vs* the rate of wood-ash amendment on B horizon soils.

concentration for all ash amended O horizon soils was 1540 mg kg^{-1}. Other soil variables measured (Zn, P, and N) did not differ significantly with ash amendment nor were any numerical trends detected. Mean concentrations for all experimental units of O horizon material were 63 mg kg^{-1}, 2036 mg kg^{-1}, and 2.8% for Zn, P, and N, respectively.

3.4. *B Horizon*

Amendment of the B horizon with ash also increased exchangeable base cations (Figure 5). The relative increase of adsorbed base cations between the control and the 20 Mg ha^{-1} treatment in $cmol_c$ kg^{-1} was:

$$K > Ca > Na >> Mg.$$

When compared with conditions in the control (Ca > K > Mg > Na) (Table I) the balance of cations changed with respect to the abundance of Ca and K. The greater adsorption of K may be due to the higher mobility of K than that of Ca. Also, the lower CEC of the mineral B horizon, as compared to the O horizon, would result in less of a competitive advantage for divalent compared with monovalent cations.

Extractable Al decreased significantly with increasing ash level (Figure 7), due

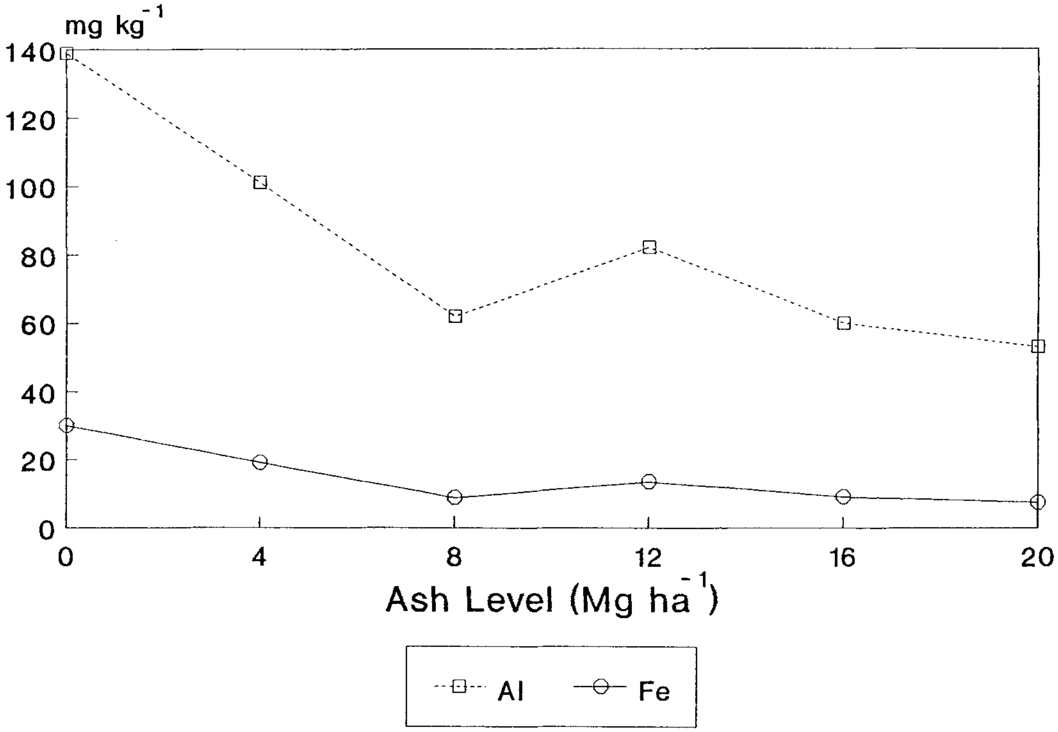

Fig. 6. Exchangeable Al and Fe *vs* the rate of wood-ash amendment on O horizon soils.

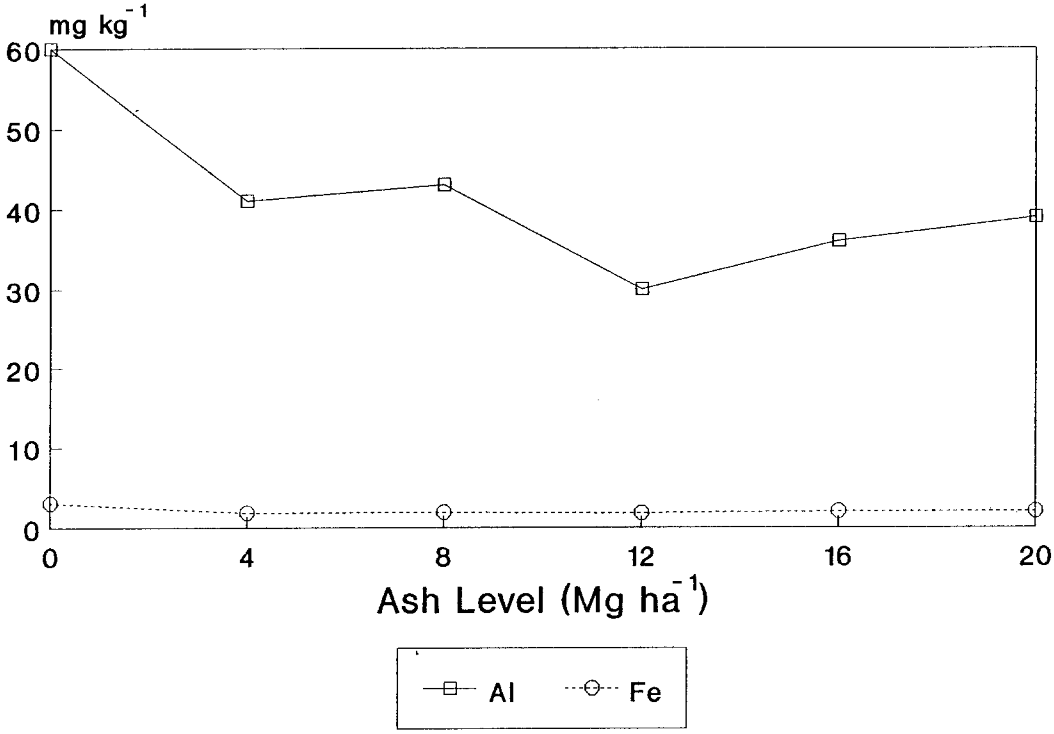

Fig. 7. Exchangeable Al and Fe *vs* the rate of wood-ash amendment on B horizon soils.

to base cations as in the O horizon (Figure 3). A numerical trend for decreasing Fe concentrations was also detected; however, it was not statistically significant (Figure 7). Similar results were reported by Matzner *et al.* (1985) in which the concentrations of both Al and especially Fe in a mineral soil decreased as a result liming.

No other trends or significant differences resulting from ash amendment were evident for other variables measured (i.e. CEC, Mn, Zn, P, and N). Mean concentrations for the experimental units amended with ash were CEC 3.06 cmol_c kg^{-1}, Mn 3.12, Zn 0.74, P 2.0 mg kg^{-1} and 0.11% N.

3.5. *Seedling Response*

Ash amendment of the O horizon had no detectable effect on the growth of seedlings for the parameters measured within the 18 week growth period; however, foliar chemistry of red maple seedlings was altered by ash additions (Table V). As a result of increased Al concentration in the soil solution, tissue concentrations of Al incresed with increasing ash amendment up to 12 Mg ha^{-1} where concentrations peaked, then began to decline. Foliar Mg concentration was significantly higher in the control than in ash treated seedlings; however no trends were apparent among ash treatments. A weak trend toward increasing Mn concentration with increasing

TABLE V

Tissue dry weight, root collar diameter (RCD), seedling heigth (Ht), and chemical composition of seedlings grown in the O horizon pooled among N treatments ($n = 8$)

Ash	Dry weight			RCD	Ht	Al	Ca	Fe	K	Mg	Mn	Na	P	Zn	N
	Foliage	Stem	Root												
Mg ha^{-1}	g			cm		mg kg^{-1}									%
0	0.49a[a]	0.27a	0.30a	0.28a	13.4a	17b	7076a	75b	4899b	4876a	1382ab	10b	2231a	48a	2.7a
4	0.54a	0.27a	0.42a	0.24a	13.4a	22b	6445ab	84ab	4743b	4335b	1566b	64b	1983a	37a	2.6a
8	0.70a	0.23ab	0.44a	0.24a	13.2a	30ab	5572b	95ab	5985ab	3885b	1248b	148ab	1972a	37a	2.8a
12	0.37a	0.18b	0.33a	0.23a	12.2a	55a	7288a	127a	7677a	3859b	1240b	359ab	2273a	37a	3.0a
16	0.43a	0.25ab	0.34a	0.25a	12.6a	38ab	6862a	83ab	6385ab	3967b	1744ab	1404a	2091a	38a	2.9a
20	0.39a	0.20ab	0.30a	0.26a	12.9a	39ab	6871a	91ab	6855ab	3997b	1903a	744ab	1863a	168a	2.9a

[a] Values followed by the same letter(s) are not significantly different at the 0.05 level using Duncan's New Multiple Range test.

ash level was evident due to ash addition. Tissue K for O horizon grown seedlings increased from control levels (Table V) with increasing ash level to the 12 Mg ha^{-1} treatment; whereas Na peaked at the 16 Mg ha^{-1} treatment. The increase in tissue Na and K was due to increased levels of soil Na and K from ash amendments, and resulted in a higher foliar ratio of Na or K to Ca or Mg.

Physical characteristics of seedlings grown in ash amended B horizon material showed a few statistically significant but weak correlations with ash amendments. When soil base cation concentrations, which were highly correlated with ash amendment, were regressed with plant growth variables several positive and significant relationships were detected (Table VI). This suggests that seedling growth was significantly affected by soil base cation composition. Seedlings appear to respond in proportion to changes in soil exchangeable base cations that result from ash amendments, rather than directly in proportion to the amounts of ash added to the soil.

Tissue analyses for B horizon grown seedlings showed Al concentrations in foliage were significantly and negatively correlated with rates of ash loading with a correlation coefficient of -0.33 (Prob $> F$ 0.02). Other tissue element concentrations (i.e. Ca, Fe, K, Mg, Mn, Na, P, and Zn) did not significantly vary with ash amendment nor were any numerical trends evident when compared to the controls (Table I). Means of foliar element concentrations for all B horizon experimental units amended with ash pooled among N treatments were Ca, 6339; K, 6325; Fe, 2108; Mg, 1925; Mn, 666; Na, 464; P, 740 and Zn, 6107 mg kg^{-1}. These overall averages are very similar to values for red maple foliage reported by Kinerson and Bartholemew (1977) and Young and Carpenter (1967), with the exception of slightly higher P and much greater Zn, Fe, and Mn. Young and Carpenter (1967) reported average values for Zn, Fe, and Mn in red maple foliage of 33, 105, and 721 mg kg^{-1}, respectively. We interpret these differences as being due to the fact that most naturally grown red maple seedlings are influenced by both O and B horizon characteristics simultaneously. It is evident from our data that although these metals appeared more abundant in the O horizon (Table I), they were much more available for uptake in the B horizon as judged by foliar chemistry (Table IV). One explanation is that high dissolved organic carbon in O horizon soil solutions complexes these metals reducing their availability.

TABLE VI

Coefficients of determination and significance level for linear regressions between B horizon soil variables and red maple seedling foliage dry weight ($n = 6$)

Variable	r^2	Prob>F
Ca	0.17	0.004
Mg	0.14	0.008
K	0.12	0.02

Often changes in soil chemistry as a result of ash amendment were not reflected by corresponding changes in seedling characteristics. For example, while base cation concentrations increased in the soil, foliar concentrations did not change except for K and Na levels in seedlings grown in O horizon material. The lack of seedling growth response to ash amendment may be the result of the short-term nature of the experiment and the young age of the seedlings.

4. Conclusions

Although wood-ash as a soil amendment is notably lacking in N, additions of fertilizer N did not result in markedly improved red maple seedling growth within the confines of this short-term greenhouse experiment. A small positive influence was evident from N additions for seedlings grown in O horizon soil. These results show the need for further investigations under field conditions, where O and B horizons together comprise the rooting zone and support seedling growth in an integrated manner. Wood-ash amendments also had little effect on seedling growth in either O or B horizon soil materials except for increased K and Na concentrations in O horizon grown foliage. If changes in soil and plant chemistry are of a similar magnitude under field conditions as those seen in this experiment, it appears that land-spreading may be suitable as a method of wood-ash recycling. Field studies are now needed to develop the dose-response models necessary for formulating regulatory policy and sound forest management practices.

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