



Wood ash effects on plant and soil in a willow bioenergy plantation

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Abstract

Intensive management for biomass production results in high rates of nutrient removal by harvesting. We tested whether wood ash generated when burning wood for energy could be used to ameliorate negative soil effects of short-rotation harvesting practices. We measured the temporal and spatial dynamics of soil nutrient properties after wood ash applications in a willow plantation in central New York State and determined the influence of wood ash application on willow growth. Wood ash was applied annually for 3 years at the rates of 10 and 20 Mg ha⁻¹ to coppiced willow, *Salix purpurea*, clone SP3. Wood ash application significantly increased soil pH in the 0–10 cm soil layer from 6.1 in the control to 6.9 and 7.1 in the 10 and 20 Mg ha⁻¹ treated plots. Wood ash application significantly increased soil extractable phosphorus, potassium, calcium, and magnesium concentrations. Potassium was the element most affected by wood ash treatment at all soil depths. Wood ash had no significant effect on nutrient concentrations of foliar, litter, and stem tissue. Wood ash did not affect either individual plant growth or plot biomass production, which declined over the course of the study; it did increase the size of stems, but this effect was balanced by a decrease in the number of stems. Applying nitrogen as well as wood ash might be required to maintain the productivity of this SRIC system.

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1. Introduction

Renewable crops have been developed as sources of bioenergy and bioproducts in the northeastern United States because of the environmental costs of fossil fuels. Short-rotation intensive cultural (SRIC) systems utilize fast-growing species, such as *Salix* spp. and *Populus*

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spp., that coppice vigorously following harvest, and have the potential to yield many successive crops with short rotation. While SRIC systems increase the rate of biomass production, nutrient removal through multiple harvests could ultimately limit production, and sustainability. For example, nutrient removals ($\text{kg ha}^{-1} \text{ year}^{-1}$) from annual biomass production of 15–22 dry Mg ha^{-1} in a willow plantation in central New York were 75–86 N, 10–11 P, 27–32 K, 52–79 Ca, and 4–5 Mg [1].

Wood ash generated during the combustion of wood for energy contains both macro- and micro-nutrient elements required for plant growth. The most abundant elements include Ca and K with fair amounts of Mg, Al, Fe, P, and small amounts of trace elements [2]. Nitrogen, including organic and inorganic forms, is present only at low levels in wood ash because it is volatilized during combustion. The properties of wood ash vary depending on species of wood burned, the amount of bark burned, conditions for growth, and contamination with materials such as soil from harvest operations or metals from treated construction debris. The conditions under which the wood is burned are also important, with carbonates and bicarbonates produced at combustion temperatures below 500 °C, while oxides and hydroxides are most prevalent at or above 1000 °C [3].

Wood ash can be applied to harvested sites as a liming amendment with major and minor nutrient elements for plant growth. Wood ash application to agricultural lands has increased growth of alfalfa [4], bean [5], and fescue [6]. Studies performed on cut-away peat land in Finland illustrate the long-term benefits of ash treatments for the production of coppiced mixed birch and willow [7,8] and Scots pine [9,10]. In northern Germany, wood ash applications improved the nutritional status of a pine stand [11]. On the other hand, wood ash treatments decreased the growth of white spruce seedlings in an Orthic Gray Luvisol soil [12] and had little effect on Norway spruce seedlings shortly after treatment [13].

The benefits of wood ash on SRIC plantations have not been studied. The first objective of this study was to describe soil nutrient concentrations

with depth and over time following wood ash applications in a willow plantation in central New York State. The second objective was to assess the influence of wood ash application on willow growth in the same plantation.

2. Material and methods

2.1. Study site

Our experimental plots are located at the Forestry Genetics Field Station of the State University of New York College of Environmental Science and Forestry in Tully, New York (42°47'N, 76°7'E). The plots receive approximately 1050 mm of precipitation annually with about 550 mm falling during the growing season, from May through October. The soil at the site is a Palmyra gravely silt loam (Glossoboric Hapludalf) on 0–3% slopes [14]. Due to the limestone and shale parent material, the pH is relatively high, ranging from medium acid to neutral. The soil has a relatively high base status with a base saturation of 60–70%. This deep, well-drained soil is a fairly productive agricultural soil with a medium to heavy texture, 24% clay to a depth of 40 cm, and high-coarse fragment fraction, as much as 32% in the 20–40 cm layer [15].

2.2. Experimental design

This study was overlaid on an existing split-plot design with 3 replicates of each treatment (Fig. 1). Fertilization (with two levels: fertilized and unfertilized) was the whole-plot factor. Fertilized plots received 336 kg ha^{-1} N as ammonium nitrate, 112 kg ha^{-1} P as triple superphosphate, and 224 kg ha^{-1} K as muriate of potash annually from 1987 to 1991, except that in 1990 N was applied as urea through an irrigation system [16]. Spacing (with three levels: 15, 30, and 45 cm) was established as the sub-plot factor in the spring of 1987. To evaluate wood ash treatment effects, we had to account for variation resulting from these other variables. Spacing effects were controlled by treating the three spacing plots as one experimental unit, and past fertilization effects were

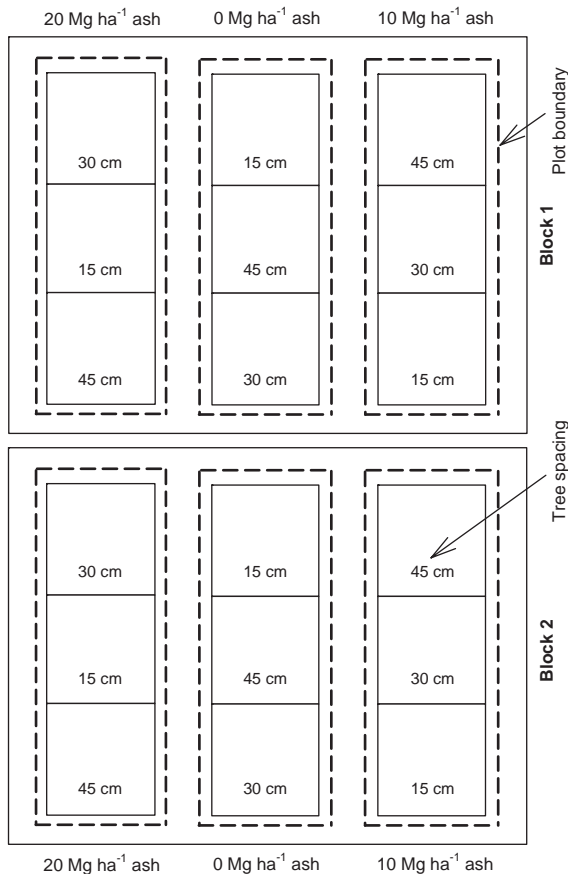


Fig. 1. Plot layout of 0, 10, and 20 Mg ha⁻¹ wood ash treatment at the Forestry Genetics Field Station of the State University of New York College of Environmental Science and Forestry.

eliminated by blocking [17]. Genetic variation was minimized by planting a single vegetative propagated clone (SP3) of *Salix purpurea* from a single source.

2.3. Wood ash application and characteristics

Wood ash was collected from a temporary storage facility of the Lyons Falls Pulp and Paper Company in New York. Prior to application, the ash was homogenized by mixing it on plastic tarps. Wood ash was applied to the treatment plots in late April 1992, 1993, and 1994 before the growing

season. Wood ash was applied by hand to each plot at the rates of 0 (control), 10, and 20 Mg dry mass ha⁻¹. The moisture content of the ash was determined at the time of spreading to achieve these application rates. Subsamples (0.5 kg) were collected at the time of application for physical and chemical characterization. Ash pH was determined from one 20 g subsample from each treated spacing plot ($n = 12$) in a 2:1 deionized water:ash mix using a glass electrode (Orion Research Digital Ionanalyser Model 601A).

A method for wood ash characterization was developed to evaluate various physical and chemical characteristics that are important in ecosystem response to wood ash treatment. The samples were ground with a mortar and pestle to break down aggregates. Acid-soluble, charcoal, and insoluble components of the ash were determined using 1 g subsamples [18]. The acid-soluble portion of the ash was extracted by digestion with 6 N HCl. The extractant was analyzed for acid-soluble total N, total P, K, Ca, Mg, and Na. Charcoal percent was determined on the acid-washed residue by loss on ignition at 470 °C for 16 h. The ash remaining after combustion was then subjected to the same acid extraction and analysis as the original wood ash. The results of the two analyses were summed to find the total ash nutrient concentration of the wood ash.

Nitrogen was determined by the macro-Kjeldahl method [19] and P was determined colorimetrically with vanadate-molybdate [20]. Concentrations of K, Ca, Mg, and Na were determined by atomic absorption spectrophotometry (AAS).

2.4. Soil sampling and analyses

Soil samples were collected before and after the wood ash was applied each year. A 7.6-cm-diameter bucket auger was used to sample at three depth increments: 0–10, 10–20, and 20–40 cm. Three samples were taken from each depth increment from randomly located points within each plot and returned to the lab for chemical analysis. Before sampling post-treatment soils, any wood ash remaining on the surface at a sample point was first removed to expose the mineral soil.

During sieving, fragments greater than 2 mm were removed, and the entire volume of each soil sample was homogenized. Air-dried soil samples were analyzed for pH; total N and extractable P; exchangeable K, Ca, and Mg; and cation exchange capacity (CEC). Soil pH was determined using a glass electrode in a 2:1 deionized water–soil mix. Total N concentration was determined via the macro-Kjeldahl method [19], and extractable P was determined using the Troug method [20]. Exchangeable K, Ca, and Mg were extracted with neutral ammonium acetate and determined by AAS. Cation exchange capacity was determined by the ammonium saturation method [21].

2.5. Plant sampling and analyses

Litter was collected weekly from mid-June through leaf-fall in November from 1992 to 1994 in tray-style samplers designed to accommodate the springtime low growth habit of coppiced willow clone SP3. Leaves were removed from the mesh surfaces of traps weekly, composited by calendar month, and weighed after oven drying. Litter production was calculated by summing the dry weights (105 °C) of monthly litter samples.

Woody biomass production (Mg ha^{-1}) was obtained from harvests of the spacing plots at the middle of December in 1992–1994. Stools were cut approximately 3 cm above the ground using a hand-held brush saw. Fresh stem weights were recorded in the field, and 1 kg subsamples from each plot were taken from the cut material to determine moisture and nutrient concentration. Annual aboveground biomass production (Mg ha^{-1}) is the sum of litter production and the harvested aboveground biomass in an annually coppiced system.

Tissue for chemical analysis was collected at the end of August in 1992–1994. Stems were randomly selected at the center of each spacing plot. The number of stems varied but was sufficient to provide 500 g of foliage when all the leaves were stripped from each stem.

To determine the seasonal maximum foliar biomass, 6 stems stratified on relative stem size (small, medium, and large) were collected in July from each spacing plot. Leaves and stem samples

were dried at 65 °C and weighed. The weights of stems harvested in December were used to estimate the foliar biomass in July, based on the ratio of foliar to stem weight measured in July.

Dried litter, foliage, and biomass samples were ground in a Wiley mill (1 mm screen) and analyzed for N, P, K, Ca, and Mg following the methods described above for extracts of wood ash samples.

2.6. Data analyses

A completely randomized design was used to compare elemental concentrations of applied wood ash. Soil nutrient concentrations were analyzed using a split-plot design with the three wood ash treatment levels as the whole-plot factor and the three different soil depths as the sub-plot factor. Foliar, litter, and stem nutrient concentrations were analyzed using a completely randomized block design with the 3 wood ash treatment levels and blocked by past plot fertilization treatment (fertilized or unfertilized). Analysis of variance (ANOVA) procedures with Tukey's multiple comparison tests were used to evaluate significant effects of the treatments at $\alpha = 0.05$.

3. Results

3.1. Wood ash characterization

Most of the nutrients in the applied wood ash were in the acid-soluble fraction (Table 1). The wood ash contained 0.03–0.09% total N, 0.5–0.6% P, 1.6–3.6% K, 7.1–15.5% Ca, 0.6–1.3% Mg, and 0.27–0.30% Na. Thus the relative abundance of nutrients in applied wood ash was $\text{Ca} \gg \text{K} > \text{Mg} \gg \text{P} > \text{Na} \gg \text{N}$. Nitrogen, including organic and inorganic forms, is only present at low levels in wood ash due to its volatilization during combustion. The contribution of charcoal to the nutrient content of the ash was negligible because concentrations in the charcoal were low.

The composition of the wood ash was not constant over the three years of the study. Because the acid-soluble fraction decreased over time, the amount of nutrient applied in wood ash

Table 1
Wood ash physical and chemical properties in 1992, 1993, and 1994^a

Year	Fraction	Proportion (%)	N (g kg ⁻¹)	P (g kg ⁻¹)	K (g kg ⁻¹)	Ca (g kg ⁻¹)	Mg (g kg ⁻¹)	Na (g kg ⁻¹)
1992	Soluble	47.2 (0.8)	0.9 (0.0)	5.6 (0.3)	35.6 (1.9)	152.8 (8.6)	12.5 (0.7)	2.9 (0.2)
	Charcoal	25.9 (0.6)	— ^b	0.3 (0.0)	0.4 (0.0)	2.6 (0.5)	0.4 (0.0)	0.1 (0.0)
	Insoluble	26.9 (0.9)	—	—	—	—	—	—
	Total	100	0.9 (0.0)	5.9 (0.3)	36.1 (1.9)	155.4 (9.1)	12.9 (0.8)	3.0 (0.2)
1993	Soluble	31.2 (0.3)	0.6 (0.0)	3.5 (0.0)	31.3 (0.4)	94.8 (0.8)	9.1 (0.2)	2.6 (0.0)
	Charcoal	16.0 (1.0)	—	0.6 (0.0)	0.4 (0.1)	0.7 (0.0)	0.2 (0.0)	0.1 (0.0)
	Insoluble	52.9 (1.1)	—	—	—	—	—	—
	Total	100	0.6 (0.0)	4.0 (0.0)	31.7 (0.5)	95.4 (0.8)	9.3 (0.2)	2.7 (0.0)
1994	Soluble	22.8 (0.1)	0.3 (0.0)	2.7 (0.0)	15.2 (0.1)	69.9 (0.5)	6.1 (0.2)	—
	Charcoal	3.4 (0.3)	—	1.9 (0.1)	0.4 (0.0)	0.9 (0.1)	0.1 (0.0)	—
	Insoluble	73.8 (0.2)	—	—	—	—	—	—
	Total	100	0.3 (0.0)	4.6 (0.1)	15.5 (0.1)	70.8 (0.5)	6.2 (0.1)	—

^aStandard errors are in parentheses ($n = 12$).

^b—, represents not detected.

also decreased over the three years of the study (Table 1).

Wood ash of this type, i.e. from clean fuel consisting of bark and whole-tree chips, is generally free of heavy metal contamination [22]. Trace metal concentration in the ash was low in our study. Concentrations of As, Cd, Cr, Pb, Hg, and Se were all below detection limits. The average pH of the wood ash was 10.6.

3.2. Soil analysis

Prior to wood ash application, soil chemical characteristics were analyzed on each treatment plot (Table 2). Soil chemical properties were not significantly different between plots before treatment, but did differ with soil depths (Table 2).

Nitrogen, P, K, Mg, and CEC on pretreated plots decreased significantly with depth, while pH and Na concentration were the highest at 20–40 cm depth.

The effects of wood ash on soil varied according to wood ash application rates and soil depth (Fig. 2). Wood ash application increased soil pH, especially at 0–10 cm depth ($p < 0.01$). In the 0–10 cm soil layer, soil pH increased from 6.1 to 6.9 in the control and 7.1, in the 10 and 20 Mg ha⁻¹ treatment plots. The increase in pH was smaller at 10–20 cm depth, ranging 6.3 in the controls to 6.5 and 6.7 in the 10 and 20 Mg ha⁻¹-treated plots. Changes in total N by wood ash application were slight, with a significant increase only at the 10 Mg ha⁻¹ treatment in 1992 ($p = 0.03$).

Table 2
Pretreatment soil chemical properties from plots receiving 0, 10, and 20 Mg ha⁻¹ wood ash treatments^a

Depth (cm)	Treatment (Mg ha ⁻¹)	pH	N (mg kg ⁻¹)	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)	Na (mg kg ⁻¹)	CEC (cmol _c kg ⁻¹)
0–10	0	6.2b	2027a	69b	135a	1602a	126a	49b	17.7a
		(0.2)	(130)	(18)	(28)	(62)	(8)	(7)	(0.8)
	10	6.2b	1901a	58a	148a	1586a	151a	50a	18.8a
		(0.3)	(73)	(13)	(29)	(200)	(26)	(6)	(0.9)
	20	6.2b	1805a	51a	141a	1651a	159a	53a	18.2a
		(0.2)	(134)	(15)	(29)	(209)	(28)	(7)	(0.7)
10–20	0	6.4ab	1678b	34b	67b	1690ab	117ab	64a	17.8a
		(0.1)	(51)	(1)	(17)	(142)	(11)	(9)	(0.6)
	10	6.3ab	1654b	32b	88b	1729ab	140ab	107a	17.7a
		(0.2)	(56)	(4)	(23)	(77)	(17)	(25)	(0.7)
	20	6.3ab	1645b	33b	77b	1640ab	132ab	86a	17.8a
		(0.1)	(74)	(4)	(23)	(159)	(23)	(14)	(0.7)
20–30	0	6.6a	969c	44b	45c	1466b	101b	71a	14.7b
		(0.1)	(33)	(2)	(7)	(43)	(6)	(9)	(0.9)
	10	6.4a	1121c	37b	59c	1472b	114b	82a	15.1b
		(0.1)	(98)	(6)	(15)	(166)	(23)	(17)	(1.0)
	20	6.4a	1183c	34b	46c ^c	1285b	89b	78a	13.8b
		(0.1)	(72)	(3)	(11)	(65)	(4)	(11)	(0.5)

^aStandard errors are in parentheses ($n = 6$). Means with the same column with the same letter are not significantly different at $\alpha = 0.05$.

Extractable P, K, Ca, and Mg concentrations were higher in wood ash-amended soils than in the control soils (Fig. 2). Extractable P concentrations increased linearly with increasing ash application at 0–10 cm depth. The concentration of P on soils receiving 0, 10, and 20 Mg ha⁻¹ was 45, 52, and 68 mg kg⁻¹ in 1992 ($p = 0.05$) and 48, 74, and 115 mg kg⁻¹ in 1993 ($p < 0.01$). There was no treatment effect, however, at greater depth.

Potassium was the element most affected by wood ash treatment at all soil depths (Fig. 2). Soil K on plots receiving 20 Mg ha⁻¹ wood ash was more than double that of the control at 0–10 cm depth in 1993 and 1994 ($p < 0.01$). The increase in K with wood ash applications was less at 10–20 cm soil depth, but still significant in 1993 and 1994 ($p < 0.01$).

Like K, Ca concentrations generally increased with increasing ash application at shallow soil depth (Fig. 2). Soil Ca concentrations at 0–10 cm soil depth significantly increased ($p < 0.01$) with increasing ash application in 1993 and 1994, with

concentrations of 2408, 4077, and 4888 mg kg⁻¹ and 1569, 3626, and 3309 mg kg⁻¹ on plots treated with 0, 10, and 20 Mg ha⁻¹, respectively. Magnesium showed similar patterns to Ca, but Mg concentrations were only 10% those of Ca. Wood ash application significantly increased Mg concentrations only at 0–10 cm depth in 1994 ($p < 0.01$). Sodium in the soil was only slightly increased by wood ash treatment. Wood ash application increased CEC significantly only in the 0–10 cm soil layer in 1994.

3.3. Plant analyses

Willow tissues were examined to determine treatment effects on biomass production and nutrient concentration (Fig. 3). Wood ash application had neither significant effect on biomass production, nor on the component stem, foliar, or litter production in 1992, 1993, or 1994. Total woody biomass production declined over time

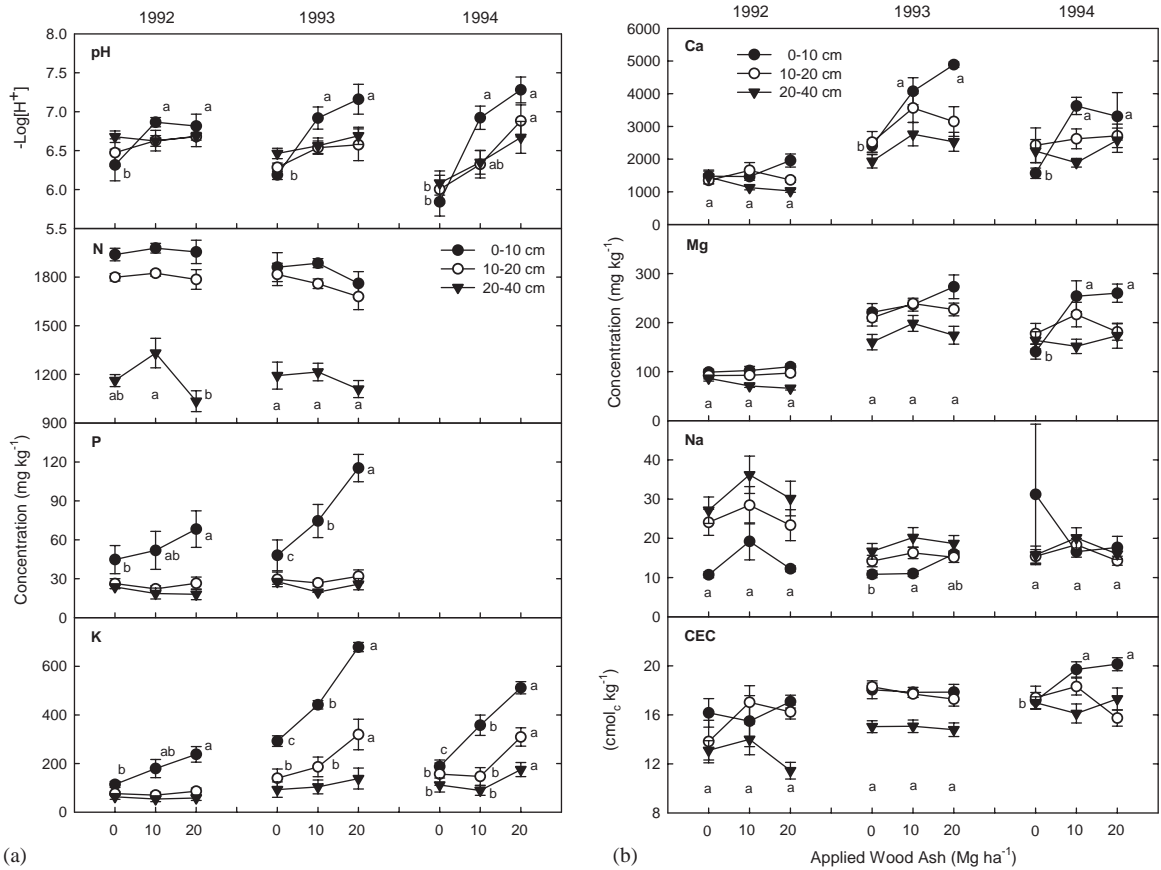


Fig. 2. Soil nutrient concentrations by soil depth, 0–10, 10–20, and 20–40 cm, for plots receiving 0, 10, and 20 Mg ha⁻¹ wood ash treatments in 1992, 1993, and 1994. Means of wood ash main effect within each year with the same letter are not significantly different at $\alpha = 0.05$. Different letters on the same soil depth within each year showed significant differences among wood ash treatments at $\alpha = 0.05$. Vertical bars represent one standard error of the mean ($n = 6$).

regardless of treatment, with the greatest decline in the stem component.

The number of stems per square meter of stool was measured only in 1992. The mean number of stems was significantly fewer in the ash-treated plots (8500 m⁻²) ($p = 0.01$) than in the control plots (9700 m⁻²). The biomass did not differ significantly by treatment ($p = 0.75, 0.49,$ and 0.74 in 1992, 1993, and 1994, respectively), because the stems grew larger when there were fewer of them.

Foliage, litter, and stem nutrient concentrations were examined to determine the effect of wood ash treatments on general nutrient status of willow (Table 3). Wood ash treatments had few significant

effects on concentrations of nutrients in foliar, litter, and stem tissue. Significant differences included decreased foliar Ca in 1994 ($p = 0.04$), increased litter P in 1994 ($p = 0.02$), and increased litter K in 1993 ($p < 0.01$) and 1994 ($p = 0.02$) with 20 Mg ha⁻¹ wood ash treatment.

4. Discussion

4.1. Ash characterization

Wood ash can supply significant nutrients to an intensively managed plantation (Table 1). Wood ash application could therefore be used to

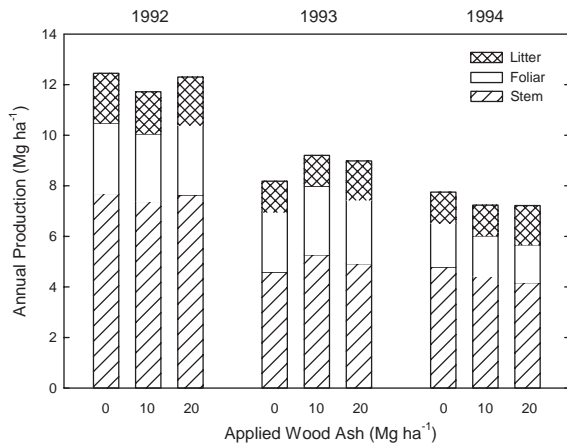


Fig. 3. Willow growth response to wood ash applications of 0, 10, and 20 Mg ha⁻¹ in 1992, 1993, and 1994. In an annually coppiced system, biomass at the end of the growing season is equivalent to annual productivity.

counteract nutrient deficiencies and imbalances in soil and to replace nutrients removed by harvesting. Wood ash also acts as a liming agent. As a liming agent, wood ash of this type would have approximately half the effect of an equivalent weight of CaCO₃ [18,23].

Even though the wood ash in this study came from the same source each year, its physical and chemical properties were not very predictable (Table 1). The sources of wood to the Lyon Falls mill probably varied by tree species and soil types, which affect the quality of the ash produced [24]. High-density hardwoods, such as shagbark hickory (*Carya ovata*), produce ash with the greatest alkalinity, while conifers and low-density hardwoods, such as silver maple (*Acer saccharinum*), produce ash of much lower alkalinity, with conifers having the lowest alkalinity [25]. To

Table 3

Nutrient concentrations in willow biomass receiving wood ash applications of 0, 10, and 20 Mg ha⁻¹ in 1992, 1993, and 1994^a

Treatment (Mg ha ⁻¹)	Foliage					Litter					Stem				
	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
1992															
0	2.34a (0.10)	0.19a (0.01)	2.15a (0.10)	1.66a (0.04)	0.20a (0.01)	1.82a (0.07)	0.16a (0.01)	0.94a (0.10)	2.09a (0.04)	0.18a (0.01)	0.67a (0.03)	0.12a (0.00)	0.43a (0.07)	0.44a (0.01)	0.05a (0.00)
10	2.13a (0.08)	0.19a (0.01)	2.05a (0.11)	1.63a (0.03)	0.20a (0.00)	1.78a (0.03)	0.16a (0.01)	0.95a (0.08)	1.98a (0.02)	0.17a (0.00)	0.68a (0.03)	0.12a (0.00)	0.43a (0.05)	0.44a (0.02)	0.05a (0.00)
20	2.26a (0.12)	0.18a (0.01)	2.16a (0.05)	1.65a (0.05)	0.21a (0.01)	1.90a (0.11)	0.16a (0.00)	0.99a (0.06)	2.01a (0.05)	0.17a (0.00)	0.77a (0.09)	0.13a (0.00)	0.38a (0.06)	0.40a (0.02)	0.05a (0.00)
1993															
0	1.94a (0.05)	0.17a (0.01)	1.62a (0.04)	1.61a (0.08)	0.19a (0.01)	1.48a (0.08)	0.13a (0.01)	0.84b (0.06)	1.92a (0.07)	0.17a (0.01)	0.61a (0.02)	0.11a (0.00)	0.39a (0.02)	0.47a (0.02)	0.05a (0.00)
10	1.89a (0.03)	0.18a (0.01)	1.59a (0.05)	1.65a (0.04)	0.19a (0.01)	1.38a (0.01)	0.14a (0.01)	1.00b (0.06)	2.01a (0.03)	0.16a (0.01)	0.60a (0.02)	0.11a (0.00)	0.39a (0.01)	0.49a (0.01)	0.05a (0.00)
20	2.07a (0.06)	0.18a (0.00)	1.67a (0.06)	1.55a (0.04)	0.18a (0.00)	1.41a (0.03)	0.44a (0.00)	1.29a (0.05)	1.90a (0.03)	0.17a (0.01)	0.62a (0.01)	0.11a (0.00)	0.39a (0.02)	0.50a (0.03)	0.05a (0.00)
1994															
0	1.93a (0.11)	0.21a (0.01)	2.11a (0.15)	1.71ab (0.08)	0.24a (0.01)	1.75a (0.05)	0.18b (0.00)	0.91b (0.03)	2.00a (0.11)	0.19a (0.01)	0.67a (0.02)	0.12a (0.01)	0.41a (0.02)	0.46a (0.02)	0.06a (0.00)
10	2.06a (0.08)	0.22a (0.01)	2.22a (0.08)	1.83a (0.08)	0.24a (0.01)	1.77a (0.10)	0.18b (0.00)	1.10ab (0.08)	2.06a (0.07)	0.18a (0.01)	0.64a (0.02)	0.12a (0.00)	0.42a (0.01)	0.46a (0.02)	0.05a (0.00)
20	2.02a (0.15)	0.23a (0.00)	2.23a (0.14)	1.58b (0.04)	0.22a (0.01)	2.05a (0.13)	0.20a (0.01)	1.23a (0.07)	1.86a (0.05)	0.19a (0.01)	0.64a (0.01)	0.13a (0.00)	0.44a (0.01)	0.44a (0.02)	0.05a (0.00)

^aStandard errors are in parentheses ($n = 6$). Means within the same column and year with the same letter are not significantly different at $\alpha = 0.05$.

ensure consistent input of major elements, it would be necessary to analyze the wood ash source before application and to prescribe application rates in terms of nutrient content rather than mass.

4.2. Soil analyses

Wood ash application significantly increased soil pH, and extractable P, K, Ca, and Mg, especially at 0–10 cm depth, while N, Na, and CEC were unchanged with wood ash applications (Fig. 2). Wood ash effects on soil pH are of primary concern in a land application program. In general, ash increases the pH of soils with increasing application rate [e.g., 26,27]. Small amounts (5 Mg ha^{-1}) of ash are capable of sustaining a significant increase of soil pH at shallow depth, but this pH change may not persist [18]. If the soil provides sufficient buffering capacity, pH may decrease as soon as three weeks after application [28]. The small particle size of wood ash contributes to its rapid reaction rate. We observed an increase in pH of 1.0, which is similar to that observed in other studies [e.g., 6].

Increased pH in soil is beneficial to microorganisms and enhances nutrient cycling [29]. For example, nitrification rates might increase in wood ash-treated soils [30,31], although the wood ash itself does not supply significant amounts of N (Table 1).

Extractable P increased at shallow depth, but there was no treatment effect in deeper soil layers. These results are supported by other researchers [32,33]. In other studies, P in the soil showed no discernible trends with ash amendment [e.g., 34–36]. Soil P change with wood ash application may depend on many factors: low P solubility in wood ash due to high pH [37], dose type such as untreated or agglomerated ash [38], soil pH buffer capacity [39], and the abundance of Ca^{2+} and Mg^{2+} ions in the soil solution [40].

Potassium was increased by wood ash treatment at greater soil depths than Ca or Mg, presumably due to the higher mobility of K. Other studies similarly found increase in soil Ca and Mg only at shallow depth [35,36,41]. The increase of exchangeable Ca and Mg in wood ash-amended soils may decrease extractable Al and Fe concentrations [42] as well as increase pH.

Soil Na increased only slightly with wood ash treatment. Other studies have shown a greater increase in soil Na and relatively high leaching with wood ash treatment [34,38].

4.3. Plant analyses

Wood ash applications had no significant effects on biomass production (Fig. 3) or plant nutrient concentrations (Table 3). The amount of nutrients that could be taken up by trees without being detected by our experimental design, given the variation in our measurements, was small compared to the amount of nutrients added by the ash. Soils with low pH or pH-induced nutrient deficiencies would be more likely to show a benefit from wood ash application. On N-rich sites (low C:N ratio), wood ash may increase tree growth and the mineralization and leaching of N in soils [43]. On N-poor sites (high C:N ratio), N may be immobilized and growth decreased by application of wood ash [44]. Because wood ash contains little N, an additional N source will be needed to create a balanced nutrient supply [45].

Rotation period for harvesting can affect biomass production in a willow plantation. Annual biomass production with triennial harvesting was higher than with annual harvesting in willow and poplar plantation [46,47]. At our research site, willow biomass production with annual harvesting reached a maximum growth the fifth growing season after planting and then decreased in subsequent years [16]. Our study was initiated 5 years after planting; nutrient uptake rates were undoubtedly higher in these sites earlier in the history of the plantation.

5. Conclusion

Wood ash can be used as a fertilizer and liming agent for forest soils, replacing nutrients removed during harvest. Wood ash acts as a low-N fertilizer (1:10:50 as N:P:K) and substantially adds to the base status of the soil to which it is applied. As a liming agent, wood ash neutralizes soil acidity, with about half the efficiency of commercial liming

materials. Heavy metal concentrations in the ash are characteristically low.

In this study, wood ash treatments increased soil pH and extractable P, K, Ca, and Mg, while effecting no change in N, Na, or CEC over 3 years of application. Nutrient uptake by willows was not significantly altered by wood ash application. Perhaps because of its low N concentration, wood ash did not improve either individual plant growth or plot biomass production. It remains possible that wood ash alone could be beneficial to growth in systems where acidity or base cation availability are limiting factors.

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