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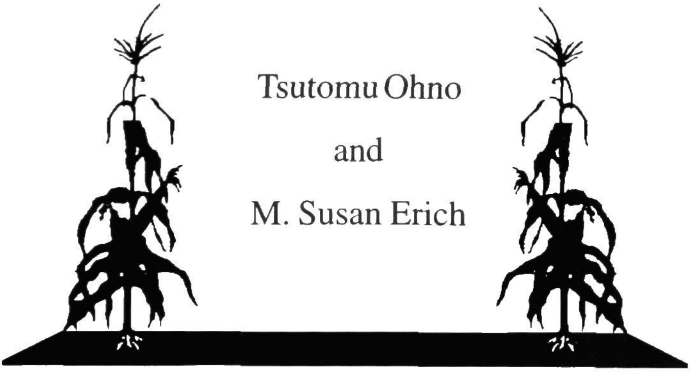

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Phosphorus and Potassium Availability in Wood Ash-Amended Soils: An Incubation Study

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INTRODUCTION

Wood ash is a residual material produced during the conversion of biomass to electrical energy by wood-burning power plants. An estimated 1.5 to 3.0 million dry tons of wood ash is generated annually in the United States with 90% of the ash being landfilled (Campbell 1990). Landspreading is an alternative disposal method which is 33%–66% less costly than landfilling (Campbell 1990).

The effectiveness of wood ash as an alternative liming agent has been demonstrated in field (Naylor and Schmidt 1986) and laboratory (Ohno and Erich 1990) studies. In addition to neutralizing acidity, wood ash amendment to soils also increases plant-available potassium (K) and phosphorus (P) (Erich 1991; Erich and Ohno 1992a). Farmers who wish to avoid inorganic fertilizers are often particularly eager to use wood ash for its nutrient-supplying power, as nutrient recycling is an important aspect of sustainable agricultural systems (Doran et al. 1987).

Conventional liming with $CaCO_3$ has been shown to alter soil solution concentrations of elements important to plant nutrition (Curtin and Smillie 1983; Simard et al. 1988). Addition of $CaCO_3$ increased calcium (Ca) concentration and decreased the concentrations of K and magnesium (Mg) in both studies. Unlike $CaCO_3$, wood ash contains K and Mg which would be expected to dissolve into soil solution along with Ca. Therefore, landspreading of wood ash would be expected to alter not only soil pH, but also the absolute and relative quantities of Ca, Mg, and K.

Because residual materials, such as wood ash, are more variable and more chemically complex than traditional agricultural chemicals, their reactions with soils are not as well understood. The reaction rate of wood ash in soils and the fate of nutrients released from ash are relatively unknown. A laboratory study showed that P released from wood ash is usually quickly sorbed by soil surfaces whereas K remains in solution (Ohno 1992). Previous studies on plant-availability of wood ash components (Erich 1991; Erich and Ohno 1992a) have been limited to short-term (<54 days) plant growth studies, with the use of standard soil extractants to assess soil nutrient levels. Changes in soil chemistry of wood ash-amended soils have not been examined over a longer time frame. Accordingly, the objective of this study was to monitor the temporal changes in soil properties and plant availability of P and K in wood ash-amended soils during a 72-week incubation period.

METHODS

Soil Collection and Analysis

Six soil samples were collected to provide a range of soil properties typical of potential sites for wood ash landspreading in the northeastern U.S.A. (Table 1). Two soils (MA and JA) were the surface mineral horizons from agricultural fields. The surface organic horizons (RMO and ENO) and the B mineral horizons (RM and EN) of two soils were collected from forested sites. The soils were sieved through a 5-mm screen to remove root fragments and coarse gravel. These soils were all acid to moderately acid since low pH soils would be used for landspreading wood ash.

Soil pH was determined using a 1:1 soil:water ratio. The pH 3, NH_4OAc extractable nutrients were measured by extracting 5 g soil with 10 mL of solution for 5 minutes (Glenn and Hoskins 1989). Cation saturation percentages were calculated by dividing each cation concentration expressed on an equivalent basis by cation exchange capacity (CEC) calculated as the sum of acidity + Ca + Mg + K components (Glenn and Hoskins 1989). The acidity value used in the CEC calculation is estimated using locally derived regression equations from the SMP lime requirement test. Exchangeable cations were determined using pH 7, NH_4OAc (Thomas 1982). Exchangeable acidity was determined by displacement with 1$\underline{N}$ KCl and titration to the phenolphthalein end point (Barnhisel and Bertsch 1982). Organic matter content of soils was determined using the Walkely-Black procedure (Nelson and Sommers 1982). The Bray P index was measured using 0.025 M HCl and 0.03 M NH_4F extracting solution (Knudsen and Beegle 1988).

Wood Ash Collection and Analysis

Wood ash was collected from a wood-burning power plant in Enfield, Maine. The ash was air dried and sieved to pass a 2-mm screen prior to use in the study. The chemical composition of this ash is shown in Table 2. The ash was characterized for total elemental composition by HF digestion and subsequent analysis by ICP-AE spectrometry. Citrate soluble P and K fraction of the wood ash were determined using the protocol of the Association of Official Analytical Chemists (AOAC) (Williams 1984). Calcium carbonate equivalence (CCE) was determined by acid dissolution followed by back titration to measure the acidity consumed in the dissolution stage (Erich and Ohno 1992b).

Table 1. Classification and selected chemical properties of the soils used in the study.

Soil	Series	Soil Classification	pH	NH$_4$OAc Extract.		KCl Acidity	Exch. Cations			Organic Carbon
				P	K		K	Ca	Mg	
				mg kg^{-1}		---------- cmol$_c$ kg^{-1} ----------				%
MA	Lamoine	Fine, illitic, nonacid, frigid, Aeric Haplaquept	5.3	3.9	281	0.35	0.57	8.94	2.79	4.07
JA	Dixfield	Coarse-loamy, mixed, frigid Typic Haplorthods	6.1	5.1	249	0.12	0.56	8.56	1.36	7.74
RM	Marlow	Coarse-loamy, mixed, frigid Typic Fragiorthods	4.1	3.5	59	3.23	0.12	0.20	0.10	6.01
EN	Adams	Sandy, mixed, frigid Typic Haplorthods	5.1	0.1	62	0.45	0.15	0.45	0.06	1.74
RMO	Marlow	Coarse-loamy, mixed, frigid Typic Fragiorthods	4.1	21.1	352	2.24	0.37	3.98	0.93	30.6
ENO	Adams	Sandy, mixed, frigid Typic Haplorthods	4.4	6.3	181	2.43	0.31	3.15	0.71	8.75

Table 2. Chemical characterization of the wood ash used in the study.

Element	Concentration
	mg kg^{-1}
Ca	248000
Si	146000
Al	57200
Mg	38000
K	29900
Mn	7300
P	5900
Fe	4900
Citrate soluble K	3700
Citrate soluble P	4500
$CaCO_3$ Equivalent	46.7%

Incubation Study

The incubation study consisted of the six soils amended with wood ash at two application rates. The incubation pots were arranged in a randomized complete block with two replications. Mineral soils (8–11 kg) and organic soils (5–6 kg) at field moist states were amended with the quantity of wood ash required to supply 3 and 9 g CCE per kilogram of dry soil. The soils were kept field moist during the incubation.

Sampling dates were at 4, 10, 25, 42, 57, and 72 weeks. Soil characterization at each sampling date consisted of the Maine standard soil test for extractable P and K, and a soil-water extract at 1:2 (soil:water) ratio for the mineral soils and 1:5 ratio for the organic soils. The cations in the soil-water extract were determined by ICP-AE analysis. Anions of the mineral soil-water extract were determined by ion chromatography for the 4-, 42-, and 72-week samples.

A plant bioassay of P and K availability in the wood ash-amended soils was conducted at each sampling period. Plastic cups were filled with 300 g of mineral soil or 150 g of organic soil on a dry weight basis. Six corn (*Zea mays* L. "Tuxedo") seeds were planted and thinned to four plants per pot after germination. On day five, 94 mg of NH_4NO_3 and 69 mg of Mg, as $MgSO_4$, was added as a blanket fertilizer treatment. Water was added to the plants every four days

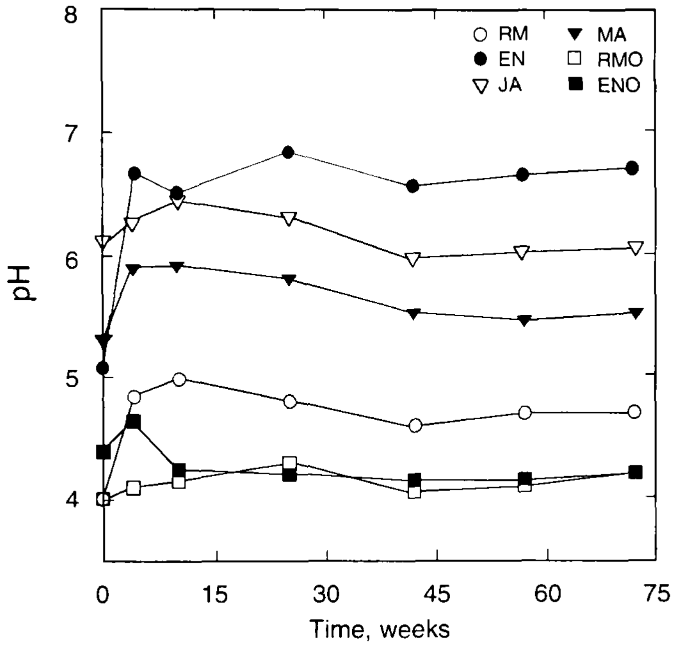

Figure 1. Soil pH as a function of incubation time for the 3 g wood ash kg^{-1} dry soil applicaton rate for the 6 soils used in this study.

to the original weight. The plant shoots were harvested on day 21. The plant tissue samples were dried and weighed to determine shoot yield. The tissue samples were ground and dry ashed for plant nutrient analysis. The ash was brought up in HCl and the elements determined by ICP. The uptake of P and K in plant shoots was calculated using the product of the element concentration and shoot dry weight.

RESULTS AND DISCUSSION

Effect of Wood Ash on Soil pH

The effect of wood ash application at 3 g kg^{-1} soil on soil pH is shown in Figure 1. The pH measurements replicated well for all soils at both wood ash application rates with a maximum coefficient of variation of 4.9%. There was a consistent pattern of rising to a peak pH value within the first 25 weeks and then a decline in soil pH with increasing incubation time until a relatively constant pH was

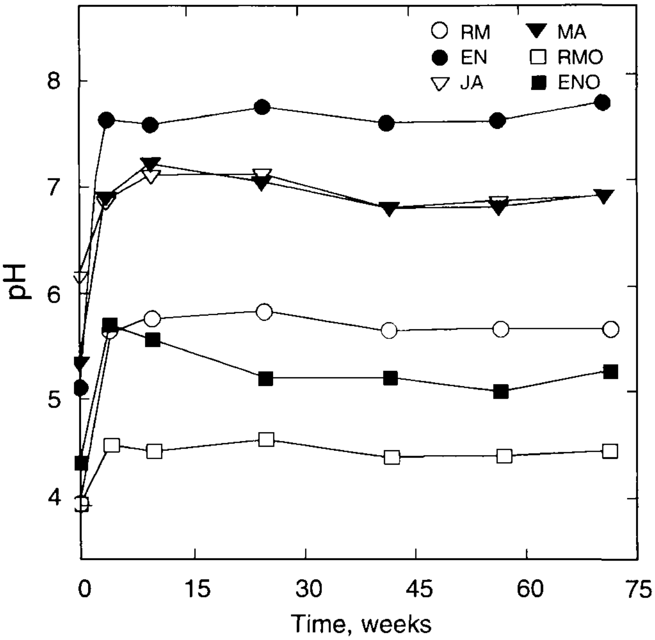

Figure 2. Soil pH as a function of incubation time for the 9 g wood ash kg^{-1} dry soil application rate for the 6 soils used in this study.

reached around week 42. The exception was the EN soil which did not show a decline in pH with incubation. This is probably due to the low organic matter content of this soil (Table 1) since organic matter contributes most of the pH buffering found in northeastern U.S.A. soils (Magdoff and Bartlett 1985; Ohno and Erich 1990).

Figure 2 shows the effect of wood ash application at 9 g kg^{-1} soil. As would be expected, the magnitude of the pH increase was greater at this higher application rate. At the higher wood ash application rate, there was either no pH decrease or only a slight decrease after the initial pH increase. The results suggest that duration of the pH increase is dependent on the amount of wood ash applied to soils. At lower application rates, the soil exchangeable acidity will start to reduce soil pH within 4 to 25 weeks after application of wood ash. At the higher application rate, soils are able to maintain elevated pH levels for a longer duration.

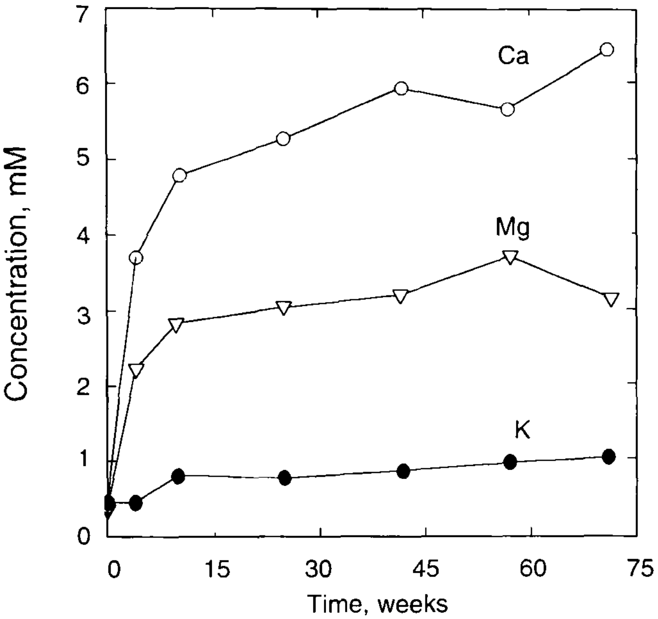

Figure 3. Concentration of Ca, Mg, and K in soil extracts averaged over the six soils as a function of incubation time.

Effect of Wood Ash on Soil Solution

The effect of wood ash application on soil solution composition for all the soils at both the 3 and 9 g kg^{-1} application rates were similar except for the higher concentrations found at the higher application rate. The data for the 9 g kg^{-1} application rate have been averaged over all six soils to show the pattern of soil solution concentrations of Ca, Mg, and K over the incubation period (Figure 3). The concentrations of the divalent Ca and Mg cations are increased over ten-fold compared to the control soil solution at the first sampling date (4 weeks). This was expected because the sharp rise in soil pH due to the neutralization of acidity by wood ash can be quantitatively accounted for by the release of Ca, Mg, K, and Na from the ash (Erich and Ohno 1992b). The Ca and Mg concentrations increased slowly during the incubation with a final average increase over control of 22- and 15-fold, respectively. The increase in K soil solution concentration was much less, with only a 21% average increase at the first sampling period and only 3-fold increase over control at the final sampling date. This relatively low

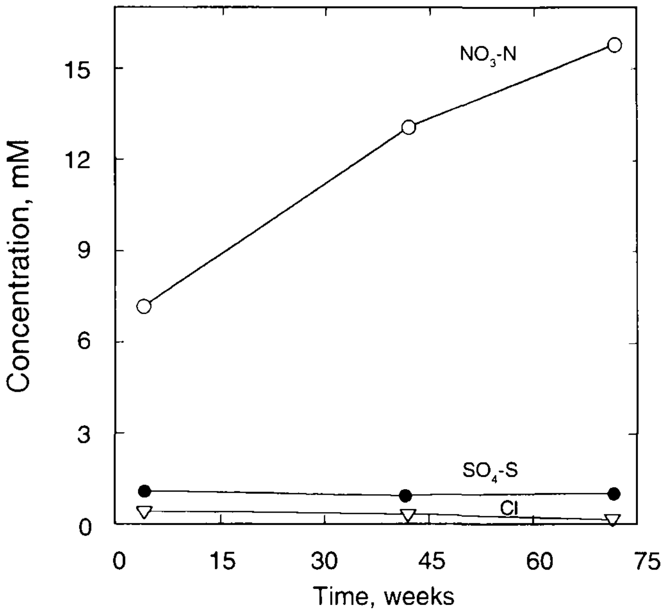

Figure 4. Concentration of NO_3-N, SO_4-S, and Cl in soil extracts averaged over the four mineral soils as a function of incubation time.

increase in soil solution K was probably due to the low citrate solubility of K in this particular wood ash (12.4%).

Soil solution concentrations of NO_3^-, SO_4^{2-} and Cl^- anions for the four mineral soil horizons are shown in Figure 4. Generally, the SO_4^{2-} and Cl^- concentrations did not show any strong trends during the incubation period. The NO_3^- concentration, however, increased with longer incubation period in all four soils. An increase in NO_3^- concentrations has been found in other laboratory incubation studies and has been attributed to microbial activity during laboratory incubation (Larsen and Widdowson 1968; Curtin and Smillie 1983).

Effect of Wood Ash on Exchangeable Cations

Unlike calcitic agricultural limestone which releases only Ca to soils, wood ash will release Ca, Mg, and K as it neutralizes soil acidity. The dissolution of wood ash will alter the balance of these exchangeable cations in soil (Ohno and Erich 1990). A standard recommendation for proper balance of nutrients for plant growth is the following saturation percentages: K, 3–5%; Mg, 10–25%; and

Table 3. Base and acid saturation of the soils prior to wood ash amendment and at the 72-week incubation sampling.

		---------------	% Saturation	---------------	
Soil	Ash	K	Mg	Ca	Acidity
MA		6.3	23.0	62.0	8.7
	+	2.5	14.0	83.5	0
JA		5.8	15.1	79.1	0
	+	3.3	15.0	81.7	0
RM		3.3	4.0	13.7	79.0
	+	1.0	19.7	77.7	1.6
EN		9.6	6.9	30.3	53.2
	+	2.4	11.6	86.0	0
RMO		6.2	14.2	56.7	22.9
	+	2.7	18.0	60.8	18.5
ENO		5.9	13.0	53.0	28.0
	+	0.8	19.8	72.4	7.0

Ca, 60–80% (Glenn and Hoskins 1989). The estimated base and acid saturations of soils prior to, and 72 weeks after, ash addition are shown in Table 3. The saturation levels of K and Mg decreased in the two agricultural soils, MA and JA. As expected Ca saturation increased, and the acidity component of the exchange sites dropped to zero. In all four forest soil horizons, addition of wood ash decreased K saturation level and increased Mg and Ca saturation. The acid-neutralizing power of wood ash sharply reduced the acidity present on exchange sites. In all soils, wood ash amendment decreased K saturation due to the greater relative release of Ca and Mg.

Effect of Wood Ash on P Availability

The pH 3, NH_4OAc P soil test levels and P availability as measured by a plant bioassay are shown for the 6 individual soils (9 g kg^{-1} addition rate) in Table 4. The P soil test values increased over time for the JA and EN soils. There was no significant effect of incubation time for the other 4 soils. The P bioavailability using corn plants showed statistically significant differences with increasing incubation time in four of the six soils. There was a steady decline in P availability in the JA soil with increasing incubation time;

Table 4. Effect of incubation on the NH_4OAc extractable phosphorus soil test value and phosphorus bioavailability as measured by a three-week plant bioassay using corn for the individual soils.

	Soil											
	MA		JA		RM		EN		RMO		ENO	
Incubation Duration	P soil test	P Bio-assay	P soil test	P Bio-assay	P soil test	P Bio-assay	P soil test	P Bio-assay	P soil test	P Bio-assay	P soil test	P Bio-assay
Weeks	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}
4	16.0	1.70	15.3	1.94	9.3	1.89	11.6	1.37	47.4	2.47	22.5	1.34
10	16.0	1.66	18.6	1.66	8.5	1.76	13.4	1.30	65.9	3.59	22.5	2.59
25	21.2	1.94	16.5	1.62	7.9	2.04	12.5	1.03	60.7	2.98	22.2	1.84
42	16.6	1.42	12.8	1.18	5.3	1.64	12.0	1.45	81.5	1.41	19.3	2.16
57	16.8	1.21	16.5	1.33	7.3	1.55	11.8	1.40	61.5	1.78	16.4	2.12
72	18.1	1.07	17.9	0.98	7.4	0.88	15.0	0.72	70.0	2.38	20.6	0.97
LSD (α=.05)	NS	0.51	1.5	NS	NS	0.63	1.7	NS	NS	0.92	NS	0.68

NS = Not significant

Table 5. Effect of incubation on NH_4OAc and Bray extractable phosphorus soil test values and phosphorus bioavailability averaged over the six soils.

Incubation Duration	NH_4OAc P	Bray P	Bioassay P
Weeks	------------- mg kg^{-1}	----------	mg pot^{-1}
4	20.4	45	1.79
10	24.2	51	2.09
25	23.5	59	1.91
42	24.6	57	1.54
57	21.7	55	1.57
72	24.8	57	1.17

whereas, in the other five soils, P availability increased initially and then decreased to a value lower than that observed at the initial sampling date.

The opposing trends in pH 3, NH_4OAc soil test P and P bioassay-available P are shown clearly in Table 5, where results are averaged over all six soils at each sampling date. The P soil test value is relatively constant during the incubation period, but P availability rises initially and then declines with increasing incubation time. Erich (1991) reported that the pH 3, NH_4OAc soil test extracting solution may not be appropriate for wood ash-amended soils due to the ability of this acid-buffered solution to dissolve unreacted wood ash and suggested that the Bray P test may be more appropriate. The Bray P test, however, also did not reflect the decrease in P availability as measured by the plant bioassay (Table 5).

Incubation effects on P concentrations in water extracts are shown in Table 6. Water soluble P concentration of the EN soil decreased significantly with time, but did not change significantly for the other five soils. The application of 9 g kg^{-1} wood ash adds 40.5 mg kg^{-1} of citrate soluble P to the soils. With the exception of the RMO organic soil, increases in pH 3, NH_4OAc soil test P were much less than the amount of P added (Tables 1 and 4). The RM soil had the lowest increase in P soil test level, with an average increase of

Table 6. Effect of incubation on the 1:2 (soil:water) mineral soil and 1:5 organic soil extract phosphorus concentration.

Incubation Duration	Soil MA	JA	RM	EN	RMO	ENO
Weeks	μmol L^{-1}					
4	15.8	14.5	12.0	8.1	203	9.7
10	21.3	18.1	7.8	5.8	294	10.7
25	15.5	14.2	9.4	6.1	268	16.8
42	nd	nd	nd	nd	nd	nd
57	20.0	18.7	16.1	5.2	264	19.1
72	14.9	13.9	11.6	5.2	229	15.2
LSD (a=.05)	NS	NS	NS	2.6	NS	NS

nd = not determined
NS = not significant

only 4.1 mg P kg^{-1}. The greatest increase was in the RMO soil, where the average increase was 43.4 mg P kg^{-1} The other four soils increased the average P concentration from 11.2 to 14.3 mg P kg^{-1}. This indicates that except for the RMO soil, these soils fix the added P in a form that is not extracted by the pH 3, NH_4OAc soil test. The decline in bioavailable P with increasing incubation time can not be accounted for simply by P concentration in the soil and soil solution, but must be some function of multiple soil chemical factors which cannot be determined in this study.

Effect of Wood Ash on K Availability

The K soil test levels and K availability as measured by a plant bioassay are shown for the 6 individual soils (9 g kg^{-1} addition rate) in Table 7. There was a significant increase in K soil test values for the JA, EN, and RMO soils. The other three soils showed no significant changes in soil test K over the course of the incubation. Plant bioavailability of K significantly declined with increasing incubation period for the MA, RMO, and ENO soils. The RMO soil was the only one in which both the K soil test and K bioassay values decreased significantly.

Table 7. Effect of incubation on the NH_4OAc extractable potassium soil test value and potassium bioavailability as measured by a three-week plant bioassay using corn for the individual soils.

	Soil											
	MA		JA		RM		EN		RMO		ENO	
Incubation Duration	K soil test	K Bio-assay	K soil test	K Bio-assay	K soil test	K Bio-assay	K soil test	K Bio-assay	K soil test	K Bio-assay	K soil test	K Bio-assay
Weeks	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}	mg kg^{-1}	mg pot^{-1}
4	188	9.81	287	8.85	101	10.2	92	7.18	462	11.8	199	9.61
10	205	8.33	310	11.4	104	10.7	98	9.12	526	10.7	151	14.9
25	237	13.7	332	11.1	117	13.1	116	7.92	629	10.8	156	10.4
42	221	7.35	358	8.18	119	11.0	135	10.9	646	3.94	150	10.9
57	244	4.92	370	8.64	109	11.6	135	9.76	588	4.96	130	9.19
72	232	6.67	366	5.65	125	4.86	136	4.75	665	7.85	142	5.13
LSD (α=.05)	NS	4.56	17	NS	NS	NS	8	NS	78	5.1	NS	5.06

NS = Not significant

Table 8. Effect of incubation on NH_4OAc extractable potassium soil test values and potassium bioavailability averaged over the six soils.

Incubation Duration	NH_4OAc K	Bioassay K
Weeks	mg kg^{-1}	mg pot^{-1}
4	222	9.6
10	232	10.9
25	265	11.2
42	272	8.7
57	263	8.2
72	278	5.8

Although Erich (1991) reported that pH 3, NH_4OAc soil test effectively predicted plant available K, the test and bioassay values indicate the soil test did not reflect decreasing K bioavailability in the latter part of this study (Table 8). The inability of the soil test to predict declining K availability may be due to the low K solubility of this particular wood ash. The wood ashes used in the study of Erich (1991) had an average citrate-K solubility of 82% versus the 12.4% for wood ash used in this study. The typical wood ash has higher levels of soluble K than the ash used in the present study, and this K typically is released rapidly to soils (Ohno 1992; Ohno and Erich 1990). In the present study the buffered acidity of the pH 3, NH_4OAc extractant may have dissolved unreacted wood ash K which would be not available to plants, thus causing soil test K levels to be higher than levels of bioavailable K.

The decrease in plant availability of K is surprising due to the sustained increase in soil solution K throughout the incubation period (Figure 3). The mole fraction of K calculated from the data in Figure 3, however, was 0.42 in the unamended, control soil solution and 0.10 for the soil solution of wood ash-amended soil at the 72-week sampling date. The large increase in both absolute and relative Ca and Mg concentration in the soil solutions probably caused a depression in K uptake due to competitive ion effects.

CONCLUSIONS

The results of this study show that wood ash application will raise soil pH rapidly. At lower rates of application, however, soil pH will start to decline after a period of 10 to 25 weeks. The pH remains elevated for longer duration at higher application rates.

Plant availability of both P and K increased for the first 25 weeks and then declined with time. The pH 3, NH_4OAc soil test for P and K and the Bray-P test did not reflect this decline in P and K bioavailability. The results of this study suggest, however, the impact of landspreading wood ash on increasing plant available P and K may be relatively short lived. The typical wood ash spread in the field is likely to increase plant uptake of K more markedly than this study suggests for two reasons. First, typically wood ash has much higher levels of soluble K than the one used in this study. Second, field soils are subject to leaching by rain, and the high levels of soluble Ca and Mg that depressed plant uptake of K in this study would not be sustained over time under field conditions.

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