

PHOSPHORUS AVAILABILITY TO CORN FROM WOOD ASH-AMENDED SOILS

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Abstract. Wood ash is a residual material produced during biomass burning. In the northeastern United States up to 80 % of the ash is spread on agricultural lands as a liming amendment with the remainder being disposed of in landfills. As well as raising soil pH, wood ash also adds plant nutrients to soil. This study is an examination of the plant availability of the P in 8 different soils amended with one wood ash. Plant availability was assessed by measuring the biomass and P concentration of corn (*Zea mays*) L.) plants grown in the greenhouse for 28 d in soil amended with either CaCO₃ (control), wood ash to supply 200 mg kg⁻¹ total P, or monocalcium phosphate (MCP) to supply 200 mg kg⁻¹ total P and CaCO₃. Both corn growth and P uptake were highest in the MCP treatments, intermediate in the wood ash treatments, and lowest in the controls for all soil types. The soil property which seemed to have the greatest influence on P availability was pH buffer capacity. The soils with the greatest capacity to buffer OH additions also tended to exhibit the greatest absolute P uptake from wood ash-amended soils and the greatest P uptake relative to that from MCP-amended soils. The ability of soil test extractants to predict uptake of P in the three soil treatments was examined. A buffered ammonium acetate extractant overestimated P availability in the ash-amended soils relative to the MCP-amended soils. An unbuffered, acid, fluoride-containing extract provided a measure of P levels that was consistent with P uptake from all soil treatments. In this study the predictive relationship was as follows: P uptake = 0.017 × (Bray P, mg kg⁻¹) + 1.19; *r* = 0.81.

1. Introduction

Biomass burning is already significant and likely to increase in the United States. Although this conversion of energy from storage in wood and bark to forms more directly usable by humans (heat and electricity) is viewed as relatively environmentally 'clean', disposal of the residual wood ash is necessary. Wood ash producers are generally either wood-burning utility plants or paper companies which burn bark, waste wood, and papermill sludge as a means of waste reduction, as well as to produce energy. Amounts of ash produced are variable depending on technology and fuel used and range between 1–100 t d⁻¹ site⁻¹ (Campbell, 1990).

In the United States as a whole disposal of the ash is primarily in landfills (90%), although in the Northeastern United States up to 80% of the ash is spread on agricultural lands (Campbell, 1990). This difference is due to the high costs of disposal in landfills in the Northeastern United States. Although landspreading of ash is subject to state regulations in most northeastern states, it is an economically attractive option in this region of the country. Currently a number of states, including Maine, New Hampshire, Vermont, New York, Idaho, Washington and Minnesota

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either have wood ash utilization programs or are considering the establishment of such programs.

Oxides, hydroxides, and carbonates of Ca, Mg, and K make up a significant fraction of wood ash (T. Ohno, unpublished FTIR spectra). Wood ashes generally have high pHs and are used primarily as liming amendments to soil. Additions are usually regulated based on the calcium carbonate equivalence (CCE) of the ash and the lime requirement of the potential soil site although this varies from state to state (Campbell, 1990).

Wood ash also adds plant nutrients to soil and the fate of these nutrients in the environment is largely unknown. The environmental impacts of fertilization practices have come under great scrutiny recently since high additions of P (and other nutrients) have the potential to adversely affect surface and groundwater (Gilliam *et al.*, 1985). The farmer's concern that his crops not be nutrient-limited must be weighed against society's concern that excess amounts of plant nutrients are not applied to land from which they can erode or leach and enter the common water supply. One purpose of soil testing programs and research-based fertilizer recommendations is to avoid application of excessive levels of nutrients to agricultural lands. However, the research on which fertilizer recommendations are based was generally conducted using a standard chemical source of nutrient rather than a residual material as a source of that nutrient. The applicability of fertilizer recommendations when a nutrient, for instance P, is added with a residual material such as wood ash rather than a standard fertilizer material is unknown. An application rate of several t ha⁻¹ of wood ash, which contains 1 to 2% P (Ohno and Erich, 1990), represents a substantial input of potentially bioavailable P.

Although several published studies have found increases in soil test nutrient levels after wood ash amendment (Naylor and Schmidt, 1986; Ohno and Erich, 1990), studies which directly assess plant availability of the nutrients in wood ash are rarer (Erich, 1991). Studies characterizing the plant availability of different sources of fertilizer P are not uncommon (Armiger and Fried, 1957; Mullins, 1988) since P fertilizer varies in solubility and, thus, plant availability. However, none of these studies have included wood ash as a P source. Phosphorus added to soils with ash amendment seems to be partially available for plant uptake (Hartikainen, 1984; Erich, 1991). However, several studies suggest that ash from coal-fired power plants contains little or no bioavailable P and may actually decrease plant availability of soil P (Moliner and Street, 1982; Adriano *et al.*, 1978). Nutrients in the ash produced by the burning of forest slash in some tropical cropping systems are generally thought to be plant available (Jordan, 1985) although few detailed studies exist.

In a previous study comparing P uptake by corn from one soil type amended with either of two wood ashes, dicalcium phosphate, or concentrated superphosphate the ashes were significantly less effective than the fertilizer materials when compared on a total P basis (Erich, 1991). However there was a plant response to P added from both ash sources. This study suggested that the citrate-extractable fraction

of the P in the wood ash serves as a reasonable approximation of the fraction of the total P expected to be plant available in the short term. The objective of this research was to assess availability of wood ash P relative to MCP to corn grown in the greenhouse on a range of soil types. Availability as measured by biomass production, plant P concentration, and extractable soil P.

2. Materials and Methods

SOIL COLLECTION

Eight soils representative of a range of soils typically used for landspreading of wood ash were selected for this study. One horizon from each of eight soils was used. Surface horizons (A) from Dixmont (coarse-loamy, mixed frigid Aquic Haplorthods), Dixfield (coarse-loamy, mixed frigid Typic Haplorthods), Marlow (Coarse-loamy, mixed frigid Typic Fragiorthods), Elmwood (coarse-loamy, over clayey, mixed, frigid aquic Dystric Eutrochepts), Mapleton (loamy-skeletal, mixed, frigid Lithic Haplorthods) and Lamoine (fine, illitic, nonacid, frigid, Aeric Haplaquepts) soils were used to represent agricultural soils. The B horizon of a Marlow and an Adams (sandy, mixed frigid Typic Haplorthods) soils were used to represent forest soils. The soils were sieved moist through a 5 mm diameter screen to remove root fragments and gravel. All were stored field moist until use.

SOIL CHARACTERIZATION

The pH was determined using a 1:1 soil:water ratio. The pH buffer curve was determined by adding 20 mL of 0, 0.012, 0.024, 0.037 and 0.051 M NaOH (standardized using KHP) to 10.00 g of soil. The suspensions were allowed to equilibrate for 1 week with daily inversion to mix the suspension (James and Riha, 1986). A soil pH buffering power coefficient was calculated from the slope of the linear regression equation of pH as a function of base added.

The Bray-P index was measured using 0.025 M HCl in 0.03 M NH_4F extracting solution (Knudsen and Beegle, 1988). The NH_4OAc -extractable P was measured by extracting 5 g soil with 10 mL of 1 M NH_4OAc (pH 3.0) for 5 min (Glenn and Hoskins, 1989). Soil CEC was determined using pH 7, 1 M NH_4OAc (Thomas, 1982). Exchangeable acidity was determined by displacement with 1 M KCl (Barnhisel and Bertsch, 1982). Organic C content of soils was assessed using the Walkley-Black procedure (Nelson and Sommers, 1982). The Bache-Williams index was used to quantify the P sorption capacity of the soils (Bache and Williams, 1982). Lime requirement was determined by the SMP single buffer method (McLean, 1982) with regressions developed locally (Glenn and Hoskins, 1989).

The hydrometer method was used to determine soil texture (Gee and Bauder, 1982). The moisture content at field capacity was determined by filling 100 g of air-dried soil into a 100 mL graduated cylinder and measuring the quantity of soil wetted by 10 mL of water in a 24-hr period (Karlen *et al.*, 1978).

WOOD ASH CHARACTERIZATION

The wood ash was air dried and sieved through a 2 mm diameter sieve to ensure a homogenous sample for use in the study. It was characterized for total P, total K and total Mg by inductively coupled plasma-atomic emission (ICP-AES) after dry-ashing at 450 °C and digestion in 2 mL conc. HNO₃ and 5 mL HF. The ash was digested to dryness at 100 to 200 °C using a sand bath. The residue was dissolved in 1:1 HCl and quantitatively transferred to a volumetric flask. The soluble P content was determined by ammonium citrate extraction (Williams, 1984). The CCE was determined using AOAC procedures (Williams, 1984).

GREENHOUSE STUDY

Plastic pots containing 800 g of soil on a dry weight basis were used in this study. All soils were maintained at field capacity during the study by watering to a pre-determined weight as needed. Watering was done as needed, approximately every 2 to 3 days after the first week. The treatments were a factorial combination of eight soil types and three P amendments (control, 200 mg P kg⁻¹ soil as wood ash and 200 mg P kg⁻¹ soil as monocalcium phosphate). The pots were arranged in a randomized complete block with four replications.

The wood ash treatments received 26.2 g ash (dry weight basis) which supplied 200 mg total P kg⁻¹ soil. The monocalcium phosphate (MCP) treatments received 5.5 g CaCO₃, 0.9 g KCl and 0.65 g MCP per pot. The control pots received 5.5 g CaCO₃ and 0.9 g KCl per pot. The CaCO₃ and KCl amendments for the control and MCP treatment pots supplied the same amount of K and acid neutralizing capacity as in the wood ash treatments. All treatment amendments were mixed into the soils, and the treated soils were incubated for 8 days before planting.

Five corn (*Zea mays* L. 'Tuxedo') seeds were planted and thinned to 3 plants per pot at 7 days after planting. On day 8, 189 mg of NH₄NO₃ per pot was added to all treatments. On day 13, 315 mg of Mg, as MgSO₄, was added to the control and MCP treatments to supply the same amount of Mg as supplied by the wood ash. A blanket application of Zn (4.6 mg), Mn (0.5 mg), Cu (0.5 mg), B (0.1 mg), and Mo (0.02 mg) was added to all pots on day 13. An additional 189 mg of NH₄NO₃ was added to all pots on day 16. The plant shoots were harvested on day 28. Soil from each pot was sampled for soil analysis.

The plant tissue samples were dried, weighed, and ground for plant nutrient analysis. Subsamples (0.500 to 1.000 g depending on treatment yield) of tissue from each pot were ashed at 550° for 5 to 6 hr. The ash was cooled and wet with d.i. water. Five mL of 1:1 HCl plus about 2mL conc. HNO₃ was added to the ash. The solutions were boiled to dryness and the crucibles cooled. Another 5 mL aliquot of 1:1 HCl was added to dissolve the residue. The solutions were quantitatively diluted in 50 mL volumetric flasks and analyzed for Ca, K, Mg, P, Al, B, Cu, Fe, Mn, Mo, and Zn by ICP-AES. Statistical analysis was performed using the Systat software package.

TABLE I
Selected properties of soils used in this study

Soil series	pH	Lime req	pH ₃ , NH ₄ OAc extrac. P	Exchangeable cations				CEC (pH 7.0)	KCL acidity	Walkley Black carbon	pH buffer capacity ^a	P sorp. index	Sand	Silt	Clay	
				K	Ca	Mg	Na									
				Mg ha ⁻¹				%				%				
				mg kg ⁻¹				cmol kg ⁻¹				%				
WP	Mapleton	5.1	15.5	2.7	0.79	6.90	0.61	0.03	17.7	.27	4.63	0.707	10.0	55	34	11
NL	Elmwood	6.2	5.8	3.3	0.30	5.97	0.62	0.04	9.3	.07	2.78	0.418	9.8	64	31	5
KH	Marlow	4.6	18.5	4.9	0.33	2.39	0.54	0.04	20.5	1.20	5.97	0.703	17.7	63	30	7
PC	Dixmont	5.1	13.1	3.3	0.63	4.83	0.59	0.03	12.8	.13	4.42	0.629	7.5	66	26	8
HT	Dixfield	4.9	10.5	3.3	0.62	2.73	0.76	0.08	17.7	1.05	7.22	0.689	14.6	63	30	7
MA	Lamoine	5.3	14.8	3.9	0.57	8.94	2.79	0.15	23.1	.35	4.07	0.691	16.8	47	40	13
RM	Marlow	4.1	27.1	3.1	0.12	0.20	0.10	0.06	28.8	3.23	6.01	0.514	>52.3	62	32	6
AD	Adams	4.5	14.3	1.8	0.09	0.26	0.03	0.02	7.1	.78	1.74	0.301	12.7	79	14	7

^a mmol OH pH⁻¹ (10g soil).

3. Results and Discussion

The wood ash used contained 12.1 g kg^{-1} total P, 18 g kg^{-1} total K and 10.7 g kg^{-1} total Mg. The ammonium citrate extractable P content was 8.3 g kg^{-1} and the CCE was 0.48. The properties of the soils used in this study are shown in Table I. Most of the soils are loams or sandy loams with relatively low pHs and correspondingly low in exchangeable bases. This is typical of agricultural and forest soils of the Northeastern U.S. Soils with low pHs were chosen for this study since soils of low pH would receive wood ash additions.

Figure 1 shows the shoot dry weights for the control, wood ash-amended, and MCP-amended soils. The MCP-amended soils produced the greatest biomass, with the ash-amended soils producing smaller amounts of biomass, and the controls the smallest amounts of biomass. A similar pattern was observed for P uptake (Table II). For both shoot dry weight and P uptake, analysis of variance revealed a significant effect of P source, a significant effect of soil, and a significant interaction between the two ($P < 0.05$). Because P uptake in the controls was significantly different among the different soils, P uptake in the controls was subtracted from P uptake in both the ash-amended and MCP-amended soils to give net uptake in the ash

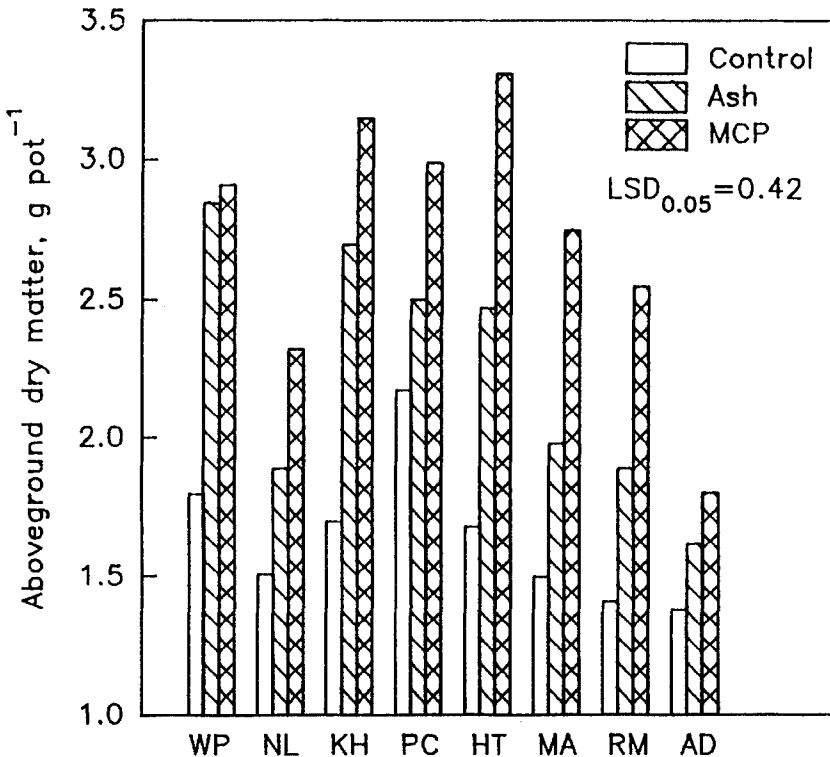


Fig. 1. Aboveground biomass of corn grown for 28 days in the greenhouse in 8 soils amended with two P sources (wood ash or MCP).

TABLE II

Phosphorus uptake by corn grown for 28 days in the greenhouse in 8 soils amended with two P sources (wood ash or MCP)

Soil	Control	Net ash ^a	Net MCP ^a	Net ash/ net MCP
	mg pot ⁻¹			
WP	1.43	1.25	1.78	0.70
NL	1.14	0.43	1.56	0.28
KH	1.40	1.02	1.84	0.55
PC	1.90	0.57	1.89	0.30
HT	1.35	0.94	2.41	0.39
MA	1.08	0.49	1.41	0.35
RM	1.02	0.47	1.44	0.33
AD	1.05	0.27	0.63	0.43
LSD _{0.05}	0.23	0.21	0.60	

^a Treatment uptake minus control uptake.

and MCP treatments. Net uptake in both the ash-amended and MCP-amended soils also differed among the different soils.

Table III shows the relationships between P uptake in the various treatments and a number of soil properties. No soil property is strongly correlated with the net ash/net MCP ratio. In other words, no soil property seems to differentially affect ash dissolution relative to fertilizer dissolution. Those soil properties correlated to net uptake in the ash treatment were correlated to net uptake in the MCP treatments as well. The soil property most strongly correlated with net uptake in the ash treatments is pH buffer capacity. Soils with higher pH buffer capacities have higher levels of available H⁺ which enable them to resist changes in pH with added base. Because a constant amount of liming power (CCE) was added to all soils in this study, probably the greater a soil's buffer capacity, the greater the dissolution of wood ash in that soil. The larger the proportion of wood ash dissolved in any given soil, the greater the amount of P solubilized in that soil.

Surprisingly uptake was not well correlated with exchangeable acidity (Table III), a parameter which would be expected to be closely related to pH buffer capacity. In addition uptake was not well correlated to lime requirement (Table III) which is an estimate of pH buffer capacity of a soil. Lime requirement is estimated by measuring water pH and buffer pH and using a regression equation relating these two parameters to lime requirements derived from incubation measurements using a test group of soils. pH buffer capacity was measured directly for each soil in this study while lime requirement was estimated from a regression equation. Therefore pH buffer capacity is a more direct estimate of H⁺ supplying power of these soils and thus of the proportion of wood ash dissolved and the amount of P solubilized in each soil. As would be expected soil organic carbon was correlated with pH

TABLE III
Pearson correlation matrix for P uptake by corn grown for 28 days in the greenhouse and selected soil properties

	pH	NH ₄ OAc P	CEC	KCl Acidity	Lime req.	Walkley Black carbon	pH buffer capacity	P sorp. index	Sand	Silt	Clay
Control P uptake	0.103	0.208	-0.201	-0.401	-0.203	0.242	0.484	-0.480	0.020	-0.053	0.078
Net ash uptake	-0.085	0.346	0.263	-0.105	0.047	0.605	0.766*	-0.205	-0.384	0.372	0.270
Net MCP uptake	0.105	0.517	0.277	-0.070	-0.186	0.798*	0.763*	-0.136	-0.392	0.481	-0.005
Net ash/net MCP	-0.222	0.001	0.087	-0.102	0.197	0.148	0.392	-0.196	-0.152	0.055	0.366

* Significant at $P < 0.05$.

buffer capacity ($r=0.72$) and thus with net uptake in the ash-amended soils.

In this study initial soil P levels (pH 3.0, NH_4OAc) were not highly correlated with net uptake in the ash-amended soils (Table III). A previous study of 6 wood ashes and 13 soils found a correlation ($r=0.61$) between initial soil P levels and percentage of wood ash P released as determined by soil testing using pH 3.0, NH_4OAc as the extractant (Ohno and Erich, 1990). In that study the amount of wood ash added varied with soil type as determined by the lime requirement for each soil. In the current study a fixed amount of wood ash was added to each soil type. In the case where a fixed amount of ash is added to soils which differ in buffering power, the extent of dissolution of the ash appears to determine the availability of the wood ash P.

In the previous study where P availability was determined by soil test P levels after wood ash addition about 2 to 16% of the total P added in the wood ash was extracted (Ohno and Erich, 1990). In the present study about 1 to 3% of

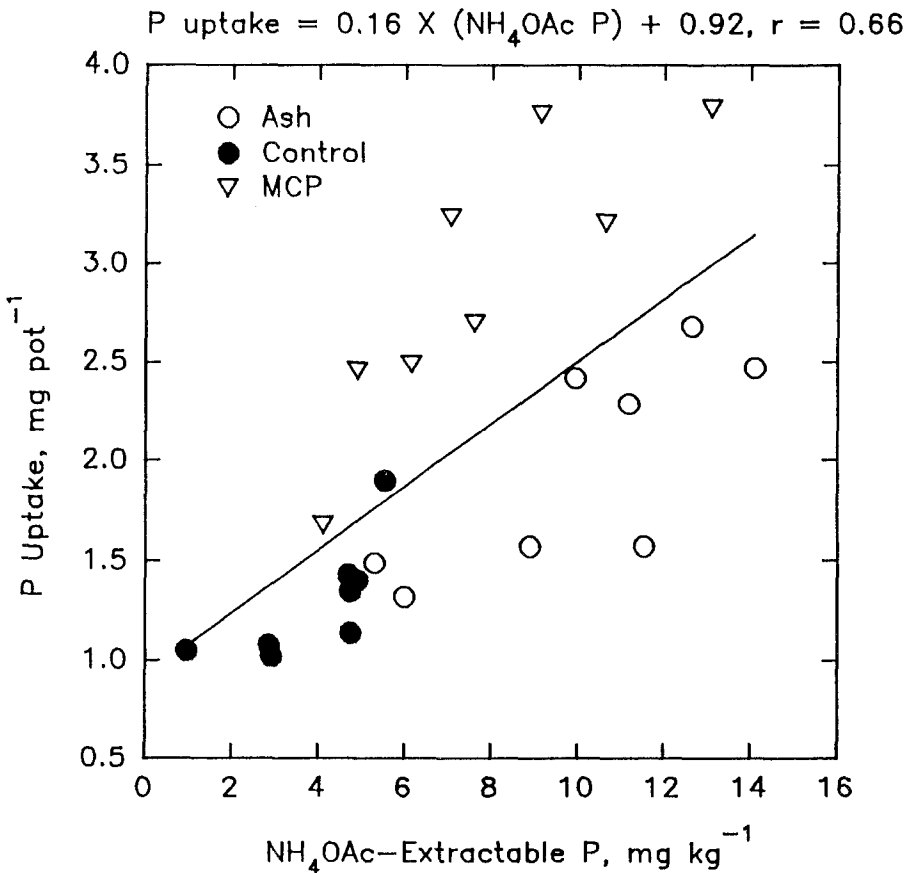


Fig. 2. P uptake of corn grown for 28 days in the greenhouse as a function of NH_4OAc -extractable P in 8 soils amended with two P sources (wood ash or MCP).

the total P added in the ash was extracted by pH 3.0, NH_4OAc , while less than 1% of the added P was taken up by the corn from the wood ash-amended soils. Part of this difference in results may be due to the different incubation times of the two studies with the current study lasting only about one-third as long as the previous study.

The ability of soil test extractants to predict uptake of P in control, ash-amended, and MCP-amended soils was examined. The soil test extractant typically used in Maine, NH_4OAc (pH 3.0), generally extracted somewhat higher levels of P in the ash-amended than in the MCP-amended soils (Figure 2). The Bray soil test extractant (0.025 M HCl in 0.03 M NH_4F), like the corn plants, extracted more P in the MCP-amended soils than in the ash-amended soils (Figure 3). The buffered NH_4OAc apparently dissolved residual ash in the ash-amended soils and extracted P which was not actually soluble or plant available in these treatments. The Bray soil test extractant provided a measure of P levels that was consistent for all the treated soils.

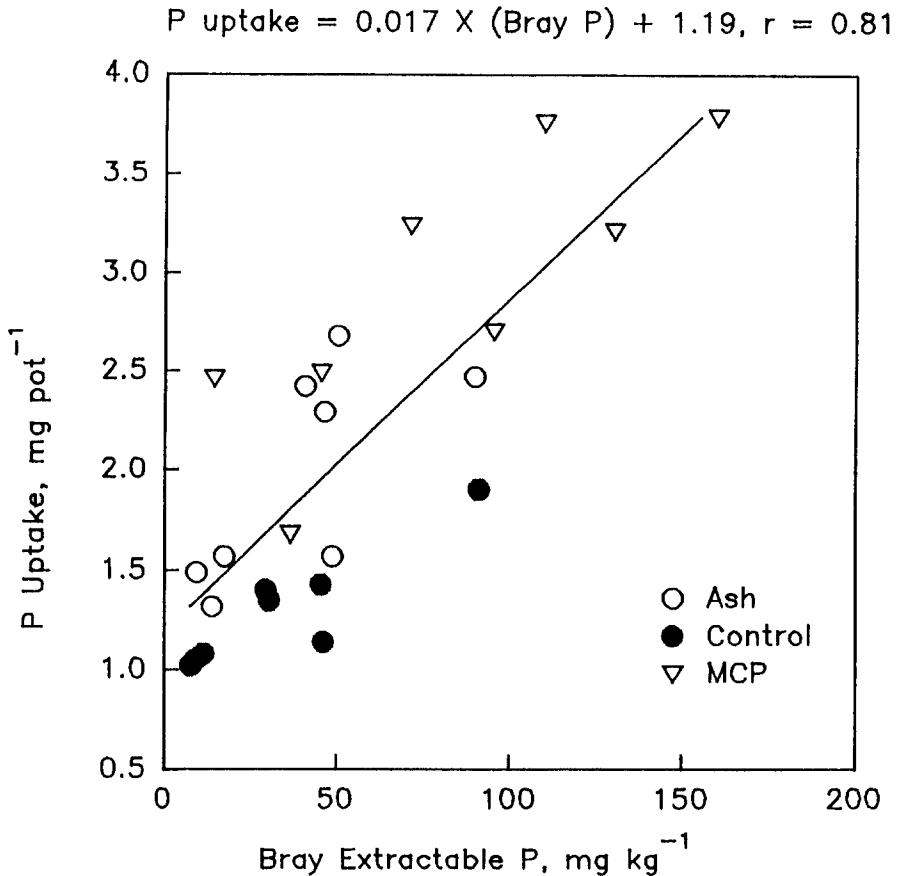


Fig. 3. P uptake of corn grown for 28 days in the greenhouse as a function of Bray-extractable P in 8 soils amended with two P sources (wood ash or MCP).

The ratio of percentage citrate-extractable P of ash (69%) to percentage citrate-extractable P of MCP (98%) was 0.70. Although in one soil the ratio of net uptake from ash-amended soil to net uptake from MCP-amended soil was also 0.7, for the majority of soils the ratio was substantially lower (Table II). In general using citrate-extractable P as a measure of plant-available P overestimates the bioavailability of wood ash P, at least as measured in a short term assay. However, citrate-extractable P is an improvement over total P as an estimate of the amount of wood ash P available for plant uptake.

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