

## ASSESSING THE EFFICACY OF ALTERNATIVE PHOSPHORUS SORBING SOIL AMENDMENTS

Michael P. Callahan<sup>1</sup>, Peter J.A. Kleinman<sup>2</sup>, Andrew N. Sharpley<sup>2</sup>, and William L. Stout<sup>2</sup>

Concern over the contribution of agricultural phosphorus (P) to fresh water eutrophication has focused attention on practices that decrease P losses from agricultural soils. At present, there are few management options for soils with P levels in excess of crop P requirements other than restricting P applications. This study assesses various readily available materials as possible P Sorbing Soil Amendments (PSSAs) by comparing their near- and long-term effects on soil P solubility and potential availability to runoff with their impact on plant available P. Specifically, anthracite refuse ash, bituminous refuse ash, by-product gypsum ( $\text{CaSO}_4$ ), siderite ( $\text{FeCO}_3$ ), steel processing sludge, water treatment residual, and wollastonite ( $\text{CaSiO}_3$ ) were incubated in three acidic and one neutral loam soils for 21 and 120 days to compare starting and ending water extractable soil P (WEP) and Mehlich-3 P concentrations. Across all soils, bituminous refuse ash, by-product gypsum, and water treatment residual decreased WEP consistently at the lowest rates of application without lowering Mehlich-3 P to less than crop requirements. In addition, no significant difference in WEP and Mehlich-3 P was observed for by-product gypsum between the 21-day and 120-day incubation periods, indicating that sorption reactions induced by this material are both rapid and stable with time. Anthracite refuse ash, siderite, steel processing sludge, and wollastonite were ineffective at decreasing WEP in soil at practical application rates. Results support the use of by-product gypsum and water treatment residual on acidic and neutral soils representing areas of high P loss potential. (Soil Science 2002;167:539-547)

**Key words:** Phosphorus, soil amendment, eutrophication, sorption, runoff.

**C**ONCERN over the contribution of agricultural phosphorus (P) to fresh water eutrophication has focused attention on management practices that decrease P loss from agricultural soils. A variety of studies have found soil P content, particularly WEP concentration, to be strongly correlated with dissolved P concentrations in surface runoff (Pote et al., 1999; Sharp-

ley, 1995). As P-based management strategies develop, a key option may be to restrict P application to soils exceeding environmental thresholds (Kleinman et al., 2000; USDA and USEPA 1999). Such restrictions may preclude land application of manure to soils representing critical source areas of watershed P export, possibly imposing financial hardship on farmers (Beegle and Sharpley, 1999). Furthermore, cessation of P additions to high P soils may not address P losses related to excess soil P concentration immediately. Years, even decades, may be required to decrease soil P concentrations to acceptable levels (Sharpley and Halvorson, 1994). McCollum (1991) found, for example, that it took approximately 14 years following cessation of P additions to a Portsmouth (Typic Umbraquilt) soil to decrease Mehlich-1 P levels from 100 to 20 mg kg<sup>-1</sup>.

<sup>1</sup>Dept. of Crop and Soil Sciences, Penn State University, 447 Agricultural Sciences Bldg., University Park, PA 16802-3504. Michael Callahan is corresponding author. E-mail: mpc150@psu.edu

<sup>2</sup>USDA-ARS, Pasture Systems and Watershed Management Research Unit, Curtin Road, University Park, PA 16802-3702.

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One proximate solution to the problem of runoff P losses from high P soils is to alter the soil P to render it insoluble. In manures, Moore et al. (2000) found that the addition of alum ( $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$ ) to poultry manure precipitates soluble inorganic P. When alum-treated poultry manure was applied to pasture soil, ensuing runoff P losses were 73% lower than from pasture soil applied with untreated manure. Elsewhere, research by Stout et al. (1998) indicates that application of materials with high concentrations of exchangeable Ca and Fe can effectively decrease P solubility in acidic soils.

To be economically viable, a PSSA must be both inexpensive from a material standpoint and effective enough to minimize transport, storage, and application costs as well. To be agronomically viable, PSSAs must not be detrimental to crop growth, i. e., they must not decrease plant available P below crop growth requirements. Thus, Stout et al. (1998) assessed changes in Mehlich-3 P, an indicator of plant P availability, when evaluating the efficacy of several PSSAs.

Phosphorus sorbing soil amendments use several mechanisms to decrease P solubility in soil. In acidic soils, PSSAs function either as electrolytes adding ions of Al and Fe to the soil solution to precipitate P or by adsorbing P onto mineral surfaces. Alum is believed to work by the former mechanism, whereas minerals such as kaolinite and gibbsite adsorb orthophosphate from the soil solution (Muljadi et al., 1966). In addition, a PSSA may induce Al- or Fe-phosphate precipitation in acidic soils through cation exchange reactions that liberate Al and Fe from a soil's cation exchange sites, such as through mass action (Stout et al., 1998). In alkaline systems, PSSAs function primarily through the introduction of Ca to the soil solution and subsequent precipitation of Ca-phosphate compounds. However, Fe may also play an important role in such soils (Castro and Torrent, 1995; Ryan et al., 1985).

For a PSSA to be effective, its mechanism of P sorption must be stable within a given soil environment. For example, P in soils is generally most soluble between pH values of 6.0 and 7.0 (Sharpley, 2000). Because of the lowered stabilities of Al, Fe, and Ca phosphate species (Havlin et al., 1999), amendments that either maintain or shift soil pH to this range may increase soil P solubility. Conversely, amendments that shift soil pH out of this range through acidification or liming may decrease P solubility.

This study assesses seven materials as possible

PSSAs. The objective was to test each material's ability to decrease WEP while maintaining adequate plant available P. In addition, possible constraints to the use of individual materials are discussed.

## MATERIALS AND METHODS

### Soils

Four soils, Berks (loamy-skeletal, mixed, active, mesic Typic Dystrudept), Lackawanna (Coarse-loamy, mixed, active, mesic Typic Fragiudept), Matapeake (Fine-silty, mixed, semiactive, mesic Typic Hapludult), and Nordic (Loamy-skeletal, mixed, superactive Typic Palecryoll) were selected on the basis of their importance as agricultural soils in the northeastern United States as well as their high P concentrations attributable to histories of intensive manure application (Table 1). Surface soil samples were collected, field sieved (2 cm), air dried, and stored at 25 °C prior to incubation with PSSAs and laboratory analysis.

### Soil Amendments

Seven readily available materials were selected as potential PSSAs (Table 2). Our goal when choosing materials was to find compounds that would sorb P strongly enough to decrease its solubility in water, yet maintain a sufficient concentration of plant available P for maximum yield potential. These materials included two minerals, wollastonite ( $\text{CaSiO}_3$ ) and siderite ( $\text{FeCO}_3$ ), and five industrial by-products: water treatment residual from the State College, Pennsylvania, water authority; bituminous refuse ash; anthracite refuse ash; by-product gypsum; and steel processing sludge (basic oxygen process, BOP).

Iron from siderite, anthracite refuse ash, steel processing sludge, and water treatment residual and Al from the alum present in the water treatment residuals were expected to induce P sorption in soil by introduction of Fe and Al compounds into the soil solution and subsequent precipitation/adsorption of P.

Wollastonite, gypsum, and bituminous refuse ash were expected to promote P sorption through

TABLE 1  
Properties of soils used in incubation experiment

Series	Location	Texture	Clay $\text{g kg}^{-1}$	CEC $\text{cmol kg}^{-1}$	pH
Berks	PA	Loam	212	13.0	5.8
Lackawanna	NY	Loam	211	14.9	5.5
Matapeake	DE	Loam	233	11.8	5.7
Nordic	VT	Loam	179	17.6	7.1

TABLE 2  
Active components and CaCO<sub>3</sub> equivalency of amendments used in the incubation experiment

PSSA†	CaCO <sub>3</sub> equivalency (%)	Active component(s)
Anthracite refuse ash	21.3	Amorphous Fe(OH) <sub>2</sub>
Bituminous refuse ash	57.3	Ca(OH) <sub>2</sub> and CaSO <sub>4</sub> ·2H <sub>2</sub> O
By-product gypsum	15.8	CaSO <sub>4</sub> ·2H <sub>2</sub> O
Siderite	14.3	FeCO <sub>3</sub>
Steel-processing sludge	21.5	Amorphous Fe(OH) <sub>3</sub>
Water treatment residual	17.3	Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> ·14H <sub>2</sub> O
Wollastonite	37.8	CaSiO <sub>3</sub>

PSSA: Phosphorus sorbing soil amendment.

the dissolution of Ca compounds in each of the materials. At higher pH (pH > 6.5), P sorption results from precipitation of Ca-phosphates (Havlin et al., 1999). At lower pH, Ca acts by mass action mechanism to release Fe and Al from cation exchange sites, and Fe- and Al-phosphates are precipitated (Stout et al., 1998). Effects of individual materials and soils on pH are clearly critical to the effectiveness of these materials as PSSAs.

#### Incubation Experiment

Potential PSSA materials were added to 100 g of each soil at rates of 10, 20, 40, and 80 g kg<sup>-1</sup> of soil (dry mass/dry mass) to simulate practical field rates. Corresponding application rates of 6.5, 13, 26, and 52 Mg ha<sup>-1</sup> were determined by assuming an incorporation depth of 5 cm (zone of soil where environmental P loss is of greatest concern) and a bulk density of 1.30 g cm<sup>-3</sup>. Unamended 100 g samples were used as controls. Material treatments were conducted in triplicate and controls in quadruplicate. Samples were incubated in open, plastic containers fitted with seven, 2-mm-diameter drain holes. The contents of each container were mixed thoroughly with a stainless steel spatula and wetted to approximately field capacity with distilled water. The containers were placed over a 1-inch thick sand bed to enable water to drain freely without pooling below the containers, thereby ensuring that anaerobic conditions could not occur. Following wetting, containers were covered to decrease evaporation and incubated for 120 days. Deionized water was added periodically to maintain moisture content in the samples. Subsamples (approximately 20 g) were taken at 21 days to see if results corresponded to research by Sharpley (1982) that found that 90% of the P that was eventually sorbed was sorbed within 3 weeks. Samples were also analyzed after 120 days to test the stability of the sorption products over time.

#### Laboratory Analyses

After incubation, all samples were dried and ground to pass through a 2-mm sieve. Three grams of each sample were extracted with 30 mL of distilled water (Kuo, 1996). Another 1 g of each sample was extracted with 10 mL of Mehlich-3 solution (0.2 N CH<sub>3</sub>COOH + 0.25 N NH<sub>4</sub>NO<sub>3</sub> + 0.015 N NH<sub>4</sub>F + 0.013 N HNO<sub>3</sub> + 0.001 M EDTA) (Mehlich, 1984). The Mehlich-3 supernatant was filtered through Whatman #1 paper<sup>a</sup>, whereas the distilled water supernatant was centrifuged (510 g for 10 min) prior to filtering through a Whatman #1 filter. Mehlich-3 and WEP concentrations were determined colorimetrically by the method of Murphy and Riley (1962).

Cation Exchange Capacity (CEC) was determined by summation of Mehlich-3 extractable cations using an ICP (Wolf and Beegle, 1995). Soil pH was determined in a 1:1 (mass/volume) soil/water suspension. Calcium carbonate equivalency for amendments was determined by reacting amendments with 1M HCl and then back titrating with 1M NaOH (Stout et al., 1988).

#### Statistical Analyses

Pair-wise comparisons of 21-day and 120-day incubation data by amendment were conducted using a Student's *t* test (Snedecor and Cochran, 1991). As a result of this comparison, we chose to present only 120-day data as they were a better indicator of the degree of stability over the long term.

This study employs a novel statistic to characterize the efficacy of particular PSSAs in decreasing the WEP concentration of a soil by 50% of the initial concentration: WEP<sub>50</sub> application rate. We chose a threshold of 50% decrease in WEP for several reasons. First, we wanted to use a single property to facilitate interpretation of the data and comparison of PSSA efficacies. The

concept of using such a property is quite common in environmental science (from Lethal Dose 90 used in toxicology to half-life comparisons used in isotope chemistry). Second, we selected a threshold of 50% as it represented approximately the mean decrease in WEP across all treatments. Finally, it represented a substantial decrease in WEP.

To estimate WEP<sub>50</sub> application rate, a non-linear least squares regression was employed to quantify the relationship between WEP concentration and PSSA application rate for the 120-day incubation by exponential model. The model was used to estimate the application rate (Mg ha<sup>-1</sup>) necessary to achieve the WEP<sub>50</sub> (50% of the initial WEP concentration) for each replication. These values were then used in ANOVA to assess differences among PSSAs. A separate ANOVA was conducted for each soil. In order to meet ANOVA assumptions, WEP<sub>50</sub> rates were log<sub>10</sub> transformed before analysis. Multiple comparisons of the WEP<sub>50</sub> means were conducted by Tukey's Honestly Significant Difference test (Neter et al., 1996). All statistical analyses were conducted using SAS statistical software (SAS Institute, Inc., 1989).

## RESULTS AND DISCUSSION

### *Comparison of 21- and 120-Day Incubations*

Differences in WEP and Mehlich-3 P concentrations between the 21-day and 120-day incubations were not significant for by-product gypsum (WEP:  $P = 0.94$ ; Mehlich-3 P:  $P = 0.93$ ) and anthracite refuse ash (WEP:  $P = 0.08$ ; Mehlich-3 P:  $P = 0.10$ ). These results suggest that sorption reactions induced by these materials are rapid and remain stable over time. From 21 days to 120 days, WEP and Mehlich-3 P concentrations decreased significantly in soils incubated with siderite (WEP:  $P < 0.001$ ; Mehlich-3 P:  $P < 0.001$ ), water treatment residual (WEP:  $P < 0.001$ ; Mehlich-3 P:  $P = 0.001$ ), and wollastonite (WEP:  $P = 0.02$ ; Mehlich-3 P:  $P = 0.01$ ), indicating slower kinetics of P sorption induced by these materials. Conversely, WEP and Mehlich-3 P concentrations increased significantly from 21 days to 120 days in soils treated with bituminous refuse ash (WEP:  $P = 0.03$ ; Mehlich-3 P:  $P = 0.04$ ) and steel processing sludge (WEP:  $P = 0.02$ ; Mehlich-3 P:  $P = 0.02$ ). These temporal variations in WEP must be considered in selecting a material as a possible PSSA. While the slower sorption kinetics of siderite, water treatment residual, and wollastonite can be addressed through management by carefully timing PSSA

applications, the instability of P sorption products resulting from bituminous refuse ash and steel processing sludge application must be considered as a potential liability.

### *Effect of Materials on Soil Properties for 120-Day Incubation*

#### *Anthracite Refuse Ash*

Application rates of 69, 48, 101, and 107 Mg ha<sup>-1</sup> correspond to WEP<sub>50</sub> concentrations in the Berks, Lackawanna, Matapeake, and Nordic soils, respectively (Fig. 1). The WEP<sub>50</sub> and Mehlich-3 P values for Berks, Matapeake, and Nordic were extrapolated as anthracite refuse ash did not halve initial WEP within the range of tested application rates for those soils (Table 3). In all soils, anthracite refuse ash substantially increased soil pH, although pH changes were smallest in the Nordic soil as a result of greater buffering. Depending on the application rate, the calcium carbonate equivalency of this material suggests that it could serve as an effective alternative to traditional liming agents (Table 2). For most soils, decreases in Mehlich-3 P at WEP<sub>50</sub> application rates were small (Table 4). A substantial decrease in Mehlich-3 P concentration at the WEP<sub>50</sub> application rate, corresponding to 36% of the initial Mehlich-3 P concentration, was observed in the Nordic soil. However, for all soils, decreases in Mehlich-3 P were never sufficient to be of concern to crop growth as they remained well above the crop response threshold of 60 mg kg<sup>-1</sup> (Beegle, 1999).

#### *Bituminous Refuse Ash*

Despite the increase in WEP concentrations observed between the 21-day and 120-day incubation periods, bituminous refuse ash proved to be one of the most efficacious PSSAs examined in this study. Bituminous refuse ash was most efficacious in the acidic soils, with a WEP<sub>50</sub> application rate of 18 Mg ha<sup>-1</sup> in the Berks, Lackawanna, and Matapeake soils and 31 Mg ha<sup>-1</sup> in the Nordic soil (Fig. 1). In addition, only small decreases in initial Mehlich-3 P concentrations were observed at WEP<sub>50</sub> application rates (Table 4), and Mehlich-3 P remained well above concentrations necessary for crop production.

Despite its effectiveness at promoting P sorption, the extremely high calcium carbonate equivalency of bituminous refuse ash (57%) induced dramatic increases in the pH of all soils (increases ranged from 2.0 to 5.2 pH units), even at the low-

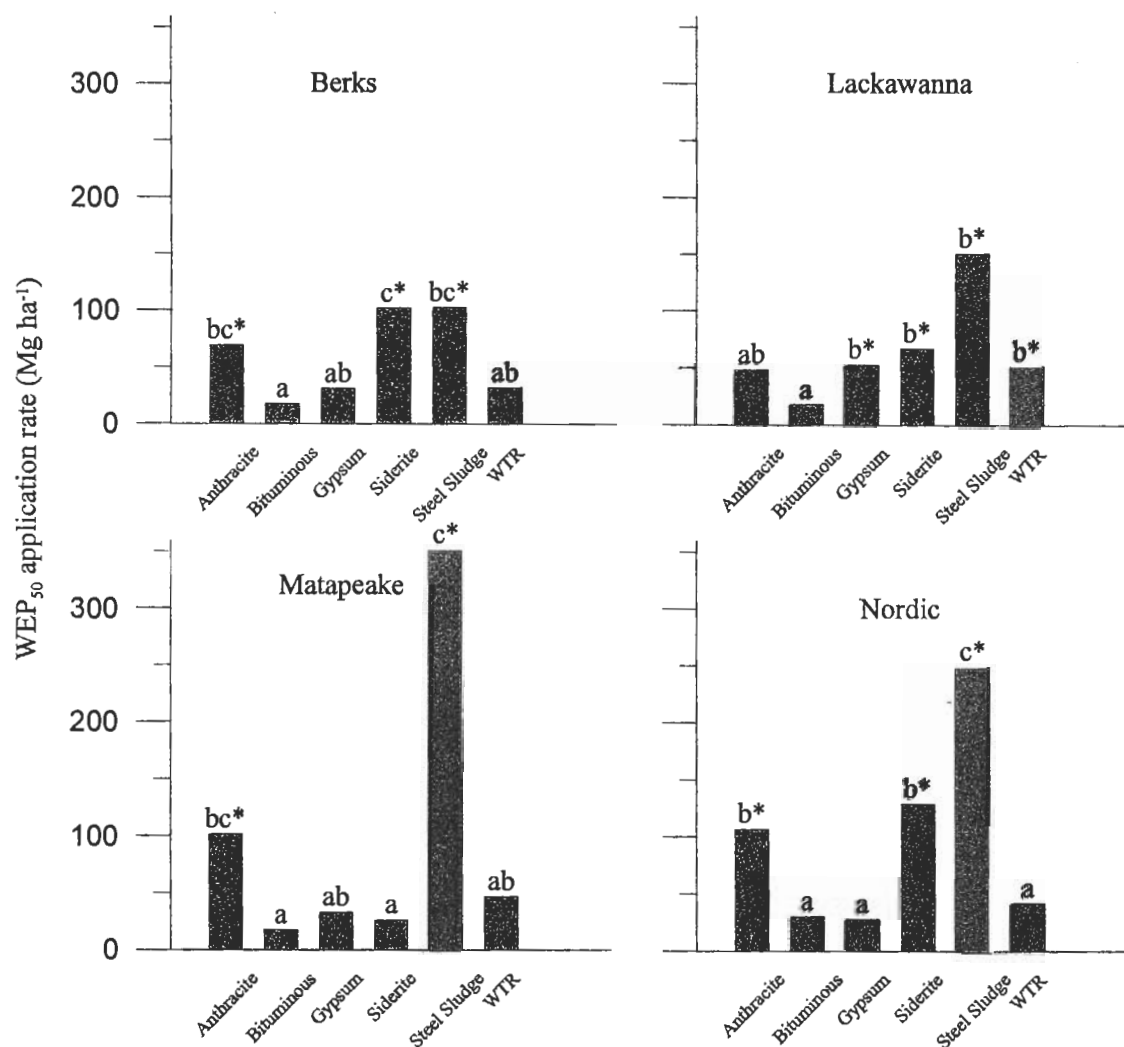


Fig. 1. Estimated WEP<sub>50</sub> application rates for phosphorus sorbing soil amendments after 120 days of incubation in four different soils. Letters above bars identify groupings of means that are not significantly different at  $P = 0.05$ . Note that groupings are soil specific. Means that had to be extrapolated are indicated by an asterisk (\*).

est rates of application, indicating negative consequences to crop production (Fig. 2).

#### By-product Gypsum

Gypsum has been used widely as a Ca and S fertilizer and also as an amendment to improve soil properties (Dontsova and Norton, 2002; Reichert and Norton, 1994). In this experiment, by-product gypsum proved to be effective at promoting P sorption, systematically decreasing WEP concentrations at comparatively small rates of addition (Table 3). For the Berks, Lackawanna, Matapeake, and Nordic soils, WEP<sub>50</sub> application rates for the 120-day incubation were estimated at 31, 53, 33 and 28 Mg ha<sup>-1</sup>, respectively (Fig. 1).

The WEP<sub>50</sub> application rate of 53 Mg ha<sup>-1</sup> for the Lackawanna soil fell slightly above our maximum tested application rate and, therefore, was extrapolated. The subsequent Mehlich-3 P at the WEP<sub>50</sub> application rate of 53 Mg ha<sup>-1</sup> is an extrapolation as well. In the three acidic soils, gypsum likely induced P sorption by the mass action release of Fe and Al from soil cation exchange sites, which, in turn, form insoluble Fe- and Al-phosphates (Stout et al., 2000). In the neutral Nordic soil, Ca-phosphate precipitation likely represents the dominant mechanism of P sorption. Mehlich-3 P concentrations at WEP<sub>50</sub> application rates for gypsum were well above agronomic requirements (Table 4).

TABLE 3  
Mehlich-3 P and WEPT concentrations ( $\text{mg kg}^{-1}$ ) following 120-d incubation of soils with PSSAs†

PSSA	Applic. rate ( $\text{g kg}^{-1}$ )	Berks						Lackawanna						Matapeake						Nordic											
		Mehlich-3 P			WEPT			Mehlich-3 P			WEPT			Mehlich-3 P			WEPT			Mehlich-3 P			WEPT			Mehlich-3 P			WEPT		
		Mean	SD	§	Mean	SD	§	Mean	SD	§	Mean	SD	§	Mean	SD	§	Mean	SD	§	Mean	SD	§	Mean	SD	§	Mean	SD	§	Mean	SD	§
Control	0	412.5	10.6	15.4	0.5		333.3	10.9	10.4	0.8		193.2	4.7	8.9	0.4		195.1	4.3	8.9	0.4		195.1	4.3	8.9	0.4		195.1	4.3	8.9	0.4	
Anthracite refuse ash	10	382.2	19.6	12.5	0.7		338.7	20.7	9.0	1.1		192.0	20.8	7.7	0.1		202.5	17.5	7.7	0.1		202.5	17.5	7.7	0.1		202.5	17.5	7.7	0.1	
	20	437.8	39.4	12.0	0.3		333.0	2.2	8.2	1.4		185.3	16.1	7.1	0.4		209.3	24.6	7.1	0.4		209.3	24.6	7.1	0.4		209.3	24.6	7.1	0.4	
Bituminous refuse ash	40	382.8	51.7	10.0	0.4		316.0	7.2	6.6	1.3		175.2	14.7	7.1	1.0		203.6	17.5	7.1	1.0		203.6	17.5	7.1	1.0		203.6	17.5	7.1	1.0	
	80	349.7	40.9	9.0	1.0		302.0	6.2	5.1	0.8		190.1	30.8	5.9	0.4		191.1	11.9	5.9	0.4		191.1	11.9	5.9	0.4		191.1	11.9	5.9	0.4	
By-product Gypsum	10	410.7	10.7	9.5	0.4		337.7	11.9	5.4	1.0		183.8	11.5	7.6	0.7		220.6	8.8	7.6	0.7		220.6	8.8	7.6	0.7		220.6	8.8	7.6	0.7	
	20	367.7	20.9	7.2	0.8		318.6	8.7	4.7	0.3		197.1	3.3	5.2	0.4		190.1	6.4	5.2	0.4		190.1	6.4	5.2	0.4		190.1	6.4	5.2	0.4	
Siderite	40	305.4	23.0	5.5	0.3		288.5	15.3	3.7	0.3		173.7	10.8	3.0	0.0		185.0	6.0	3.0	0.0		185.0	6.0	3.0	0.0		185.0	6.0	3.0	0.0	
	80	220.6	37.4	3.6	0.0		210.6	17.0	2.7	0.1		120.6	6.3	1.6	0.3		147.4	6.7	1.6	0.3		147.4	6.7	1.6	0.3		147.4	6.7	1.6	0.3	
Steel Proc.	10	387.9	8.7	8.4	0.8		351.4	9.4	6.3	0.1		193.0	7.8	4.9	0.1		184.4	15.3	4.9	0.1		184.4	15.3	4.9	0.1		184.4	15.3	4.9	0.1	
	20	409.0	10.1	12.7	1.1		328.3	2.6	8.8	1.1		190.4	4.1	5.8	0.7		211.3	10.2	5.8	0.7		211.3	10.2	5.8	0.7		211.3	10.2	5.8	0.7	
Sludge	40	385.7	22.2	12.9	1.6		309.6	8.3	7.2	0.5		176.6	12.0	4.5	0.7		209.6	13.9	4.5	0.7		209.6	13.9	4.5	0.7		209.6	13.9	4.5	0.7	
	80	375.1	41.2	10.8	0.6		304.6	8.3	6.5	0.1		177.3	8.5	2.5	0.2		210.9	15.3	2.5	0.2		210.9	15.3	2.5	0.2		210.9	15.3	2.5	0.2	
Water treat.	10	433.5	16.3	15.6	2.2		307.9	12.8	9.4	1.1		189.2	90.7	7.7	0.8		208.2	1.6	7.7	0.8		208.2	1.6	7.7	0.8		208.2	1.6	7.7	0.8	
	20	449.3	32.5	15.3	2.5		310.3	8.8	8.6	0.7		187.2	28.7	7.7	0.9		209.3	4.0	7.7	0.9		209.3	4.0	7.7	0.9		209.3	4.0	7.7	0.9	
Wollastonite	40	399.4	59.6	11.6	2.9		307.2	4.2	7.4	0.6		198.7	13.6	6.1	0.1		205.6	18.1	6.1	0.1		205.6	18.1	6.1	0.1		205.6	18.1	6.1	0.1	
	80	401.6	54.0	9.9	2.9		300.7	17.3	7.5	1.0		191.1	24.7	7.4	0.4		200.3	19.3	7.4	0.4		200.3	19.3	7.4	0.4		200.3	19.3	7.4	0.4	
Residual	10	183.5	16.8	11.8	1.2		317.8	3.6	8.7	1.4		220.7	17.0	5.6	0.3		264.0	58.6	5.6	0.3		264.0	58.6	5.6	0.3		264.0	58.6	5.6	0.3	
	20	181.5	19.3	10.4	0.4		306.0	4.3	7.7	0.3		187.5	9.4	5.4	0.6		283.5	83.6	5.4	0.6		283.5	83.6	5.4	0.6		283.5	83.6	5.4	0.6	
Residual	40	186.0	7.9	7.7	1.3		294.6	3.3	7.1	0.5		204.9	30.3	6.3	3.6		276.1	27.5	6.3	3.6		276.1	27.5	6.3	3.6		276.1	27.5	6.3	3.6	
	80	145.4	22.9	5.5	0.6		245.8	11.4	5.1	0.5		158.1	15.1	3.4	0.3		245.6	22.3	3.4	0.3		245.6	22.3	3.4	0.3		245.6	22.3	3.4	0.3	
Residual	10	410.7	20.6	22.4	0.9		326.1	13.0	11.8	2.8		197.1	5.0	14.5	2.1		279.2	16.2	14.5	2.1		279.2	16.2	14.5	2.1		279.2	16.2	14.5	2.1	
	20	363.9	21.2	21.2	1.2		331.1	9.2	15.1	1.3		179.9	7.2	16.9	0.8		301.3	48.7	16.9	0.8		301.3	48.7	16.9	0.8		301.3	48.7	16.9	0.8	
Residual	40	399.4	12.6	22.2	0.9		328.4	6.4	17.0	1.4		185.4	6.6	17.8	1.2		288.1	47.3	17.8	1.2		288.1	47.3	17.8	1.2		288.1	47.3	17.8	1.2	
	80	372.1	8.0	22.8	0.9		335.6	7.0	16.8	0.6		183.4	3.1	18.5	0.6		310.6	17.4	18.5	0.6		310.6	17.4	18.5	0.6		310.6	17.4	18.5	0.6	

†WEPT: Water extractable phosphorus; †PSSA: Phosphorus sorbing soil amendment; §SD: Standard deviation.

TABLE 4  
Mehlich-3 P values at WEP<sub>50</sub><sup>†</sup> application rates

Soil	PSSA <sup>‡</sup>						WTR <sup>§</sup>
	Initial	Anthracite	Bituminous	Gypsum	Siderite	Steel	
				mg kg <sup>-1</sup>			
Berks	413	296*	347	402	366*	307*	164
Lackawanna	333	313	309	378*	324*	518*	247*
Matapeake	193	293*	185	173	178	0*	169
Nordic	195	71*	182	196	92*	0*	277

<sup>†</sup>WEP<sub>50</sub>: Application rate of amendment at 50% decrease in water extractable phosphorus; <sup>‡</sup>PSSA: Phosphorus sorbing soil amendment; <sup>§</sup>WTR: Water treatment residual; Mehlich-3 P values at WEP<sub>50</sub> application rates that had to be extrapolated are indicated by an\*.

It was noted that pH decreased slightly in the Lackawanna soil following gypsum addition, whereas pH increased somewhat with the addition of gypsum to the Matapeake soil (Fig. 2). Although pure gypsum would not be expected to have an effect on pH, one must be aware that the gypsum used in this experiment was an impure by-product and, indeed, has a calcium carbonate equivalency of almost 16 (Table 2). Indeed, other researchers have found that not only does by-product gypsum contain impurities that affect pH, but it may also react faster than mined gypsum due to higher dissolution rates associated with the by-product's finer particles (Keren and Shainberg, 1981; Reichert and Norton, 1994).

#### Siderite

Siderite decreased WEP concentrations in all soils, but very high rates of application were required before substantial changes were observed in most soils (Table 3). During the 120-day incubation period, WEP<sub>50</sub> application rates were estimated at 102, 68, 27, and 129 Mg ha<sup>-1</sup> for Berks, Lackawanna, Matapeake, and Nordic soils, respectively (Fig. 1). The WEP<sub>50</sub> and Mehlich-3 P values for all soils, excluding Matapeake, were extrapolated because the rates of siderite addition were insufficient to halve initial WEP concentrations. Except for the Nordic soil (53% decrease from control), Mehlich-3 P concentrations did not appear to be negatively impacted by siderite addition (Table 4), nor were substantial changes in soil pH observed.

#### Steel Processing Sludge

Application rates of 102, 151, 352, and 250 Mg ha<sup>-1</sup> corresponded to WEP<sub>50</sub> concentrations in the Berks, Lackawanna, Matapeake, and Nordic soils (Fig. 1). All WEP<sub>50</sub> values were extrapolated for steel processing sludge, and these values were

used to extrapolate Mehlich-3 P values at those application rates. As with anthracite refuse ash, steel processing sludge has a high calcium carbonate equivalency and likely shares similar reactive components. The pH of all three acidic soils increased with increasing rates of steel processing sludge, whereas the pH of the Nordic soil did not appear to change. Mehlich-3 P concentrations at WEP<sub>50</sub> application rates were lowered to detrimental levels in the Matapeake and Nordic soils after steel sludge application (Table 4). In addition to its poor performance in decreasing P solubility, other properties inherent to steel processing sludge, such as its heavy metal content, may be of concern to its application as a PSSA (USX Corporation – U.S. Steel Group, 1999).

#### Water Treatment Residual

Estimated WEP<sub>50</sub> application rates of 32, 52, 47, and 42 Mg ha<sup>-1</sup> for the Berks, Lackawanna, Matapeake, and Nordic soils, respectively, were, on average, slightly higher than those obtained for by-product gypsum, yet still comparable (Fig. 1). Although water treatment residual decreased substantially, Mehlich-3 P concentrations in most soils at WEP<sub>50</sub> application rates, concentrations remained well above plant needs (Table 4). Water treatment residual seemed to have little effect on the soil pH (Table 2).

#### Wollastonite

Wollastonite did not decrease WEP in the four soils. In fact, contrary to the findings of Miyake et al. (1987), who found wollastonite to decrease P solubility in acidic aqueous environments, wollastonite actually increased soil WEP in this study (Table 3). Apparently, these soils are not sufficiently acidic to dissolve wollastonite. Therefore, wollastonite does not appear to be an appropriate PSSA for these soils.

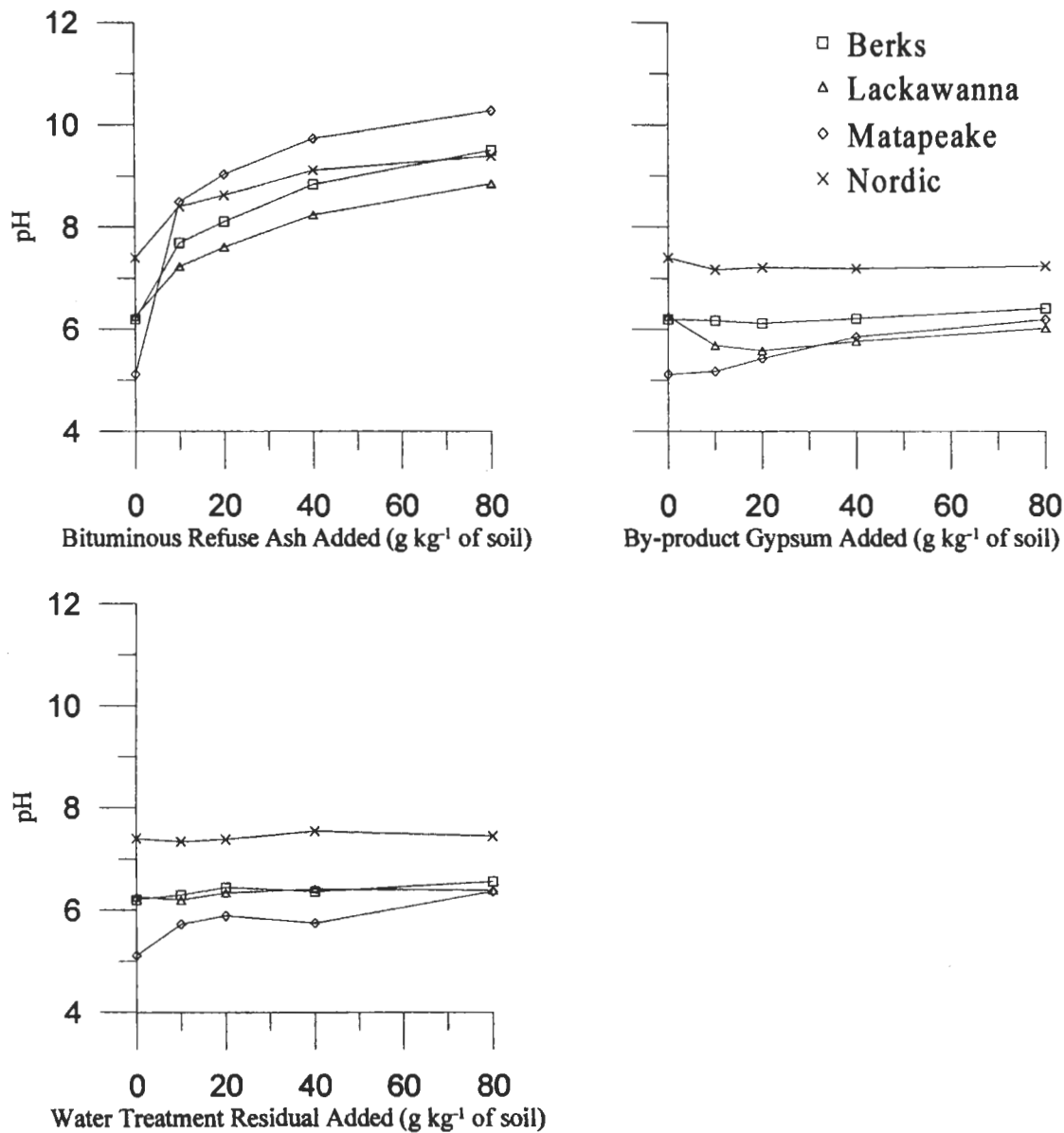


Fig. 2. Change in soil pH following application of phosphorus sorbing soil amendments.

### CONCLUSIONS

For the four soils included in this study, bituminous refuse ash, by-product gypsum, and water treatment residual consistently resulted in the largest decreases in WEP concentrations at the lowest rates of addition. However, bituminous refuse ash possessed a high calcium carbonate equivalency, increasing soil pH above levels acceptable for crop production at the application rates simulated. By-product gypsum and water treatment residual presented no apparent agronomic liabilities.

Anthracite refuse ash had three out of four of its WEP<sub>50</sub> application rates above the highest tested rate of 52 Mg ha<sup>-1</sup>, indicating high application rates may limit the use of this material as a PSSA. Siderite, steel processing sludge, and wollastonite were not sufficiently effective at decreasing WEP to be considered further as possible PSSAs.

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