Plant and Soil **195:** 129–136, 1997.

Effect of phosphate rock, coal combustion by-product, lime, and cellulose on ryegrass in an acidic soil

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Received 17 December 1996. Accepted in revised form 10 June 1997

Key words: aluminium, cellulose, coal combustion by-product, lime, *Lolium perenne*, phosphate rock, phosphorus, ryegrass, Ultisol

Abstract

Remediation of soil acidity is crucial for increasing crop production and improving environmental quality of acid infertile soils. Soil incubation and greenhouse pot experiments were carried out to examine the interactions between phosphate rock (PR), coal combustion by-product (BP), dolomitic lime (L), and cellulose (C) in an acidic soil and their effects on ryegrass (*Lolium perenne* L. cv 'Linn') growth. BP and PR application increased plant P content and dry matter yield (DMY) of shoots and roots by improving soil Ca availability and reducing Al toxicity. Application of BP at low rates (5 to 10 g BP kg^{-1}) with PR appeared to decrease both plant P content and DMY compared to PR application alone. The reduced DMY is due to an increased Al concentration in soil solution as a result of displacement of sorbed Al by Ca of BP. Increases in DMY were obtained by addition of lime along with PR and BP at low rates or by increasing BP application rates above 15 g kg^{-1}. This improved plant response was likely related to alleviation of Al toxicity by $CaCO_3$ contained in the BP. In addition to raising the pH to an acceptable level for plant growth, the dolomitic lime supplied needed Mg for plants, thereby maintaining a good balance between available Ca and Mg for plants in the BP- and PR-amended soils. The addition of cellulose to the BP- and PR-amended soils reduced water-soluble Al and increased DMY. Plant growth increased PR dissolution by 2.4 to 243% in a soil with low available P. Use of BP at moderate rates with PR and dolomitic lime appears to be the best combination in increasing crop yields on infertile acidic soils.

Introduction

Acid soils occupy approximately 30% of the world's ice-free land area and have a high potential for agriculture and agroforestry production (Von Uexküll and Mutert, 1995). However, low nutrient availability (P, Ca, Mg) and acidity related toxicty (Al, Mn) in these soils make normal plant growth difficult. Application of liming materials, fertilizers, and organic manures are generally essential for reduction of acidity-related constraints and to improve the crop production potential of these soils.

Phosphate rock (PR) has received attention as a low-cost P fertilizer for acid soils (Chien and Menon, 1995; Kasawneh and Doll, 1978). The availability of P from the applied PR is largely affected by soil properties such as pH and status of Ca and P (Chien et al., 1980; He et al., 1996a,b; Kanobo and Gilkes, 1987; Robinson and Syers, 1990; Smyth and Sanchez, 1982; Wright et al., 1992). Coal combustion by-products (BP) high in $CaSO_4$ are becoming increasingly available as electric power plants turn to scrubbing to reduce SO_2 emissions. Agricultural use of BP for improving acidic soils has potential both for beneficial utilization and for reducing the cost of disposal (Korcak and Kemper, 1993; Ritchey et al., 1994). Application of

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BP decreased acidity effects and increased crop production on acidic soils (Clark et al., 1995; Sumner, 1994). However, addition of dolomitic limestone with or without BP considerably decreased PR dissolution in acidic soils (Hanafi et al., 1992; He et al., 1996a, 1996b). This decrease in PR dissolution by lime or BP could be partially countered by cellulose addition which enhanced microbial activity (He et al., 1996c).

It was hypothesized that the beneficial effect of each amendment on plants could be enhanced, when more than two amendments are combined at proper proportion. An understanding of interactions among BP, lime, organic matter, and PR, and their consequences for plant growth, is essential to the formulation of amendments in proper proportions for improvement of acidic soils. The objectives of this study were to investigate interactive effects of BP, lime, cellulose, and PR on plant-availability of P in soils and on crop growth and to examine the possibility of formulating a proper combinations of these amendments for cost-effective crop production.

Materials and methods

Materials

The soil used in this study was a pH_{Ca} 3.9 (0.01 *M* $CaCl_2$) Lily loam (Typic Hapludult; sand 51%, silt 38%, and clay 11%). The amendments were a wallboard-quality gypsum BP (BP -#22 from the Beckley ARS collection), PR from Texasgulf Inc., an unburned ground dolomitic limestone, and pure cellulose (SIGMACELL, type 100) [1] (He et al., 1996a). The soil was collected from the 0 to 50 cm layer, mixed, passed through a 2.0 mm sieve, and stored below 4 °C prior to initiation of the incubation experiment. A subsample was air-dried for chemical analysis. Relevant properties of the soil and amendments were described by He et al. (1996a).

Greenhouse pot and incubation experiment

Portions of fresh soil were weighed and mixed with amendments for the treatments as follows: 1) BP at application rates of 0, 5, 10, 15, 25, and 50 g kg^{-1} soil (on a dry-weight basis); 2) treatments listed in (1) plus PR at 397 mg P kg^{-1} soil; 3) treatments listed in (2) plus dolomitic limestone at 3.41 g kg^{-1}, to bring the soil pH to around 6.0, according to a soil pH_w vs. limestone rate relationship curve previously determined with this limestone; and 4) treatments listed in (2) plus cellulose at 10 g kg^{-1}. There were six pots for each amendment treatment; three were used for plant growth, and the other three were used in a soil incubation study (under the same conditions but without growing plants). Nitrogen (200 mg N kg^{-1} as NH_4NO_3) and potassium (l00 mg K kg^{-1} as K_2SO_4) were applied, and 0.3 kg (oven-dry basis) of the mixtures was placed in 400-cm^3 plastic pots (diameter 8.0 cm and height 8 cm). The moisture content of the mixtures was adjusted to 70% of field capacity, and lost moisture was supplemented by addition of water every other day by weighing throughout the experiment and by estimating the weight of fresh plants. After 3 days' soil incubation, 40 ryegrass (*Lolium perenne* L. cv 'Linn') seeds were sown after they had been sterilized with 0.5% NaOCl (household bleach; 1 NaOCl: l0 water, V:V) and thoroughly rinsed with distilled water. One week after germination, 30 of the healthy seedlings were retained in each pot. The plants were grown in a growth chamber with 25/20 °C, 60/70% relative humidity, 14/10 h (light/dark) with a photon flux density of 400 $\mu E\ s^{-2}\ m^{-2}$ derived from incandescent and fluorescent (Sylvania Cool White VHO 215) lamps.

After 45 days of growth, plants were harvested, and roots and shoots were separated, the roots were washed several times to remove the adhering soil. The shoots and roots were oven-dried, weighed separately, and all plant materials were ground to pass through 1.0 mm sieve. The concentrations of Ca, Mg, and P in the plant materials were determined by ICP (inductively coupled plasma spectrophotometry, model JY 46P, Lorgjumeace Cedex, France) following wet digestion (Kingston and Jassie, 1988). At the time of plant harvest, soil samples were collected from the pots with and without plants and analyzed for PR dissolution (He et al., 1996a), and Olsen-P (Olsen and Sommers, 1982), pH_w (soil/water ratio = 1:1), and water-extractable Al (soil/water ratio = 1:2). Aluminum in the extract was determined by ICP After filtered by Whatman No 42 (Jones, 1977).

The increase in plant P content (plant P concentration × dry matter yield) from soil with PR compared to soil without PR is defined as increased plant P (IPP) in mg P kg^{-1} soil. This IPP is considered in the following calculation of effective PR dissolution (EPRD) due to

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[1] Mention of particular companies or commercial products does not imply recommendations or endorsement by Virginia Polytechnic Institute and State University or the US Department of Agriculture over other companies or products not mentioned.

plant growth:

$$\mathrm{EPRD}(\%) = \{[(\text{PR dissolution})_p - (\text{PR dissolution})_c + \text{IPP}] \div (\text{PR dissolution})_c\} \times 100\%$$

where $(\text{PR dissolution})_p$ and $(\text{PR dissolution})_c$ are the PR dissolution in soil (mg P kg^{-1} soil) with and without plant, respectively, as measured with $\triangle$ NaOH-P procedure (He et al., 1996a).

Results and discussion

Effects of BP, PR, lime, and cellulose on soil properties and plant growth

Application of BP and lime raised soil pH and increased soil exchangeable Ca and Mg, whereas PR provided the soil with available P and Ca after dissolution (He et al., 1996a,b). Cellulose addition, on the other hand, promoted nutrient turnover and availability through an enhanced microbial activity (He et al., 1997).

As a consequence of soil remediation by the amendments, dry matter yields (DMY) of ryegrass increased with increases in BP application (Table 1). The DMY at 50 g kg^{-1} BP was about three times higher than that of the control without BP (Figure 1a). Plant P concentration significantly decreased as BP increased (Table 2 and Figure 2a), which may be due in part to a dilution effect from higher DMY of plants at higher BP. P amount absorbed by plants (Figure 2b) showed trends similar to those of DMY with a correlation coefficient (r) of 0.96 ($p < 0.01$) between plant P content and BP rates (Table 1). The BP contained 90% $CaSO_4$, 5% calcium carbonate equivalent, and a small amount of Mg (Clark et al., 1995). The benefit of BP to plant growth was primarily due to an increased Ca availability to plants (Figure 2c) and a raised soil pH (Figure 3a). There were significant relationships between plant Ca content, plant Mg content and BP rates (Table 1). Some of the increases in plant productivity at BP addition rates successively higher than 15 g BP kg^{-1} may have been due to precipitation of the displaced Al from the solution phase by the calcium carbonate contained in the BP (Figure 3b), as soil pH was positively closely related to BP rates (Table 1).

PR markedly increased ryegrass DMY to a level above that produced by the highest rate of BP without PR (Figure 1a). This indicates that P availability may have been the dominant factor for plant growth on this soil. But, in general, the beneficial effect of BP addition to PR on plant growth was apparent, as indicated by the correlations between DMY, plant Ca content, plant Mg content and BP rates (Table 1). In the presence of PR, ryegrass DMY was decreased slightly by BP application at low rates (5 to 10 g kg^{-1}) but tended to increase slightly at higher BP rates (> 15 g kg^{-1}). A similar pattern occurred for the treatments of PR plus BP and cellulose (Figure 1a). The decrease in DMY of ryegrass at low BP rates was likely related to the displacement of sorbed $Al(OH)_n^{(3-n)+}$ by Ca^{2+} from the applied BP. That BP displaced Al is suggested by high water-extractable Al in soil at the low BP rates (Figure 3b). The decrease in water-extractable

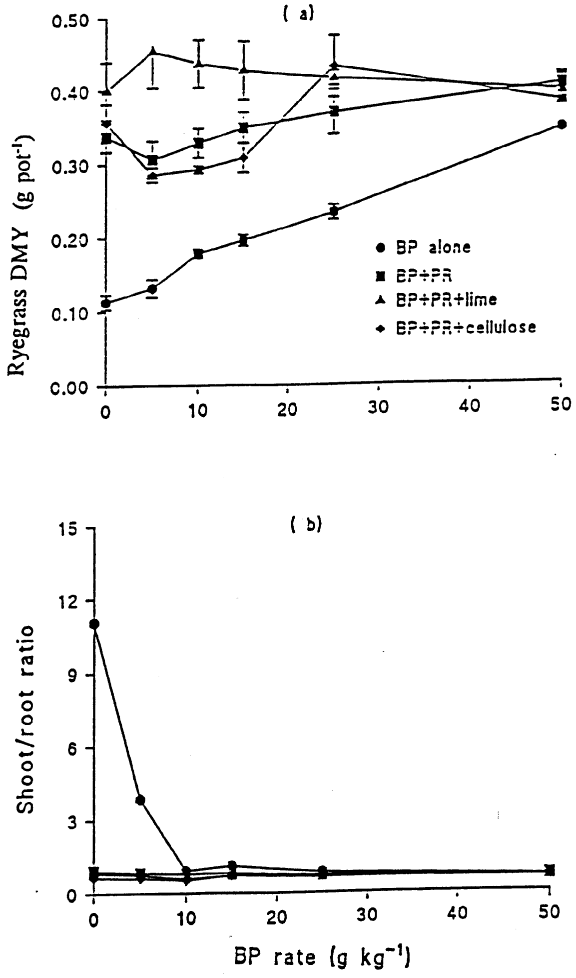

Figure 1. Effect of BP, PR, lime, and cellulose on ryegrass yield (**a**), and shoot/root ratio (**b**). BP - coal combustion by-product, PR-phosphate rock: 397 mg P kg^{-1}, L - lime: 3.41 g kg^{-1}, C - cellulose: 10 g kg^{-1}, I - standard deviation.

Table 1. Regression equations and correlation coefficients (r) between soil and plant growth and BP application rates with and without PR, lime and cellulose

Parameters	BP alone[a]	BP with PR	BP with PR and lime	BP with PR and cellulose
DM yield (g pot^{-1})	y=0.119+0.00459x r=0.99**[b]	y=0.318+0.00176x r=0.92*	y=0.432-0.00062x r= -0.51	y=0.311+0.00177x r=0.55
Plant P concentration (g kg^{-1})	y=1.638-0.0142x r=-0.94*	y=1.698-0.0084x r= - 0.93*	y=1.423-0.0073x r= -0.82*	y=1.371+0.0019x r= - 0.32
Plant P content mg pot^{-1})	y=0.206+0.0029x r=0.96**	y=0.545+0.00049x r= - 0.58	y=0.608-0.0037x r= -0.92*	y= 0.413+0.0021x r=0.52
Plant Ca content (mg pot^{-1})	y=0.724+0.0561x r=0.95*	y=2.191+0.060x r=0.99**	y=3.343+0.0254x r=0.78	y=1.804+0.0907x r=0.94*
Plant Mg content (mg pot^{-1})	y=0.117+0.0051x r=0.99**	y=0.308+0.0043x r=0.95*	y=1.494-0.0582x r= -0.86*	y=0.295+0.0026x r=0.58
Soil pH$_w$	y=4.02+0.013x r=0.99**	y=4.23+0.013x r=0.98**	y=5.67+0.015x r=0.99**	y=4.31+0.016x r=0.99**
Labile P (mg kg^{-1})	y=3.85+0.0038x r=0.25	y=34.0-0.423x r= - 0.82*	y=6.25+0.0638x r= -0.61	y=28.6+0.516x r= -0.68

[a] BP - coal combustion by-product applied at rates of 0, 5 10, 15, 25, and 50 g kg^{-1}, PR - North Carolina phosphate rock at 397 mg P kg^{-1}, L - limestone at 3.41 g kg^{-1}, C - cellulose at 10 g kg^{-1}.

[b]* Significance at $p < 0.05$, and ** significance at $p < 0.01$.

Table 2. Plant P concentration in soil with and without PR

Treatments[a]	Plant P concentration (mg kg^{-1})	Treatments	Plant P concentration (mg kg^{-1})
BP 0	0.67 ± 0.12	PR(397 mg P kg^{-1}) +BP 0	1.83 ± 0.30
BP 5(g kg^{-1})	0.69 ± 0.06	PR+BP 5(g kg^{-1})	1.77 ± 0.15
BP 10	0.86 ± 0.10	PR+BP 10	1.76 ± 0.03
BP 15	0.87 ± 0.06	PR+BP 15	1.82 ± 0.15
BP 25	0.89 ± 0.12	PR+BP 25	1.84 ± 0.10
BP 50	1.18 ± 0.27	PR+BP 50	1.71 ± 0.12
BPO+L	0.80 ± 0.10	PR+BPO+L	2.09 ± 0.27
BPO+C	0.37 ± 0.03	PR+BPO+C	1.41 ± 0.10

[a] BP - coal combustion by-product applied at rates 0, 5, 10, 15, 25, and 50 g kg^{-1}, PR - North Carolina phosphate rock at 397 mg P kg^{-1}, L - limestone at 3.41 g kg^{-1}, C - cellulose at 10g kg^{-1}.

[b] Error ± 1 SE (Standard error).

Al at BP rates > 10 g kg^{-1} may be explained by the neutralizing effect of $CaCO_3$ from BP; consequently, ryegrass DMY was increased by increasing BP rates. The negative effect of BP on DMY of ryegrass was not evident when BP wa applied alone at low rates (5 to 10 g kg^{-1}), probably because such effect was masked by P deficiency, as shown by the much lower DMY in soils without PR than with PR (Figure 1a).

In general, plant P content was increased by PR (Figure 2b), although plant P concentrations were low-

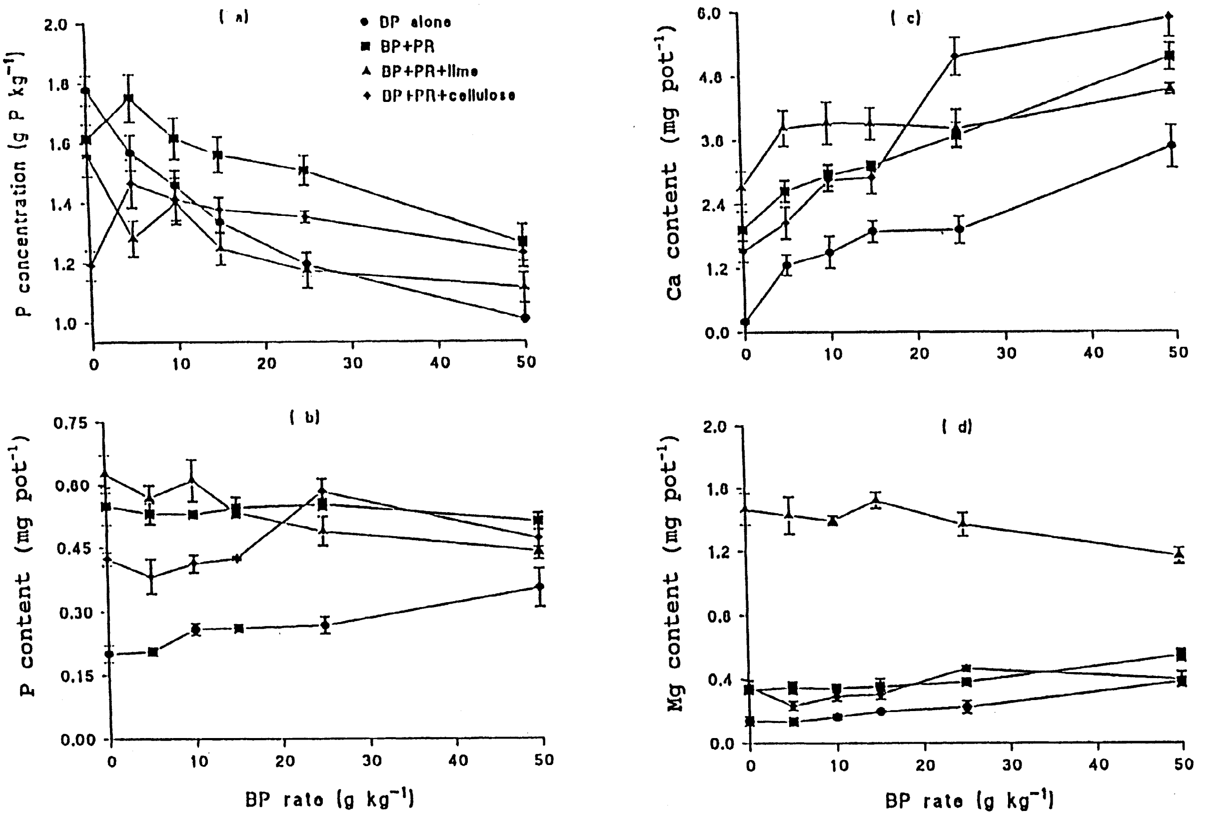

Figure 2. Effect of BP, PR, lime, and cellulose on plant P concentration (**a**), plant P content (**b**), plant Ca content (**c**), and plant Mg content (**d**).

er for the PR treated soils than for the soil without PR and BP or with low BP (< 10 g BP kg^{-1}) plus lime or cellulose (Figure 2a). This was in part due to a dilution effect of the higher DMY for the PR treated soils and also to seed P on P concentrations in plants with low DMY for the soil without PR and BP or with low BP. Plant P concentrations were generally decreased by increasing BP, to some extent, because of decreased PR dissolution (Figure 3c). Since total plant P content was not affected by different BP rates (Figure 2b), we can conclude that P availability was not limiting to plant growth in soils with PR even at high BP rates. A peak in plant P concentration occurred at 5 g BP kg^{-1} with PR, possibly because high soluble-Al caused a relatively low yield (Figures 1a and 3b).

Generally, there were negative correlations between DMY, plant P concentration, plant P content, plant Mg content, and BP rates when BP was applied along with PR and lime (Table 1). However, the highest ryegrass DMY obtained in soils with PR plus lime and BP at 5 to 10 g kg^{-1} (Figure 1a) shows that a small amount of BP had a beneficial effect on plant growth even in a limed soil. For these treatments the low water-soluble Al and sufficient supply of P, Ca, and Mg in the soils favored growth of plants as was evidenced by high amounts of P, Ca, and Mg absorbed by plants (Figures 2b, c and d) and a very low level of water-extractable Al in the soil (Figure 3b). The slight decrease in DMY at higher BP rates (> 15 g kg^{-1}) was likely caused by a decrease in PR dissolution (He et al., 1996a). Consequently, the plant availability of soil P decreased as indicated by the decrease in plant P concentration, P uptake, and Olsen-P in the soils (Figures 2a, b and 3b). It is therefore recommended that PR plus lime and a small amount of BP (<10 g kg^{-1}) be applied in order to attain an optimum crop yield from this soil, provided that the displaced-Al by Ca from BP could not be leached from root zone by limited water sources.

Addition of cellulose with PR reduced water-soluble Al (Figure 3b), but did not improve plant growth in the soil with PR and low BP rates (5 to 10 g kg^{-1}) (Figure 1a). This was likely due to a decrease in Ca and Mg availability to plants as shown by the

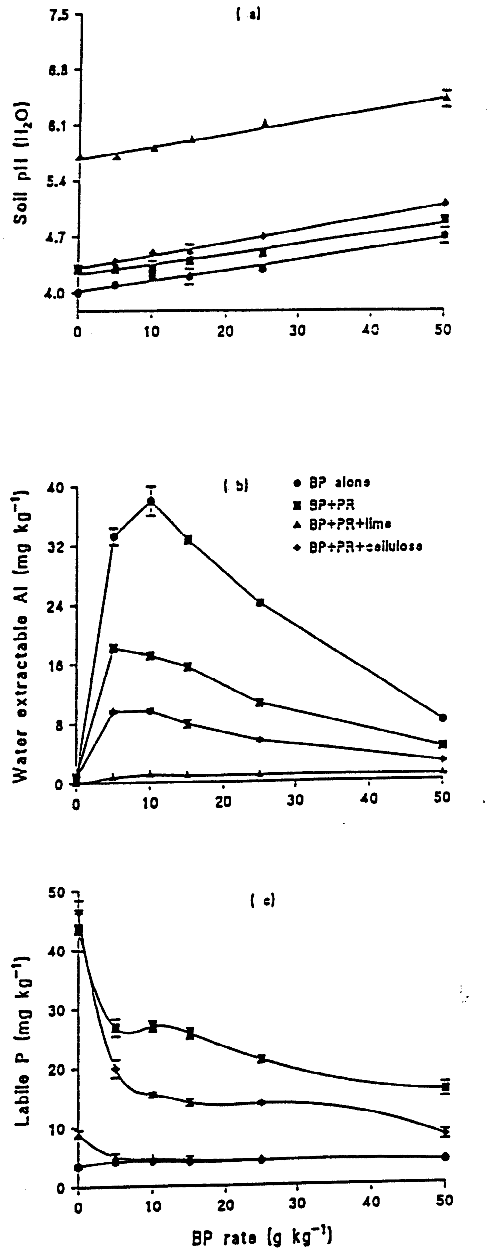

Figure 3. Effect of BP, PR, lime, and cellulose on soil pH (H_2O) (**a**), water extractable Al (**b**), and labile P measured by Olsen-P procedure (**c**) in soil.

decreased Ca and Mg contents in plants (Figures 2c and d). However, with higher BP rates (> 25 g kg^{-1}), ryegrass DMY and plant P, Ca, and Mg content were increased by cellulose and PR application (Figures 1a, 2b, c and d).

Rationalization of BP PR lime and cellulose effects on plant growth

The soil used in this study had very low contents of plant-available P, Ca, and Mg but had high acidity and exchangeable Al (He et al., 1996a). The application of BP high in $CaSO_4$ and with a small amount of $CaCO_3$ and $MgCO_3$ increased the plant availability of Ca and Mg (Clark et al., 1995). The enhanced plant growth and root development, and the decrease in shoot/root ratio, with increasing BP rates (Figures 1a, b) would be expected if Al toxicity were alleviated by the raised Ca/Al ratio in soil solution (Kinraide and Parker, 1987). Moreover, $CaCO_3$ in the BP increased pH ($r > 0.98$, $p < 0.01$), i.e., pH increased by approximately 0.13 unit per 10 g kg^{-1} applied BP (Figure 3a and Table 1). The BP used in this study was reported to steadily increase maize (*Zea maize* L.) DMY up to a rate of 250 g kg^{-1} (Clark et al., 1995) and, therefore, has potential for agricultural use. A negative influence of low BP rates on plant growth in unlimed treatments receiving supplemental P was also observed by Clark et al. (1995), and ascribed to the marked increase in water-extractable Al (Figure 2b). This problem was overcome by lime application or by increasing BP rates to precipitate Al (Figure 1a). It has been reported that SO_4^{2-} could reduce Al toxicity by the formation of $AlSO_4^+$ or $AlOHSO_4$ complexes which are nontoxic to plants (Kinraide and Parker, 1987). However, SO_4^{2-} concentration from BP was not sufficient to completely eliminate the toxicity of displaced Al to plants in this soil.

Therefore, addition of lime is necessary to overcome the displaced-Al toxicity in the BP-amended soil, especially if the BP does not contain sufficient liming materials and where the displaced-Al cannot effectively be leached out of the root zone because of limited water sources.

The beneficial effects of PR addition were probably due to its supply of both P and Ca after dissolution (Figure 2c), for Ca and the increase in Olsen-extractable P (Figure 3c), plant P concentration, and plant P content (Figures 2a and b). The effect of PR on plant growth was much greater than that of BP, lime, or cellulose, showing that PR could supply both P and Ca needed for plant growth in this soil. In addition, the liming effect during PR dissolution increased soil pH (Figure 3a).

Lime application benefited plants by raising soil pH to favorable levels (5.7 to 6.2) and eliminating Al toxicity. The dolomtic lime supplied Mg to the soil and

Table 3. PR dissolution in soil with and without plant growth, increased plant P (IPP) and effective PR dissolution (EPPD)

Treatments[a]	PR dissolution (ΔP mg kg^{-1})		Difference (mg kg^{-1})	IPP[c] (mg kg^{-1})	EPRD[d] (%)
	With plant	Without plant			
PR(397mg P kg^{-1})+BP 0	145.5 ± 5.2[b]	143.1 ± 4.5	2.4	1.16	2.4
PR+BP 5(g kg^{-1})	90.5 ± 6.4	80.6 ± 2.3	9.9	1.08	13.6
PR+BP 10	75.8 ± 5.6	66.0 ± 2.0	9.8	0.90	16.2
PR+BP 15	46.0 ± 1.5	38.4 ± 0.8	7.6	0.95	22.3
PR+BP 25	22.2 ± 2.0	18.0 ± 1.2	4.2	0.95	28.6
PR+BP 50	5.3 ± 1.0	1.7 ± 0.2	3.6	0.53	242.9
PR+BPO+L	27.7 ± 0.7	24.5 ± 1.9	3.2	1.29	18.3
PR+BPO+C	130.9 ± 1.8	125.6 ± 6.4	5.3	1.04	5.1

[a] BP - coal combustion by-product applied at rates of 0, 5, 10, 15, 25 and 50 g kg^{-1}, PR - North Carolina phosphate rock at 397 mg P kg^{-1}, L - limestone at 3.41 g kg^{-1}, C - cellulose at 10 g kg^{-1}.

[b] Error ± 1 SE (Standard error).

[c] IPP (increased plant P): difference in plant P concentration from soils with PR compared to soil without PR.

[d] EPRD (effective PR dissolution): EPDR (%) = $\{[(\text{PR dissolution}_P\text{-(PR dissolution)}_C\text{+IPP}] \div (\text{PR dissolution})_C)\} \times 100\%$ where $(\text{PR dissolution})_p$ and $(\text{PR dissolution})_C$ being PR dissolution in soils with and without plants, respectively.

thus maintained a good balance between plant available Ca and Mg, as was evident by the increased plant Mg content after lime addition (Figure 2d). According to Clark et al. (1995), a Ca/Mg ratio of 200 or more in plants could result in Mg deficiency. Therefore, application of dolomitic lime is particularly important for crop production in acid soils amended with low-Mg BP.

The influence of cellulose on plant growth was more complicated than any other amendment. Although some of the effects of cellulose addition, such as decreased labile P levels, can be attributed to incorporation of P into microbial biomass, more research is needed to understand mechanisms responsible for the effects of organic C in BP-amended soils.

In summary, the addition of PR to this acid soil with low available P, Ca, and Mg greatly improved crop yields, principally by supplying P, Ca, and Mg, but also by raising pH. Application of low levels of BP ($CaSO_4$) increased soil solution Al levels, which led to a decrease in DMY; but increasing rates of BP improved DMY of ryegrss, probably by the liming effect of the small amount of $CaCO_3$ contained in the product. Supplementation of BP with dolomitic limestone eliminated this problem, showing the benefit of combining various soil amendments.

Effect of plant growth on PR dissolution in BP-amended soils

PR dissolution is soil was enhanced in the presence of plant, particularly where PR dissolution was low (Tables 2 and 3). As the BP rate increased from 0 to 50 g kg^{-1}, PR dissolution decreased from 143 mg P kg^{-1} to 1.7 mg P kg^{-1}. The presence of plants increased effective PR dissolution (EPRD) from 2.4% (at 0 BP) to 243% (at 50 g BP kg^{-1}) (Table 3). For the treatments of PR plus lime with BP at rates over 15 g BP kg^{-1}, PR dissolution was not detected by NaOH extraction procedure (He et al., 1996a), but plants still absorbed P from the PR source and maintained a moderate high yield of dry matter in the soil (Figure 1a). These results indicated that plants enhanced PR dissolution through their root activities, especially under low P conditions. These experimental results indicate that PR dissolution estimation from laboratory incubations should be corrected for the plant growth effects in order to predict effective PR dissolution for fertilization recommendations.

Acknowledgements

This research was supported by a specific cooperative agreement with the number 58–1932–2–036 between USDA-ARS, Beaver, West Virginia and Virginia Polytechnic Institute and State University, Blacksburg, Virginia. The authors wish to thank Donald P Day of Texasgulf Inc., Raleigh, North Carolina, for providing the North Carolina phosphate rock sample; Ms B Sweeney for her technical assistance; and Dr D J Parrish, and Dr N K Fageria for their helpful comments on the manuscript.

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Section editor: E Delhaize