

Effectiveness of Coal Combustion By-Products in Controlling Phosphorus Export from Soils

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ABSTRACT

Phosphorus (P) export from high P soils is a major cause of eutrophication in fresh waters. Recent work has shown that the solubility of P in high P soils can be reduced with coal combustion by-products (CCBs), decreasing the potential for dissolved phosphorus (DP) export from these soils. However, the effect of such treatments on plant-available P and P export has not been quantified. We measured P uptake by canola (*Brassica napus* L.) from three high P (130–370 mg kg⁻¹ Mehlich-3 P) soils treated with two CCBs, fluidized bed combustion flyash (FBC), flue gas desulfurization (FGD) CaSO₄ anhydride, and agricultural gypsum (GYP). We measured DP, particulate phosphorus (PP), and total phosphorus (TP) concentrations in runoff from grassed and bare soils treated with these materials and subjected to simulated runoff. Phosphorus, As, Cd, and Pb uptake by canola were unaffected by CCB treatment, and dry-matter yields were unrelated to treatment. On grassed soils, FBC, FGD, and GYP reduced DP concentration in runoff by 20, 43, and 33%, respectively, but did not affect As, Cd, or Pb concentrations in runoff. Also on grassed soils, the high application rate of FGD reduced TP in runoff by 35%. On bare soils where erosion of PP controlled P loss, CCBs and GYP had no effect on DP concentration in runoff. Application of CCBs to high P soils in zones of high surface runoff potential, where there is little erosion, has the potential to reduce P export without affecting crop production.

IN THE northeastern USA, high rates of fertilizer and manure application have resulted in the majority of agricultural soils having excessive amounts of plant-available P compared with crop needs (Sharpley et al., 1994, 1998). Soils with high P levels are an environmental rather than agronomic concern, as runoff from these soils can contain increased amounts of P that can contribute to eutrophication in receiving freshwaters (Carpenter et al., 1998; USEPA, 1996). The conventional options for minimizing agricultural P export focus on controlling source (reducing P inputs, manure, and soil amendments) and transport loss in surface runoff (conservation tillage, buffer zones) (Sharpley and Rekolainen, 1997). Dissolved P is an important algal-available component of this P export, and its loss in surface runoff can be reduced by lowering its solubility in heavily manured and fertilized soils. Under certain conditions, this may be effectively accomplished by applying CCBs to critical P source areas (Stout et al., 1999). An important requirement is that erosion is controlled; where erosion is the dominant means of exporting P, this DP control strategy may be much less effective.

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As a result of Clean Air legislation, large amounts of CCBs are being produced annually by power plants (USEPA, 1988). Previous work has also shown that these types of CCBs can be safely used to increase soil pH and decrease subsoil acidity (Stout et al., 1988; Stout and Priddy, 1996). Recent research has also shown that two of these CCBs, FBC and FGD, can greatly reduce the solubility of soil P without appreciably decreasing the plant-available P, as measured by the Mehlich-3 soil test (Stout et al., 1998). The Ca²⁺ and OH⁻ in CCBs applied to soil converts P to the less soluble P fractions. Application to critical P source areas on a watershed has the potential to substantially reduce DP export overall by treating only this small portion of the watershed (Stout et al., 1999). However, the effect of CCB amendments on dry matter (DM) yield; plant uptake of P, Cd, Pb, and As; and P losses in surface runoff has not yet been determined experimentally.

The objectives of this research were to determine the effects of amending soils with FBC, FGD, and GYP on P, Cd, Pb, and As uptake by plants, plant DM yield, and on P transport in surface runoff from three P-enriched Pennsylvania soils.

MATERIALS AND METHODS

Soils and Amendments

The surface 10 cm were collected from three central Pennsylvania soils, Klinesville (loamy-skeletal, mixed, mesic Lithic Dystrachrept), Hagerstown (fine, mixed, semiactive, mesic Typic Hapludalf), and Watson (fine-loamy, mixed, mesic Typic Fragiuudult) and used in this study (Table 1). Because of long-term fertilizer and manure applications, the P content of these soils was excessive in terms of crop requirements (Beegle, 1996). The relatively high organic C concentration, with respect to cation exchange capacity (CEC), of the Watson reflects even more recent manure applications. These soils are representative of the shale- and limestone-derived soils common to the livestock farming areas of the northeast USA.

Soils used in the plant growth study were sieved through a 3-mm sieve in the field, air-dried, and sieved through a 2-mm sieve prior to treatment. Soils used in the surface runoff study were not sieved when collected in the field but were allowed to air dry before treatment.

The two CCBs used were FBC flyash containing Ca(OH)₂ equivalent to 310 g kg⁻¹ CaCO₃ and about 100 g kg⁻¹ CaSO₄, and FGD gypsum that exceeds 95% CaSO₄. Agricultural gypsum was also used as a treatment in the study. The water-soluble P concentration was 0.25, 0.15, and 1.43 g kg⁻¹ for the FBC, FGD, and GYP, respectively. In a previous study, the two CCBs were shown to reduce DP in high P soils (Stout et

Abbreviations: CCB, coal combustion by-product; DAP, days after planting; DM, dry matter; DP, dissolved phosphorus; FBC, fluidized bed combustion flyash; FGD, flue gas desulfurization; GYP, agricultural gypsum; PP, particulate phosphorus; TP, total phosphorus.

Table 1. Selected properties of soils used to test effects of coal combustion by-products.

Name	pH	CEC†	Exchange acidity	Al	Mehlich-3 P	Organic C
			cmol kg ⁻¹		mg kg ⁻¹	
Hagerstown	5.8	10.1	2.5	5.2	128	2.17
Klinesville	5.5	10.4	4.1	8.5	370	1.73
Watson	6.8	9.7	0	1.0	259	9.7

† Cation exchange capacity.

al., 1998). All three of these materials were analyzed for Cd, Pb, and As by a RECI laboratory in Beaver, WV, using the toxicity characteristics leachate procedure (TCLP) and the procedure for total sorbed metals (USEPA, 1986). The TCLP concentrations of all three materials were below the USEPA 503 regulatory concentrations of 1.0, 5.0, and 5.0 mg L⁻¹ for Cd, Pb, and As, respectively (Table 2).

Plant Uptake

Two sequential crops of canola were grown in the growth chamber to determine the effect of FBC, FGD, and GYP application on DM yield and plant uptake of P, As, Cd, and Pb. Canola seedlings have a high requirement for P and should be sensitive to changes in plant-available P in the soil brought about by the CCB treatments (Hall and Jung, 1992). Also, *Brassica* species are accumulators of heavy metals, thereby providing a rigorous test of how CCB treatments effect Cd and Pb uptake by plants.

Growth chamber study treatments were an untreated check and 5, 10, and 20 g kg⁻¹ of FBC, FGD, and GYP applied to all soils in triplicate. The 10 g kg⁻¹ treatment was previously determined to be the most efficient rate for reducing DP without appreciably affecting plant-available P as measured by the Mehlich-3 P test (Stout et al., 1998). Treatments were prepared by thoroughly mixing each amendment with 1 kg of soil, which was put in 1-L plastic pots with six 5-mm holes drilled in the bottom for drainage. Each pot was brought to field capacity with distilled water and incubated in the growth chamber at 21°C for a total of 21 d. After 7 and 14 d, the pots were removed from the growth chamber, allowed to dry, remixed, rewet, and returned to the growth chamber. More than 90% of soil P equilibration achieved in 1 yr occurs during the first 21 d of incubation (Rajan and Fox, 1972; Sharpley, 1982).

In preparation for canola planting, the soils were air-dried, remixed, and returned to the plastic pots. Six canola seeds were placed on top of the soil, covered with a 1-cm layer of vermiculite, and wetted with distilled water. The vermiculite was added to provide a germination environment and prevent crusting of the soil surface.

After seeding, the pot was placed randomly in a growth chamber at a constant 21°C temperature with 16 h of light (Grinsted et al., 1982). At 14 days after planting (DAP), the number of germinated plants was thinned to three. The plants were then watered with 250 mL of 1/4 strength P-deficient Hoagland solution [i.e., 1 mM Ca(NO₃)₂, 1.5 mM KNO₃, and 0.5 mM MgSO₄] (Hoagland and Arnon, 1950). At 35 DAP,

the plants were exhibiting N deficiency and the strength of the Hoagland's solution was increased to full strength [i.e., 4 mM Ca(NO₃)₂, 6 mM KNO₃, and 2 mM MgSO₄]. The plants were harvested 38 DAP, at which time the plants had recovered from the N deficiency and were starting to compete for growing space within the chamber. After harvest, the plants were dried at 70°C, ground (1 mm), and analyzed for P, As, Cd, and Pb by the Penn State University Agricultural Analytical Services Laboratory (Dahlquist and Knoll, 1978).

After the first harvest, soil from the pots was air-dried and mixed. Because N deficiency occurred in the first growth period, full strength Hoagland's solution was used for the entire second growth period. Canola was harvested after 28 d, dried at 70°C, ground (1 mm), and analyzed. After the second growth period, soil in the pots was air-dried, sieved (2 mm), and along with plant material, analyzed by the Penn State University Agricultural Analytical Services Laboratory for P (Wolf and Beegle, 1991), pH (Eckert and Sims, 1991), and Cd and Pb (American Society for Testing and Materials, 1993). A suitable soil test was not readily available for As.

Surface Runoff

Plywood runoff boxes, 20-cm wide, 120-cm long, and 10-cm deep, were packed with soil. A metal gutter at the down-slope end of the runoff box diverted all surface runoff water to a plastic collection bottle. In this phase of the experiment, treatments for the three soils consisted of an untreated check; 10 and 20 g kg⁻¹ of FBC, FGD, and GYP; and bare and with a perennial ryegrass (*Lolium perenne* L., cv. Bastion) cover. The bare and grassed runoff boxes were designed to simulate two application scenarios of the CCBs and GYP to: (i) field crops such as corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.] and (ii) a grassed area such as pasture, hayland, or a grass buffer strip. For the bare soils, the surface 5 cm of soil was removed, weighed, mixed with an appropriate amount of amendment, and returned to the box. For the grassed treatments, grass was grown to heading stage, harvested to about a 5-cm stubble height, and removed from the box. The amendments were then applied to the surface of the grassed boxes. After treatment, the boxes were wet to approximately 25%

Table 3. Dry-matter yields and P, Cd, Pb, and As concentrations in canola grown on soils treated with three rates of fluidized bed combustion flyash (FBC), flue gas desulfurization gypsum (FGD), and agricultural gypsum (GYP).

Material	Rate	Yield	P	Cd	Pb	As
	g kg ⁻¹	g pot ⁻¹	g kg ⁻¹			
Check		3.48a*	3.84a	0.25b	0.61a	2.06a
FBC	5	3.14ab	3.78a	0.28ab	0.59a	1.36b
	10	3.06b	3.67a	0.28ab	0.48a	1.22b
	20	3.09b	3.79a	0.22ab	0.47a	1.32b
FGD	5	3.25ab	3.76a	0.26ab	0.59a	1.22b
	10	3.27ab	3.81a	0.30ab	1.32a	1.65ab
	20	3.24ab	3.78a	0.29ab	0.47a	1.44b
GYP	5	3.05b	3.96a	0.27ab	0.85a	1.67ab
	10	3.35ab	3.91a	0.29ab	0.62a	1.64ab
	20	3.32ab	3.84a	0.33ab	0.77a	1.57ab

* Means in the same column followed by the same letter are not significantly different by Duncan's multiple range test ($P > 0.05$).

Table 2. Toxicity characteristics leachate procedure (TCLP) and total sorbed metals concentrations of Cd, Pb, and As in leachate and matrix of fluidized bed combustion flyash (FBC), flue gas desulfurization gypsum (FGD), and agricultural gypsum (GYP).

Metal	Leachate			Matrix		
	FBC	FGD	GYP	FBC	FGD	GYP
	mg L ⁻¹			mg kg ⁻¹		
Cd	<0.025	<0.025	<0.025	1.65	0.062	<0.025
Pb	<0.50	<0.50	<0.50	19.7	<1.00	1.24
As	0.64	<0.10	<0.10	60.2	<1.00	<1.00

Table 4. Soil test results for soils treated with three rates of fluidized bed combustion flyash (FBC), flue gas desulfurization gypsum (FGD), and agricultural gypsum (GYP).

Material	Rate	pH	Mehlich-3			
			Acidity	P	Cd	Pb
			mg kg ⁻¹			
Check	5	6.72ab	0.89cd	184bc	0.098ab	3.18abc
FBC	5	6.64bc	1.33bc	175cd	0.111a	3.00abc
	10	6.74ab	0.67d	181cd	0.103ab	3.00abc
	20	6.87a	0.44d	191ab	0.091abc	2.71c
FGD	5	6.41def	1.78ab	198a	0.083bcd	3.27abc
	10	6.29e	2.06a	200a	0.060d	2.91abc
	20	6.33ef	2.00a	174cd	0.067d	3.04abc
GYP	5	6.40def	1.39bc	170d	0.070cd	3.36abc
	10	6.51cd	1.56ab	173cd	0.102ab	3.00abc
	20	6.46de	1.33bc	179cd	0.070dc	3.44a

* Means in the same column followed by the same letter are not significantly different by Duncan's multiple range test ($P > 0.05$).

w/w moisture and incubated for 21 d at 21°C, with periodic wetting to maintain this soil moisture.

A rainfall simulator with four TeeJet 1/2HH-SS30WSQ¹ nozzles, placed 190.5 cm (45 in) apart and 305 cm (10 ft) above the soil surface, was used (Miller, 1987). The nozzles and associated water piping, pressure gauge, and electrical wiring are mounted on an aluminum frame and fitted with plastic tarps to provide a windscreen. Water pressure at the nozzles was regulated to 28 kPa (4.1 psi) to establish a water flow rate of 126 mL s⁻¹ at each nozzle. Shelton et al. (1985) found this pressure to give the best coefficient of uniformity and produce drops with size, velocity, and impact angles approximating natural rainfall. For the simulator used in the present study, a uniformity coefficient of 85% was obtained.

Two 30-min rainfall events of 5 cm h⁻¹ were applied at 1 d intervals to each box angled at a 5% slope. All surface runoff from each box was collected and the concentration of DP, TP, and suspended sediment was determined. Dissolved P was determined on filtered (0.45 µm) runoff samples by the molybdenum-blue method of Murphy and Riley (1962). The same method was used for TP, following digestion of unfiltered water samples with a semimicro Kjeldahl procedure (Bremner and Mulvaney, 1982). The concentration of PP was determined as the difference between TP and DP concentrations. Runoff samples were analyzed for total As, Cd, and Pb by a RECI Laboratory in Beaver, WV, using a strong acid extraction (USEPA, 1983). Successive rainfalls were used as replicates in time.

Statistical Analyses

All data were analyzed using the GLM procedure in SAS (SAS Institute Inc., 1987). An analysis of variance was used to determine the significance of differences at specific treatment rates rather than a regression analysis of the whole treatment response. This was done because a previous study showed that

the effect of the treatments is discreet rather than continuous (Stout et al., 1998). Because the plant response data sets were balanced, Duncan's multiple range test was used to separate the treatment means. However, because of the failure of some runoff boxes, the runoff data sets were unbalanced. Therefore, least square means of the runoff data sets were separated using the PDIF option in the LSMEANS statement in GLM. Treatment differences discussed in the text are significant at the 0.05 level.

RESULTS AND DISCUSSION

Plant Uptake Experiment

There was no significant interaction between CCB treatment and harvest, nor CCB treatment and soils that affected DM yields (Table 3). The two highest FBC treatments were the only CCB treatments that had a significant effect on DM yields of canola. These significantly decreased DM yield from that of the check by about 12%. In contrast, the lowest GYP treatment decreased DM yield from that of the check by about 12%. Because this decrease did not occur at the higher GYP treatments, it may be an artifact.

As in the case of DM yields, there were no significant interactions between CCB treatments and harvest or CCB treatment and soils that affected plant P concentration. Furthermore, CCB and GYP treatments had no significant effect on plant P concentrations (Table 3). This would be consistent with the fact that the Mehlich-3 P concentration of each soil was two to six times greater than the recommended 60 mg kg⁻¹ soil test concentration (Beegle, 1996) (Table 1). Also, at the levels applied in this study, the two CCBs have been shown to have very little effect on the Mehlich-3 P content across a wide range of P-enriched soils (Stout et al., 1998).

All of the FGD and GYP treatments decreased soil pH (Table 4). Correspondingly, all of the FGD and one of the GYP treatments increased acidity. This was due to the displacement of exchange acidity by mass action with Ca²⁺ from the FGD and GYP. A similar response to FGD application was observed in the previous incubation experiment (Stout et al., 1998). The CCB and GYP treatments had mixed effects on Mehlich-3 P (Ta-

Table 5. Dissolved, particulate, and total phosphorus export and concentrations in runoff from grassed and bare soils.

Soil	Dissolved	Export Particulate	Total
		mg	
Grassed	2.80a*	2.12b	4.92b
Bare	0.94b	9.19a	10.1a
		Concentration	
	Dissolved	Particulate	Total
		mg L ⁻¹	
Grassed	1.04a	0.78b	1.82b
Bare	0.34b	3.18a	3.52a

* Means in the same column followed by the same letter are not significantly different ($P > 0.05$).

¹ Mention of trade names does not imply endorsement by the USDA.

Table 6. Dissolved P in runoff generated from grassed and bare soils treated with fluidized bed combustion flyash (FBC), flue gas desulfurization gypsum (FGD), and agricultural gypsum (GYP).

Soil	Check 0	FBC, g kg ⁻¹		FGD, g kg ⁻¹		GYP, g kg ⁻¹	
		10	20	10	20	10	20
mg L ⁻¹							
Grassed							
Hagerstown	1.69	1.24	1.09	1.02	0.72	1.07	0.90
Klinesville	1.21	1.07	1.01	0.48	0.66	0.91	0.97
Watson	0.98	0.77	1.03	0.77	0.76	—	0.74
Mean	1.29	1.03*	1.04*	0.75*	0.71*	NE	0.87*
Bare							
Hagerstown	0.45	0.37	0.31	0.31	0.32	0.45	0.47
Klinesville	0.25	0.33	0.38	0.33	0.29	0.41	0.36
Watson	0.25	0.19	0.40	0.37	0.35	0.40	0.26
Mean	0.32	0.30	0.37	0.34	0.32	0.42	0.36

* Indicates a least square treatment mean significantly ($P < 0.05$) different from the check.

NE Indicates a non-estimable least square mean.

— Indicates empty data cells.

ble 4). The two lowest FGD treatments increased it, the lowest GYP treatment decreased it, and the FBC treatments had no effect. Regardless of these effects, Mehlich-3 P remained high and would be more than sufficient for crop production. The two lowest FGD and the lowest GYP treatments significantly reduced Cd. However, this reduction in Cd is small and may be the result of reduction of acidity at the colloid surface. None of the treatments affected Pb concentration.

When any by-product, especially CCBs, is applied to cropland, Cd, Pb, and As uptake by plants can be of concern. No amendment increased the plant concentration of Cd, Pb, or As in relation to the untreated check (Table 3). This would be consistent with the soil-based results for Cd and Pb. In fact, plant As concentrations from all the FBC and the highest FGD treated soils were significantly lower than the untreated check. This lack of plant uptake would be expected because of the very low levels of As, Cd, and Pb contained in the CCBs.

Surface Runoff Experiment

Grassed versus Bare Soils

The total amount of runoff between grassed soils (2.74 L event⁻¹) and bare soils (2.90 L event⁻¹) was not signifi-

cantly different. However, there were significant differences between the grassed and bare treatments for DP, PP, and TP loss (Table 5). The TP export from the bare soils was more than twice that from the grassed soil. Furthermore, about 90% of the TP exported from the bare soils was exported as PP. In contrast, the majority (57%) of the TP exported from the grassed soils was exported as DP. The grass cover protected the surface from soil erosion, causing DP to be the main form of P transported. For bare soils, surface soil detachment and erosion resulted in the export of sediment-associated PP. Both P transport processes operate at the field and watershed scales (Sharpley et al., 1992). The DP and PP concentration patterns are similar: DP dominates in runoff from grassed soils and PP in the runoff from the bare soils (Table 5).

Coal Combustion By-Product and Agricultural Gypsum Treatments: Grassed Soils

Both CCB and GYP treatments significantly reduced the DP concentration of runoff from grassed soils (Table 6). The FGD treatments were significantly more effective than the FBC treatments in reducing DP. However, no significant differences were observed due to rates of

Table 7. Particulate P in runoff generated from grassed and bare soils treated with fluidized bed combustion flyash (FBC), flue gas desulfurization gypsum (FGD), and agricultural gypsum (GYP).

Soil	Check 0	FBC, g kg ⁻¹		FGD, g kg ⁻¹		GYP, g kg ⁻¹	
		10	20	10	20	10	20
	mg L ⁻¹						
Grassed							
Hagerstown	0.94	0.78	1.04	0.91	0.50	0.96	0.67
Klinesville	0.73	0.90	0.21	0.51	0.53	0.60	0.72
Watson	0.67	0.62	1.24	1.05	0.66	—	0.77
Mean	0.78	0.77	0.83	0.82	0.56	NE	0.72
Bare							
Hagerstown	2.15	2.94	2.57	2.59	3.45	1.23	1.42
Klinesville	4.90	5.97	6.28	4.84	7.49	3.69	4.71
Watson	1.75	2.16	2.92	2.94	1.65	1.58	1.66
Mean	2.93	3.69	3.92	3.46	4.34	2.17	2.60

* Indicates a least square treatment mean significantly ($P < 0.05$) different from the check.

NE Indicates a non-estimable least square mean.

— Indicates empty data cells.

Table 8. Total P in runoff generated from grassed and bare soils treated with fluidized bed combustion flyash (FBC), flue gas desulfurization gypsum (FGD), and agricultural gypsum (GYP).

Soil	Check 0	FBC, g kg ⁻¹		FGD, g kg ⁻¹		GYP, g kg ⁻¹	
		10	20	10	20	10	20
mg L⁻¹							
Grassed							
Hagerstown	2.63	2.02	2.12	1.92	1.23	2.03	1.57
Klinesville	1.94	1.97	1.37	0.99	1.18	1.51	1.70
Watson	1.34	1.40	2.27	1.81	1.42	—	1.52
Mean	1.97	1.80	2.03	1.58	1.28*	NE	1.60
Bare							
Hagerstown	2.60	3.31	2.88	2.90	3.79	1.68	1.89
Klinesville	5.15	6.30	6.67	5.17	7.78	4.10	5.08
Watson	2.00	2.34	3.32	3.31	2.00	1.99	1.92
Mean	3.25	3.98	4.29	3.80	4.52	2.58	2.96

* Indicates a least square treatment mean significantly ($P < 0.05$) different from the check.

NE Indicates a non-estimable least square mean.

— Indicates empty data cells.

treatments in reducing DP concentration in the runoff. Averaged within treatments, DP was reduced by 20, 43, and 33% for the FBC, FGD, and GYP treatments, respectively.

The order of CCB effectiveness in reducing DP in surface runoff differs from an earlier soil incubation study where water-extractable P was reduced 71% by FBC and 48% by FGD treatments (Stout et al., 1998). Although the CCBs contain water-soluble P, the amounts are too small and similar to account for the shift in response to FBC. If all of the soluble P (0.042 mg) in the largest FBC application (168 g box⁻¹) was dissolved in the runoff collected in the two storm events (5.58 L), the DP concentration in the runoff would only be increased by 0.007 mg L⁻¹. The differences in FBC effectiveness may result from the initial FBC dissolution rates being less than FGD, thereby decreasing the short-term effectiveness of FBC to reduce the solubility of soil P.

The high FGD treatment significantly reduced TP in the grassed runoff by 35% (Table 8). This was due to the combination of this treatment causing the greatest reduction in DP loss (Table 6) and having the lowest PP loss (Table 7). No other treatment significantly reduced TP.

Coal Combustion By-Product and Agricultural Gypsum Treatments: Bare Soils

Application of the CCBs and GYP did not reduce the DP concentration of surface runoff from bare soil (Table 6). The controlling mechanism for P export on the bare soils was detachment and transport of PP rather than the dissolution of DP. Neither CCBs nor GYP decreased PP or TP transport from either grassed or bare soil (Tables 7 and 8). This is consistent with the fact that CCBs and GYP reduce DP transport by reducing the water solubility of soil P, but sediment-associated P fractions will still be susceptible to erosion during rainfall and runoff.

Arsenic, Cadmium, and Lead

The majority of the surface runoff samples from the runoff boxes analyzed for total As, Cd, and Pb had concentrations below the detection limits of 0.01, 0.001, and 0.01 mg L⁻¹, respectively, for these three elements. Those concentrations that were below the detection limit were assigned the detection limit in the statistical analysis. Cadmium and Pb concentrations in runoff from all treatments and the check and on the grassed soils were below the detection limits. Arsenic concentration in the highest FBC treatment on the grassed soil (0.012 mg L⁻¹) was the only one that was different than the check (0.01 mg L⁻¹), but was well within the USEPA drinking water standard of 0.05 mg L⁻¹ (USEPA, 1996). Cadmium and Pb concentrations in runoff from all the treatments and check on the bare soils averaged 0.009 and 0.022 mg L⁻¹. However, there were no differences in Cd and Pb concentrations in runoff between the check and any of the treatments on the bare soil. Similar to the grassed soils, As concentration in the highest FBC

treatment on the bare soils (0.017 mg L⁻¹) was the only one that was different than the check (0.011 mg L⁻¹), but was also well within the USEPA drinking water standard (0.05 mg L⁻¹).

CONCLUSIONS

Treatment of high P soils with CCBs to reduce P loss in surface runoff had a negligible effect on canola DM yield and no effect on the uptake of P, As, Cd, or Pb. Both CCBs and GYP reduced DP concentration in surface runoff, with no increase in Cd or Pb concentration in the runoff from the treated soils. Arsenic in runoff from the highest FBC treatment was slightly increased on grassed and bare soils, but was within USEPA drinking water standards. However, these amendments reduce DP in runoff only under conditions where the soils were grassed. To be most effectively and beneficially applied in the field, surface treatments with CCBs or GYP should be applied to grassed high-risk areas. These are where high P soils and runoff-contributing areas of the watershed coincide.

Because surface-applied FBC was less effective in reducing DP than in reducing P solubility when mixed with soil (Stout et al., 1998), it should be incorporated when possible in the field. However, when FBC is incorporated into high P soils in the field, such soils probably need to be seeded to a grass cover to help prevent the transport of PP to become the mechanism controlling P export.

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