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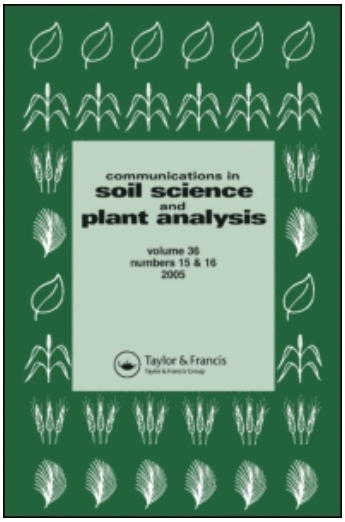

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Fluidized Bed Combustion By-Product Treatment and Leaching of Acid Soil Affects Growth and Boron Acquisition of Maize

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ABSTRACT

Fluidized bed combustion bottom ash (FBCBA) from coal burning power plants often contain substances that detrimentally affect plant growth [(e.g., boron (B)] when applied to soil. Leaf symptoms similar to B toxicity appeared when maize (*Zea mays* L.) was grown during Year-1 of a field experiment where FBCBA was incorporated (6,790 and 13,580 kg ha^{-1}) in an acidic soil (Aquic Hapludult). Soil extractable B increased with increased levels of FBCBA in Year-1 and in Year-2. Although levels in Year-2 were lower than in Year-1 they were still sufficiently high to raise concern about B toxicity. Acquisition of B in leaves of maize grown in Year-1 was relatively high at the 5-leaf stage of growth, and at a normal level in the ear leaf; ear leaf B in

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Year-1 was greater than ear leaf B in Year-2. Grain and fodder yields of plants grown with added FBCBA were reduced in Year-1, but not in Year-2. A greenhouse study was conducted to determine leachability of B through acidic soil (Typic Hapludult) columns whose surface had been treated with FBCBA at 0, 6, and 12 g kg^{-1} soil and leached with different amounts of water (25, 200, and 800 mm). Maize was also grown on the leached soil columns to determine effects of compounds leached from FBCBA on growth and B acquisition in leaves. The application of 800 mm of water reduced soil levels of B, and increased the amount of B leached from the columns. Maize shoot and root dry matter (DM) were enhanced with FBCBA. Increased DM associated with higher FBCBA levels may reflect increased soil pH in this acidic soil. Shoot B concentrations decreased with greater amounts of water used to leach columns. Shoot B concentrations were closely related to levels of B present in the 0-15 cm layer of soil in the column and field experiments.

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INTRODUCTION

Large quantities of coal combustion by-products (CCBs) are produced by power plants that burn coal (ACAA, 1993; USEPA, 1988). Clean Air Act regulations require reductions in sulfur dioxide (SO_2) emissions into the atmosphere, especially when high-S coal is burned. One clean coal technological system is the injection of limestone along with pulverized coal into a fluidized bed combustion boiler to capture S. At high furnace temperatures, limestone converts to CaO that combines with SO_2 to form $CaSO_3$ and/or $CaSO_4$. The residual fluidized bed combustion bottom ash (FBCBA) contains these compounds plus some unreacted sorbent and bottom ash. To reduce landfilling of CCBs, some of these by-products might be used on agricultural, pasture, and/or forest soils. Alkaline calcium and magnesium carbonates and hydroxides in FBCBAs can raise soil pH, benefitting plant growth and soil properties.

The use of FBCBAs on acidic agricultural and forest soils (or minespoil sites) may not only be to mitigate acidity, but to provide beneficial mineral nutrients, such as Ca, Mg, and S, to plants grown on these soils. The FBCBAs sometimes contain relatively high amounts of B, which is required for plant growth, but may also be present in excess. A narrow range between deficiency and toxicity levels of B exists for plants (Marschner, 1995). Plants differ in B requirements (e.g., dicotyledonous usually require more B than graminaceous species), and some plants tolerate higher levels of B than others (Marschner, 1995). Boron in FBCBAs and some other CCBs, especially fly ash, is often sufficiently high to induce B toxicity in some plants unless removed or leached from the product (Adriano et al., 1980). Boron in FBCBA and other CCB residues is normally water soluble and should be readily available to plants (Elseewi et al., 1978).

The level of B in FBCBAs and other CCBs applied to soil must be considered when desired plants are to be grown (Adriano et al., 1978; Stout et al., 1988).

Leaching and/or weathering to reduce B content in FBCBAs that may induce plant toxicity have been recommended when fly ash is applied to soil (Sharma et al., 1988; Townsend and Gilliam, 1975). Boron levels were relatively high in the soil incorporation zone when mixtures of FBCBA and fly ash were added simultaneously to reduce soil acidity (Stehouwer et al., 1994). Maize grown on acid soil amended with FBCBA at 10 g kg^{-1} in unleached containers (greenhouse) had reduced DM (Clark et al., 1995), and B levels in leaf tissue were sufficiently high to implicate B toxicity (R.B. Clark and S.K. Zeto, unpublished data).

Experiments were conducted to examine effects of (1) amending acidic soil with FBCBA on growth and B acquisition of maize in field studies, and (2) FBCBA added to acidic soil columns on B distribution in soil and on growth and B acquisition of maize in laboratory studies.

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MATERIALS AND METHODS

Field Study

The field study was initiated in 1993 (Year-1) with three treatments (limestone and two levels of FBCBA) to determine the effects of FBCBA amendment on maize growth on acidic Cotaco silt loam (fine-loamy, mixed, mesic Aquic Hapludult). The site was located in Raleigh County, West Virginia (37°41'N, 81°7'W) as part of a larger experiment on use of CCBs on acidic agricultural soils.

The soil before incorporation of limestone or FBCBA had pH_w (1 soil/1 water) of 4.42, pH_{Ca} (1 soil/1 0.01M $CaCl_2$) of 4.00, and EC (1 soil/1 water) of 0.039 dS m^{-1}. Soil B from the field experiment was determined by the hot water extractable method with azomethine-H for color development (Bingham, 1982). The field site had not been fertilized for ~40 years. The site was cleared of shrubs (bush-hogged), moldboard-plowed, and rotary-tilled in the Spring of Year-1. Fertilizer was applied at 36 nitrogen (N), 69 phosphorus (P), and 132 potassium (K) kg ha^{-1} as 5-20-20 urea-diammonium phosphate-KCl blend and at 94 kg ha^{-1} N as ammonium nitrate. Magnesium (Mg) was added to the FBCBA amended plots at 268 kg Mg ha^{-1} as magnesium oxide. Dolomitic limestone [11% Mg and 104% calcium carbonate equivalency (CCE)] was added at 4 650 kg ha^{-1} to the lime-treated plots, which were used to compare with the FBCBA treated plots. The FBCBA (screened to pass 2 mm) was applied at 6 790 (Low FBCBA) and 13 580 (High FBCBA) kg ha^{-1}. The limestone and FBCBA were applied uniformly on the surface and incorporated into the surface 15-20 cm soil by rotary-tiller. The experimental area was cultipacked and seeded to Pioneer 3592 maize hybrid (18 June) at 68 200 seeds ha^{-1} with 76 cm between rows (six rows per plot). The experimental design was completely randomized blocks with four replications (9.1 m long x 4.6 m wide plots). Some chemical properties of the FBCBA were pH_w 12.4; 6.2 dS m^{-1} EC (both at 1:1 FBCBA:H_2O); 41.4% calcium (Ca) (55% CCE); 3 650 mg Mg kg^{-1}; 171 g SO_4-S kg^{-1}; 3.2 g SO_3-S kg^{-1}; and 171 mg B kg^{-1}.

TABLE 1. Soil B level, soil pH, leaf B concentration, plant height, and grain and fodder yields of maize grown in the field with lime and FBCBA amendments.

		Soil treatment		
Trait	Unit	Lime (4,650 kg ha^{-1})	Low FBCBA (6,790 kg ha^{-1})	High FBCBA (13,580 kg ha^{-1})
Year-1				
B added	kg ha^{-1}	<0.02	1.16	2.32
Soil B (17 DAP††)	mg kg^{-1}	0.44 b†	1.36 a	1.62 a
Leaf B (17 DAP)	mg kg^{-1}	60 c	122 b	154 a
Plant height (39 DAP)	cm	83 a	72 b	58 a
Ear leaf B (72 DAP)	mg kg^{-1}	16.4 b	23.6 ab	29.8 a
Grain DM	kg ha^{-1}	4,410 a	3,318 a	2,033 b
Fodder DM	kg ha^{-1}	5,688 a	4,580 b	3,766 c
Year-2				
Soil pH$_W$ (0-15 cm)		5.08 ab	4.96 b	5.43 a
Soil B	mg kg^{-1}	0.11 c	0.45 b	0.93 a
Plant height (25 DAP)	cm	32 a	31 a	29 a
Ear leaf B (80 DAP)	mg kg^{-1}	12.3 a	12.9 a	15.0 a
Grain DM	kg ha^{-1}	13,690 a	13,970 a	14,000 a
Fodder DM	kg ha^{-1}	12,280 a	12,360 a	13,350 a

†Values followed by similar letters within a row are not significantly different at P=0.05 according to Duncan's Multiple Range test.

††Days after planting.

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Additional properties of this FBCBA (labeled as BP-#26) have been reported (Clark et al., 1995).

The two oldest leaves of plants were collected for tissue analysis at the 5-leaf stage of growth [17 days after planting (DAP)] when leaf disorders appeared on plants. Soil samples at 0-15 cm depth were collected at this time. The first appreciable rainfall occurred 24 DAP, and sufficient moisture was obtained thereafter that plants did not undergo water stress. Plant heights were measured 39 DAP. Ear leaf samples at early silk were collected 72 DAP. Even though a severe frost occurred before kernel black layer formed in Year-1, grain and fodder yields were measured (November harvest).

Plots were sampled in 1994 (Year-2) on 20 April, and fertilized similarly as Year-1, except additional Mg was not added. The field experiment was rotary-tilled, cultipacked and planted (23 May) to the same maize hybrid as Year-1. Total precipitation between the initial application of FBCBA in Year-1 and planting in Year-2 was 1120 mm. Rainfall during the growing season of Year-2 was sufficient to maintain plants free from water stress. Ear leaf samples from 12 plants per plot were collected at full silk (80 DAP). Maize grain and fodder were harvested after kernel black layer formed (October harvest).

Greenhouse Experiment

Columns (10 cm diameter x 40 cm long) made from PVC (polyvinyl chloride) pipe were lined with two layers of 4 mil plastic film (9.8 cm diameter for soil). The bottom of each column was covered with landscaping cloth through which soil solution could drain. Each column was filled with 22.5 cm of air-dried (5% moisture) acidic Lily soil (fine-loamy siliceous, mesic, Typic Hapludult), and packed to 1.12 g cm^{-3} bulk density. Properties of the soil before added amendments were 63% sand, 31% silt, and 7% clay; 5.0% organic matter; 4.7 pH_w, 4.0 pH_{Ca}, 0.06 dS m^{-1} EC, and 0.18 μg g^{-1} hot-water-extractable B.

On top of each column with the 22.5 cm of packed soil was placed 15 cm of the acid Lily soil mixed with 200 kg P ha^{-1} as $CaH_4(PO_4)_2 \cdot H_2O$ plus 0, 6, and 12 g FBCBA kg^{-1} soil (same FBCBA as used in the field experiment). The 6 g FBCBA kg^{-1} level approximated the High FBCBA (13 580 kg ha^{-1}) rate in the field (Table 1). The soil columns were leached with 25, 200, and 800 mm of distilled water (equivalent to approximately 1, 8, and 32 weeks of rainfall in West Virginia). Water was added in three increments per week with maximum of 100 mm per week for the 200 and 800 mm water leaching treatments, and in four equal increments over a period of 4 h for the 25 mm water leaching treatment. Fertilizer N (107 kg ha^{-1}) and K (300 kg ha^{-1}) as KNO_3 were dissolved in the last 25 mm of water added to the soil columns. In the case of the 25 mm water leaching treatment, the fertilizer was added to the only water added to the column for leaching. In addition, the 25 mm water leached soil columns had 110 mm of water placed at the bottom of each column to allow moisture to rise in the columns to match soil moisture of the 200 and 800 mm water leaching treatments before seedlings were transplanted to columns. The leaching regimes were scheduled so that the last water addition for all leaching treatments was on the same day. During the plant growth phase of the experiment, additional water was applied to prevent drought.

The pH and EC values were determined when leachates were collected, after which leachates were filtered, acidified with 50 μL 15.6M HNO_3 to pH$\leq$2.0, and stored at 4°C until analyzed for B by ICP spectroscopy.

Maize seeds (Pioneer 3592 hybrid) were germinated between moistened filter paper in petri dishes for 3 d. Several 3-d-old maize seedlings were transplanted to each column one week after the conclusion of the leaching. Seedlings were thinned

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to three per column 7 d after transplanting. Plants were grown 21 d, after which shoots were severed ~0.5 cm above the soil surface, dried at 65°C, and weighed.

The plastic film enclosing soil in the columns was pulled from the cylinders. Each column of soil was cut into two segments; the top 15 cm and the remainder of the column. Soil samples were collected from each soil segment and analyzed for pH, EC, and B. Roots from each soil segment were thoroughly rinsed clean of soil on a screen, blotted dry, dried at 65°C, and weighed.

Dried ground shoot material was prepared for B analysis by weighing tissue (50-100 mg) into a Teflon container and adding digestion solution (1.7 mL 15.8M HNO_3+0.2 mL 11.4M HCl+0.1 mL 28.9M HF). These containers were placed into microwave digestion bombs and microwaved for 2 min at full power (635-W delivered) then 4 min at 70% power before being allowed to cool 5 min in the microwave and 30 min at ambient temperature. Digested plant samples were transferred to 10.0 mL volumetric flasks, brought to volume with distilled deionized water, filtered, and stored at 4°C until analyzed by ICP spectroscopy. Boron in the soil from columns was determined by extraction with 0.01M mannitol-0.01M $CaCl_2$ solution and color was developed with azomethine-H (Bingham, 1982).

The experimental design was a factorial randomized complete block that included 3 FBCBA levels x 3 water leaching regimes (prior to transplanting maize) and 3 replications. Data for soil and plant analyses were statistically analyzed using analysis of variance procedures in a General Linear Model of SAS (SAS User's Guide, 1990). Least significant differences (LSD, $P \leq 0.05$) from the columns with 27 entries were used to assess mean differences.

RESULTS

Field Experiment

Plants grown on the FBCBA plots in Year-1 had symptoms of a disorder, suspected as B toxicity, when plants were at the 5-leaf stage of growth (17 DAP). Leaf tips of lower leaves were yellow and the upper leaves were dull, occasionally showing water-soaked symptoms. These symptoms were not noted in Year-2.

Soil pH_W in Year-2 had increased from 4.4 for unlimed control plots to 5.0 and 5.4 for the Low and High FBCBA treatments, respectively, and to 5.1 for the Lime treatment. Boron concentrations in leaves of plants at 17 DAP in Year-1 were different for plants grown on each of the Lime and Low and High FBCBA treatments (Table 1). Also in Year-1, B concentrations in ear leaves of maize at 72 DAP were considerably lower than at 17 DAP, but had similar differences for Lime/FBCBA treatments as the younger plants. In Year-2, ear leaf B concentrations were lower than in Year-1 and did not differ among treatments (Table 1).

Extractable B concentrations in soil sampled 18 days after application of FBCBA in Year-1 were greater than for the Lime treated plots (Table 1). Soil B concentrations in Year-2 were lower than in Year-1 and the treated plots had similar differences as in Year-1 (Table 1).

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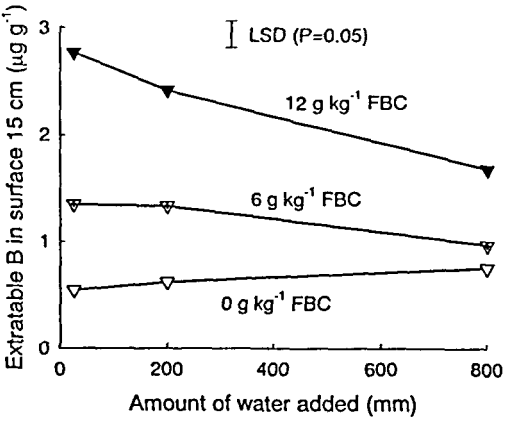

FIGURE 1. Extractable B concentrations in the surface 15-cm soil layer after leaching and plant growth as affected by level of FBCBA added and by leaching.

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Grain and fodder yields at harvest were highest for plants grown on the dolomitic limestone treatment, and lowest for plants grown on the High FBCBA treated plots in Year-1 (Table 1). Grain and fodder yields were considerably higher in Year-2 than in Year-1, and Year-2 grain and fodder yields were not different for the Lime and FBCBA treatments (Table 1).

Greenhouse Experiment

Soil pH_{Ca} of columns increased from 4.1 without FBCBA treatment to 5.1 with 6 g FBCBA kg^{-1} soil and to 6.1 with 12 g FBCBA kg^{-1} soil, regardless of amount of water used to leach columns.

Extractable B concentrations in the surface 15-cm soil layer after leaching and plant growth increased as level of FBCBA added to columns increased (Figure 1). Leaching with both 200 and 800 mm water reduced residual B for the 12 g FBCBA kg^{-1} soil treatment. Leaching with 800 mm water reduced B in the 6 g FBCBA kg^{-1} soil treatment, but not leaching with 200 mm water. Regardless of the amount of water used to leach columns, residual soil B remained similar where FBCBA was not added.

Water at 25 and 200 mm leached relatively little of the added B from columns, and most of the added B remained in the upper 15 cm of soil (Table 2). Water at 800 mm leached nearly all of the added B to columns at the 6 g FBCBA kg^{-1} soil level and leached about two-thirds of the B added to columns at the 12 g FBCBA kg^{-1} soil level.

Shoot and root DM were lowest when plants were grown on control soil not treated with FBCBA, and highest and relatively comparable for plants grown on soil treated with 6 and 12 g FBCBA kg^{-1} soil (Table 2). Shoot B concentrations

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TABLE 2. Residual soil B, B leached from soil, shoot and root dry matter (DM), and shoot B concentrations of maize grown on soil columns supplied with varied levels of FBCBA to the surface 15 cm soil and leached with varied amounts of deionized water (greenhouse).

FBCBA added	B added	Water leaching regime	Residual soil B †		B leached from column	Shoot DM	Root DM	Shoot B concentration
			0-15 cm	15-37.5 cm				
g kg^{-1}	µg	mm	µg			mg plant^{-1}		mg kg^{-1}
0		25	689	1,135	2.0	165	320	28
6	1,330	25	1,710	1,120	3.0	282	391	140
12	2,661	25	3,510	599	0.6	253	367	201
0		200	783	357	34	160	310	29
6	1,330	200	1,685	1,283	51	297	513	139
12	2,661	200	3,041	1,163	43	307	410	138
0		800	958	804	203	175	311	19
6	1,330	800	1,229	1,392	1,325	267	462	61
12	2,661	800	2,129	1,697	1,697	278	519	92
LSD (P=0.05)			315	613	117	58	156	13

†Soil extracted with 0.01M mannitol-0.01M $CaCl_2$ solution and color developed with azomethine-H.

generally increased as level of FBCBA added to columns increased. The highest B concentration in shoots was noted in plants grown on soil treated with 12 g FBCBA kg^{-1} soil and leached with 25 mm water (Table 2). At the 12 g FBCBA kg^{-1} soil level, shoot B concentrations decreased as the amount of water used to leach columns increased. Leaching columns with 25 or 200 mm water had little effect on shoot B concentrations with FBCBA added at 0 and 6 g kg^{-1} soil.

DISCUSSION

Field Experiment

The leaf B concentrations for Year-1 plants at the 5-leaf growth stage in the Lime treatment (60 mg kg^{-1}) were slightly above normal according to published values (Clark, 1975; Marschner, 1995; Reuter, 1986). Boron concentrations in leaves at the 5-leaf stage of growth for plants grown on the FBCBA treated plots (122 and 154 mg kg^{-1}) were sufficiently high to raise concern about B toxicity. Leaf symptoms noted on these maize plants grown with FBCBA at this stage of growth showed characteristics typical of B toxicity (Bennett, 1993). Boron concentrations of >25 mg kg^{-1} in maize when plants were less than 30 cm in height have been reported to be high (Plank, 1979), and normal ranges of B in young maize leaves (up to tasseling) have been between 5-25 mg kg^{-1} (Reuter, 1986). Shoot/leaf B concentrations considered to be toxic have been reported to be >100 mg kg^{-1} (Reuter, 1986). Normal B concentrations of young maize leaves of plants grown in nutrient solutions were ~25-30 mg kg^{-1} (Clark, 1975). Mean B concentrations in leaves of young maize grown on acid soil with varied lime rates in several experiments ranged from 10-40 mg kg^{-1} (R.B. Clark and S.K. Zeto, unpublished data), and shoot DM decreased when B was ~250-300 mg kg^{-1} in 24-d-old maize grown on acid soil with varied levels of B in greenhouse studies (R.B. Clark and S.K. Zeto, unpublished data).

The soil pH_W at the highest level of added FBCBA increased about one pH unit compared to no added FBCBA (4.4 to 5.4), and did not change sufficiently to dramatically affect plant acquisition of B from soil. Boron acquisition by plants often decreases as pH increases (Marschner, 1995).

Boron concentrations in maize ear leaves at silking for plants grown on FBCBA treated plots were lower (24-30 mg kg^{-1}) than in leaves of plants at the 5-leaf stage of growth in Year-1 (122-154 mg kg^{-1}). Ear leaf B concentrations in plants grown on the FBCBA treated plots in Year-2 were lower (12-15 mg kg^{-1}) than in Year-1. The higher B concentrations in leaves of plants at the 5-leaf stage of growth compared to the ear leaf B concentrations of plants in Year-1 and the higher ear leaf B concentrations in Year-1 than in Year-2 most likely occurred because B had leached from the soil in the root growth zone or was diluted by rainfall. Boron acquisition may also have been lower during the later compared to the early stages of plant growth. The B concentrations in ear leaves for plants grown on the Lime and Low FBCBA treatments in Year-1 were within the 5-25 mg kg^{-1} range

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considered normal for maize (Plank, 1979; Reuter, 1976). The ear leaf B concentration for plants grown on the High FBCBA treated plots in Year-1 (30 mg kg^{-1}) could also be considered in the normal range. Leaves of maize plants grown in nutrient solutions where B was continuously supplied had continued accumulations of B as leaves aged; the ear leaf accumulated ~50 mg kg^{-1} near silking and increased to as high as 100-130 mg kg^{-1} at maturity (Clark, 1975). Higher accumulations of B were also noted in leaves at higher positions on the maize stalk above the ear leaf, which progressively increased as plants aged. The flag (uppermost) leaf on the plants had ~200 mg kg^{-1} at maturity and no toxicity symptoms appeared.

Leaf B concentrations indicated that incorporation of this FBCBA material into this acidic soil at levels of 6 790 to 13,580 kg ha^{-1} immediately before planting, in combination with lack of rainfall until 24 DAP in Year-1, may have caused B toxicity. The lack of rainfall may have concentrated fertilizer salts sufficiently to have imposed a salinity stress in the root zone of the seedlings. Manchanda and Sharma (1991) found that salinity stress markedly increased the sensitivity of wheat to levels of soil B that otherwise would not be toxic. The symptoms typical of B toxicity disappeared later in Year-1, and did not appear in Year-2. Reduced grain and fodder yields in Year-1 for plants grown on the FBCBA treatment compared to plants grown on the Lime treatment might be attributed to the high B levels in the soil. However, no grain or fodder yield reductions were noted in Year-2. The alleviation of symptoms of the disorder and subsequent absence of reduction in grain and fodder yields of Year-2 were likely due to leaching of B from the soil by rainfall, and possibly from the absence of drought. Overall grain and fodder yields were also reduced in Year-1 because of the late planting and an early frost.

An alternative hypothesis to explain the poor growth and yield depression of the FBCBA-treated maize during Year-1 is the possibility that other constituents of the FBCBA (e.g., small amounts of $CaSO_3$ or CaS) could have been toxic to the plants. Toxic levels of SO_2 gas were produced when $CaSO_3$ was mixed with acidic soil (Ritchey et al., 1995), and CaS might generate H_2S gas under acidic conditions (Windholz, 1976). However, the soil in direct contact with FBCBA would not likely remain acidic because of $Ca(OH)_2$ or CaO present in the FBCBA, which would raise pH and prevent generation of toxic gases (Ritchey et al., 1995).

Greenhouse Experiment

The benefits of the leaching treatments in reducing soil levels of B resulting from treatment with FBCBA were clearly demonstrated in the greenhouse experiment. The amount of B found in leachates from the 800 mm leaching treatment was equivalent to nearly all the B added at the 6 g FBCBA kg^{-1} soil level, and more than half of the B added at the 12 g FBCBA kg^{-1} soil level. Foliar B concentrations also decreased as residual soil B levels decreased (Figure 2).

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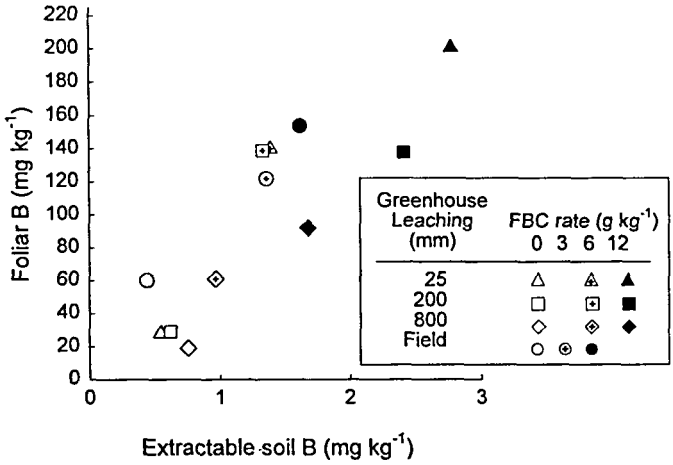

FIGURE 2. Boron concentrations in shoots of young maize plants as a function of hot-water-extractable soil B (field study) and mannitol-extractable soil B (greenhouse study).

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The concentration of B in the leachates from the 800-mm water treatment reached 1.3 to 1.7 mg L^{-1}, which were in the range considered to be toxic (>0.5-1.0 mg kg^{-1} in soil solution) for many plants (Bingham, 1982).

Although plant growth in the greenhouse experiment was generally less vigorous than in comparable experiments (Clark et al., 1995), FBCBA increased DM production. Improved shoot and root DM with FBCBA application to acidic soil compared to no FBCBA application likely occurred because of increased soil pH, while the B added with the FBCBA was not sufficient to restrict growth below that of the acidic soil receiving no added FBCBA. Aluminum and Mn toxicity and Ca, Mg, and P deficiencies are common problems for plants grown on acidic soils (Clark, 1984; Foy, 1992). Both soil and foliar Al and Mn concentrations were reduced and Ca and Mg concentrations were increased with FBCBA applications. Foliar Mn, at 1,830 mg kg^{-1} in dry plant tissue at the 0 g FBCBA kg^{-1} soil treatment was decreased to 760 mg kg^{-1} with 6 g FBCBA kg^{-1} soil, and foliar Al fell from 122 to 64 mg kg^{-1}. Overcoming toxicity and/or deficiency constraints appeared to be sufficient to counterbalance potential yield limitations from high B.

Shoot B was closely related to the amount of B present in the 0-15 cm layer of soil in the column as well as in the field study (Figure 2). Yield decreases observed in the field with foliar B concentrations similar to those in the greenhouse study might be attributed to increased sensitivity to B caused by salinity stress associated with early drought in the field study.

CONCLUSIONS

The FBCBA studied was effective in raising pH and counteracting the effects of toxic levels of Al and Mn in greenhouse and field studies. Potential B toxicity problems may have arisen when maize was grown on acidic soil supplied with FBCBA in the field, especially under droughty conditions. Rainfall of 1,120 mm was sufficient to reduce foliar B concentrations to near 15 mg kg^{-1} and ameliorate B toxicity. The results of the column experiment in the greenhouse indicated that 800 mm of leaching water reduced foliar B by more than half compared to 25 and 200 mm of leaching water.

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