EVALUATION OF FLY ASH AS A SOIL AMENDMENT FOR THE ATLANTIC COASTAL PLAIN: I. SOIL HYDRAULIC PROPERTIES AND ELEMENTAL LEACHING

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Abstract. A major limitation to crop yields in the Atlantic Coastal Plain is drought stress caused by the low moisture-holding capacities of the coarse-textured soils common to the area. Because coal fly ash is comprised primarily of silt and clay-sized particles, it has the potential, if applied at high enough rates, to permanently change soil texture and increase moisture holding capacity. A series of soil column studies were conducted to evaluate the effects of high rates of fly ash on soil hydraulic properties and elemental leaching of trace metals and boron. Fly ash from two Delaware power plants (EM=Edgemoor and IR=Indian River) was incorporated in a Hammonton loamy sand (fine-loamy, siliceous, mesic, Typic Hapludults) at six rates (0, 5, 10, 20, 30, and 40%, by weight). The effect of fly ash on soil moisture holding capacity, hydraulic conductivity, and wetting front velocity was determined. Leachates from columns amended with 30% fly ash were analyzed for B, Cd, Ni, Pb, Cu, and Zn. Soil moisture holding capacity was increased from 12% in the soil alone to 25% in the soil amended with 30% fly ash. Boron and soluble salts leached rapidly from ash amended soils while only trace quantities of Cd, Ni, Pb, Cu, and Zn were detected in column leachates.

1. Introduction

Disposal of industrial wastes and by-products is an increasing concern for most industries. At present, the most common disposal method for many wastes is landfilling. The availability of sites suitable for landfills is limited. Furthermore, the increased costs and potential environmental impacts of landfilling on ground and surface waters has caused industries and regulatory agencies to seek alternative methods for the disposal of industrial wastes. In many instances, land application programs that make constructive use of the physical and/or chemical properties of a waste will be preferred alternatives to other approaches such as landfilling or incineration. Land application programs, however, require thorough evaluation of the short and long-term effects of wastes on soil properties and vegetation, as well as an assessment of the potential for waste constituents to pollute ground and surface waters.

A major limitation to crop yields in the Atlantic Coastal Plain is drought stress caused by the low moisture-holding capacities of the coarse-textured soils commonly found in this physiographic region. Current agronomic responses to the detrimental effects of soil moisture stress are increased use of drought-tolerant crops and irrigation. Research conducted in other areas with drought-prone soils has identified a third alternative, permantly increasing soil moisture holding capacity by altering soil texture with coal ash (Chang *et al.*, 1977; Erickson *et al.*, 1987;

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Salter *et al.*, 1971). Coal ash, the residue of coal combustion by electric power plants, is an amorphous, ferro-alumino silicate mineral, consisting of small, spherical, glass-like particles ranging in particle size from 0.01 to 100 μM (Page *et al.*, 1979). Characterization of a western fly ash found that 4, 63 and 33% of the ash was distributed as clay, silt, and sand-sized particles, respectively (Chang, 1977). British investigators reported that the particle fractions of coal ash samples ranged from 45 to 70% silt and 1 to 4% clay (Townsend and Hodgson, 1973). Several other studies have shown that fly ash is dominated by silt-sized particles (Adriano *et al.*, 1980; Furr *et al.*, 1977). Use of fly ash at high rates, therefore, has the potential to alter soil texture by increasing the percentage of silt-sized particles, and thus to permanently increase soil moisture holding capacity.

Amendment of coarse-textured soils with coal ash, however, has had inconsistent effects on soil physical properties and plant growth. The moisture-holding capavity of sandy loam soils was increased from 20 to 33% in two California soils and from 24 to 93% in British studies (Chang, 1977; Salter *et al.*, 1971). Fly ash rates required to effect significant increases in soil moisture ranged from 250 to 1200 Mt/ha. The objectives of this study, therefore, were to evaluate the benefits and potential adverse effects of high rates of coal fly ash on soil physical and hydraulic properties, and to assess the elemental leaching behavior of fly ash-amended soil to devise environmentally and agronomically sound management practies. In a related study, Sims *et al.* (1995) evaluated the effect of similar rates of the same fly ashes on soil chemical properties and plant growth.

2. Materials and Methods

2.1. ASH COLLECTION AND CHARACTERIZATION

Six fly ash (Class F ash) samples were obtained from each of two Delaware power plants (IR=Indian River and EM=Edgemoor) during a two-week period in August and September of 1990. The twelve ash samples were analyzed for pH, soluble salts, particle size (% sand, silt, clay), Mehlich 1 (0.025 N H_2SO_4 + 0.05 N HCl) extractable P, K, Ca, Mg, Mn, Cu, Zn, Cd, Cr, Ni, and Pb, and not water soluble B by standard methods of the University of Delaware Soil Testing Laboratory (Sims and Heckendorn, 1991). As preliminary chemical and physical analyses indicated considerable similarity in properties between the initial samples collected at each location, a composite sample from each location (IR, EM) was used in subsequent soil column studies examining the effects of fly ash on soil hydraulic properties and elemental leaching. The composite samples were prepared by thoroughly mixing equivalent weights of each of the six ash subsamples. The ash composites were then analyzed by the the same procedures as the intial ash samples.

2.2. ASH EFFECTS ON FIELD CAPACITY AND PLANT-AVAILABLE SOIL WATER

A Hammonton loamy sand soil (fine-loamy, siliceous, mesic, Typic Hapludults) alone or amended with 5, 10, 20, 30, and 40% (w:w) of EM or IR fly ash, was packed at a known bulk density (1.5 g cm^{-3}) into small soil cores and saturated with water at normal atmospheric pressure. The soil cores were placed on a porous ceramic plate in a pressure chamber and subjected to pressures of 0, 0.03 , 0.1, and 0.2 Mpa. Gravimetric moisture content of the soil in the cores was measured after 24 h of equilibration at each pressure.

2.3. WATER TRANSPORT AND ELEMENTAL LEACHING

Water flow and elemental leaching experiments were conducted in uniformly packed columns containing a 30% fly ash-soil mixture (w:w). To prepare a uniformly packed soil column, a pre-determined weight of soil (Hammonton ls) or ash-amended soil was packed into a cylindrical plexiglass column at a density similar to the bulk density expected under field conditions. The columns used in this study had a 5 cm inner diameter and were 75 cm long, of which 60 cm was filled with soil or ash-amended soil. After packing the soil, a few layers of glass beads were placed directly on the surface of the soil in the column to minimize surface disturbance during water application. Marriott bottles (water application devices capable of maintaining a constant height of water in a reservoir) were used to maintain a 5 cm constant head of deionized water on the surface of each column.

Water flow was monitored under transient (during soil wetting) and steady state (soil column completely wet) conditions and appropriate water flow parameters such as wetting front velocity transient water flux and water content, saturated water flux, and saturated hydraulic conductivity were measured or subsequently calculated. The effect of fly ash on these water flow parameters was then compared to those of the unamended soil. In addition to the water flow measurements, the same soil columns were used to monitor the dissolution and leaching of soluble salts, boron (B), and certain heavy metals. Leachates were collected from all columns at several time intervals and analyzed for Cd, Cu, Ni, Pb, Zn by atomic absorption spectrophotometry, B by colorimetry, and soluble salts content with an electrical conductivity meter. Each column was leached with a cumulative volume equivalent to one and a half years of rainfall under Delaware conditions (150 cm). This volume of water was also approximately equivalent to six pore volumes (the amount of water required to flush all the water held in the soil column). In addition to the analysis of the leachates, when leaching was completed the soil in all columns was allowed to drain freely until gravitation flow ceased then removed, sectioned into 10 cm increments and analyzed for gravimetric moisture content, soil test extractable (Mehlich 1, 0.05N HCl + 0.025N H_2SO_4) heavy metals, hot-water extractable B, and total soluble salts as described above.

TABLE I

Selected physical and chemical properties of the Hammonton loamy sand and fly ash from Indian River (IR) and Edgemoor (EM) power plants

Property	Soil	IR Fly Ash		EM Fly Ash	
		Range	Mean	Range	Mean
pH	5.6	5.5–8.3	7.1	7.8–8.6	8.3
EC (mmho/cm)	0.2	2.0–3.0	2.5	1.7–2.5	2.2
Sand (%)	86	0.1–16	4	0.1–11	6
Silt (%)	7	74–86	79	71–80	76
Clay (%)	7	10–23	17	13–22	18

TABLE II

Particle size distribution of soil-fly ash mixtures

Ash	Indian River			Edgmoor		
(%)	Sand (%)	Silt (%)	Clay (%)	Sand (%)	Silt (%)	Clay (%)
0	86	7	7	86	7	7
5	82	11	7	81	12	7
10	75	15	8	77	15	8
20	71	21	8	71	21	8
30	66	24	10	68	23	9
40	57	32	11	59	30	11

3. Results and Discussion

3.1. Physical Properties of Fly Ash and Ash-Amended Soils

The fly ashes used in this study possessed physical and chemical properties within the ranges reported in literature reviews documenting the use of fly ash in agriculture (Adriano *et al.*, 1980; Page *et al.*, 1979). Physically, the ash samples were fine-textured materials, with approximately 80% and 17% of the ash found as silt or clay sized particles, respectively (Table I). Both ash samples used in this study were finer-textured than ash used in studies in Michigan (56-68% silt+clay), or England (46-74% silt+clay) (Chang *et al.*, 1977; Jacobs *et al.*, 1991; Townsend and Hodges, 1971).

In contrast to the ash samples, the Hammonton loamy sand used in this study, typical of the coarse-textured soils of the Atlantic Coastal Plain, contained 86%

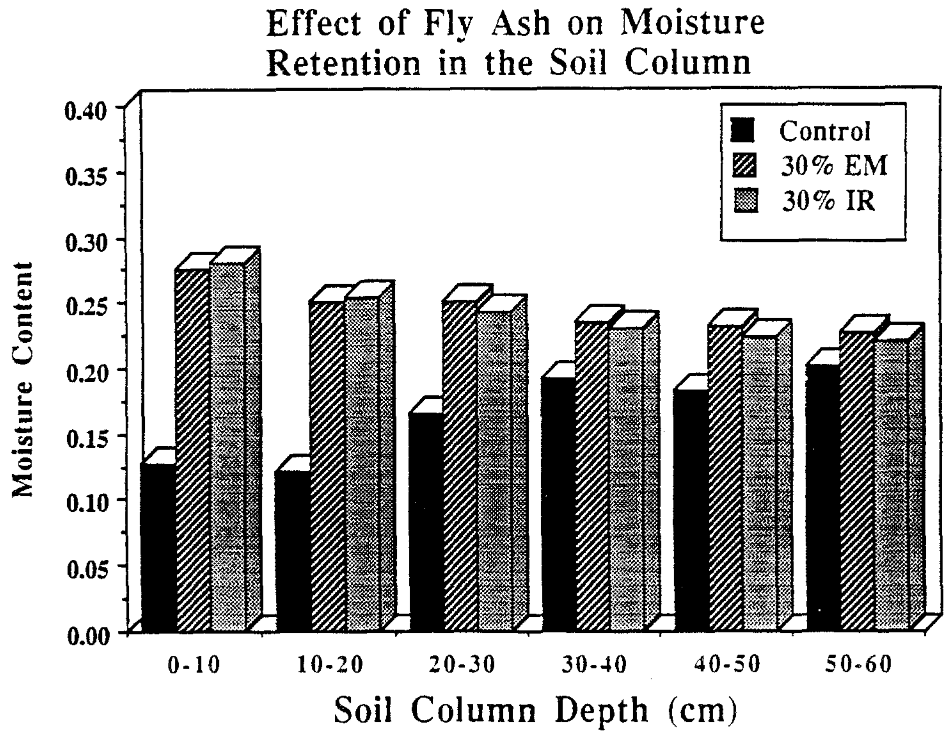

Fig. 1. Effect of different rates of IR and EM fly ash on soil water retention at various imposed pressures

sand, 7% silt and 7% clay. Amending this soil with 20% or 40% fly ash increased the percentage of silt+clay from 14% to about 29% or 42%, respectively, and altered the soil texture from a loamy sand to a sandy loam (Table II).

3.2. Fly ash effects on plant available water and soil water movement

Amending the soil with fly ash markedly increased the retention of soil water at all pressures evaluated (Figure 1). As anticipated, this sandy soil had little native ability to retain moisture, possessing a gravimetric soil moisture content of 10.1% at 0 bars (normal atmospheric pressure). Increasing the imposed pressure, analogous to the effects of soil drying and plant water uptake, decreased gravimetric moisture content linearly. For the soil alone the gravimetric moisture content in the range considered optimum for normal plant growth (0.033 to 0.1 Mpa) ranged from ∼7–9%. In comparison, in the ash amended soils the soil water content at 0.033 Mpa, the moisture tension generally used to estimate the amount of plant available water in a soil, ranged from ∼ 12% at the 5% ash rate to ∼30% at the highest ash rate (40% ash) (Figure 1). At the drier end of the available soil water continuum (0.1 Mpa), the ash amended soils still contained from ∼ 10 to 25% water, depending upon ash rate. This striking increasing in the amount of plant available water was probably caused by two significant differences in the physical properties of the ash-amended soils, relative to the native soil. First, the fine-sized ash particles should increase the total porosity (air space) of the soil, and second, and more importantly, adding fly ash should shift the pore size distribution from primarily large or 'macropores' to a greater percentage of small 'micropores'. Soils with more pore space and a higher percentage of micropores have more ability to retain water at both normal atmospheric pressure and at the greater imposed pressures that accompany soil drying. The ash-amended soils are, therefore, expected to hold more water initially, and retain more water during periods of drought stress, than the unamended Hammonton loamy sand.

Another important factor related to soil moisture in coarse-textured soils is the speed at which water moves through the soil. Many coarse-textured soils are classified as 'excessively well-drained', indicating that water, and contituents dissolved in the water, will move through these soils quite rapidly. There are two implications of this type of water flow. First, much of the water added to the soils in rainfall or irrigation may move below the crop rooting zone where it is of little value to the crop; and second, potentially harmful elements or compounds in the soil (e.g. nitrate-N, and/or pesticides) may also move deeper in the soil profile and potentially enter groundwater supplies. Amending the Hammonton soil with fly ash, because ot its effects on soil porosity, resulted a in dramatic reduction in the flow of water through this soil. For example, addition of 30% fly ash to the soil resulted in an almost threefold reduction in the wetting front velocity of soil water, and even greater decreases in saturates hydraulic conductivity (12 to 15% of that in unamended soil) (Figure 2). These changes are quite significant and could be expected to slow considerably the flow of water through this soil under field conditions. Also, as would be expected, the fly ashes caused a 41% increase in the water content of the soil column following transient flow (Figure 2). The final moisture content of these soil columns, following initial saturation and free drainage, represents another, perhaps more realistic estimate of the field capacity of ash amended soils. Soil moisture contents in columns amended with 30% fly ash were greater at all depths measured than in the unamended soil (Figure 3). Furthermore, the increased moisture content resulting from the ash was greatest at the upper part of the soil column (0–30 cm), the soil depth most readily accessible to plant roots.

In summary, amending the Hammonton soil with fly ash changed the texture from a loamy sand to a sandy loam, increased the amount of plant available water, and decreased the rate of water flow through the soil. These effects have significant implications for crop yields and the potential for groudwater contamination from fertilizers, manures, and pesticides used in crop production. In Delaware and other states in the Atlantic Coastal Plain, for example, the yield goal for non-irrigated corn grown in fine-textured, silt loam soils is $\sim$ 9500 kg ha^{-1}, compared to $\sim$ 4700 kg ha^{-1} for coarse-textured, loamy sands. Permanently changing the texture of a loamy

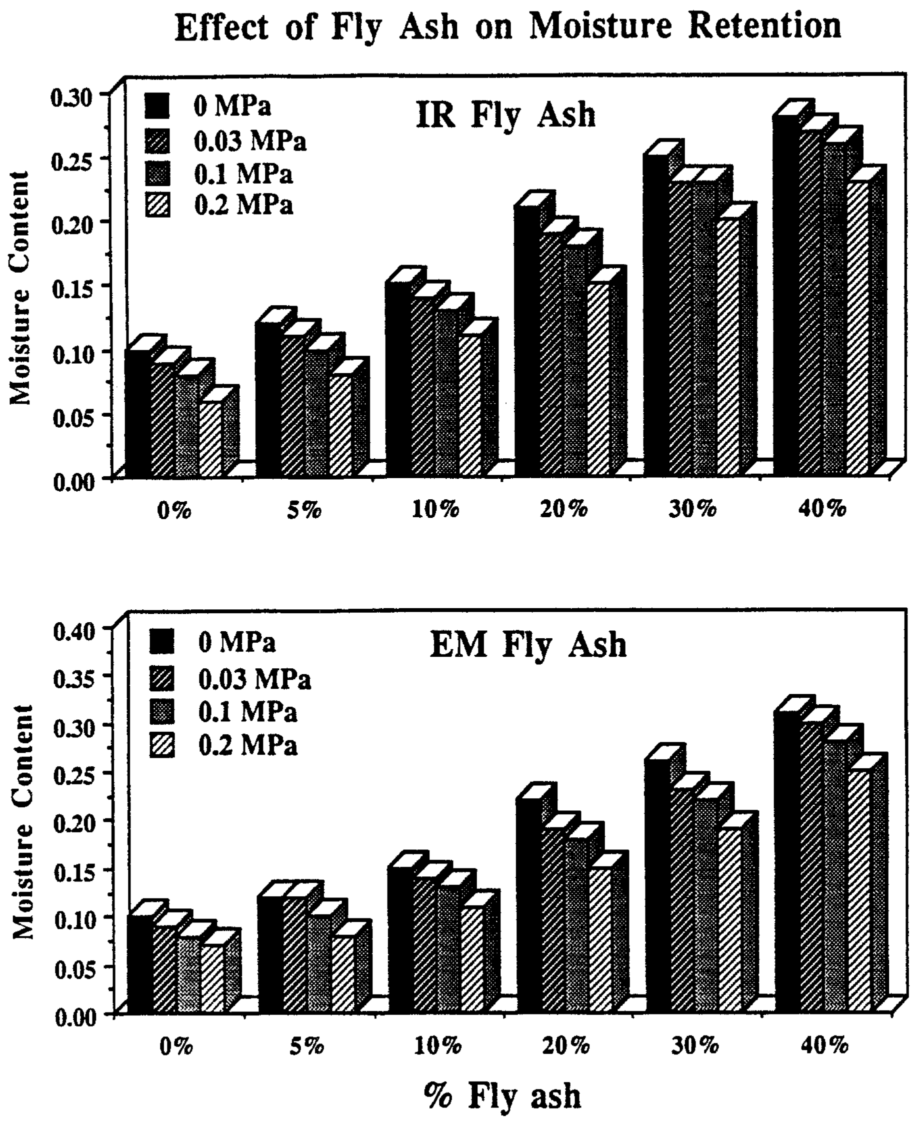

Fig. 2. Effect of fly ash on soil hydraulic properties. Values for amended soils are presented relative to the values for unamended soil.

sand by adding fly ash could markedly increase the yield potential of large areas of cropland in this region. Further, commercial fertilizers and/or poultry manure are commonly applied to corn and other agronomic crops to meet the N requirements of these crops. The easily leached nature of the soils of southern Delaware, in combination with shallow groundwater tables, has made nitrate-N contamination of groundwaters the major nonpoint source pollution issue currently facing the state (Sims, 1990). Pesticide occurrence in groundwaters has been documented in Delaware as well (Ritter *et al.*, 1987; Ritter, 1990). Reducing the rate of water flow

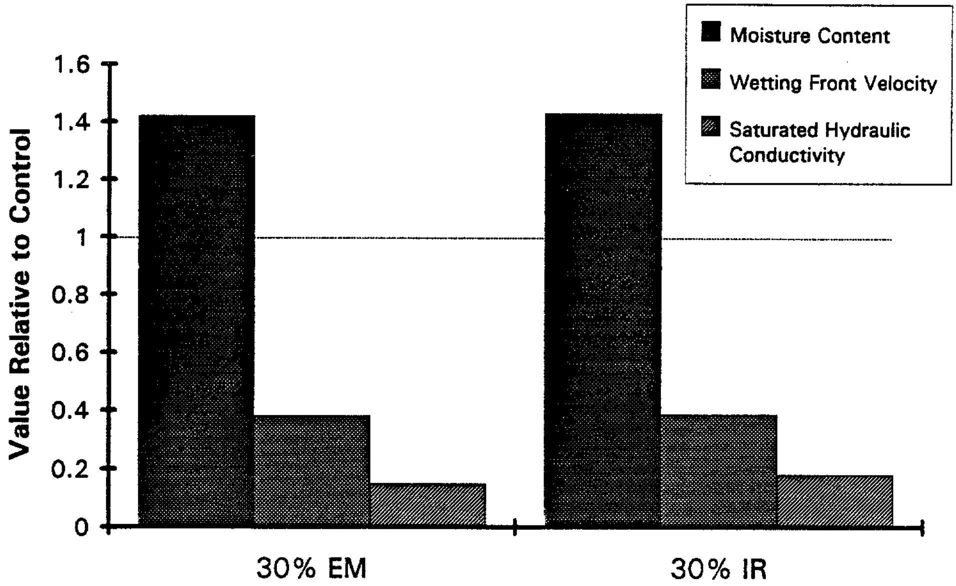

Fig. 3. Effect of fly ash on final distribution of soil moisture content in 60 cm long columns at the conclusion of free drainage.

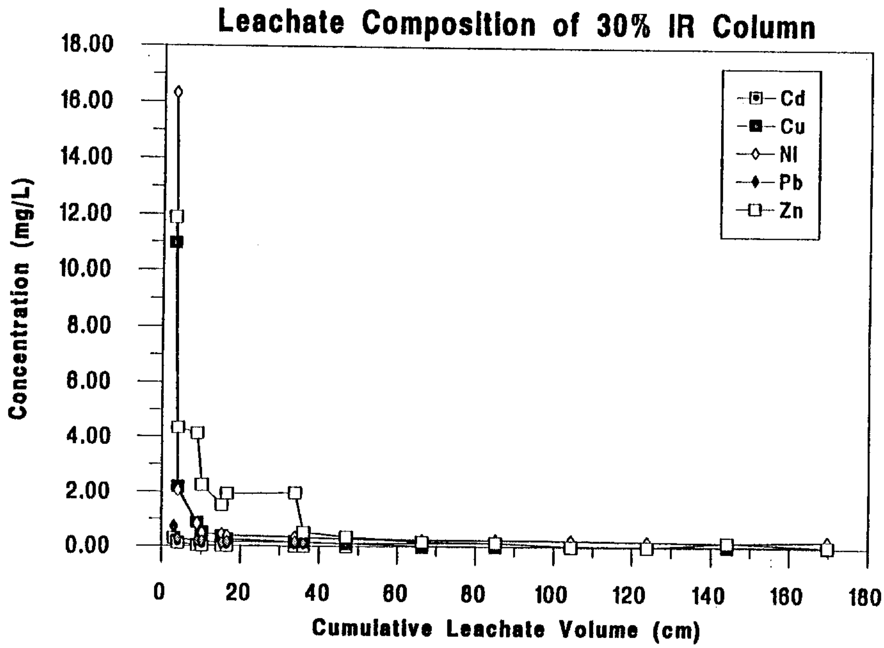

Fig. 4. Release of heavy metals from soil columns amended with 30% IR fly ash.

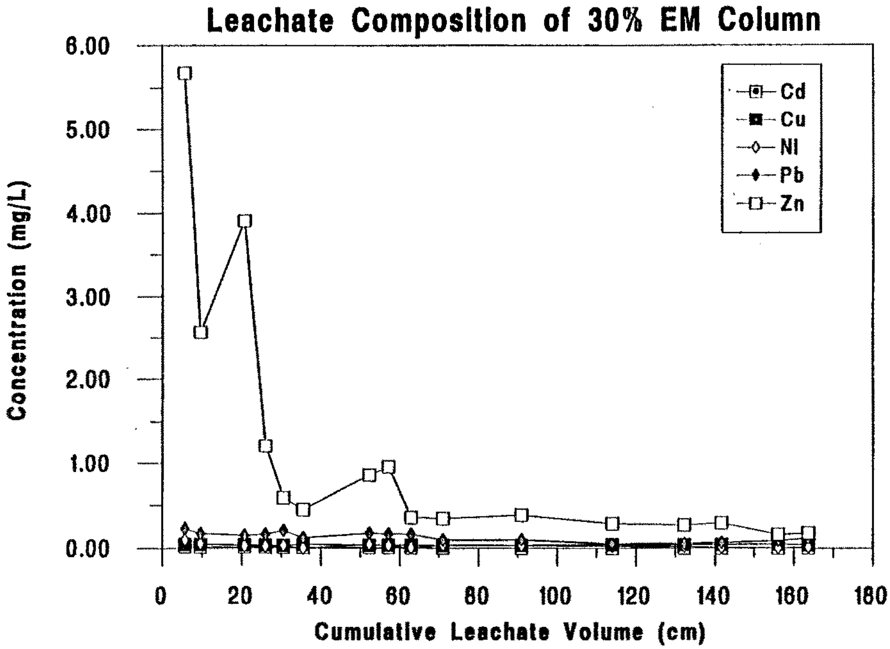

Fig. 5. Release of heavy metals from soil columns amended with 30% EM fly ash.

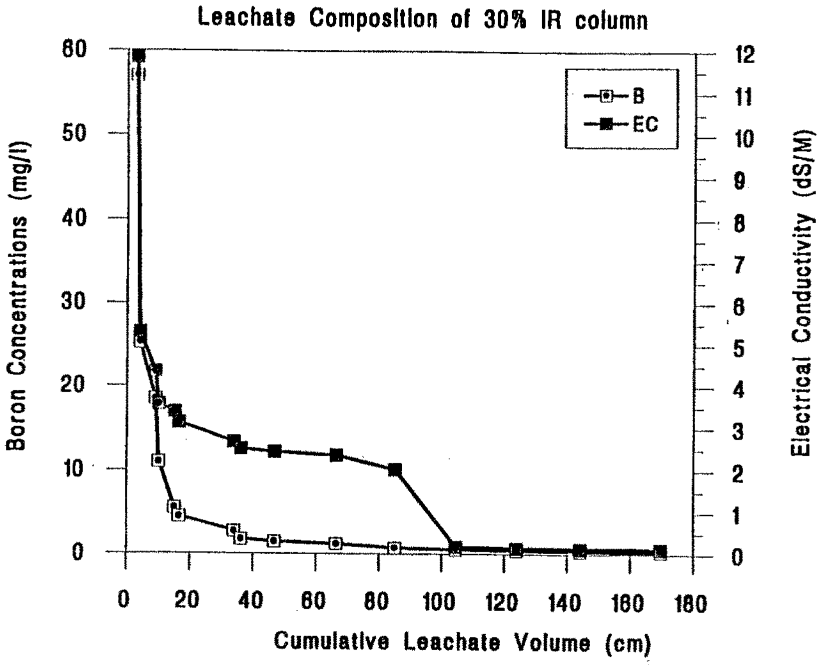

Fig. 6. Release of boron and soluble salts from soil columns amended with 30% IR fly ash.

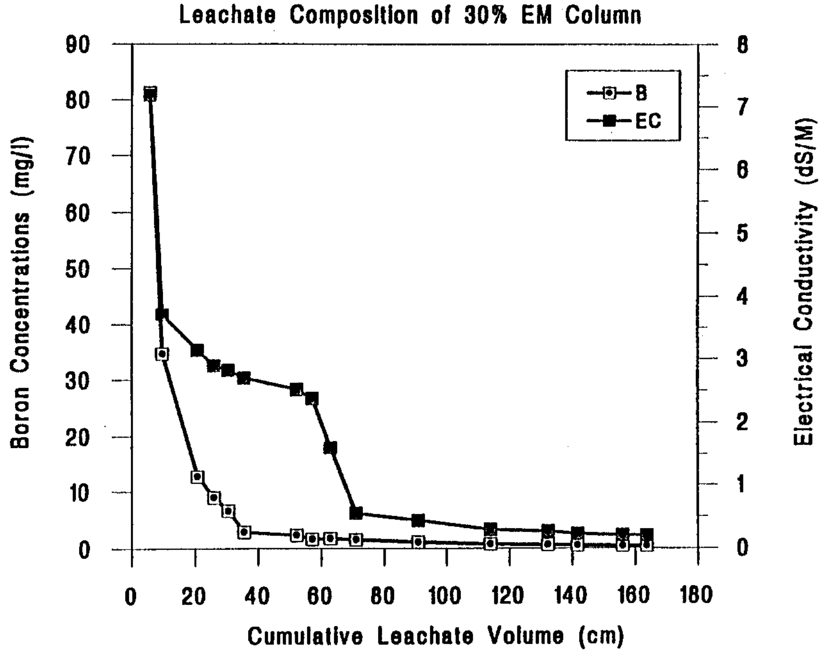

Fig. 7. Release of boron and soluble salts from soil columns amended with 30% EM fly ash.

through the sandy soils of southern Delaware could, therefore, have positive effects on groundwater quality in the area, particularly for nitrate-N which is completely soluble in soil water.

3.3. Heavy Metal Leaching in Ash Amended Soils

An important environmental concern when waste products are added to the soil is the solubilization and leaching of heavy metals to groundwaters. As addition of the IR and EM fly ashes to the soil was shown to increase both extractable soil metal levels and plant metal concentrations in several instances (Sims *et al.*, 1994), an assessment of their potential to leach below the crop rooting zone was also necessary.

The concentrations of Cd, Cu, Ni, and Zn in leachate from the soil alone were very low (< 0.1 mg L^{-1}). Metal concentrations in the leachate from the ash-amended columns were greater initially, reflecting the presence of soluble heavy metals in the ash (Figures 4 and 5). Initial leachate concentrations of Cu and Ni with the IR ash, and Zn, for both ashes, were much greater than the control, ranging from 4 to 16 mg L^{-1}. However, after application of 400 mL of water ($\sim$ 25 cm of rainfall), concentrations of all metals but Zn (IR and EM ashes) were < 0.5 mg L^{-1} and, by the end of the study, little difference existed between the leachate from the soil and the ash-amended soils for all metals.

The total amount of heavy metals leached from the ash-amended soils by the application of 150 cm of rainfall, adjusted by substraction of the amount leached from the soil alone, ranged from less than 0.1 mg kg^{-1} for Cd and Pb to as much as 1.4 mg kg^{-1} for Zn. On the average, 14% of the metals added to the soil in the IR and EM ashes were leached by the equivalent of the amount of rainfall received in Delaware over a one and one-half year period. The relatively low amounts of metal leached can probably be attributed to the pH values of the 30% ash-amended soil (pH of 6.4 to 6.7) which would have contributed to reduced metal solubility. Reversion of metals to more soluble forms as ash-amended soil become acidified by natural processes and/or fertilization practices could occur and should be considered when designing a long-term fly ash management program. However, it is also important to note that these data only represent the leaching of metals from the upper portion of the crop rooting zone. Even in the shallower soils of southern Delaware, approximately 2.3 m of subsoil and parent material remain between the rooting zone and the upper portions of the shallow groundwater table. Further, this subsoil material frequently has a greater metal adsorptive capacity than surface horizons due to its greater content of clay and oxides of Fe and Al. Hence if metal reversion to more soluble forms should occur, due to soil acidification, subsoils likely represent a considerable buffer against metal leaching to groundwaters. It should also be noted that the annual groundwater recharge is always a fraction of total precipitation. For example, in Delaware, the average effective recharge is 25 to 30% of annual precipitation. Consequently, the 150 cm of cumulative leaching which was imposed in this study is in effect equivalent to five to six years of groundwater recharge.

In summary, the low concentrations of metals in the leachate, the sharp decrease in metal concentration of the leachates after the first few leaching fractions, and the fact that in most cases the metals were uniformly distributed in the soil column at the conclusion of the leaching (data not shown), suggest that metal leaching in ash-amended soils will be an extremely slow process, unlikely to have serious impacts on groundwater quality.

3.4. Leaching of Boron and Soluble Salts

In addition to heavy metals, environmental screening of coal ash samples must address the fate of B and soluble salts because application of high rates of coal ash has been shown to cause B and salt toxicity in sensitive plants. Results of leaching studies from soil columns amended with 30% fly ash indicated that, unlike the heavy metals, B leached rapidly from soils amended with 30% fly ash (Figures 6 and 7). The initial concentrations of B in column effluents were 58 and 82 mg BL for the IR and EM columns, respectively, but were decreased to background levels by $\sim$ 30 cm of leaching. For the EM ash, B concentrations were 6.6, 1.8, 1.1, 0.6, and 0.45 mg L^{-1} following each subsequent pore volume of leaching. Analysis of samples collected from amended columns as the conclusion of the study showed that more than 92% of the B initially present in the ash-amended soil had leached from the column after 150 cm of irrigation. The residual concentration of B in the column was similar with depth and was consistently less han 0.35 mg kg^{-1} for the 30% IR and 0.6 mg kg^{-1} for the 30% EM samples. Although slightly greater than the unamended soil, this level of soil B would be acceptable for most crops (Keren and Bingham, 1985).

Virtually identical trends were noted for soluble salt levels (EC) in the column leachate as were observed with B (Figures 6 and 7) although a slight lag phase existed between 10 and 35 cm of leachate. The two distinct phases in soluble salt leaching are quite likely due to differential mobility of very soluble ions, such as B and NO_3-N (rapid decrease in EC) and moderately leachable ions such as K^+, Ca^{2+} and $SO_4{}^{-2}$ (slow decrease in EC).

The depth of the soil-ash mixture in these leaching experiments (60 cm) was three to four times the actual depth to which the ash would be present under field conditions, hence results are representative of a worst-case scenario. Even under these conditions, it appears likely that the annual precipitation common to this area ($\sim$ 150 cm) would be more than adequate to reduce B concentrations in topsoils amended with 30% ash to natural background levels. However, timing of ash application, relative to rainfall patterns and planting will be an important factor to consider when using high rates of fly ash. From a management perspective, application of fly ash in the fall, followed by a fallow period or planting of a salt and B tolerant crop would probably be the most effective approach to use when incorporating high rates of fly ash. This should allow for adequate leaching of salt and B from ash-amended soils during the winter and spring recharge period and prior to planting cash grain crops the following year.

4. Summary

The results of this study on the feasibility of amending the coarse-textured soils of the Atlantic Coastal Plain with high rates of coal fly ash were promising. The Hammonton loamy sand soil used had a greater soil moisture holding capacity and a reduced rate of water flow through the soil profile following amendment with fly ash. These changes have the potential to increase crop yields by reducing moisture stress and to reduce the leaching of nutrients and pesticides to the shallow groundwaters underlying the sandy soils of southern Delaware. Although the fly ash contained soluble heavy metals, only small percentages of most metals were leached through the equivalent of the crop rooting zone by the application of enough water to simulate 150 cm of rainfall. Soil column leaching studies demonstrated that B and soluble salt should leach rapidly from sandy Atlantic Coastal Plain soils reducing the likelihood of phytotoxic effects from these ash constituents.

Acknowledgments

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