CCGP
coal combustion and
gasification products

Web: www.coalcgp-journal.org

ISSN# 1946-0198

Volume# 7 (2015)

Editor-in-chief: Dr. Jim Hower, University of Kentucky Center for Applied Energy Research

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Suggested Citation format for this article:

Dzantor, E.K, Adeleke, E., Kankarla, V., Ogunmayowa, O., Hui, D., 2015, Using Coal Fly Ash Agriculture: Combination of Fly Ash and Poultry Litter as Soil Amendments for Bioenergy Feedstock Production. *Coal Combustion and Gasification Products* 7, 33-39, doi: 10.4177/CCGP-D-15-00002.1

CCGP Coal Combustion and Gasification Products

ISSN 1946-0198

journal homepage: www.coalcgp-journal.org

Using Coal Fly Ash in Agriculture: Combination of Fly Ash and Poultry Litter as Soil Amendments for Bioenergy Feedstock Production

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ABSTRACT

Increasing fiscal, human, and environmental costs of coal fly ash (FA) management are leading to advocacy for greater beneficial uses of the by-products as soil amendments in agriculture. Greenhouse experiments were conducted in Armour silt loam (ASL) soil that was amended with FA (10%, wt/wt) with and without poultry litter (PL = 75 mg N/kg). Biomass productivity of eastern gamagrass (GG), a warm-season perennial grass, was measured to serve as complementary biofuel feedstock to switchgrass (SG). FA was obtained from a site at the 2008 ash spill in Kingston, TN. GG and SG were grown individually in 15-cm-wide × 41-cm-high tree pots, each containing 6 kg of oven-dry soil equivalent (ods) and treated with the following combinations: 0FA/0PL, 10FA/0PL, 0FA/PL, and 10FA/PL. Each treatment was replicated eight times. The tree pots were randomly arranged on greenhouse benches and watered as needed. Biomass production was assessed in soil adjusted to initial pH = 4.5 or 6.5. After 12 weeks at initial pH = 4.5, GG produced significantly higher biomass ($p < 0.05$) in acidic ASL soil that was amended with a combination of 10FA/PL (21.8 g/tree pot) than in unamended ASL soil (13.3 g/tree pot). At initial pH = 6.5, total biomass productivity of GG ranged from 13.2 to 15.7 g/tree pot, and the differences were not significant. Biomass productivity of SG trended similarly, with the highest biomass productivity (18.2 g/tree pot) observed in ASL soil amended with the 10FA/PL combination, which was significantly higher than the control (14.3 g/tree pot). The treatment combinations did not have a significant effect on biomass productivity of SG at pH = 6.5. X-ray imaging and analysis of selected washed roots grown at pH = 4.5 confirmed significant enhancements of root system architecture traits, including root length and area, in the 10FA/PL treatments compared with other treatments. We conclude that FA and PL can be beneficially used to produce biofuel feedstock in acid-impacted soil.

ARTICLE INFO

Article history: Received 23 March 2015; Received in revised form 7 August 2015; Accepted 10 August 2015

Keywords: coal fly ash; poultry litter; bioenergy feedstock; eastern gamagrass; soil acidity; root system architecture

1. Introduction

Coal combustion currently generates about 45% of the U.S. electricity requirement (World Coal Association, 2015). However, burning coal to generate electricity produces large amounts coal combustion products (CCPs) that require careful disposal. CCPs are traditionally regarded as waste; however, they are increasingly being reexamined as by-products that can serve as raw material for other industrial production (Heidrich et al., 2013). This reexamination is spurred by the diverse range of physicochemical properties that CCPs possess and the potentially beneficial exploitation of these properties (Parab et al., 2012; Tsadilas, 2014).

About 50% of CCPs are composed of fly ash (FA), which consists primarily of Si, Al, and Fe oxides, with significant amounts of Ca, Mg, K, and Na, and trace elements such as As, Be, B, Cd, Cr, Co, Pb, Mn, Hg, Mo, Se, Sr, Th, and Va (Vassilev and Vassileva, 2007). Currently, beneficial utilization of FA is largely limited to the

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doi: 10.4177/CCGP-D-15-00002.1

construction industry. In 2013, about 44% of 53.4 million tons (Mt) of FA produced in the United States was used in concrete, concrete products, blended cement, and structural fills (American Coal Ash Association [ACAA], 2013). This means most of the remaining 56% was disposed of by traditional, but increasingly costly storage in ash ponds or landfills.

One solution that has been gaining recent attention for FA utilization is in agricultural production (Yunusa et al., 2012). FA possesses desirable properties such as moisture retention (Lee et al., 2006; Yao et al., 2015) and can contain appreciable levels of major, secondary, and trace elements that can enhance plant growth (Arivazhagan et al., 2011; Parab et al., 2012; Tsadilas, 2014). Furthermore, it can be used to ameliorate acidic and alkaline soil pH depending on the parent coal from which it was derived (Kishore et al., 2010; Tsadilas, 2014). However, the potential presence of toxic elements in FA (e.g., As, Cd, Cr, Cu, Hg, and Se) has prevented greater exploitation of the by-product in agriculture. In 2013, about 0.03% of the 53 Mt of FA produced in United States found its way to an agricultural application (ACAA, 2013).

Some of the renewed enthusiasm for potential beneficial use of FA is based on the successful application of bio/phytoremediation strategies for overcoming its physicochemical and biological limitations to plant growth at FA disposal sites (Juwarkar and Jambhulkar, 2008; Haynes, 2010; Pandey 2012). This neutralization of adverse attributes of FA is leading to the point that FA can be used routinely to enhance crop productivity. In fact, major coal-based, power-generating countries such as India and Australia have intensified explorations of the agricultural benefits of FA. For example, combinations of FA and various organic amendments have been used to improve yields of food crops including rice, maize, peanuts, pulses, and mustard (Mittra et al., 2005; Arivazhagan et al., 2011; Singh et al., 2011; Patra et al., 2012) and oilseed crops such as canola (Manoharan et al., 2010).

In the United States, the emerging focus on bioenergy derived from cellulosic herbaceous perennials (CHPs) provides excellent opportunities to use FA as a soil amendment together with organic wastes for enhancing bioenergy feedstock production. The CHP that was selected by the Department of Energy (DOE) as bioenergy feedstock was switchgrass (*Panicum virgatum* L.), a warm-season perennial grass (WSPG) from the tallgrass prairie ecosystem and native to central North America. Selection of switchgrass (SG) as the bioenergy model was based on an exhaustive evaluation of its desirable attributes such as perennial growth, abundant biomass production, excellent nutrient-use efficiency, wide geographic distribution, and tolerance to abiotic stressors (McLaughlin et al., 1999; Sanderson et al., 2007; Wright and Turhollow, 2010). These are precisely the characteristics that can facilitate coupling FA consumption to biofuel feedstock production, especially in marginal, degraded, and/or abandoned lands.

Although SG was selected as the model bioenergy feedstock, several native WSPGs possess similar desirable qualities. Eastern gamagrass (GG; another WSPG), for example, has been mentioned as a bioenergy feedstock (Anderson et al., 2008; Ge et al., 2012), but information about such use is limited. GG is better known for its excellent and palatable forage quality, and it is also renowned for its tolerance of acid and Al-toxic conditions, utilizing roots that can penetrate high-strength soils (Gilker et al., 2002). Suitability of GG for biomass production on acid-impacted land is particularly important because it is estimated that more than 30% of the world's arable lands are degraded in this way (von Uexküll and Mutert, 1995). Information on GG productivity will not only help diversify biofuel feedstock, but it will also extend its routine production radius to include areas with highly acidic soils.

An important feature that describes the ability of plants to tolerate soilborne abiotic stressors such as acidity is the root system architecture (RSA), which is defined as the spatial configuration, age, and identity of all roots derived from a single plant (Lynch, 1995; Zhu et al., 2011). RSA is under genetic and edaphic controls that allow for modifications of root system functions as needed to optimize productivity (Iyer-Pascuzzi et al., 2010; To et al., 2010; Smith and De Smet, 2012). A rapidly growing need for crop production under abiotic stressors is leading to a surge of techniques for qualitatively and quantitatively assessing RSA to allow its manipulation to enhance crop productivity on infertile and/or degraded lands.

This article describes investigations on biomass productivity of GG grown in soil amended with mixtures of FA and poultry litter (FA/PL). We used X-ray imaging and image analysis of washed roots to provide information about selected attributes of RSA and relate these attributes to biomass productivity by GG under conditions of soil acidity and FA/PL amendment combinations. Biomass productivity of GG under these conditions was related to that of SG, the model bioenergy feedstock, in order to broaden and diversify information on bioenergy feedstock production by WSPGs.

2. Materials and Methods

2.1. Soil, grasses, and amendments

Armour silt loam (fine-silty, mixed, thermic Ultic Hapludalfs) was collected from Tennessee State University Research and Education Experimental Station, Nashville. Selected soil characteristics of Armour silt loam (ASL) are as follows: sand, 25%; silt, 70%; clay, 5%; organic matter (OM), 2.2; pH, 5.9.

Highlander eastern GG was obtained gratis from Jimmy May Gamagrass Co., Cave Springs, KY. Alamo SG was purchased from Star Seed Inc., Osborn, KS.

Coal FA was obtained through arrangements with the Tennessee Valley Authority, Kingston Plant (Neil Carriker and William Rogers, personal communication, 2011). The pH of the batch of FA used was 7.5. Table 1 shows a limited analysis of the batch of FA used in these experiments.

Pelletized poultry litter (PL) was purchased from Natural Organic Warehouse (NOW), Andover, KS. Analysis of the product was reported as 2-4-2.

2.2. Soil preparation and experimental design

Portions of ASL were sieved through a 2-mm sieve and separately adjusted to initial pH = 4.5 or 6.5 following modifications of protocols originally described by Islam et al. (2004).

Briefly, increments of $AlK_2(SO_4)_3 \cdot 18H_2O$ or $CaCO_3$ were added to 10 g of air-dried soil, each in 250-mL plastic bottles containing 50 mL of 10 mM $CaCl_2$. The contents were agitated on a reciprocating shaker for 24 hours. Three replicates were prepared for each dose of chemicals. Dose-response curves of pH versus amount of chemical were generated that enabled determination of the amount of chemicals required to bring a known amount of soil to desired pH_{CaCl2} (1:5, wt:vol, soil:10 mM $CaCl_2$). Soils thus amended were mixed using a Westward 10N693 wheelbarrow mixer (www.grainger.com), placed in large plastic bins, and soaked with distilled water. After 2 days and

Table 1
Elemental analysis of batch of fly ash (FA) used in tree pot experiment and U.S. soil range

Element	Batch average (mg/kg)[1]	U.S. soils (mg/kg)[2]	
		Average	Range
Al	13,000	72,000	700–>10,000
As	**77**	7.2	<0.4–97
Be	1.4	0.92	<1–15
B	11[3]	33	<20–300
Cd	BDL[4]	–[5]	–
Ca	4233	24,000	100–320,000
Cr	**21**	24	1–3000
Cu	**43**	25	<1–700
Hg	0.08	0.09	<0.01–4.6
Ni	21	19	<5–700
Pb	19	19	<10–700
Se	BDL	0.39	<0.1–4.3
Th	BDL	9.4	2.2–31
Zn	35	60	<20–2000

[1] Average of three determinations by ESC Lab Sciences, Mt. Juliet, TN; those highlighted in leachate experiment are shown in bold.

[2] Compiled from Shacklette and Boerngen (1984).

[3] One replicate contained 33; two replicates were below the detection level.

[4] BDL = below detection level.

[5] – = no values available for Cd.

then for the next several days (depending on volume of soil), the soils were thoroughly mixed by periodic overturning until pH readings had stabilized. FA was added to designated portions of pH-adjusted soils to provide 10% (wt/wt). The 10% level of application used in these investigations was selected partly based on values in the literature (e.g., 2–50%; reviewed by Pandey et al., 2009) and partly based on our own preliminary studies. Those experiments found that soil amended with FA alone at rates of 0% and 2.5% (wt/wt) did not affect biomass productivities of SG, GG, and big bluestem (BB); however, a 20% level of FA amendment generally caused slight decreases in biomass productivities of the grasses with observed problems of water permeation (Dzantor et al., 2013). PL was added to appropriately designated portions of soil to simulate the addition of 75 mg N/kg.

Before planting, GG and SG seeds were germinated in potting mix (Fafard® #2 mix). At the 3- to 4-leaf stage, seedlings were transplanted into 15-cm-wide × 41-cm-high tree pots (Stuewe and Sons, https://www.stuewe.com/products/treepots.php), each containing 6 kg of soil (ods) appropriately amended and pH adjusted. Treatment combinations consisted of FA and PL amendments alone or in combination, and controls consisted of ASL at initial pH = 4.5 or 6.5 (no FA or PL). Each treatment was replicated eight times. The tree pots were randomly arranged on greenhouse benches and watered as needed.

2.3. Biomass characterization

After 3 months in ASL soil, shoots of the grasses were harvested by cutting the tops of plants in each tree pot to a height of 2 cm from the soil surface. Shoots from each replicate were placed in separate paper bags and dried at 70°C to constant weight. For determining root biomass, roots were physically separated by carefully washing away soils and rinsing thoroughly under a gentle stream of water. Prior to drying to constant weight, six replicates from selected treatments were shipped overnight on dry ice for root X-ray analysis by Phenotype Screening Corporation, Knoxville, TN (http://www.phenotypescreening.com/contact.html).

2.4. Column leaching experiments

Column experiments were conducted with ASL containing mixtures of FA with or without PL amendments and without plants to determine potentials for leaching selected metals from the preparations. We were interested in assessing potentials for leaching arsenic (As), chromium (Cr), and copper (Cu) in the 10FA/PL mixture. These elements were selected for our investigations because of their known elevated levels in fly ashes in general (Özkök et al., 2013) and, specifically, in the batch of FA used for our tree pot experiments. Table 1 shows a limited analysis of the batch of FA used in the column studies. Corresponding levels of the elements in soil are given for comparison. The experimental protocol used was modified from Palumbo et al. (2007). Briefly, 50-g samples of air-dried equivalents of ASL, adjusted to pH = 4.5 and containing appropriate amounts of amendment mixtures, were packed into 60-cm^3 syringes with the bottom of the barrel lined with glass wool. Treatments tested were ASL at pH = 4.5 and in the following combinations: ASL/10FA, ASL/PL, and ASL/10FA/PL. The tests also included ASL only at field pH = 5.5, 100% FA, and 100% PL.

Each treatment was replicated three times with the columns held in clamps on retort stands. At the start of the experiment, a 100-mL aliquot of 10 mM $CaCl_2 \cdot 2H_2O$ solution was gently added through the top of each column, and amounts of leachates collected were recorded. Leachates from all the tests were filtered using Whatman glass microfiber filters, and the filtrates were shipped for analysis to Empirical Laboratories Inc., Nashville, TN.

2.5. Statistical analysis

Biomass data were analyzed by SAS using analysis of variance. Mean comparisons were made by the t test (least significant difference) at $p < 0.05$.

3. Results and Discussion

3.1. Biomass productivity of GG in FA- and PL-amended soil

These experiments simultaneously address the need for developing beneficial uses of FA that accumulates at coal-based, power-generation utilities and diversifying the feedstock that may be used for bioenergy production under appropriate conversion platforms. We selected GG as a WSPG to complement SG, the bioenergy model, because of its reported tolerance to soil acidity, an abiotic stressor that impacts 30% of the world's arable lands (von Uexküll and Mutert, 1995). Accordingly, our attention was focused on biomass productivity of GG at an initial (adjusted) pH = 4.5. However, relevant comparisons were made with GG grown at an initial pH = 6.5, which we describe as agronomic pH. We used PL as a proven, low-cost fertilizer capable of supplying essential plant nutrients and organic matter to soil and thereby aiding in improving biomass productivity and soil quality.

In the acidic soil, GG produced significantly higher total biomass when ASL was amended with a combination of 10FA/PL (21.8 g/tree pot) than the control ASL soil that was left unamended, i.e., 0FA/0PL (13.2 g/tree pot) (Table 2). Total biomass productivity in ASL soil that was amended with FA alone (i.e., 10FA/0PL) was 15.5 g/tree pot and was not significantly different from the 0FA/0PL control. Furthermore, biomass productivity of GG grown with PL alone (i.e., 0FA/PL) was 17.0 g/tree pot, a value that was not

Table 2
Biomass productivities of eastern gamagrass and switchgrass in Armour silt loam soil under indicated pH conditions

	Mean values (g/tree pot)															
	Eastern gamagrass (GG)								Switchgrass (SG)							
	Acidic soil				Neutral soil				Acidic soil				Neutral soil			
Treatment	Total	Shoot	Root	R/S	Total	Shoot	Root	R/S	Total	Shoot	Root	R/S	Total	Shoot	Root	R/S
0FA/0PL	13.2 b	4.2 b	9.0 b	2.1	13.8	4.9	8.9	1.8	14.3 b	7.4 b	6.9 a	0.9	14.4	7.1	7.3	1.0
10FA/0PL	15.5 b	5.4 b	10.1 b	1.9	13.2	5.1	8.1	1.6	15.2 b	7.6 b	7.7 b	1.0	12.9	6.4	6.4	1.0
0FA/PL	17.0 ab	5.5 b	11.5 ab	1.2	13.2	4.8	8.3	1.7	16.9 ab	8.8 ab	8.1 a	1.0	13.8	6.3	7.5	1.2
10FA/PL	21.8 a	7.8 a	14.0 a	1.8	15.7	5.3	10.4	2.0	18.2 a	9.4 a	8.8 a	1.0	16.2	7.6	8.6	1.2

Note: Means in a column with the same letter or no letter under specified pH are not significantly different according to the *t* test (least significant difference) at $p < 0.05$. R/S = root/shoot ratio; FA = fly ash; PL = poultry litter.

significantly greater than the 13.2 g/tree pot produced by the control (Table 2).

Shoot biomass production in the 10FA/PL mixture (7.8 g/tree pot) was significantly higher than that observed for all the other treatments, i.e., 0FA/PL (5.5), 10FA/0PL (5.4), and 0FA/0PL (4.2) mixtures (Table 2). Furthermore, the significantly higher shoot biomass productivity by GG in the 10FA/PL treatment was accompanied by a correspondingly high root biomass production (14.0 vs. 9.0 g in control), keeping the root/shoot ratio (R/S) near 2. This observation suggested some synergistic relationship between the 10FA and PL amendments that caused simultaneous and significant enhancement of both root and shoot biomass productivities of GG in the acidic soil. This observation is discussed further below. In contrast to observations in the acidic soil, there were no significant differences in total, shoot, or root biomass productivities of GG at the agronomic pH (Table 2).

3.2. *Side-by-side comparison between biomass productivities of GG and SG*

A major purpose of this study was to diversify bioenergy feedstock by extending production to GG. This necessitated a side-by-side comparison with SG, the bioenergy feedstock model. Table 2 show biomass productivities of SG under the same treatments described for GG. Similar to GG, the 10FA/PL amendment of ASL at acidic pH produced significantly higher total SG biomass (18.2 g/tree pot) than control ASL soil (14.3 g/tree pot) (Table 2). Also, there were no differences in total biomass productivities of SG at agronomic pH.

However, with only one exception, SG consistently produced significantly higher shoot biomass than GG, regardless of amendment combinations. For example, SG shoot biomass ranged from 7.4 to 9.4 g/tree pot in acidic pH and from 6.3 to 7.6 g/tree pot at agronomic pH. Furthermore, biomass was nearly equally allocated to shoots and roots, i.e., R/S nearly equal to 1 (Table 2). The equitable allocation of substrate by SG for biomass production is desirable from the standpoint of biomass conversion to bioenergy since it involves aboveground biomass only.

In contrast to the observations of SG, shoot biomass productivity by GG ranged from 4.2 to 7.8 g/tree pot in acidic soil and, more narrowly, from 4.8 to 5.3 g/tree pot in soil at the agronomic pH (Table 2). Additionally, R/S ratios for GG tended to approach 2, which suggests that GG inherently favors greater belowground than aboveground biomass production. The exception to the relatively low shoot biomass productivity of GG was when grown at acidic pH with the 10FA/PL amendment combination. This treatment produced significantly higher shoot biomass (7.8 g) compared with other GG biomass productivities, which ranged from 4.2 to 5.5 g/tree pot (Table 2). Furthermore, this shoot biomass was associated with equally high root biomass (14.0 g), keeping R/S close to 2 as noted earlier (Table 2). Thus, in acidic soil, the 10FA/PL combination allowed simultaneously high shoot and root biomass production by GG. Finally, in this treatment, shoot biomass productivity by GG was within the range of shoot biomass productivities of SG (7.4–9.4 g/tree pot). This suggested that potential exists for enhancing GG productivity under acidic and soil-amendment conditions to levels similar to that of SG.

Further investigations are needed to precisely determine levels and types of FA and organic amendments that could improve GG productivity even further. In addition, understanding the inherent and edaphic factors that influence GG productivity and, potentially, that of other biomass feedstocks could lead to enhanced bioenergy production.

3.3. *Root system characterization of selected GG and SG in FA- and PL-amended soils*

Improvements in crop productivity have traditionally focused on increasing shoot biomass and seed yield, invariably overlooking the importance of root systems (Den Herder et al., 2010). An ever-increasing human population and resulting need for land allocation for food, feed, and bioenergy in the face of ongoing soil degradation have necessitated unprecedented attention to be focused on roots as central to enhancement of crop productivity, especially under soil stressors (Lynch and Brown, 2006; Den Herder et al., 2010). The root attribute that is increasingly recognized as a driver for productivity enhancement is the RSA. This is the genetically and soil environment–controlled spatial configuration of roots, which determines plants' abilities to explore and acquire resources (Lynch and Brown, 2006); it allows for modifications of root system functions as needed to optimize productivity (Iyer-Pascuzzi et al., 2010; Smith and De Smet, 2012), including that for bioenergy feedstock production (To et al., 2010).

Potentials for GG serving as complementary bioenergy feedstock under a FA/PL soil amendment regimen led us to investigate RSA in our studies. In particular, we wanted to find out the roles, if any, played by RSA in apparent differences in substrate allocation by GG for shoot versus roots under the 10FA/PL amendment conditions. For this project, root imaging and quantitative image analyses were performed by Phenotype Screening Inc., Knoxville, TN, using a low-energy X-ray system consisting of an Oxford Instruments X-ray generator operating at 25 kVp. A Rad-icon digital X-ray camera and a set of computer-controlled digital stages allowed for positioning and imaging of the entire root

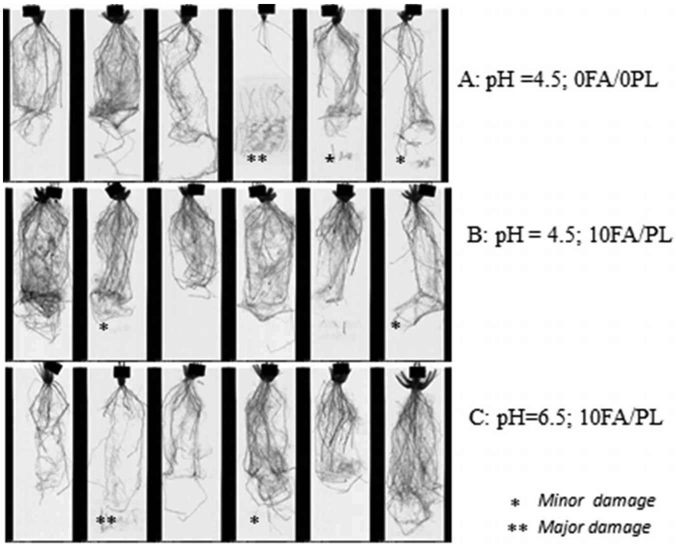

Fig. 1. X-ray images of selected gamagrass (GG) roots under growth and soil amendment conditions shown at right. FA = fly ash; PL = poultry litter.

system to 60-μm resolution. Root traits descriptive of RSA were quantified from the images using proprietary RhizoTraits software (http://www.phenotypescreening.com/).

Figures 1A–C are X-ray images of washed roots of GG plants grown individually in tree pots as described in section 2.2. The images represent six randomly selected replicates each for the following treatments: 0FA/0PL (control), pH = 4.5 (Figure 1A); 10FA/PL, pH = 4.5 (Figure 1B); and 10FA/PL, pH = 6.5 (Figure 1C). The experiment was designed for eight replicates per treatment. However, cost considerations prevented analysis of all the replicates for each treatment.

Some of our root samples sustained damage during shipment for imaging; however, the images qualitatively suggested enhanced GG root systems at pH = 4.5 in ASL containing the 10FA/PL amendment (Figure 1B) compared with unamended soil (Figure 1A). This was consistent with the significant total root biomass enhancement that we measured (Table 2; section 3.1). For purposes of comparison, X-ray images of GG grown at initial pH = 6.5 with the combination of 10FA/PL are shown in Figure 1C.

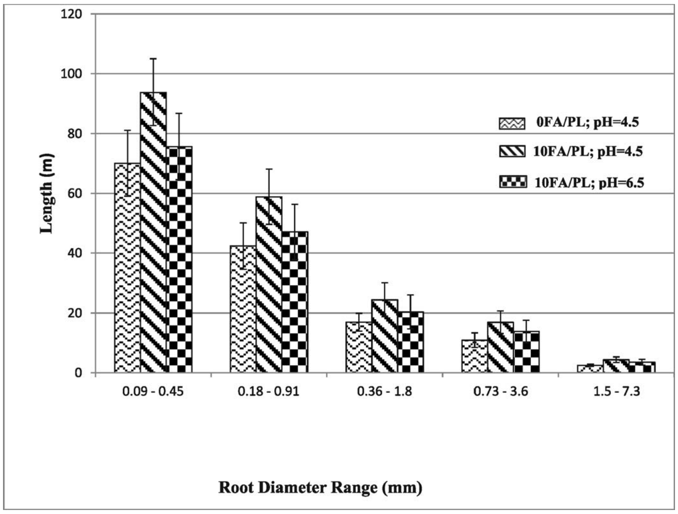

Fig. 2. Mean total root length (m) of gamagrass (GG) roots by treatment and by root diameter range. FA = fly ash; PL = poultry litter.

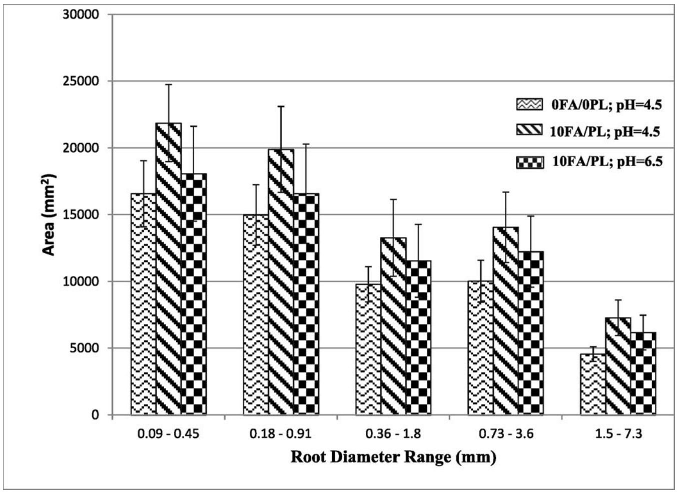

Fig. 3. Mean projected area (mm^2) of gamagrass (GG) roots by treatment and by root diameter range. FA = fly ash; PL = poultry litter.

Although Figures 1A–C may allow qualitative comparative and generalized deductions to be made about roots under a defined set of conditions, they are limited in interpreting the magnitude of responses that are involved in these manifestations. Figure 2 represents quantitative analyses of the images in Figures 1A–C (images for 0FA/PL and 10PL/0PL not included). The graph shows the means of total root length, an attribute of RSA, for each of the five overlapping root diameter ranges by treatment. The RhizoTraits software used for quantification of RSA not only measures total root length, but it also allows for the classification of root length by root diameter range. Analysis of our results shows larger means in each root range under the 10FA/PL amendment combinations at the initial pH = 4.5 compared with 0FA/0PL controls or GG grown at pH = 6.5 with the same 10FA/PL amendment regimen (Figure 2). Corresponding mean projected root areas of GG by treatment and by root diameter range showed a similar trend (Figure 3). Because of large standard deviations, it was not possible to draw definitive conclusions about the RSA traits in the experiment. Some of this problem stems from the unevenness and difficulty in germination for which GG is noted. Future related studies should increase the number of replications as well as minimize sample damage during shipment.

SG treatments did not exhibit any unusual responses during this experiment; accordingly, imaging and image analysis were limited to SG roots in agronomic soil containing 10FA/PL amendments for comparative purposes only. Figures 4 and 5 are side-by-side comparisons of total root length and mean projected area of GG and SG roots, respectively, by diameter range.

As discussed earlier, the variability associated with our data precluded definitive conclusions to be made; however, the side-by-side comparisons suggest that at least at pH = 6.5, RSA of GG was at least equally developed for GG as for SG. Additional studies are needed to confirm our observations about RSA traits and extend these protocols to other biomass production scenarios by GG and possibly other WSPGs.

3.4. Column leaching experiments

Prospects for FA utilization as a soil amendment to produce bioenergy feedstock necessitate investigation of potentials for toxic substances to leach into soils and sediments. For our

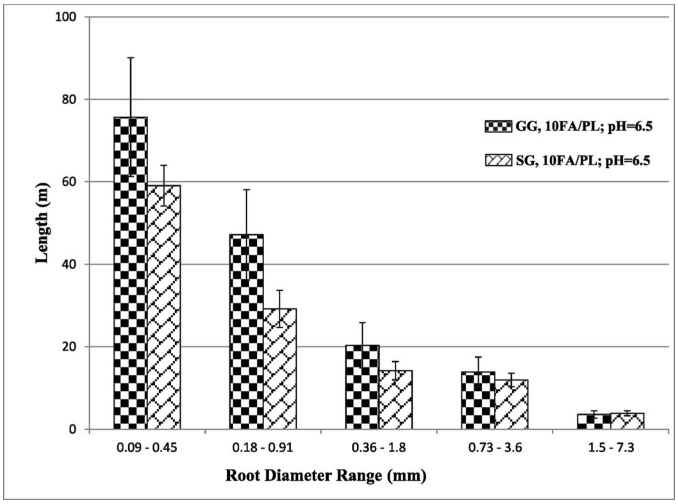

Fig. 4. Mean total root length (m) of gamagrass (GG) and switchgrass (SG) under similar treatments. FA = fly ash; PL = poultry litter.

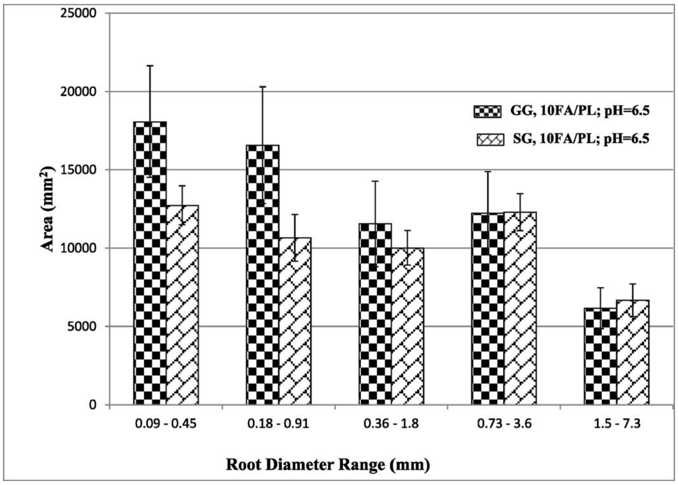

Fig. 5. Mean projected area (mm^2) of gamagrass (GG) and switchgrass (SG) under similar treatments. FA = fly ash; PL = poultry litter.

investigation, we adapted the soil leaching protocol described by Palumbo et al. (2007) for a short-term column leaching experiment to provide a rapid assessment of potentials of the selected elements to leach from our ASL/FA/PL preparations. It is important to point out that only a long-term experiment can accurately explain the mechanisms underlying the long-term behavior and stability of the selected elements in the soil/FA/organic mixtures. Of the three elements investigated in this study, only Cu was present in leachate samples. Arsenic is considered by some as the contaminant of the greatest concern in most soils where FA is applied. However, it is not usually mobile and is rather strongly adsorbed onto soil particles (Qafoku et al., 1997). This may explain the absence of the element in our leachate samples. Still, the oxyanion behavior of As in FA-soil mixtures would have predicted higher mobility of the element at the 4.5 pH tested in the columns (McLean and Bledsoe, 1992) and, therefore, the presence of the element in leachate. Similarly, sorption could be the dominant process behind the behavior of Cr. At pH = 4.5, Cu was expected to be mobile; accordingly, its presence in leachate was not completely unexpected. However, a combination of sorption on FA and PL was not enough to prevent the metal from leaching in this experiment. Our group is currently investigating this further.

Other investigators have reported minimal potential for leaching of toxic levels of metals from FA-amended soils. For example, Sajwan et al. (2006) found that the concentration of most metals in the leachate following the application of low to moderate rates of FA and sewage sludge mixtures generally did not exceed the maximum contaminant levels stipulated by the U.S. Environmental Protection Agency (USEPA) (Sajwan et al., 2006). In their studies, the investigators found that quantities of metals leached from an FA plus sewage sludge mixture at an application rate of 148 Mg/ha were lower than combined quantities of the metals leached from the soil column, which received 74.1 Mg/ha of either FA or sewage sludge. Also, Palumbo et al. (2005, 2007) performed a series of leaching experiments, including toxicological profiling with the Microtox© system, to show little potential for toxicity of leachate from FA ranging in pH from 3.7 to 12.4. These investigators reported further that when leachate from the pH 12.4 system was neutralized, toxicity was eliminated (Palumbo et al., 2005, 2007). Taken together, these observations strongly suggest that judicious applications of FA and organic amendments may be viable options for the beneficial utilization of FA in agriculture.

4. Conclusions

1. Prospects for using combinations of coal FA and organic amendments in soil to produce bioenergy feedstock are feasible and highly desirable.
2. Given the magnitude of past, present, and future accumulations of FA, agricultural utilization possesses arguably the greatest opportunity for significant consumption of the product.
3. An emerging focus on bioenergy biomass production in marginal, degraded, or abandoned lands provides excellent opportunities for enhancing biofuel feedstock production on such lands, by the use of FA and organic by-products.
4. There is a need for a greater understanding and improvement of root system responses to biomass production on degraded/marginal lands (including FA-amended and other stressed lands) for suitability to profitably produce bioenergy biomass.
5. A major concern about agricultural utilization of FA is leaching of toxic metals. There is increasing evidence that judicious agricultural-land applications of the by-product can be made without exceeding USEPA limits on environmental pollution.

Acknowledgments

This research was funded in part through the U.S. Department of Agriculture Evans-Allen Program, project no. TENX-1306-SE. The authors wish to thank Phenotype Screening Corporation, Knoxville, TN, for assistance in root imaging, image analysis, and interpretation.

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