FLUID FERTILIZER'S ROLE IN SUSTAINING SOILS USED FOR BIO-ENERGY FEEDSTOCK PRODUCTION

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SUMMARY

The use of corn (*Zea mays* L.) as a bio-energy feedstock has attracted the attention of many producers. Recently, the focus has shifted from grain-based to cellulose-based ethanol production. In addition to biological conversion of corn stover to ethanol, thermal conversion (pyrolysis) of stover is being explored. Regardless of post-harvest processing, it is important to understand the short- and long-term effects of both increasing grain yields and removing stover on soil nutrient cycling, physical properties, and biological activity, so that soil productivity and ecosystem services are maintained. Our objectives for 2012 were to evaluate: (i) the use of surface or subsurface bands of N-P-K-S fluid fertilizers to optimize positional and temporal availability of nutrients; and (ii) the effect of biochar application on P availability and cycling in Clarion-Nicollet-Webster soils. Corn was grown in a field trial under a variety of management systems including 30-inch row spacing with standard fertility management and a twin-row, high-population treatment with increased nutrient additions applied in split-applications. In 2012, whole-plant N concentrations at the V6 growth stage were below the published critical value of 3.5%, regardless of management. At mid-silk, both N and K concentrations in ear-leaf tissue were below the critical values. The hot, dry growing conditions may have limited N and K availability and uptake. In 2012, management scenario, tillage, and previous stover removal affected corn grain yield, although yields were likely influenced by the availability of water. Grain yields tended to be lower when corn stover was not removed than when ~50% or ~90% was removed. Crop rotation had the most striking effect on corn grain yields. Corn grown in rotation with soybean (*Glycine max* L. Merr.) yielded 174 bu/A compared with a mean grain yield of 143 bu/A for continuous corn. Biochar application and cover crop growth had no effect on grain and stover yields. Dry stover yields were higher for the 90% removal (low cut) treatments of all management scenarios. As during the three previous growing seasons, the intensively managed (twin row) plots did not produce more grain or dry stover than the conventional plots. In a separate controlled-climate chamber study, biochar and P fertilizer amendments affected soil P supply and corn seedling growth during five consecutive production and harvest cycles. Plants grown in soil with only 100 lb. P_2O_5/A had the highest shoot and root dry matter values, while those grown in soil amended with biochar in 2007 (legacy) without P fertilizer had the lowest values. Addition of 100 lb. P_2O_5/A numerically increased shoot and root dry matter values regardless of legacy or fresh biochar amendment. Although cumulative shoot dry matter production tended to be higher for treatments without biochar, the overall agronomic efficiency of the P fertilizer was improved by biochar application. Further statistical analysis of plant growth and nutrient uptake data should provide a clearer picture of any biochar-fertilizer interactions. The effect of biochar application on soil supply of nutrients is complex. Current research suggests that marginal soils will benefit most.

INTRODUCTION

The use of corn as a bio-energy feedstock has attracted the attention of many producers, especially in the Cornbelt states. Recently, the focus has shifted from grain-based to cellulose-based ethanol production, with corn stover (stalks and cobs) being an important feedstock material (Bridgwater, 2006). In addition to biological conversion of corn stover to ethanol, thermal conversion (pyrolysis) of stover to bio-oil, syngas, and biochar is being explored as an alternative platform (Laird, 2008). Regardless of post-harvest processing, it is important to understand the short- and long-term effects of both increasing grain yields and removing stover on soil nutrient cycling, physical properties, and biological activity, so that soil productivity and ecosystem services are maintained. Up to this point, the bio-energy industry has been forced to use estimates, such as those offered by Johnson et al. (2006), to determine the amount of crop residues that must remain in the field. Research has shown that the use of no-tillage production can reduce the rate of residue decomposition, thus offering a mechanism to maintain soil organic carbon after removing some portion of the stover (Perlack et al., 2005). A significant amount of research has addressed fertility requirements and nutrient cycling in conventional grain production systems, but only recently has information on bio-energy feedstock systems become available (Heggenstaller et al., 2008; Blanco-Canqui and Lal, 2009). To provide more quantitative fertility guidelines, soil management studies focusing on cropping systems, tillage, fertilizer rates and placement, use of cover crops, and controlled wheel traffic are needed. Because it would be difficult to address all of these variables in a single project, our research focuses on nutrient requirements, specifically phosphorus (P), potassium (K) and sulfur (S), for no-till corn bio-energy production systems.

There has also been significant interest in the use of biochar as a soil amendment for sequestering carbon and improving agricultural soil quality. Crop yield increases and improvements in soil physical and chemical properties have been reported, but variability among the responses has been significant (Glaser et al., 2002; McHenry, 2009). Biochars have some plant nutrient content, but nutrient availability can vary widely (Chan et al., 2007; McHenry, 2009). Biochars cannot be considered a substitute for fertilizers, although Chan et al. (2007) reported that yields of radish (*Raphanus sativus*) increased with increasing rates of biochar in combination with N fertilizer, suggesting that biochar played a role in improving N-use efficiency. Application of biochar to soils may also enhance P availability and improve P-use efficiency. Preliminary research has shown that additions of biochar tend to increase Mehlich 3-extractable P and reduce P leaching when applied in combination with animal manures (Laird et al., 2010).

The overall goal of this project is to evaluate the use of N-P-K-S fluid fertilizers to enhance corn grain and stover productivity. A secondary goal is to determine the role biochar application may have in nutrient cycling. This project is part of a long-term corn grain and stover removal study that focuses on standard and intensive fertility management, tillage, biochar additions to test the “charcoal vision” (Laird, 2008) for sustaining soil quality while producing bio-energy products, and use of cover crops to build soil carbon and help off-set potential negative impacts of stover removal. Our specific objectives for 2012 were to evaluate (i) the use of surface or subsurface bands of N-P-K-S fluid fertilizers to optimize positional and temporal availability of nutrients, and (ii) the effect of previous and recent biochar application on P availability and cycling in Clarion-Nicollet-Webster soils.

METHODS AND MATERIALS

Biomass Removal Study

The 25-acre field study established in 2007 on the Clarion-Nicollet-Webster soil association at the Iowa State University Agronomy & Agricultural/Biosystems Engineering Research Center (AAERC), southwest of Ames in Boone County, Iowa, was continued. This study currently focuses on rates of residue removal (0, ~50%, and ~90%), tillage (chisel plow versus no-tillage), a one-time biochar addition (4.32 and 8.25 tons/A), benefits of an annual cover crop, and effectiveness of a corn-soybean crop rotation. The rotation treatment was established in 2011 to replace a perennial cover crop treatment. One set of plots (40 x 280 ft.) is managed with standard Iowa production practices, and a second set of plots is managed in a twin-row configuration with higher inputs. Conventional weed and insect control practices are being followed. The study includes 22 treatments that are replicated four times. Soil samples (0-2 and 2-6 inches) were collected with a hand probe from each plot 6 November 2011, and analyzed for pH, organic matter content, available P, exchangeable K, Ca, and Mg, extractable SO^{4-}, and CEC (Table 1). Pioneer Brand P0461xr corn was planted 25 April 2012. With the exception of N, fertilizer applications in 2012 (Table 2) were based on 2011 grain and stover removals and fall soil test results. In 2012, total N applied to conventional treatments was 200 lb/A, and to twin-row treatments was 225 lb/A. Early-season whole-plant samples at the V6 growth stage (30 May 2012) and ear-leaf samples at the mid-silk stage (13 July 2012) were collected and analyzed to determine the nutritional status of the crop. Beginning 18 September, corn grain and stover were harvested with an experimental, single-pass, dual-stream harvester, based on a John Deere 9750 STS combine equipped with an 8-row head. Sub-samples of stover and grain are being analyzed for nutrient content so that a more complete nutrient balance can be calculated.

Table 1. Average soil test levels for two depth increments within a Clarion-Nicollet-Webster soil association prior to imposing treatments for 2012. The range indicates plot variability within the study site.

Soil Test Parameter	Composite	Range	Composite	Range
	0-2 inch		2-6 inch	
Bray-1 P, ppm	38	18 – 72	21	7 – 49
Exch. K, ppm	149	104 – 196	89	67 – 126
Exch. Ca, ppm	2326	1593 – 3231	2427	1723 – 3599
Exch. Mg, ppm	256	166 – 376	268	166 – 396
Extract. S, ppm	4	1 – 8	5	2 – 8
pH	5.5	4.7 – 6.2	5.7	4.9 – 6.5
O. M., %[†]	3.5	2.5 – 5.1	3.3	2.3 – 4.5
CEC, cmol(+)/kg	19.8	14.6 – 26.8	19.6	15.3 – 27.6

[†] Ignition method.

Table 2. Fertilizer management for the conventional and high-input (twin row) systems in 2012.

System	Stover Removal, %	Timing	Source
Conventional		Fall 2011	11-52-0 + 0-0-60
200+72+51+20S	0	Starter	32-0-0 (UAN)
200+85+90+20S	50		12-0-0-26S (ATS)
200+93+110+20S	90	Sidedress	32-0-0 (UAN)
Twin-Row		Fall 2011	11-52-0 + 0-0-60
225+73+52+30S	0	Starter	32-0-0 (UAN)
225+87+97+30S	50		12-0-0-26S (ATS)
225+90+109+30S	90	Sidedress	32-0-0 (UAN)

Biochar Study

Surface soil (0-6 inches) was collected from two adjacent plots within the bio-energy field trial site at the Iowa State University AAERC in April 2010. One plot was a control that had standard management, chisel plow tillage, and 90% residue removal. The second was a biochar plot (8.25 ton/ac., fall 2007) that also had standard management, chisel plow tillage, and 90% residue removal. The soil for both plots is classified as Clarion loam (fine-loamy, mixed, mesic Typic Haplaquolls). Initial soil physical and chemical properties were measured (Table 3).

To determine effects of previous (2007) biochar, fresh biochar, and liquid P fertilizer applications on soil P supply, a laboratory/climate chamber experiment was initiated. Commercially available hardwood-based biochar was added at rates equivalent to 0 or 8 tons/acre to subsamples of unamended soil. The biochar was the same material applied to the field plots in 2007. Ammonium polyphosphate (APP, 10-34-0) was then applied to provide the equivalent of 100 lb. P_2O_5 per acre. Nitrogen, K, and S fertilizers were also applied to ensure adequate amounts of those nutrients. The biochar and fertilizer were thoroughly mixed with the soil. Unamended soil served as a control treatment. After the amendments were added, the soils were incubated in a moist condition for four weeks. Following incubation, soil solution was displaced and analyzed for total P, and Bray 1-extractable P was determined in both the treated and untreated soils. Relative changes in these soil P supply parameters are being used to quantify the effects of the legacy and fresh biochar amendments.

Table 3. Initial soil test levels for Clarion loam collected in 2010. Legacy biochar refers to an 8 ton per acre application to this soil in the fall of 2007.

Soil Test Parameter	Control Soil	Legacy Biochar Soil
Bray-1 P, ppm	65 (VH)	50 (VH)
Exchangeable K, ppm	159 (VH)	119 (L)
Exchangeable Ca, ppm	2034	1981
Exchangeable Mg, ppm	206	213
Extractable S, ppm	4	4
pH	5.6	5.7
Organic Matter, %	2.8	2.8
CEC, cmol(+)/kg	15.1	14.8

A pot experiment was then initiated. Pre-germinated corn (Pioneer Brand 36V75) seedlings were planted two per pot, and pots were placed in a controlled-climate chamber with

16 hours of light and 22°C/12°C day/night temperature. Each treatment combination was replicated four times. After 20 days, plants were harvested. Corn roots were separated from soil, and after fertilizing with replacement N (but not P), the same soil was returned to each pot. New corn seedlings were planted and allowed to grow another 20 days. In order to investigate the effect of biochar addition on depletion of plant-available P, the treatment soils were subjected to five growth cycles. Following each harvest, we measured shoot and root dry matter production, nutrient uptake, and water-use efficiency from each treatment. The agronomic efficiency of the P fertilizer and P uptake efficiency were also calculated. These data are being used to determine: i) the P fertilizer value of the biochar; ii) if biochar-P fertilizer interactions occurred; and iii) the differences between legacy and fresh biochar as it relates to the nutrition of the corn.

RESULTS AND DISCUSSION

Biomass Removal Study

Plant Nutrition

Whole-plant N concentrations at the V6 growth stage were below the published critical value of 3.5% (Mills and Jones, 1996), regardless of management scenario, tillage, and the amount of residue removed from the field with the 2011 harvest (Table 4). This suggests that pre-plant N fertilizer (50 lb N per acre) and soil N were not sufficient to support the corn crop before additional N was sidedressed six weeks after planting, and four days after the plants were sampled. Levels of all other primary and secondary macro-nutrients were adequate for optimal growth (Table 4).

At mid-silk in 2012, no differences in ear-leaf nutrient concentrations were detected among the treatments (Table 5). However, both N and K concentrations in the tissue were below the critical values, while P and S concentrations in ear leaves were within the sufficiency ranges of 0.25% to 0.50% for P and 0.10% to 0.30% for S for all treatments (Mills and Jones, 1996; Jones et al., 1990). Low N and K uptake suggests that the soil supply was not sufficient to meet crop demand by mid-silk, although up to 174 lb N per acre were applied six weeks after planting. The hot, dry growing conditions in central Iowa during late June, July, and early August (Hillaker, 2013) may have limited N and K availability and uptake.

The plant analysis results suggest that fertilizer inputs and nutrient removals may be balanced, but in-season growing conditions greatly affect the capture of soil nutrients by the crop. During the first growing season of the trial in 2008, N, K, and S deficiencies were recorded (Kovar and Karlen, 2010), and N deficiencies persisted in 2009. These deficiencies were not a problem in 2010 and 2011, but re-emerged in 2012. As pointed out by Johnson et al. (2010), K nutrition will need to be monitored closely in coming growing seasons.

Corn Grain and Stover Yield

In 2012, management scenario, tillage, and previous stover removal affected corn grain yield (Table 6), although yields were likely influenced by the availability of water more than anything else. Warm weather in central Iowa during early spring gave way to hot, dry conditions during late June, July, and early August (Hillaker, 2013). These conditions during pollination and grain fill likely decreased final yield of the crop. The biochar and cover crop treatments had no effect on grain and stover yields, so data were pooled with the conventional treatments. As in 2009 and 2010, grain yields tended to be lower when corn stover was not removed than when ~50% or ~90% was removed. This result has been observed in other studies (Karlen et al., 2013), although Blanco-Canqui and Lal (2009) reported yield decreases when plant residues were removed. Plant residues remaining in the field can both slow soil warming early in the growing season and lead to greater N immobilization, which negatively affect plant growth and subsequent grain yields. The effect of inadequate rainfall on grain yields was most pronounced in treatments without stover removal (Table 6). Loss of soil water as a result of tillage operations likely decreased grain yields in chisel plow plots as compared to plots under no-till. Crop rotation had the most striking effect on corn grain yields. In 2012, corn grown after a 2011 soybean crop yielded 174 bushels per acre compared with a mean grain yield of 143 bushels per acre for all continuous corn treatments.

As expected, the amount of dry stover collected was higher for the 90% removal (low cut) treatments of all management scenarios. Similar to previous years, the intensively managed (twin row) plots did not produce more dry stover than the conventional plots (Table 6). Whole plants collected at physiological maturity and residue samples from the machine harvest are being analyzed to determine elemental composition, so that the total amount of nutrients removed can be calculated. These values will be used to guide fertilizer recommendations for the 2013 trial.

Table 4. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) critical values and concentrations in whole plants at the V6 growth stage for five management scenarios in 2012. Values (%) are means of 8 to 16 replications depending on treatment. Standard deviations are in parentheses below each mean.

Nutrient	Critical Value	Control	Biochar 1†	Biochar 2‡	Twin-Row	C-S Rotation§
N	3.50	2.78	2.76	2.87	2.82	2.92
		(0.21)	(0.19)	(0.23)	(0.20)	(0.22)
P	0.30	0.35	0.37	0.36	0.35	0.36
		(0.03)	(0.04)	(0.03)	(0.05)	(0.03)
K	2.50	3.15	3.34	3.32	3.14	3.29
		(0.38)	(0.38)	(0.27)	(0.41)	(0.24)
Ca	0.30	0.46	0.48	0.48	0.46	0.43
		(0.05)	(0.04)	(0.05)	(0.05)	(0.02)
Mg	0.15	0.34	0.37	0.36	0.33	0.35
		(0.06)	(0.04)	(0.05)	(0.05)	(0.04)
S	0.20	0.20	0.20	0.20	0.20	0.21
		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)

†4 tons biochar/A; ‡8 tons biochar/A; §Soybean in 2011.

Table 5. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) critical values and concentrations in ear leaves at mid-silk stage for five management scenarios in 2012. Values (%) are means of 8 to 16 replications depending on treatment. Standard deviations are in parentheses below each mean.

Nutrient	Critical Value	Control	Biochar 1†	Biochar 2‡	Twin-Row	C-S Rotation §
N	2.70	2.52	2.50	2.47	2.47	2.53
		(0.16)	(0.14)	(0.15)	(0.13)	(0.12)
P	0.25	0.27	0.27	0.29	0.27	0.28
		(0.03)	(0.04)	(0.02)	(0.03)	(0.03)
K	1.70	1.40	1.39	1.48	1.35	1.57
		(0.12)	(0.16)	(0.08)	(0.19)	(0.17)
Ca	0.21	0.50	0.51	0.52	0.50	0.53
		(0.04)	(0.05)	(0.03)	(0.04)	(0.04)
Mg	0.20	0.33	0.34	0.34	0.34	0.36
		(0.04)	(0.04)	(0.03)	(0.04)	(0.03)
S	0.10	0.15	0.15	0.15	0.15	0.16
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)

†4 tons biochar/A; ‡8 tons biochar/A; § Soybean in 2011.

Table 6. Management system, tillage, and residue removal effects on corn grain and stover yields in 2012. Values are means of 4 to 12 replications depending on treatment. Standard deviations are given in parentheses.

Treatment	Tillage	Percent Removal	Grain† (bu/ac)	Stover (t/ac)
Conventional	No-tillage	0	130 (20)	0
Conventional	No-tillage	50	142 (14)	1.55 (0.57)
Conventional	No-tillage	90	143 (28)	2.36 (0.36)
Conventional	Chisel Plow	0	106 (35)	0
Conventional	Chisel Plow	50	148 (15)	1.45 (0.27)
Conventional	Chisel Plow	90	146 (25)	2.10 (0.50)
Twin-Row	No-tillage	0	131 (13)	0
Twin-Row	No-tillage	50	146 (17)	1.44 (0.48)
Twin-Row	No-tillage	90	147 (11)	2.40 (0.21)
Twin-Row	Chisel Plow	0	118 (23)	0
Twin-Row	Chisel Plow	50	139 (20)	1.85 (0.36)
Twin-Row	Chisel Plow	90	146 (14)	2.39 (0.37)

† Grain yields adjusted to 15.5% moisture.

Biochar Study

Both biochar and P fertilizer amendments affected soil P supply and corn seedling growth during five consecutive production and harvest cycles. Relative differences in shoot and root dry matter production observed after the initial 20 days of growth (Harvest 1), tended to hold until Harvest 5 (Fig. 1). Through the first four growth cycles, plants grown in soil amended with 100 lb. P_2O_5 per acre alone had the highest shoot and root dry matter values, while those grown in

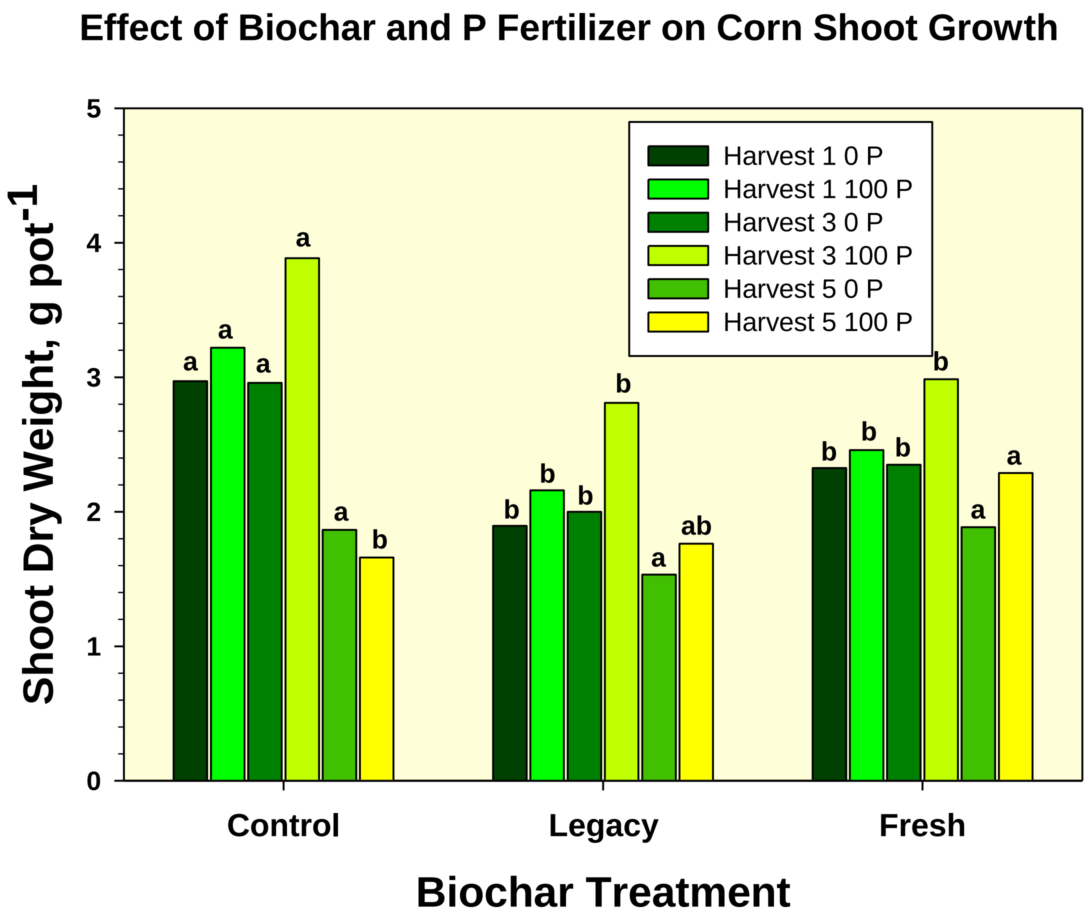

Fig. 1. Corn shoot dry matter production after five consecutive harvests of plants grown in soil without biochar, soil amended with biochar in 2007 (legacy biochar), and soil amended with biochar at the initiation of this study (fresh biochar). Phosphorus fertilizer was applied at 0 and 100 lb. P_2O_5 per acre. Within a harvest and P fertilizer rate, values (bars) with the same letter are not significantly different at the 0.05 level.

soil amended with biochar in 2007 (legacy biochar) without P fertilizer had the lowest values. At the fifth harvest, plants grown in biochar-amended soil produced as much dry matter as those grown in unamended soil, while those grown in biochar-amended soil with P fertilizer produced more dry matter than those grown in unamended soil.

Cumulative shoot and root dry matter production tended to be greater when no biochar was added to the soil, and less in soil amended with biochar in 2007 (Table 7). Addition of 100 lb. P_2O_5 per acre numerically increased shoot and root dry matter accumulation, regardless of biochar amendment. This result was somewhat unexpected, given the initial high levels of available soil P (Table 3). Higher root:shoot dry weight ratios were calculated for the legacy biochar treatment without P fertilizer, suggesting that the plants were partitioning more resources to root growth, rather than shoot growth. Although cumulative shoot dry matter production tended to be higher for the treatments without biochar, the overall agronomic efficiency of the P fertilizer was improved by biochar application (Table 7). Neither biochar application nor P fertilizer affected shoot P concentrations, which ranged from 0.15% to 0.37%. Mean shoot P concentration was 0.21%, which is well below the critical value of 0.30% for corn at this growth stage. The reason for the low shoot P concentrations is not clear, although the low temperatures under which the plants were grown may have affected P uptake. These temperatures, however, were set to mimic those in the field after corn planting. Mean N and K tissue concentrations were 3.24% and 3.34%, respectively. These values are near or above the critical levels of 3.5% for N and 2.5% for K, suggesting that P nutrition was the problem. Further statistical analysis of plant growth and nutrient uptake data should provide a clearer picture of any biochar-fertilizer interactions. The effect of biochar application on soil supply of nutrients is complex. Current research suggests that marginal soils will benefit most (Jeffery et al., 2011).

Table 7. Corn shoot and root dry matter accumulation, root:shoot ratios, and agronomic efficiency of phosphorus (P) fertilizer as affected by legacy (2007) and fresh (2010) biochar application. Plants were harvested after 20 days of growth in a controlled-climate chamber. Data represent cumulative dry matter production after five harvests. Values are least square means of four replications. Standard deviations are shown in parentheses.

Treatment	P Fertilizer	Shoot Dry Weight	Root Dry Weight	Root:Shoot Ratio	Agronomic Efficiency
	lb. P_2O_5/A	g	g		g shoot DM/g P
Control	0	10.13a‡	7.40ab	0.73b	
	100	10.87a	8.03a	0.74b	17.1 (6.9)
2007 Biochar†	0	7.71c	6.57bc	0.85a	
	100	8.93b	5.81c	0.65bc	28.3 (12.1)
2010 Biochar†	0	9.10b	6.14bc	0.67bc	
	100	10.08ab	6.17bc	0.61c	22.7 (6.7)

† 8 tons biochar/A; ‡ Values in a column with the same letter are not significantly different at the 0.05 level.

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