

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

John L. Kovar and Douglas L. Karlen  
USDA Agricultural Research Service (ARS)  
National Laboratory for Agriculture and the Environment (NLAE)  
2110 University Blvd., Ames, IA 50011  
[john.kovar@ars.usda.gov](mailto:john.kovar@ars.usda.gov) (515) 294-3419

## ABSTRACT

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, the short- and long-term effects of both increasing grain yields and removing stover on soil nutrient cycling, physical properties, and biological activity must be understood to ensure that soil productivity and ecosystem services are maintained. Our objectives for 2011 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. Analysis of whole plants at V6 and ear leaves at mid-silk showed adequate levels of all macronutrients, which suggests that nutrient management was balanced for the two planting scenarios and the amount of stover removed from the field with the 2010 harvest. Management scenario, tillage, and previous stover removal did not affect corn grain yields, which varied from 172 to 182 bu/ac in 2011. In addition, biochar application and cover crop growth had no effect on grain and stover yields. As expected, the amount of dry stover collected was higher for the 90% removal (low cut) treatments of all management scenarios. In 2011, 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<sub>2</sub>O<sub>5</sub>/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<sub>2</sub>O<sub>5</sub>/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 the fertilizer value of the biochar, any biochar-fertilizer interactions, and whether legacy or fresh biochar affect the nutrition of juvenile corn in different ways.

## 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, the short- and long-term effects of both increasing grain yields and removing stover on soil nutrient cycling, physical properties, and biological activity must be understood to ensure 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 is also 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 (D.A. Laird, unpublished data).

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 2011 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 2008 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 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 9 November 2010, and analyzed for pH, organic matter content, available P, exchangeable K, Ca, and Mg, extractable  $\text{SO}_4^{4-}$ , and CEC (Table 1). Pioneer Brand P0461xr corn was planted 2-3 May 2011. With the exception of N, fertilizer applications in 2011 (Table 2) were based on 2010 grain and stover removals and fall soil test results. In 2011, the 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 (15 June 2011) and ear-leaf samples at the mid-silk stage (22 July 2011) were collected and analyzed to determine the nutritional status of the crop. Beginning 1 November, 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 2011. The range indicates plot variability within the study site.

Soil Test Parameter	Composite		Composite	
	0-2 inch	Range	2-6 inch	Range
Bray-1 P, ppm	40	13 – 72	29	11 – 62
Exch. K, ppm	171	114 – 278	115	79 – 198
Exch. Ca, ppm	2723	1954 – 3903	2935	1962 – 4041
Exch. Mg, ppm	285	186 – 424	313	185 – 504
Extract. S, ppm	6	4 – 7	4	2 – 10
pH	5.8	5.2 – 6.4	6.0	5.2 – 6.6
O. M., % <sup>†</sup>	3.3	2.5 – 4.9	3.1	2.4 – 4.0
CEC, cmol(+)/kg	20.2	14.2 – 28.1	20.6	15.2 – 28.3

<sup>†</sup> Ignition method.

Table 2. Fertilizer management for the conventional and high-input (twin row) systems in 2011.

System	Stover Removal, %	Timing	Source
Conventional		Fall 2010	11-52-0 + 0-0-60
200+68+49+20S	0	Starter	32-0-0 (UAN)
200+79+124+20S	50		12-0-0-26S (ATS)
200+88+188+20S	90	Sidedress	32-0-0 (UAN)
Twin-Row		Fall 2010	11-52-0 + 0-0-60
225+65+46+30S	0	Starter	32-0-0 (UAN)
225+76+118+30S	50		12-0-0-26S (ATS)
225+82+165+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 (Table 3) were measured.

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. Ammonium polyphosphate (APP, 10-34-0) was then applied to provide the equivalent of 100 lb. P<sub>2</sub>O<sub>5</sub> 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-P was determined for the treated and untreated soils. Relative changes in these soil P supply parameters are being used to quantify legacy and fresh biochar amendment effects on P.

Table 3. Initial soil test levels for Clarion loam collected in 2010. Legacy biochar refers to an 8 ton/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. At this point, measurements are complete, but data analyses are incomplete. Total dry matter production and nutrient uptake from each treatment are being compared. The agronomic efficiency of the P fertilizer and P uptake efficiency are being calculated for the various treatments. 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 P nutrition of the corn. Because of the time and effort involved in carrying out this study, concurrent measurements of K and S uptake efficiency will also be evaluated. In addition, we monitored water-use efficiency.

## RESULTS AND DISCUSSION

### Biomass Removal Study

#### Plant Nutrition

Management scenario, tillage, and the amount of residue removed from the field with the 2010 harvest did not affect early plant growth and nutrient content of whole plants at the V6 stage. Levels of all primary and secondary macro-nutrients were adequate for optimal growth (Table 4). Nitrogen concentrations were well above the published critical value of 3.5% (Mills and Jones, 1996), suggesting that pre-plant N fertilizer and soil N were sufficient to support the corn crop before additional N was sidedressed six weeks after planting.

At mid-silk in 2011, no differences in ear-leaf nutrient concentrations were detected among the treatments (Table 5). Unlike previous years, N concentrations in the tissue were above the critical value. Phosphorus and K concentrations in ear leaves were also within the sufficiency ranges of 0.25% to 0.50% for P and 1.7% to 3.0% for K for all treatments (Mills and Jones, 1996). In addition, S concentrations were within the sufficiency range of 0.10% to 0.30% (Jones et al., 1990).

The plant analysis results suggest that fertilizer inputs and nutrient removals are more balanced than in previous years, although since the hybrid was changed, that could have also affected nutrient uptake and use efficiency. 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 with the P0461xr hybrid in 2011.

#### Corn Grain and Stover Yield

In 2011, management scenario, tillage, and previous stover removal had little effect on corn grain yield (Table 6). In addition, the biochar and cover crop treatments had no effect on grain and stover yields, so data were pooled with the conventional treatments. In 2009 and 2010, grain yields tended to be lower when corn stover was not removed than when ~50% or ~90% was removed, but this was not the case in 2011. These results lend support to previous work

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 2011. 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 <sup>†</sup>	Biochar 2 <sup>‡</sup>	Twin-Row	Annual CC <sup>§</sup>
N	3.50	3.82 (0.25)	3.69 (0.16)	3.66 (0.21)	3.93 (0.27)	4.00 (0.18)
P	0.30	0.44 (0.04)	0.42 (0.04)	0.45 (0.05)	0.45 (0.03)	0.47 (0.04)
K	2.50	3.94 (0.30)	3.82 (0.35)	4.15 (0.28)	4.01 (0.31)	4.14 (0.28)
Ca	0.30	0.53 (0.04)	0.52 (0.04)	0.54 (0.04)	0.53 (0.04)	0.54 (0.03)
Mg	0.15	0.38 (0.05)	0.36 (0.04)	0.36 (0.04)	0.37 (0.04)	0.40 (0.03)
S	0.20	0.29 (0.02)	0.28 (0.02)	0.29 (0.02)	0.30 (0.02)	0.29 (0.01)

<sup>†</sup>4 tons biochar/A; <sup>‡</sup>8 tons biochar/A; <sup>§</sup>CC = cover crop.

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 2011. 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 <sup>†</sup>	Biochar 2 <sup>‡</sup>	Twin-Row	Annual CC <sup>§</sup>
N	2.70	3.06 (0.13)	3.07 (0.12)	2.99 (0.11)	3.01 (0.13)	3.11 (0.13)
P	0.25	0.44 (0.03)	0.45 (0.03)	0.47 (0.03)	0.44 (0.03)	0.45 (0.03)
K	1.70	1.80 (0.11)	1.83 (0.09)	1.90 (0.14)	1.81 (0.15)	1.82 (0.09)
Ca	0.21	0.49 (0.04)	0.50 (0.04)	0.51 (0.04)	0.47 (0.04)	0.52 (0.04)
Mg	0.20	0.33 (0.03)	0.33 (0.03)	0.33 (0.03)	0.32 (0.03)	0.34 (0.03)
S	0.10	0.19 (0.01)	0.19 (0.01)	0.19 (0.01)	0.19 (0.01)	0.19 (0.01)

<sup>†</sup>4 tons biochar/A; <sup>‡</sup>8 tons biochar/A; <sup>§</sup>CC = cover crop.

demonstrating yield decreases when plant residues are removed (Blanco-Canqui and Lal, 2009). Although greater N immobilization related to the residues remaining in the soil would negatively affect mid-season corn growth and subsequent grain yields, fertilizer N rates for the 2011 crop appear to have been sufficient to offset decreased N availability. The warm and humid weather in central Iowa during the late spring/early summer (Hillaker, 2012) provided ideal growing conditions for the corn crop, although high humidity kept overnight low temperatures persistently higher than usual, which may have negatively impacted corn pollination. Precipitation was greater than normal for five of the first six months of the year, which continued the very wet pattern of the previous three years. However, dry conditions quickly developed during late July and continued into August and September (Hillaker, 2012). These conditions during grain fill likely decreased final yield of the crop.

As expected, the amount of dry stover collected was higher for the 90% removal (low cuts) treatments of all management scenarios. Similar to 2009 and 2010, the intensively managed (twin row) plots did not produce more dry stover than the conventional plots. 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 2012.

Table 6. Management system, tillage, and residue removal effects on corn grain and stover yields in 2011. Values are means of 4 to 12 replications depending on treatment. Standard deviations are given in parentheses.

Treatment	Tillage	Percent Removal	Grain <sup>†</sup> (bu/ac)	Stover (t/ac)
Conventional	No-tillage	0	178 (6.1)	0
Conventional	No-tillage	50	177 (5.9)	1.63 (0.57)
Conventional	No-tillage	90	178 (2.8)	2.68 (0.28)
Conventional	Chisel Plow	0	173 (2.8)	0
Conventional	Chisel Plow	50	182 (2.9)	1.74 (0.19)
Conventional	Chisel Plow	90	176 (3.7)	2.94 (0.65)
Twin-Row	No-tillage	0	177 (6.1)	0
Twin-Row	No-tillage	50	182 (4.4)	1.86 (0.23)
Twin-Row	No-tillage	90	175 (10.6)	3.22 (0.96)
Twin-Row	Chisel Plow	0	172 (2.7)	0
Twin-Row	Chisel Plow	50	179 (5.8)	1.90 (0.24)
Twin-Row	Chisel Plow	90	170 (7.0)	2.69 (0.35)

<sup>†</sup> 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 at Harvest 1, 20 days after planting, tended to hold throughout the trial (Table 6). Plants grown in soil amended with 100 lb. P<sub>2</sub>O<sub>5</sub>/A alone had the highest shoot and root dry matter values, while those grown in soil amended with biochar in 2007 (legacy biochar)

without P fertilizer had the lowest values. Addition of 100 lb. P<sub>2</sub>O<sub>5</sub>/A, 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 recorded for the legacy biochar treatments, suggesting that the plants were partitioning more resources to root growth, rather than shoot growth. Without plant nutrient content data, however, it is difficult to speculate on the reason for this result. 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 6). Further statistical analysis of plant growth and nutrient uptake data should provide a clearer picture of the fertilizer value of the biochar, any biochar-fertilizer interactions, and whether legacy or fresh biochar affect the nutrition of juvenile corn in different ways.

Table 6. 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 dry matter accumulation after one harvest and after five harvests. Values are 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 <sub>2</sub> O <sub>5</sub> /A	G	g		g shoot DM/g P
<i>Harvest 1</i>					
Control	0	2.97 (0.17)	1.68 (0.14)	0.57	
	100	3.22 (0.10)	2.08 (0.08)	0.65	5.8
2007 Biochar <sup>†</sup>	0	1.90 (0.10)	1.49 (0.08)	0.78	
	100	2.16 (0.15)	1.60 (0.06)	0.74	6.2
2010 Biochar <sup>†</sup>	0	2.33 (0.16)	1.51 (0.05)	0.65	
	100	2.46 (0.14)	1.57 (0.18)	0.64	3.1
<i>Cumulative<sup>‡</sup></i>					
Control	0	10.13 (0.81)	7.40 (1.11)	0.73	
	100	10.87 (0.30)	8.03 (0.72)	0.74	17.1
2007 Biochar <sup>†</sup>	0	7.71 (0.10)	6.57 (0.42)	0.85	
	100	8.93 (0.52)	5.81 (0.23)	0.65	28.3
2010 Biochar <sup>†</sup>	0	9.10 (0.31)	6.14 (0.35)	0.67	
	100	10.08 (0.29)	6.17 (0.56)	0.61	22.7

<sup>†</sup>8 tons biochar/A; <sup>‡</sup> Values are cumulative for five harvests of dry matter.

## ACKNOWLEDGEMENTS

The authors are grateful to Twin State, Inc., of Davenport, IA, for providing the fertilizer materials for this study. We would also like to thank AgSource – Harris Laboratories of Lincoln, NE, for providing soil analyses, and Servi-Tech Laboratories of Dodge City, KS, for providing plant tissue analyses.



## REFERENCES

- Blanco-Canqui, H., and R. Lal. 2009. Corn stover removal for expanded uses reduces soil fertility and structural stability. *Soil Sci. Soc. Am. J.* 73:418-426.
- Bridgwater, T. 2006. Review: Biomass for energy. *J. Sci. Food Agric.* 86:1755-1768.
- Chan, K.Y., L. Van Zwieten, I. Meszaros, A. Downie, and S. Joseph. 2007. Agronomic values of greenwaste biochar as a soil amendment. *Australian J. Soil Res.* 45: 629-634.
- Glaser, B., J. Lehmann, and W. Zech. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. *Biol. Fertil. Soils* 35:219-230.
- Heggenstaller, A.H., R.P. Anex, M. Liebman, D.N. Sundberg, and L.R. Gibson. 2008. Productivity and nutrient dynamics in bioenergy double-cropping systems. *Agron. J.* 100:1740–1748.
- Hillaker, H. 2012. Iowa annual weather summary 2011. IDALS Climatology Bureau. [Online] Available: <http://www.iowaagriculture.gov/climatology/weatherSummaries/2011/pas2011.pdf>.
- Johnson, J.M.F., R.R. Allmaras, and D.C. Reicosky. 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. *Agron. J.* 98:622–636.
- Jones, Jr., J.B., H.V. Eck, and R. Voss. 1990. Plant analysis as an aid in fertilizing corn and grain sorghum. *In*: R.L. Westerman (ed.) *Soil testing and plant analysis – Third edition*. SSSA Book Series No. 3. ASA, CSSA, and SSSA, Madison, WI.
- Kovar, J.L., and D.L. Karlen. 2010. Optimizing nutrient management for sustainable bioenergy feedstock production. *Fluid J.* 18(3). Available: <http://fluidjournal.org/1gsdgs-S10/S10-A2.pdf>
- Laird, D.A. 2008. The charcoal vision: A win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agron. J.* 100:178-181.
- McHenry, M.P. 2009. Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: Certainty, uncertainty and risk. *Agric. Ecosys. Environ.* 129:1-7.
- Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility if a billion-ton annual supply DOE/GO-102005-2135 and ORNL/TM-2005/66. Oak Ridge National Laboratory, Oak Ridge, Tennessee.