THE USE OF BIOCHAR AS A FERTILITY AMENDMENT IN TROPICAL SOILS

Jonathan L. Deenik[1] and A. Tai McClellan[2]
[1]Department of Tropical Plant and Soil Sciences, University of Hawaii, Honolulu, HI
[2]Department of Crop and Soil Sciences, Washington State University, Pullman WA

ABSTRACT

Biochars made from modern pyrolysis methods have attracted widespread attention as potential soil amendments to improve plant productivity in the infertile soils of the tropics. Feedstock and pyrolysis conditions affect the physico-chemical properties of biochar with important implications for soil fertility and plant growth. Specifically, biochar volatile matter (VM) significantly affect soil inorganic nitrogen (N) status and ash content impacts soil elemental composition and pH. This paper highlights collaborative research on biochar and its potential use as a soil amendment conducted by the Department of Tropical Plant and Soil Sciences and the Hawaii Natural Energy Institute (HNEI) at the University of Hawaii.

INTRODUCTION

Biochar is defined as charcoal made to be applied to soils as a soil conditioner (Verheijen et al., 2009). The 'Terra Preta do Indio' a sustainable fertile soil of central Amazonia from pre-Columbian origin (Major et al., 2005) provided the model for using charcoal in agriculture as a mean for C sequestration and soil fertility improvement (Glaser et al., 2002; Lehmann et al., 2006; Sombroek, 1966; Lehmann et al., 2003). Biochar exhibits certain physico-chemical properties that make it not only a potential soil amendment, but also an attractive alternative for mitigating the negative effects of greenhouse gas emissions via long-term C sequestration. It is a porous media with high surface area, which imparts high water holding capacity, a high capacity for the sorption of organic and ionic compounds, and a beneficial habitat for soil microorganisms (Verheijen et al., 2009). Exhibiting a high degree of aromaticity, biochar is resistant to microbial degradation and can persist in the soil environment for centuries offering (Baldock and Smernik, 2002).

Feedstock and pyrolysis conditions determine the physico-chemical properties of biochar, and thus determine its effects on soil and plant growth. Biochar made from wood and grass materials at the same temperature, for example, show distinctly different properties; woody materials are characterized by high surface area and low ash content, whereas grasses have low surface area and high ash content. For the same feedstock, increasing pyrolysis temperature increases ash content and surface area up to 600 °C and decreases VM and total N content. Biochar physico-chemical properties appear to be optimized for the use as a soil fertility amendment when produced at temperatures between 500 and 600 °C; the range at which surface area, cation exchange capacity (CEC), and ash content are highest (Keiluweit et al., 2010).

In this paper, we provide characterization data for a range of biochars produced at the HNEI and summarize the results of a series of laboratory incubations and greenhouse pot experiments investigation biochar effects on soil properties and plant growth.

MATERIALS AND METHODS

A range of biochars from varying feedstocks subjected to differing pyrolysis conditions and severity were created at the HNEI (Table 1). The high volatile matter macnut shell (HVM MN) and corn cob (HVM CC) biochars were produced according to the flash carbonization process at low temperature (<300 °C) whereas the low volatile matter (LVM) chars were produced at

Table 1. Selected chemical properties of the biochars used in the greenhouse experiments.

	VM	Ash	fC†	pH_{H2O} (1:5)	P‡	Exchangeable Cations ($cmol_c$ kg^{-1})			
Biochars		%			(mg kg^{-1})	K^+	Ca^{2+}	Mg^{2+}	Na^+
HVM MN	22.5	0.33	77.2	5.7	NA	18.5	0.74	0.74	0.15
LVM MN	6.30	4.18	88.7	8.2	NA	17.2	1.25	3.73	0.31
HVM CC	63.4	1.57	35.1	4.5	263	19.2	0.35	2.68	0.15
LVM CC	7.68	5.19	87.1	10.0	237	35.7	0.32	2.42	0.30
GAS	2.22	18.1	79.7	10.7	689	2.09	36.7	100	0.21
Kiawe	23.9	1.17	75.0	7.9	25.1	0.57	7.14	0.22	0.27

†fixed carbon (fC) = 100%-%VM - %ash; ‡Modified truog extractable P

approximately 550 °C (Antal et al., 2003; Deenik et al., 2010; Diarra et al., *in review*). Two woody biochars were also included; one made from *Leucaena leucocephala* wood (GL) using a gasification procedure at 850 °C (Turn et al., 1998) and the other a commercially available barbecue charcoal made from *Prosopis pallida* (kiawe) wood produced by traditional means. Biochar pH, extractable P, exchangeable cations, chemical structure by fourier transform infared spectroscopy (FTIR), and the chemical composition of the VM [by gas chromatography mass spectrometry (GC-MS)] were determined following the procedures outlined in Deenik et al. (2010) and McClellan et al. (*in review*). Biochar effects on plant growth and soil properties were assessed through a series of greenhouse pot experiments using a highly infertile, acid Ultisol (Leilehua series, Very-Fine, Ferruginous, Isothermic Ustic Kanhaplohumults) as the test soil and implemented following the procedures in Deenik et al. (2010) and Diarra et al. (*in review*). A laboratory incubation was also conducted to evaluate biochar effects on soil nitrogen (N) transformations and soil microbial activity as outlined in McClellan et al. (*in review*).

RESULTS AND DISCUSSION

FTIR spectra showed that there were significant structural differences between the low and high VM CC biochars (Fig. 1). The LVM biochar showed a high degree of thermal alteration with an FTIR spectra similar to activated charcoal indicating extensive aromaticity with distinct peaks at 1560 and 1250 (carboxylic functional

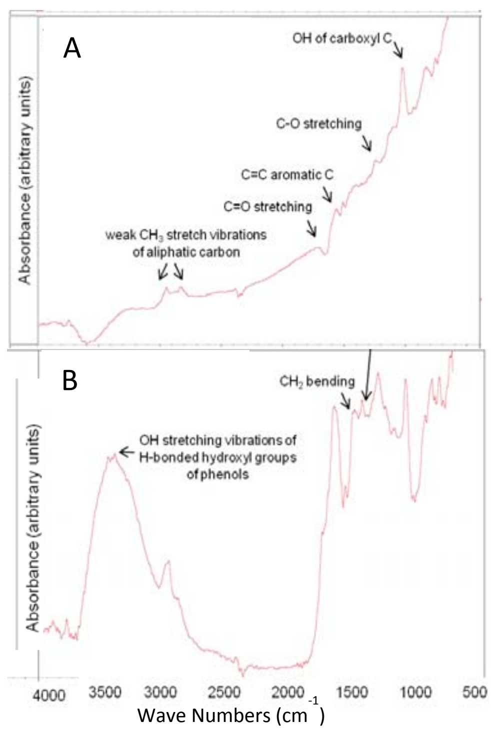

Figure 1. FTIR spectra for LVM (A) and HVM (B) CC biochars

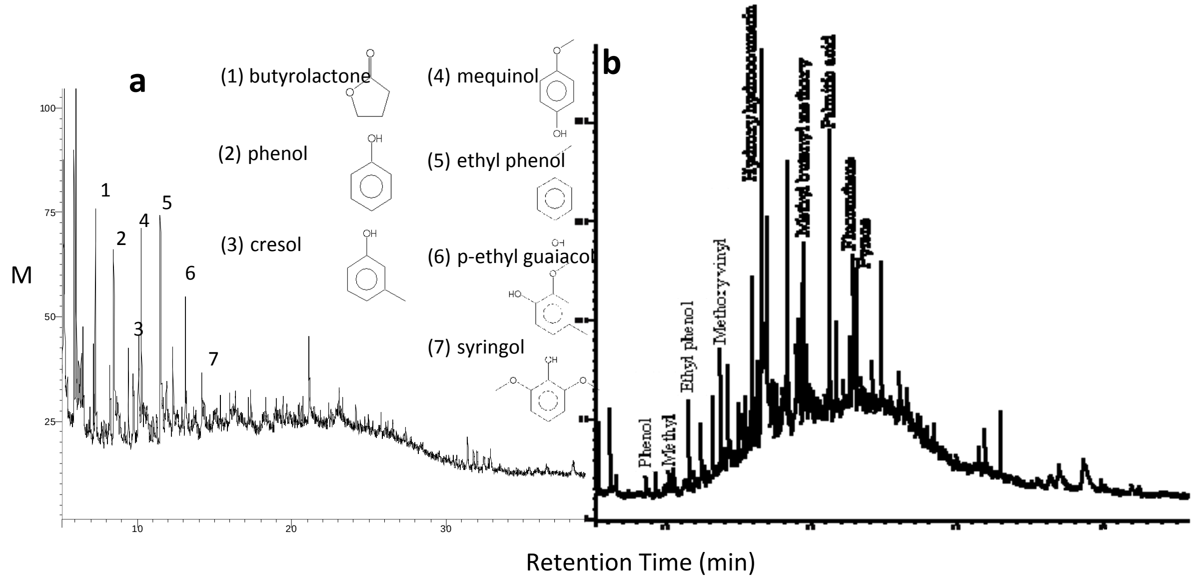

Figure 2. GC-MS chromatograms for the acetone extract of the HVM MN (a) and HVM CC (b) biochars.

groups). On the other hand, the HVM biochar showed strong peaks at 3360-3400 cm^{-1}, for OH-stretching of phenols and H-bonded water. The presence of phenolic compounds is indicative of a lower temperature char with higher VM content.

We used GC-MS spectroscopy to characterize the chemical composition of the VM in the high and low VM MN and CC biochars. GC-MS spectra of the acetone extracts of high VM MN and CC biochars showed the presence of a range of volatile compounds. The HVM MN biochar contained a range of phenolic compounds (Fig. 2a) and the HVM CC biochar was also rich in phenolics with additional peaks for a fatty acid (palmitic acid), polycyclic hydrocarbons (PAH) (fluoranthene and pyrene), and hydroxyl hydrocoumarin (Fig. 2b). In contrast, chromatograms for the acetone extract of all the LVM biochars showed no peaks.

Biochars with high VM content consistently caused a decrease in soil inorganic N in short term controlled incubation experiments. Incubation jars with HVM CC biochar supplemented with 50 mg kg-1 N showed a rapid and sustained decline in extractable NH_4^+ (Fig. 3A) and NO_3^- (data not

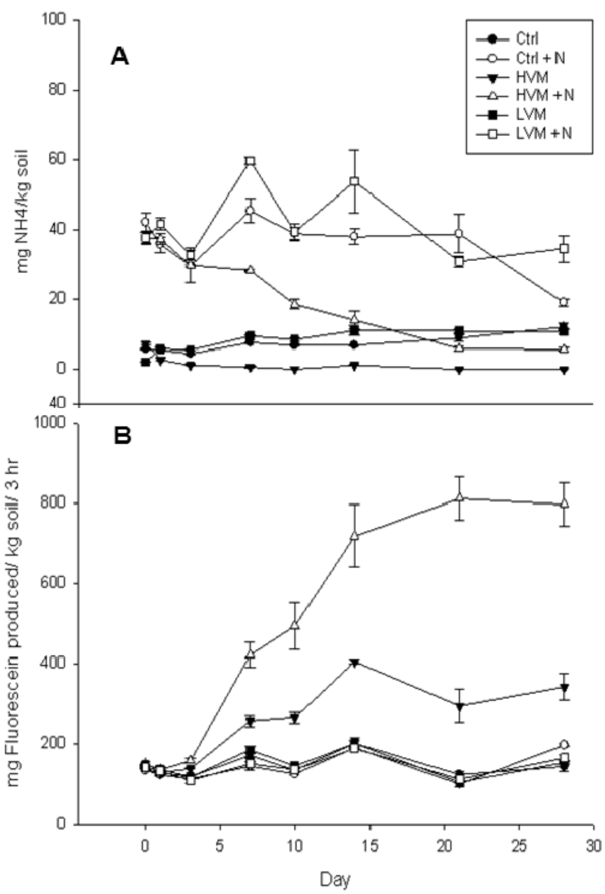

Figure 3. Biochar effects on soil inorganic N (A) and hydrolytic enzyme activity (B) in a 30-day incubation.

shown) compared with the LVM CC biochar and control soil with supplemental N, which maintained high concentrations of soil NH_4^+. The HVM biochar treatments showed a significant increase in hydrolytic enzyme activity corresponding with the decline in soil inorganic N (Fig. 3B). However, the LVM and control treatments showed no change in enzyme activity throughout the incubation. The simultaneous increase in enzyme activity and decline in inorganic N in the HVM treatments provides indirect evidence that the compounds in the HVM biochar served as a source of bioavailable C fueling microbial proliferation and inducing N immobilization.

Variations in VM and ash content significantly impacted maize growth in the greenhouse experiments for the MN and CC biochars. The high VM biochars caused significant reductions in growth compared with the control treatment and corresponded with low N in the above ground biomass of the biochar amended soils. The apparent N deficiency is likely explained by N immobilization in the microbial biomass that grew as a result of bioavailable C in the biochar VM as we showed occurred in the incubation study reported above. We observed positive growth responses in the low VM MN and CC treatments. The response was best explained by significantly higher potassium (K) uptake from the K-rich MN and CC biochars (Table 1).

To evaluate the persistence of the observed biochar effects on maize growth, we ran a sequence of three consecutive planting cycles. Figure 4 shows significant effects of biochar on maize growth in the first planting cycle with the low VM biochar producing an increase and the high VM biochar reducing growth. During the second and third planting cycles, however, there were no significant differences between biochar treatments and the control. Our results indicate that both the negative effect of high VM biochar and positive effect of low VM biochar were temporary. A comparative analysis of high VM (HVM CC) biochar amended soils before and after the first crop cycle showed the disappearance of bioavailable phenolic compounds presumably due to microbial activity. Maize growth in the high VM CC biochar treatment recovered during the second crop cycle showing no difference compared with the control with similar results observed in the third crop cycle. These findings indicate that bioavailable compounds in high VM biochar are rapidly consumed by soil microorganisms and that the subsequent period of N immobilization is short (≈6

Table 2. Results from greenhouse experiments showing maize growth response to biochars from different feedstocks with either high or low VM content. Growth response is measured against the soil control.

Feedstock	Rate % (w/w)	VM	Ash	Growth Response
			-------------%------------	
MN	5	High	0.33	NS
	10	High	0.33	-22
	20	High	0.33	-73
MN	10	Low	4.18	+38
CC	2.5	High	1.57	-45
	2.5	Low	5.19	+64
Kiawe	2.5	High	1.17	NS
Leuceana	2.5	Low	18.1	NS

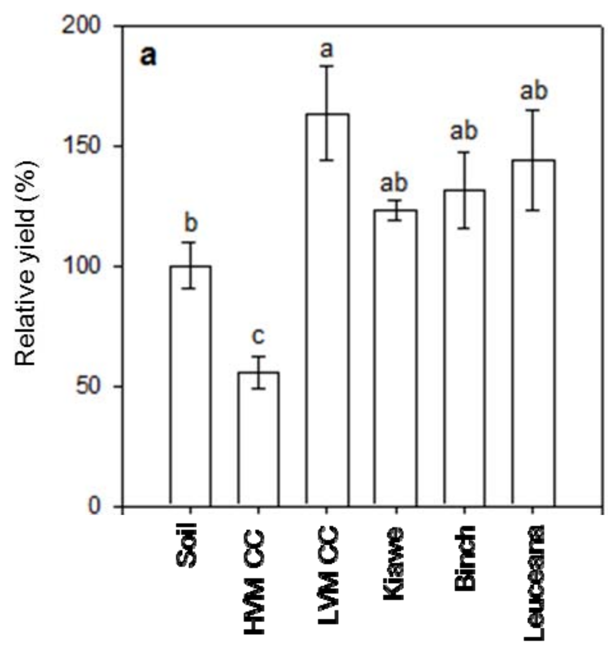

Figure 4. Biochar effects on maize growth in the first cropping cycle.

weeks). Similarly, we observed that the positive effects associated with the low VM biochar did not persist past the first cropping cycle.

Biochar application to a highly weathered and infertile Ultisol showed differential effects on soil chemical properties that varied primarily with ash content. Biochars high in ash served as good liming materials significantly increasing soil pH and reducing Al saturation. The ash component of the low VM MN and CC biochars were also excellent sources of K significantly enhancing soil K supply to the maize plants. The K contribution, however, did not persist one cropping cycle. A number of studies have reported increased CEC in soils amended with biochar (Lehman et al., 2003; Liang et al., 2006), our laboratory work shows that while certain biochars may exhibit CEC in a water suspension, biochars exhibit pH-dependent charge properties and their surfaces can be dominated by positive charge when the soil-biochar mixture pH falls below the biochar's isoelectric point (pH_0, the pH at which negative and positive surface charge are equal for variable charge surfaces). For example, the pH_0 of the low VM CC charcoal was 7.1, however, the low VM biochar amended soil pH was 4.96, which was much lower that the biochar pH_0 suggesting that the biochar surface would be net positively charged. In soil systems with variable charge minerals, such as the Leilehua soil, constituents that lower the pH_0 values increase the CEC whereas amendments that increase pH_0 values increase positive charge with a corresponding decrease in CEC (Uehara and Gillman, 1981). Soil organic matter and phosphate applications to variable charge soils, for example, will lower the pH_0 and increase the CEC of the system (Gilman and Fox, 1980; Gilman, 1985). The Leilehua soil was characterized by net negative charge as its pH in water was higher than its pH_0. Biochar additions showed negligible effects on pH_0 of the soil/biochar mixtures indicating no significant effect on CEC.

SUMMARY

Our experiments show that both the positive and negative effects of charcoal on plant growth are temporary, and in general charcoal applications to the Leilehua soil are neither significantly beneficial or detrimental to plant growth. Charcoals can potentially benefit plant growth by directly modifying soil chemistry (a liming effect or contribution of essential elements), increasing nutrient retention by contributing negative surface charge (CEC), and improving the physical properties of the soil (lowering bulk density and increasing aggregation and water holding capacity) (Sohi et al., 2009). We have shown that charcoals high in ash content ameliorate soil chemistry by increasing pH and depending upon feedstock contributing essential nutrients leading to temporary benefits to plant growth. We demonstrate that although three of the charcoals may exhibit CEC in a water suspension, when they are added to an acid soil they do not lower pH_0, instead the surfaces gain positive charge due to their high isolectric points. The Leilehua soil is characterized by excellent physical properties – low bulk density, stable aggregates, and high water holding capacity – and we would expect the charcoal applied at 2.5 % to have negligible effects on soil physical properties. The charcoal amendments and the soil receiving the amendment are very similar in two key physico-chemical properties that exert considerable influence on soil behavior; they are both characterized by high surface area and their surfaces possess variable charge. In essence, we are adding "like to like" and therefore, the fact that we observe only small effects on plant growth may not be surprising. On the other hand, as Sohi et al. (2009) suggest, adding charcoal materials to coarsely textured soils with low porosity and surface area should have beneficial effects on water retention and CEC, especially if the charcoal surfaces are negatively charged. It is clear that more research is needed to relate charcoal physico-chemical properties to effects on soil properties and plant growth across a range of soils varying in texture and mineralogy.

ACKNOWLEDGEMENTS

We thank Dr. Michael Antal for providing biochar samples along with proximate analysis data. We also thank Aminata Diarra, Sonia Campbell and Yudai Tsumiyoshi for assistance with laboratory analysis, and Dr. Uehara for contributing knowledge on variable charge systemns. Funding for this research came in part from USDA HATCH project 863H and USDA-TSTAR project# HAW00890-08G.

REFERENCES

Antal, M.J. and M. Gronli. 2003. The Art, Science, and Technology of Charcoal Production. Industrial & Engineering Chemistry Research 42:1619-1640.

Baldock, J.A. and R.J. Smernik. 2002. Chemical composition and bioavailability of thermally altered Pinus resinosa (Red pine) wood. Organic Geochemistry 33:1093-1109.

Deenik, J.L., T. McClellan, G. Uehara, M.J. Antal Jr., and S. Campbell. 2010. Charcoal Volatile Matter Content Influences Plant Growth and Soil Nitrogen Transformations. Soil Science Society of America Journal 74(4): 1259-1270.

Diarra, A., J.L. Deenik, G. Uehara, S. Campbell, Y Sumiyoshi, and M.J. Antal Jr. Charcoal Ash and Volatile Matter Effects on Soil Properties and Plant Growth in an Acid Ultisol. Soil Sci. (*In Review*)

Gillman, G.P. 1985. Influence of organic matter and phosphate content on the point of zero charge of variable charge components in oxidic soils. Aust. J. of Soil Res. 23:643-646.

Gillman, G.P. and R.L. Fox. 1980. Increases in the cation exchange capacity of variable charge soils following superphosphate applications. Soil Sci. Soc. Am. J. 44:934-938

Glaser, B., J. Lehmann, and W. Zech. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. Biology and Fertility of Soils 35:219-230.

Keiluweit, M., P.S. Nico, et al. 2010. Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar). Environmental Science & Technology 44(4): 1247-1253.

Lehmann, J., J. Gaunt, and M. Rondon. 2006. Bio-char Sequestration in Terrestrial Ecosystems – A Review. Mitigation and Adaptation Strategies for Global Change 11:395-419.

Lehmann, J., J.P. da Silva, C. Steiner, T. Nehls, W. Zech, and B. Glaser. 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil 249:343-357.

Liang, B., J. Lehmann, D. Solomon, J. Kinyangi, J. Grossman, B. O'Neill, J.O. Skjemstad, J. Thies, F.J. Luizao, J. Petersen, and E.G. Neves. 2006. Black Carbon increases cation exchange capacity in soils. Soil Science Society of America Journal 70:1719-1730.

Major, J., A. DiTommaso, et al. (2005). "Weed dynamics on Amazonian Dark Earth and adjacent soils of Brazil." Agriculture Ecosystems & Environment 111(1-4): 1-12.

McClellan, A. T., J.L. Deenik, W.C. Hockaday, S. Campbell, G. Uehara, and M.J. Antal, Jr. Characterization of charcoal volatile matter content as influenced by the degree of carbonization and feedstock. Organic Geochemistry. (*In Review*)

Sombroek, W.G., F.O. Nachtergaele, and A. Hebel. 1993. Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. Ambio 22:417-426.

Uehara, G. and G.P. Gillman. 1981. The Mineralogy, Chemistry and Physics of Tropical Soils with Variable Charge Clays Westview Press, Colorado.

Verheijen, F.G.A., S. Jeffery, et al. (2009). Biochar Application to Soils - A Critical Scientific Review of Effects on Soil Properties, Processes and Functions. Office for the Official Publications of the European Communities, Luxembourg, EUR 24099 EN: 149 pp.

PROCEEDINGS
OF THE
WESTERN NUTRIENT
MANAGEMENT CONFERENCE

Volume 9

MARCH 3-4, 2011
RENO, NEVADA

Program Chair:
Robert Flynn, Program Chair
New Mexico State University
67 E Four Dinkus Road
Artesia-NM 88210
(575) 748-1228
rflynn@nmsu.edu

Coordinator:
Phyllis Pates
International Plant Nutrition Institute
2301 Research Park Way, Suite 126
Brookings, SD 57006
(605) 692-6280
ppates@ipni.net