BIOCHAR VOLATILE MATTER CONTENT EFFECTS ON PLANT GROWTH AND NITROGEN TRANSFORMATIONS IN A TROPICAL SOIL

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ABSTRACT

Biochars made from modern pyrolysis methods have attracted widespread attention as potential soil amendments with agronomic value. A series of greenhouse experiments and laboratory incubations were conducted to assess the effects of biochar volatile matter (VM) content on plant growth, nitrogen (N) transformations, and microbial activities in an acid tropical soil. High VM biochar inhibited plant growth and reduced N uptake with and without the addition of fertilizers. Low VM charcoal supplemented with fertilizers improved plant growth compared with the fertilizer alone. The laboratory experiments showed that high VM biochar increased soil respiration and immobilized considerable quantities of inorganic N. This research shows that biochar with high VM content may not be a suitable soil amendment in the short-term.

INTRODUCTION

The use of biochar as a soil amendment is modeled on the C-rich anthropogenic soils known as “Terra Preta do Indio” (Indian black earth) found in Amazonia and associated with habitation sites of pre-contact Amerindian populations dating as far back as 7,000 cal yr BP (Glaser, 2007). The defining characteristic of Terra Preta soils is the presence of large quantities of charcoal in the soil organic matter to depths of 1 m or greater (Glaser et al., 2000; Sombroek et al., 1993). These soils are remarkable because they have remained fertile and enriched in soil C compared with adjacent forest soils despite centuries of cultivation.

Recent efforts to replicate the “Terra Preta” phenomenon using biochars created from modern pyrolysis techniques show that charcoal additions can have an ameliorating effect on highly weathered, infertile tropical soils by increasing CEC and plant nutrient supply, reducing soil acidity and aluminum toxicity, and improving fertilizer efficiency due to reduced nutrient leaching (Glaser at al., 2002; Lehmann et al., 2003). Plant growth response to charcoal amended soils has been variable with both negative and positive results reported in the scientific literature (Glaser at al., 2002). Several studies have reported that plant growth responses are largest when charcoal and fertilizers are combined suggesting a synergistic relationship (Chan et al., 2007; Lehmann et al., 2003; Steiner et al., 2007). Gundale and Deluca (2007) observed that laboratory produced charcoal from ponderosa pine and Douglas-fir had a negative effect on plant growth whereas the same charcoal created from wildfires showed a positive effect on plant growth. The authors speculated that the low temperature charring method used to create the charcoal in the laboratory either created toxic compounds that inhibited plant growth or acted as a source of labile carbon (C) stimulating microbial growth and N immobilization. The objectives of the present research were to determine the effects of charcoal volatile matter content on plant growth and N transformations in a tropical acid soil. We hypothesized that biochar created at low temperatures with high VM would increase microbial activity resulting in a decrease in plant available N due to immobilization.

MATERIALS AND METHODS

Two greenhouse bioassays and two laboratory incubations were conducted to test the effects of biochar VM content on plant growth and N transformations. The soil was an infertile, acid Leilehua series (very-fine, ferruginous, isothermic, ustic kanhaplohumults) collected from the 30-80 cm depth at the Waiawa Correctional Facility, Mililani, Oahu Island (N21°26’53”, W157° 57’ 52”). The charcoal feedstock used in our experiments was macadamia nut shells. The charcoal was made using a flash carbonization process developed at the Natural Energy Institute at the University of Hawaii (Antal et al., 2003). Selected chemical properties of the soil and biochars used in the different experiments are presented in Table 1. Total C and N content of the biochars were determined by dry combustion on a LECO CN-2000. Biochar pH was measure in 1:1 slurry of charcoal to deionized water. Base cations were extracted with 1M ammonium acetate at pH 7 and Al^{+++} was extracted with 1M KCl and measured in solution by inductive coupled plasma spectrophotometer. The effective cation exchange capacity (ECEC) of the biochars and soil was determined by summing the exchangeable cations.

Table 1. Selected chemical properties of the Leilehua soil, and the biochars used in the greenhouse and laboratory experiments (LVM = low VM content and HVM = high VM content).

	VM	Ash	OC	TN	pH	P	K	Ca	Mg	Na	Al	ECEC
		%				mg kg^{-1}			cmol$_c$ kg^{-1}			
Soil												
Leilehua			4.28	0.12	4.70	2.22	0.09	0.72	0.52	0.29	1.61	3.22
Charcoal												
LVM MacNut	6.30	4.18	88.7	0.45	8.16		17.2	1.25	3.7	0.31	0.011	22.5
HVM MacNut	22.5	3.33	85.2	0.45	5.72		18.5	0.74	0.7	0.15	0.032	20.2

In the first greenhouse bioassay we imposed five treatments consisting of a control (unamended soil), soil+lime, soil+biochar, soil+lime+NPK and soil+biochar+lime+NPK arranged in randomized block design with four replications. The biochar contained 22.5 % VM and was considered a high VM biochar. Biochar was applied to achieve 10% (w/w), lime to achieve 2 T ha^{-1}, N as NH_4NO_3 at a rate of 200 mg N kg^{-1}, P as $Ca(H_2PO_4)_2$ to achieve a rate of 750 mg P kg^{-1}, K and Mg were added in solution at a rate equivalent to 200 and 100 kg ha^{-1} respectively, and the micronutrients Cu, Mn, and Zn were added in solution at a rate of 10 kg ha^{-1}. We used corn (*Zea mays*, var super sweet #9) as the test crop. Eight corn seeds were planted into each pot and thinned to four plants after emergence. The second greenhouse bioassay consisted of five treatments (unamended soil, soil+lime+NPK, soil + high VM biochar, soil + low VM biochar, soil + low VM biochar + NPK) installed in a complete randomized block design with four replicates. Lime and fertilizers were applied at the same rates as in the first experiment and corn was the test crop. At harvest time, above-ground biomass was cut at the soil surface dried at 70°C for 72 hours, weighed and tissue analyzed for nutrient content according to standard procedures (Hue et al., 2000).

We conducted two laboratory studies to evaluate the effect of biochar VM content on net N mineralization rates and on CO_2 respiration. Both experiments consisted of three treatments, a control (untreated Leilehua soil) and the Leilehua soil amended with high and low VM macadamia nut biochar applied at the same rate as in the greenhouse experiment. For the N study, the biochar was mixed thoroughly with 50 g (oven dry equivalent) of soil followed by the addition of the appropriate volume of deionized water required to bring the soil to 75% of water holding capacity. The soils were placed in 100 mL beakers, weighed at the outset of the incubation, covered with perforated parafilm, and incubated at constant temperature (28°C) and moisture. Soils were sampled and analyzed for inorganic N, protease activity, and K_2SO_4 extractable organic C and TN after 2, 7, and 14 days. The soluble C fraction of the biochar was determined by shaking 3 g of biochar in 30 mL deionized water for 1 hour and filtering through a 45 µm nylon membrane. For the CO_2 respiration study, we used the alkali adsorption method where 50 g of treated and untreated soils and 50 ml of 0.05 *M* NaOH were sealed in airtight 1 L mason jars and incubated at 28°C for 14 days (Alef, 1995). The beaker containing the NaOH solution was removed from the mason jar at 48 hour intervals and titrated with 0.05 M HCl following the addition of 0.5 *M* $BaCl_2$. Four mason jars with the 0.05 M NaOH solution, but without soil were used as controls.

RESULTS AND DISCUSSION

The high VM biochar used in the first greenhouse bioassay had a significant negative effect on corn growth compared to the control (Fig. 1). Amending the soil with conventional inorganic fertilizers (lime+NPK) produced significant increases in corn growth, but the beneficial effects of the fertilizer was erased when combined with charcoal. Indeed, by combining charcoal with the fertilizer there was an approximately 50% decline in corn growth compared with the fertilized soil. Corn plants growing in the control soil showed very low N, P and K concentrations in the tissue (data not shown). Tissue N and K concentrations remained low after the addition of charcoal, but P concentrations increased significantly. Applying NPK fertilizers significantly increased tissue N, P, and K concentrations and the accompanying significant rise in dry matter production indicated that the Leilehua soil was severely deficient in N, P, and K. The biochar in combination with fertilizers, however, significantly decreased tissue N, P, and K concentrations compared to the fertilizer control treatment. Our observations were in disagreement with a recent greenhouse experiment reporting that biochar significantly improved N fertilizer use efficiency by radish plants (Chan et al., 2007). We speculated that the relatively high VM content of the biochar used in this experiment may have played a role in inhibiting corn growth.

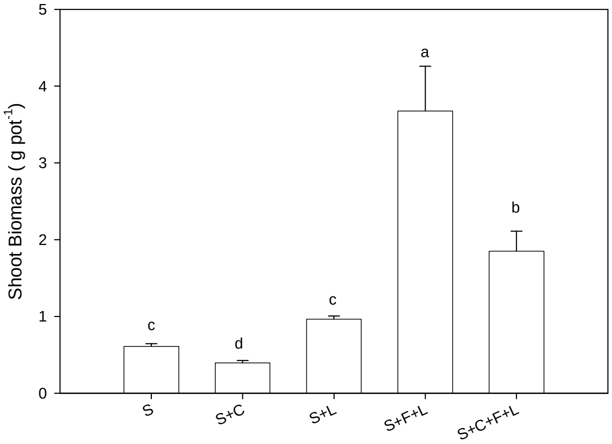

Figure 1. Treatment effects on above ground corn dry matter production in an infertile Leilehua soil amended with high VM biochar and fertilizer (S = soil, S+C = soil + biochar, S+L = soil + lime, S+F+L = soil + NPK + lime, S+C+F = soil + biochar + NPK).

The results of the second greenhouse experiment showed that biochar VM content had significant effects on plant growth. High VM biochar significantly reduced shoot dry matter compared with the control whereas low VM biochar had no significant effect on dry matter production (Fig. 2). Corn growth was significantly better in the low VM charcoal treatment than in the high VM charcoal treatment. The low VM biochar combined with fertilizer showed a significant increase in dry matter production compared with the fertilizer alone treatment. The high VM biochar reduced N uptake by 50% compared with the control. On the other hand, the low VM biochar did not reduce N uptake in either biochar alone treatment or the biochar augmented with fertilizer treatment. Although the low VM biochar with fertilizer treatment did not show as high an increase in plant growth nor a significant increase in N uptake compared with the fertilizer treatment as in the results reported by Chan and his group (2007), our results provide evidence that the VM content of the biochar is an important factor affecting its agronomic value as a soil amendment. We suspected that high VM charcoal is a source of labile C for soil microorganisms, and the high C:N ratio of the C source stimulated immobilization of the plant available N in the soil causing N deficiency in the growing plants. A recent experiment reported similar results showing that charcoal produced at low temperature (350°C) had a negative effect on plant growth (Gundale and DeLuca, 2007), and the researchers speculated that the decline in plant growth was caused by N immobilization due to high concentrations of soluble and total phenols in the charcoal, which served as a high C:N carbon source for soil microorganisms.

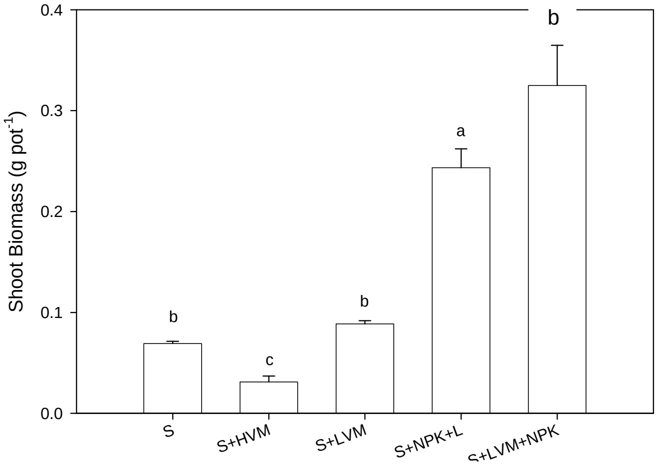

Figure 2. Treatment effects on above ground corn dry matter production in an infertile Leilehua soil amended with high and low VM biochar and fertilizer (S = soil, HVM = high VM biochar, LVM = low VM biochar).

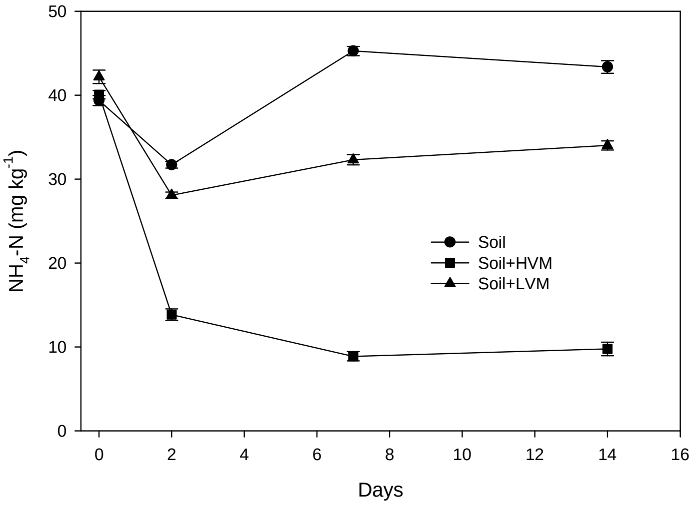

Figure 3. Biochar effects on soil NH_4^+-N in a 14 - day incubation.

Results from the two incubation experiments confirmed that biochar VM exerts a strong influence on N mineralization and microbial respiration. The untreated soil showed an initial drop in soil NH_4^+-N after two days from 39.4 to 31.7 mg kg^{-1} followed by a slow increase to 45.3 and 43.4 mg kg^{-1} after seven and fourteen days respectively (Fig. 3). The soil amended with high VM biochar, however, showed a dramatic decline in soil NH_4^+-N that persisted throughout the fourteen day incubation. The low VM biochar had a much smaller effect on soil NH_4^+-N decreasing it to around 30 mg kg^{-1}. In the CO_2 respiration study, the high VM biochar amendment caused a steep increase in respiration reaching a peak at four days followed by a gradual decline through the 12th day (Fig. 4). At day 2 and day 6 the high VM biochar treatment showed a respiration rate threefold higher than the control, which remained at least twice as high as the control throughout the remainder of the incubation period. The low VM treatment showed an initial spike in respiration at day 2 followed by a rapid decline matching the control values by the eighth day. The relatively high CO_2 respiration rate combined with the dramatic decline in soil NH_4^+-N concentration observed in the high VM biochar treatment is strong evidence that N immobilization by the microbial biomass was an important factor explaining the observed decline in plant growth and N uptake in the high VM biochar treatments. The high water extractable C content of the high VM biochar (265 mg C kg^{-1}) compared with the low VM biochar (53 mg kg^{-1}) provided a labile source of C fueling the observed stimulation of microbial activity in the high VM treatment. With the high C:N ratio of the biochar, the microbial biomass was forced to scavenge soil N inducing N deficiency in the growing plants.

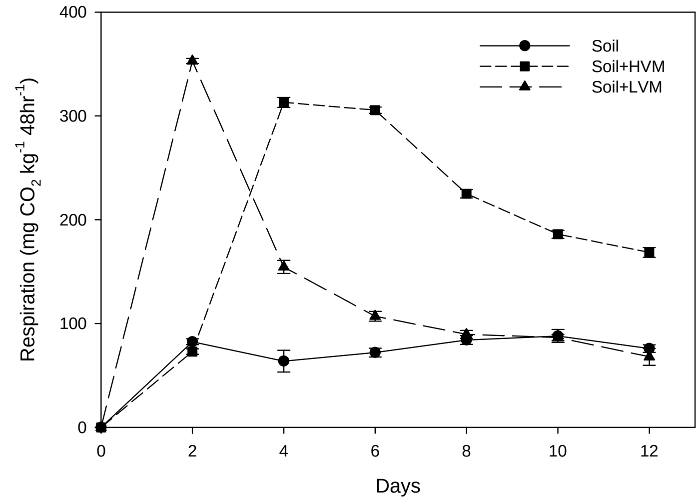

Figure 4. Biochar effects on CO2 respiration in a 12-day incubation.

SUMMARY

This research shows that biochar VM content, or the degree of carbonization, can play a critical role in determining its agronomic value as a soil amendment. Our results provide clear evidence that biochars that are high in VM content (i.e., a typical barbecue charcoal) would not be good soil amendments because they can stimulate microbial activity and immobilize plant available N in the short-term. On the other hand, more fully carbonized biochars with lower VM content containing a smaller labile C component have a smaller effect on soil microbial activity and N immobilization. While our research provides one explanation for why some biochars have a negative effect on plant growth, it still remains unclear why low VM biochars in combination with fertilizer appear to have a beneficial effect on plant growth. Despite our findings elucidating the role of VM content in inhibiting N mineralization, research at the field scale is required to truly assess the agronomic value of biochars as soil amendments.

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