Application of Low-Temperature Produced Biochar on Plant Growth in Californian Alfisol Soil

Erica Fong

ABSTRACT

As the scientific and political community works to reduce greenhouse gases in the atmosphere, there has been greater support for wide-scale biochar use as a form of carbon sequestration. Biochar has also increased soil fertility and plant growth in studies suggesting potential environmental and economic benefits of agricultural use. While California could benefit from biochar use, there has been limited research done on biochar interactions with varying plants and agricultural practices in Californian Alfisol soils. I conducted a greenhouse experiment to determine whether low-temperature produced biochar at varying application concentrations with and without fertilizer would affect *Lolium multiflorum* plant growth in Californian Alfisol soil. After 7 weeks of growth, I weighed the dry root and shoot masses and used a two-way ANOVA to find whether biochar affects plant growth and if fertilizer affects biochar's influence on plant growth. Shoot plant growth increased most with 25 tons per hectare (t/h) biochar and fertilizer applied which improved shoot growth by 7.77g from the control (no fertilizer and 0t/h biochar applied) and 1.52 g from the fertilized and 0 t/h biochar applied group. Fertilizer increased plant growth most ($p=1.704 \times 10^{-14}$). However, the minimal plant growth within the fertilized group seemed to be attributed to biochar additions but could not be verified as biochar's effect on plant growth was insignificant ($p=0.4424$). Biochar and fertilizer's combined effect on plant growth was insignificant ($p=0.7239$). The statistical insignificance suggests a larger study is needed to verify possible biochar benefits on plant growth with fertilization in Alfisol soils.

KEYWORDS

soil fertility, carbon sequestration, Lolium multiflorum, agriculture, climate change

INTRODUCTION

As greenhouse gas concentrations in the atmosphere rise, contributing to mounting climate change effects, carbon sequestration technology has become a popular mitigation strategy (Molina et al., 2009). Carbon sequestration transfers atmospheric carbon dioxide (CO_2) into the soil sinks, which secure the carbon and slows its emission to the atmosphere (Lal et al., 2008). As agriculture and degraded soils have a carbon sink capacity to hold 50-66% of the historic carbon, these soils provide a substantial carbon pool for mitigation purposes (Lal et al., 2008). Through varying carbon sequestration techniques, greenhouse gases such as CO_2 and methane (CH_4) are sequestered from the atmosphere into sinks (Lal et al., 2008). It has been proposed that carbon sequestration could offset 5-15% of current fossil-fuel emissions (Lal et al., 2008). Thus, carbon sequestration techniques seem to hold promise as components for climate change mitigation portfolios.

One of the most promising methods of carbon sequestration is the use of biochar. Biochar is biomass-derived carbon formed through the pyrolysis processes, or the decomposition of organic matter in the absence of oxygen at varying temperatures (Lopez-Capel et al., 2009). Biochar additions to soil allows for the capture of carbon in a solid form that would naturally be emitted into the atmosphere through biomass degradation (Tenebaum, 2009). Biochar usage has been shown to improve soil nutrient quality and stabilize soil better than organic matter (Lehmann and Joseph, 2009). Along with improving soil nutrient quality, pyrolysis process of biomass produces biofuel and bio-gas fuel products including biochar which can significantly reduce carbon emissions by removing an equivalent of 1.2 billion metric tons per year (Tenenbaum, 2009). The benefits of biochar sequestration have created legislative interest through initiatives such as the Carbon Harvesting and Restoration (WECHAR) Act of 2009 as well as the 2008 farm bill to increase biochar development and projects (Bracmort, 2009). Data suggests that biochar may be a promising way to reduce carbon emissions as well as to increase the quality of soils.

Because biochar has shown to improve both soil nutrient quality and reduce greenhouse emissions, wide scale agricultural biochar use would be beneficial to California. Biochar usage on agricultural systems can increase agricultural profitability, which could improve California's agricultural economy (McHenry, 2009; California Department of Food and Agriculture, 2009).

The economic benefits of biochar addition to agricultural soils are caused by the potential increase in agricultural yield, increase of nitrogen fertilizer usage efficiency, reduction of N_2O emissions which could lead to tax reductions and reduce costs of agricultural waste disposal reduction by using the biomass to produce biochar (Roberts, Lehmann, Gloy, Scott, & Joseph, 2010). The large-scale use of biochar in agricultural systems could potentially have large environmental outcomes by enabling farmers to trade their application methods and expand on technologies that could improve farm productivity and energy (McHenry, 2009). Biochar use not only reduces carbon emissions, but it could be economically profitable for California agriculture and economy as it increases crop yield using less fertilizer and creating profitable biochar from the crop residues.

Despite its potential benefits, biochar technology is not widely used in Californian agriculture, due in part by the limited studies on the effects of various biochars and plants with California's Alfisol soils. Possible biochar benefits to Californian soils as indicated through biochar experiments on Australian Alfisol soils include reduced nitrogen leaching, reduced fertilization leaching, and increased soil nutrient quality (Chan, Van, Meszaros, Downie, & Joseph, 2008; Singh, Hatton, Balwant, Cowie, & Kathuria, 2010). However, biochar can alter the soil nutrient characteristics and biological activity differently with every soil type and plant grown so it is uncertain how biochar will affect various crop growths in Californian Alfisol soils (Rondon, Lehmann, Ramairez, & Hurtado, 2007; Lehmann & Joseph, 2009). Also, the varying pyrolysis processes create distinctive biochars, which can react differently with various soils (Lehmann & Joseph, 2009). In order for Californian wide-scale biochar implementation to occur, more comprehensive research on these biochar interactions with Californian soil, plant and agronomic practices is needed because current studies on biochar additions are relatively immature (McHenry, 2009; Roberts et al., 2010).

This study aims to resolve this knowledge gap by examining whether low temperature biochar will increase plant growth in Alfisol soils with and without the addition of fertilizer. I will create biochar through low temperature pyrolysis (350°C) and then determine crop yield from a greenhouse experiment using biochar and Italian ryegrass. Since Alfisol soil already has high nutrient quality and clay matter that serves to reduce nutrient leeching, I believe that biochar will not have a significant effect on plant growth; rather, fertilizer will have a greater effect.

METHODS

Greenhouse Study

The experiment took place in a greenhouse in Berkeley, CA. I used 48 replicates of 6” round plastic pots with depth of 5” filled with 1300 grams of dry soil and containing varying amounts of biochar to grow Italian ryegrass (Figure 1). There were 6 replicates of the following biochar application rates: 0, 10, 25, 50 tons/hectare (t/h) (0, 0.0051, 0.0128, 0.02551 grams of biochar/ grams of soil). To determine if fertilizer had an affect on ryegrass growth, I had 24 pots fertilized with 20-20-20 Professional Water Soluble General Purpose fertilizer every other day and the other 24 pots unfertilized as a control. I applied 15 ryegrass seeds to each pot at ¾ inch from the top of the soil. To simulate natural day-length spring lighting for optimum ryegrass growth, I put the pots in the 21.1- 26.6 °C greenhouse that had 10 hours of natural and artificial light per day. The greenhouse watered the each pot to saturation as needed until sprouting occurred and then switched to watering all the pots every day.

Preparation of soil/biochar

I created the biochar from the ALL Power Labs in Berkeley, CA and received the A horizon soil from Hopland, CA. To determine the soil’s dry weight, a sample of the soil was weighed and then oven dried for 48 hours at 40°C before weighing again to determine its saturation ratio. Using the ratio, I filled the pots with the saturated soil equivalent to 1300 grams of dry soil. To ensure homogeneity of the biochar, I ground the biochar using a mortar and pestle as well as a coffee grind and only used sieved particles <2mm in size. For each pot, I weighed the proper amount of biochar and combined it with the soil by hand.

Plant Sampling and Analysis

To compare plant growth differences between the various pots, I compared the plant biomass differences by weighing the uprooted plants after 7 weeks of growth. To ensure the weight measured was due to purely biomass, I washed the roots of any soil after the plant was uprooted. I put the plant mass in a paper bag and dried at 70° C for 48 hours to guarantee only the dry weight of the plant was measured. I weighed the roots and shoots separately.

Statistical Analysis

To compare plant growth with biochar and fertilizer application, I used a factorial ANOVA test with replication to determine the effect of type and levels of biochar and fertilizer on plant growth. I used the factorial ANOVA test because I measured growth against two nominal variables (biochar concentration rates and fertilizer application). I did statistical analysis using *R-Commander* to find whether biochar was significant to plant growth and which type of biochar was most effective. Direct application effects on plant growth with P-values <0.05 or a confidence interval of 95% were considered significant.

RESULTS

Plant Biomass Weight

I found shoot plant biomass weight after 7 weeks was highest in more intensive biochar treatment concentrations and fertilization but the optimum root biomass was in the unfertilized treatment. For shoot biomass weight, the ryegrass treatment group of 25 t/h biochar and fertilizer had the greatest overall growth (13.2g) and the untreated control group had the least growth (5.4g) (Table 1). For the root biomass weight, the ryegrass treatment group of 25 t/h biochar and without fertilizer had the greatest overall growth (19.6g) while the fertilized with the highest biochar concentration had the least growth (10.6g) (Table 2).

Table 1. *Lolium multiflorum* Shoot Biomass Weight After 7 Weeks. Weight in grams.

	Biochar Treatment (T/ha)	Replicate						
		1	*2*	*3*	*4*	*5*	*6*	**Mean**
Unfertilized	*0*	6.8	4.5	5.8	5.0	4.8	5.4	**5.4**
	10	7.5	3.0	8.7	5.2	4.9	5.6	**5.8**
	25	5.9	9.0	6.2	4.1	5.3	5.6	**6.0**
	50	7.2	7.2	5.8	9.5	6.9	4.7	**6.9**
Fertilized	*0*	12.1	12.9	13.5	6.2	14.9	10.2	**11.6**
	10	14.0	10.9	16.1	10.3	13.0	13.1	**12.9**
	25	14.5	12.7	15.7	9.7	12.6	13.7	**13.2**
	50	14.6	13.3	12.0	11.4	11.7	11.8	**12.5**

Table 2. *Lolium multiflorum* Root Biomass Weight After 7 Weeks. Weight in grams.

	Biochar Treatment (T/ha)	Replicate						
		1	*2*	*3*	*4*	*5*	*6*	**Mean**
Unfertilized	*0*	17.8	9.4	13.8	22.6	19.2	7.6	**15.1**
	10	23.0	1.8	12.4	10.0	20.8	22.6	**15.1**
	25	11.0	31.5	21.3	17.8	16.0	19.7	**19.6**
	50	14.6	16.5	27.0	22.7	9.6	8.3	**16.5**
Fertilized	*0*	19.1	18.2	15.9	6.0	9.5	10.4	**13.2**
	10	26.2	9.4	17.9	16.4	10.0	10.7	**15.1**
	25	17.1	21.7	5.2	8.6	10.5	9.4	**12.1**
	50	14.0	16.5	8.2	12.1	6.8	6.2	**10.6**

The shoot means masses were greater in the fertilizer treatment and increased biochar concentration level with the exception of the fertilized biochar treatment of 50 t/h (Figure 1). However, the shoot plant growth was minimally higher at increased biochar addition levels. A root weight trend was not as visible because the root means had great variability within treatment groups (Figure 2).

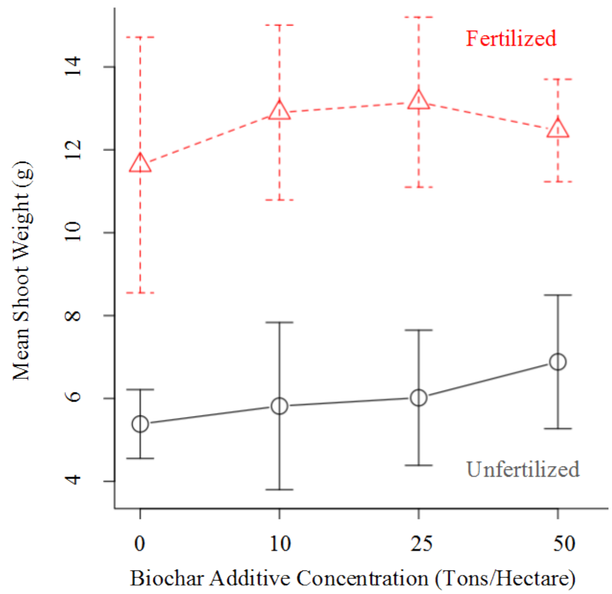

Figure 1. Shoot Biomass Weight Means with Fertilizer and Biochar Treatments. Weight in grams, biochar treatments in tons per hectare. Dots represent means. Whiskers represent standard deviations.

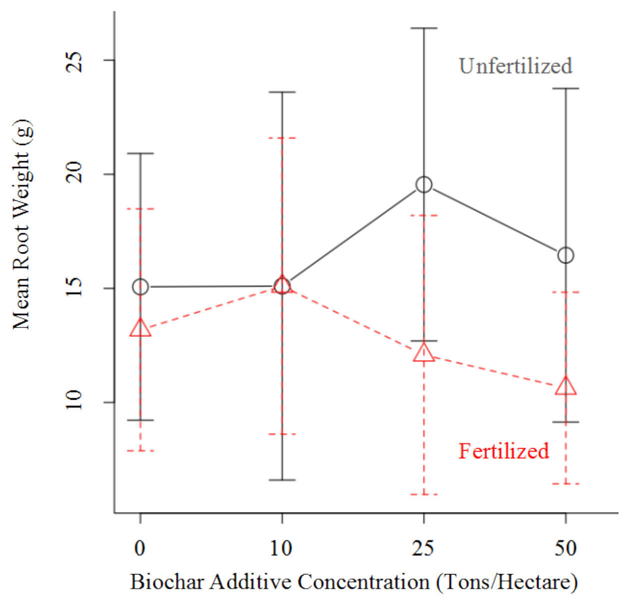

Figure 2. Root Biomass Weight Means with Fertilizer and Biochar Treatments. Weight in grams, biochar treatments in tons per hectare. Dots represent means. Whiskers represent standard deviations.

Statistical Analysis

The factorial ANOVA of biomass shoot and root weights indicated a significant effect on ryegrass growth by the addition of fertilizer ($p=1.704 \times 10^{-14}$ for shoots; $p=0.04811$ for roots) (Table 3 and 4). However, the biochar treatment ($p=0.4424$ for shoots; $p=0.82829$ for roots) and combined treatments of biochar and fertilizer ($p=0.7239$ for shoots and $p=0.47053$ for roots) did not have a significant effect on ryegrass growth (Table 3 and 4).

Table 3. Factorial ANOVA of Shoot Weight Response to Supplements.

Supplements	Sum Sq	Df	F Value	P Value
Biochar	10.20	3	0.915	0.4424
Fertilizer	508.95	1	137.0222	1.704×10^{-14}
Biochar Treatment and Fertilizer	4.93	3	0.4425	0.7239

Table 4. Factorial ANOVA of Root Weight Response to Supplements.

Supplements	Sum Sq	Df	F Value	P Value
Biochar	36.81	3	0.2957	0.82829
Fertilizer	172.52	1	4.1591	0.04811
Biochar Treatment and Fertilizer	106.01	3	0.8585	0.47053

DISCUSSION

Biochar application seemed to increase shoot ryegrass growth minimally, but the effects were overshadowed by fertilizer's effect on plant growth. Further ANOVA analysis suggested biochar effects associated with ryegrass growth are insignificant under these experimental factors. The results contrast with other low temperature biochar (450°C) experiments on Alfisol soil that suggest significant increases in plant growth were associated with increased biochar concentration and fertilization (Chan, Van, Meszaros, Downie, & Joseph, 2007; Chan et al., 2008; Singh et al., 2010).

Plant Growth

Effect of Fertilizer

Fertilizer additions increased shoot plant growth significantly ($p=1.704x10^{-14}$) and improved soil nutrient quality most when 25 t/h of biochar was applied. A root plant growth trend was not as apparent because the root data had high variability due to my non-uniform root washing method in which root loss was high. But using the shoot data, the nitrogen fertilization almost doubled ryegrass plant growth that simulated the increased growth effect of fertilization on dry radish matter in an Alfisol soil study (Chan et al., 2007). Lolium multiflorum requires high nitrogen, phosphorus, and calcium for optimum yield and fertilization would have fulfilled the phosphorous soil deficiency associated with Alfisol soils (Carey, 1995; Chan et al., 2007).

Biochar Effect

Biochar increased ryegrass crop yield with increasing biochar additions but biochar additions did not significantly attribute to plant growth ($p=0.4424$). The increase in plant growth within the fertilized and unfertilized treatment groups was only 1-2 grams of difference among the biochar treatments suggesting biochar's limited effect on plant growth. The limited effectiveness of biochar may be due to the Alfisol soil's high nutrient richness and increased soil content, which alone causes high plant growth and, in comparison, diminish biochar's effects on plant growth (University of Idaho College of Agricultural and Life Sciences, 2011). Other studies may have produced positive crop yield results in Alfisol soils because those soils were taken from an area with a history of cropping which suggests higher nutrient deficiency due to moderate leaching over time by Alfisol soils (Chan et al., 2007; Chan et al., 2008; University of Idaho College of Agricultural and Life Sciences, 2011) In those situations, the reduced nutrient state of the soil allowed biochar's chemical and physical properties to better influence soil properties such as soil pH, bulk density, water holding capacity, and porosity (Lehmann & Joseph, 2009; Chan et al., 2007).

There was a trend of increased shoot growth with increasing biochar application, but biochar stunted yield at 50 t/h (12.5g) in comparison with the plants grown at 10 t/h or 25 t/h (12.9g; 13.2g). Biochar applied above 25 t/h possibly diminished crop yield by altering the soil chemistry. Biochar has been shown to increase the soil carbon content, thereby increasing the carbon-nitrogen ratio, and causing nitrogen immobilization in the Alfisol soil (Lehmann et al., 2002). In a similar experiment on grain yield, N application produced no increased grain yield response at higher biochar concentrations since the high biochar concentrations caused N limitations which even nitrogen fertilizer could not overcome (Asai et al., 2009). The reduced nitrogen plant availability would decrease Alfisol crop yield in comparison to the control (Carey, 1995). The nitrogen limitation could be resolved by producing biochar from different materials such as poultry manure and for longer durations, which can increase sorption capacity and limit nitrogen leaching (Singh et al., 2010). However, the unfertilized 50 t/h biochar replicates did not seem to decrease in plant growth in comparison to the other unfertilized plants. If applied to Californian agronomic soil, biochar may need to be applied at a lower application rate if soil testing indicated high soil C/N ratios since higher application rates could impede plant growth (Karhu, Mattila, Bergstrom, & Regina, 2010).

Combined Fertilizer and Biochar Effect

Although biochar's effect on ryegrass growth was minimal in comparison to the fertilization result, biochar has been known to increase fertilizer efficacy on crop yield and was more successful over time (Asai et al., 2009). Biochar has been shown to significantly reduce applied fertilizer leaching and can increase plant uptake of P, K, Ca, Zn, and Cu (Lehmann et al., 2002). A study of various biochar amendments on maize yield produced similar results as biochar plus NPK fertilization contributed 59% more biomass than just NPK application alone (Peng, Ye, Wang, Zhou, & Sun, 2011). Also biochar has been known to enhance biological nitrogen fixation as well as improve soil biology (Rondon et al., 2007; Chan et al., 2008). In a more long-term study with leaching events, biochars were more effective at reducing nitrogen leaching over time as biochars decreased leaching by 55-93% from the first to second leaching events (Singh et al., 2010). So it is suggested that proper biochar additions can increase plant nitrogen uptake in the predominately Californian Alfisol agricultural soil thereby increasing agricultural crop yield and productivity (Lehmann et al., 2003).

Limitations

As a result of time and budget constraints of the project, the long-term effects of biochar with fertilizer on ryegrass crop yield could not be determined. The project aims to increase biochar usage in large-scale agricultural settings so a long-term field study of biochar on crop yield is an important step in reaching that goal. As biochar absorption and fertilizer leaching changes over time, long-term studies could provide a better understanding of biochar's effect on sustained soil fertility and nutrient dynamics (Lehmann et al., 2002; Ding, Wu, Liu, Shi, Yang, & Zhong, 2010). While my short-term study did not show that increasing biochar application produced significant changes in crop yield, multiple year on-site studies of biochar on crop yield suggest increasing biochar additions with well-managed fertilizer treatment increases crop yield (Kimetu et al., 2008; Asai et al., 2008). Along with time, money limited the scale of my project through minimal replicates thereby possibly reducing biochar's effectiveness on ryegrass growth and diminishing the predictive accuracy and statistical power of the results (McDonald, 2009).

Further Directions

Further, long-term field research on biochar's effect on crop yield should be conducted using conditions similar to common agricultural practices. In order to fully address biochar's effect on ryegrass crop yield, there should be more analyses of the effect of biochar on soil nutrient quality, water retention capacity, and crop nutrient uptake through varying stages of soil degradation (Kimetu et al., 2008). There should also be an evaluation as to the material and temperatures with which biochar should be produced to attain optimum ryegrass crop yield in Alfisols since biochar-soil interactions vary (Chan et al., 2007). Finally, to encourage biochar usage in Californian agricultural soils, a life-cycle assessment and cost-benefit analysis on the use of different biochars to increase plant growth in Alfisol soils should be completed to investigate whether biochar has long-lasting economic benefits (Roberts, Lehmann, Gloy, Scott, & Joseph, 2010).

Conclusions & Broader implications

The results of this study suggest that biochar could increase ryegrass crop yield, which shows promise for use in wide-scale California agricultural farming. The interactions between biochar and Alfisol soil in affecting plant growth is better understood and, while larger long-term field experimentation would determine more conclusive answers, plant growth has been shown to increase as a result of biochar additions (Peng et al., 2011). Better understanding of biochar feedstock selection can lead to greater economic and environmental stability ensuring farmers, environmentalists and government agencies of the benefits of biochar implementation (Roberts et al., 2010). If greater support leads to large-scale agricultural biochar usage in California, proper biochar additions could be economical and serve as a climate change mitigation technique through significant carbon sequestration (Roberts et al., 2010). The large-scale agricultural use of biochar would be a contribution toward the reduction of the 29% net rise in atmospheric carbon seen today thereby reducing the effects of global warming (Tenenbaum, 2009).

ACKNOWLEDGEMENTS

I'd like to thank my mentor Andrew Crane-Droesch, MS/ PhD candidate of the UCB Energy and Resources Group (ERG), whose help and support was instrumental to the completion of this project. I'd also like to thank John Harte and the Harte Lab allowing me to use their space; I am especially thankful to Danielle Svehla Christianson and Laurie Koteen for being so gracious and sharing what little space was there. Thank you to the Oxford Tract Greenhouse for taking care of my plants and manager Barb Rotz for helping me with any problem I had. Also, thank you to the ALL Powers Lab who helped create the biochar for me. Lastly, I'd like to thank the ES 196 faculty especially Patina Mendez and Seth Shonkoff for helping me with all my questions and guiding me through the whole process of the project.

REFERENCES

Asai, H., Samson, B. K., Stephan, H. M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., ... Horie, T. (January 01, 2009). Biochar amendment techniques for upland rice production in Northern Laos. *Field Crops Research, 111*, 1, 81.

Bracmort, K. S., & Library of Congress. (2009). *Biochar: Examination of an emerging concept to mitigate climate change*. CRS report for Congress, R40186. Washington, DC: Congressional Research Service, Library of Congress.

California Department of Food and Agriculture. (2009). *California Agricultural Resource Directory 2008-2009- Vegetable and Melon Crops*. Retrieved from http://www.cdfa.ca.gov/statistics/.

Carey, J. H. (1995). Lolium multiflorum: Fire Effects Information System. *U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory*. Retrieved from http://www.fs.fed.us/database/feis/.

Chan, K. Y., Van Zweiten, L., Meszaros, I., Downie, A., & Joseph, S. (January 01, 2007). Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research*, *45*(8), 629-634.

Chan K.Y., Van Zwieten, L., Meszaros, I., Downie, A., & Joseph, S. (2008) Using poultry litter biochars as soil amendments. *Soil Research* **46**, 437–444.

Ding, Y., Wu, W.-X., Liu, Y.-X., Shi, D.-Z., Yang, M., & Zhong, Z.-K. (November 01, 2010). Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. *Water, Air, and Soil Pollution*, *213,* 47-55.

Fox, J., Andronic, L., Ash, M., Boye, T., Calza. S., Chang, A., Grosjean, P., Heiberger, R., Kerns, G. J., Lancelot, R., Lesnoff, M., Ligges, U., Messad, S., Maechler, M., Muenchen, R., Murdoch, D., Neuwirth, E., Putler, D., Ripley, B., Ristic, M., and Wolf, P. (2009). Rcmdr: R Commander. R package (Version 1.5-4) [Computer software]. Retrieved April 15, 2011. Available from http://CRAN.R-project.org/package=Rcmdr.

Karhu, K., Mattila, T., Bergstrom, I., & Regina, K. (2011). Biochar addition to agricultural soil increased CH4 uptake and water holding capacity - Results from a short-term pilot field study. *Agriculture Ecosystems and Environment*, *140,* 309-313.

Lal, R., et al. (January 01, 2004). Soils--The Final Frontier - Viewpoint - Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science*, *304*, 5677, 1623.

Lehmann, J., & Joseph, S. (2009). Biochar for environmental management: Science and technology. London: Earthscan.

Lehmann, J., da Silva Jr., J.P., Steiner, C., Nehls, T., Zech, W., & Glaser, B. (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*,2, 343-357.

Lopez-Capel, E., Hartcher, M., Krull, E. S., Bol, R., Sohi, S., & CSIRO Land and Water. (2009). *Biochar, climate change and soil: A review to guide future research*. Canberra, A.C.T.: CSIRO Land and Water.

McDonald, J. H. (2009). *Handbook of Biological Statistics*. Baltimore, MD: Sparky House Publishing.

McHenry, M. P. (2010). Carbon-based stock feed additives: a research methodology that explores ecologically delivered C biosequestration, alongside live weights, feed use efficiency, soil nutrient retention, and perennial fodder plantations. *Journal of the Science of Food and Agriculture, 90,* 2, 183-7.

McHenry, M. P. (January 01, 2009). Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: Certainty, uncertainty and risk. *Agriculture, Ecosystems and Environment, 129,* 1-7.

Molina, M., Zaelke, D., Sarma, K. M., Andersen, S. O., Ramanathan, V., & Kaniaru, D. (December 08, 2009). Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO~2 emissions. *Proceedings-National Academy of Sciences Usa, 106,* 49, 20616.

Peng, X., Ye, L. L., Wang, C. H., Zhou, H., & Sun, B. (January 31, 2011). Temperature- and duration-dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an Ultisol in southern China. *Soil & Tillage Research, 112,* 2, 159-166.

R Development Core Team (2009). R: A language and environment for statistical computing [Software]. Vienna, Austria: R Foundation for Statistical Computing. Retrieved April 15, 2011. Available from http://www.R-project.org.

Roberts, K. G., Lehmann, J., Gloy, B. A., Scott, N. R., & Joseph, S. (January 15, 2010). Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. *Environmental Science and Technology, 44,* 2, 827-833.

Rondon, M., Lehmann, J., Ramâirez, J., & Hurtado, M. (January 01, 2007). Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions. *Biology and Fertility of Soils, 43,* 6, 699-708.

Singh, B. P., Hatton, B. J., Singh, B., Cowie, A. L., & Kathuria, A. (January 01, 2010). Influence of Biochars on Nitrous Oxide Emission and Nitrogen Leaching from Two Contrasting Soils. *Journal of Environmental Quality, 39,* 4, 1224-1235.

Tenenbaum, D. J. (February 27, 2009). Biochar: Carbon mitigation from the ground up. *Environmental Health Perspectives, 117,* 2.

University of Idaho College of Agricultural and Life Sciences. (2011) *The Twelve Soil Orders Soil Taxonomy, Soil Orders, Alfisols*. Retrieved from http://soils.cals.uidaho.edu/soilorders/alfisols.htm.