Biochar Field Studies: An IBI Research Summary

Updated: May 2013
Authors: Josh Laufer and Thayer Tomlinson

Note: IBI Research Summaries are intended to provide updated information about biochar science for the general public. These summaries are based on IBI's review of published scientific literature. As this literature is updated, IBI will update these summaries. Please contact IBI at info@biochar-international.org if you have questions or information to share.

Table of Contents

Introduction

Biochar is a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment. Biochar can be used as a product itself or as an ingredient within a blended product, with a range of applications as an agent for soil improvement, improved resource use efficiency, remediation and/or protection against particular environmental pollution, and as an avenue for greenhouse gas (GHG) mitigation.

Biochar is actually a spectrum of materials with certain characteristics, depending on how it is produced and the feedstock that is used, including forestry, crop waste, and animal manures. Specific production parameters (temperature, residence time, rate of temperature increase, pre- and post-processing, among others) also affect the resulting attributes and quality of the biochar, and can impact the nutrient availability to crops, the physical and chemical properties of the biochar, and the amount of stable carbon (C) sequestered. The consistent reporting of biochar properties will ensure that pertinent information about biochars for use in soil applications is systematically communicated, regardless of feedstock type, production process, or final properties. Note that the literature referenced in this research summary did not adequately analyze the properties of the biochar products in a manner that might help to better explain some of the results. It is IBI's hope and desire that, over time, researchers will use a common set of tests or properties to characterize their biochar when utilizing and reporting biochar in research trials and publications. IBI's Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil (aka *IBI Biochar Standards* see: http://www.biochar-international.org/characterizationstandard) can serve as that guide to characterizing biochar for use in field trials and other research trials, as well as for commercial applications.

This research summary highlights the impact of biochar on crop yield, economic performance, fertilizer use efficiency and soil fertility, water uptake/availability, mycorrhizal fungi colonization and microbial activity, and greenhouse gas flux measured and reported in peer-reviewed, published field studies. It exclusively examines biochar field studies, defined as biochar experiments that were located, measured, and observed in the outdoors for an extended period of time (at least one growing season). While not excluding post-growing season lab analyses, this summary does not include any examinations of the effects of biochar in a controlled laboratory setting. The field studies that are included in this research summary range in plot size from 1m x 2.25m to 1,000m$^{2.}$ These studies were conducted in geographically dispersed regions, including Western Kenya; Georgia, USA; Northern Laos; Llanos Orientales, Colombia; Quebec, Canada; Ejura, Ghana; Jiangsu Province, China; Brandenburg, NE Germany; Central Italy; various grape growing field sites in Europe (Switzerland, Spain, France, and Italy); various farms in the United Kingdom; and numerous regions in Australia including New South Wales, Western Australia, and Southern Australia.

At the time of this publication, the results of over 31 biochar field studies at different scales have been published, only three of which are large-scale, which is operationally defined as having a plot size that is at least 30x30 meters. However there are at least four known field studies, most of which are large-scale (i.e., over 30x30 meters), in process with publication of results expected within 1 to 2 years. Dr. David Laird, from Iowa State University's Department of Agronomy, as of last year was in his "fourth year of large plot field studies evaluating the impact of biochar applications and residue harvesting on soil quality, C sequestration, and crop productivity" (Laird 2011). Laird is evaluating "whether biochar applications can help sustain soil quality when 50 or 90% of above ground residue is harvested for bioenergy production in continuous corn production systems." Barry Husk, President of BlueLeaf Inc., with the collaboration of an independent consultant, is conducting field studies in Quebec, Canada on biochar's effects on soybean and forage crop yield, nutritional quality of forage, and its effect on projected milk production in addition to previously published data (Major 2011).

A meta-analysis of biochar results has been published to date (Jeffery, et al. 2011). This analysis included both pot and field trials and used all available published literature with quantitative results up to March 2010. Overall, the mean results for each analysis performed within the meta-analysis covered a wide range (from −28% to 39%), but found that when compared to a control, biochar application to soils showed a small but statistically significant benefit to crop productivity, with a grand mean increase of 10%. The greatest (positive) effects for soils were seen in acidic (14%) and neutral pH soils (13%), and in soils with a coarse (10%) or medium texture (13%). These results suggest that three of the main benefits to biochar addition to soil are a liming effect (increased pH) and water holding capacity, and improved nutrient availability. The greatest positive result (39%) was seen in biochar applications at a rate of 100 tonnes per hectare (t/ha). An additional meta-analysis of seven field trials conducted in the United

Kingdom found a significant ($p<0.05$) positive effect for all biochar treatments, increasing average yield by 0.4 tonnes per $hectare^{-1}$ (Hammond et al. 2013).

Crop Yield

Nearly every field study included in this summary focused on the biochar amendment's impacts on crop yield in various locations, soil types, and climates. This section reviews the reported results of twenty six studies on crops including maize, wheat, rice, soybeans, other legumes, mixed forage, and grapes.

A number of experiments examined the yield of corn with biochar-amended soils. In some studies, biochar application increased crop yields of maize over the control by between 2.2 tonnes per hectare (Kimetu et al. 2008, Van Zwieten et al. 2009, Sukartono et al. 2011, Islami et al. 2011). Other studies found increases in maize yield due to biochar amendment ranging from 20% to 140% above control plots (Major et al. 2010, Oguntunde et al. 2004, Crane-Droesch and Clare 2012). However, one study showed no significant difference in maize yield (Jones et al. 2011), and another showed declines in maize yield compared to control plots with peanut hull biochar for year 1, but no statistical difference between biochar amended plots and the control in year 2 (Gaskin et al. 2010).

Rice is another common crop used for biochar field studies. One investigation focused on biochar's effect on grain yields of upland rice (*Oryza sativa* L.) and soil physical properties in northern Laos (Asai et al. 2009). Some plots from that study that were amended with biochar yielded more rice than the control, while in others the opposite was true. On average, biochar amendment on rice fields did not significantly increase rice yields. However, another field trial on the effect of biochar on rice (*Oryza sativa* L.) production in Tai Lake plain, China observed yield increases (Zhang et al. 2010). Biochar amendment of rice fields at application rates of 10 t/ha and 40 t/ha improved rice yields by 12% and 14% respectively, in unfertilized plots, and 8.8% and 12.1% in soils with nitrogen (N) fertilization. Other studies also observed increases in yield of rice grown in biochar-amended plots compared to control plots (Shackley et al. 2012, Zhang et al. 2012, Petter et al. 2012).

The effects of biochar-amended soil on wheat production were also evaluated. An oil-mallee-derived biochar applied at a rate of 6 t/ha in Pindar, Western Australia, along with half the recommended rate of soluble fertilizer increased yields of wheat by 340kg/ha, or 18% over the control (Solaiman et al. 2010). Wheat grown with mineral fertilizer and 1.5 t/ha biochar increased grain yield by 46% over the control. In a separate study, banded biochar application most effectively increased wheat grain yield over the control when applied at a rate of 1 t/ha combined with 50kg/ha of phosphorous (P) fertilizer (Blackwell et al. 2010). The authors of one study concluded that the increase in soil temperature, due to the reduction of surface albedo of soil with an application of biochar, can have positive impacts on seed germination, crop establishment, and early crop growth (Genesio 2012). They add that this finding is particularly pertinent in the case of low or no-till fields.

Soybean is another crop that has been tested with biochar in the field. Biochar produced from fast pyrolysis had been applied at 3.9 t/ha/year in an ongoing large-scale study in Quebec, Canada since 2008 (Husk and Major 2011). Soybeans were planted in 2008, while mixed forage species were grown in 2009 and 2010. Soybean plant biomass production in the biochar-amended plot was 20% greater than the control plot. Forage plant biomass increased by 17% in the biochar-amended plot over the control in 2009, and the next year in 2010 a second forage crop in biochar-amended plot showed a growth increase of 4.1% over control forage crops that year.

The effects of biochar soil amendment on the yield of other types of legumes as well as grapes have also been examined. In a mixed planting of six legumes, both the NPK fertilizer and rice husk biochar plots had larger plant diameters than the control after the fourth year (Sovu et al. 2011). However, rice husk biochar application was not statistically significantly different from the NPK fertilizer for seedling survival rates. Growth of the plants was not significantly different with or without application of biochar. In a study with field trials on six different grape growing sites around Europe (Switzerland, Spain, France and Italy), the authors found a wide spectrum of results with different patterns of reactions in biochar amended soils (Niggli and Schmidt 2012). The major nutritional elements, e.g., phosphorus (P) and potassium (K), show a clear positive trend in the nutrient uptake by the vine in biochar amended soils compared to the control. In some cases, they observed decreased growth of grape leaves in biochar amended soils compared to the control plot, which may have been due to nutrient blockages associated with the use of non-nutrient inoculated biochar in the experiments.

Economic Performance

The studies that evaluated economic performance of biochar amendments are generally positive. One Australian study completed an economic valuation of fertilizer (N, P, K, and $CaCO_3$) and C trading value of three different types of biochar (assuming a C trading value of $30 AU/ton CO_2) in AU dollars (Van Zwieten et al. 2009). Poultry litter biochar was considered the most beneficial with a combined fertilizer and C sequestration value of $329 AU/tonne, greenwaste biochar was valued at $85 AU/tonne, and papermill biochar at $72 AU/tonne.

Another Australian study also had favorable economic outcomes with biochar amendment in soils (Blackwell et al. 2010). It found that low banded biochar application rates can improve the economic viability of biochar as a soil amendment in northern areas of the Western Australian wheat belt. A total biochar cost of AU $170/ha is affordable if it facilitates a 10% yield augmentation over 12 years.

One study also looked at the economic viability of selling biochar under different scenarios. The value of rice husk char, if sold commercially in Cambodia as a soil additive, was calculated to be approximately $3 per tonne (Shackley et al. 2012). If the C credits associated with rice husk char were sold under the Clean Development Mechanism (where biochar is currently not included), the final value of the char ranges from $9 to $15 per tonne (depending on how the C credits are calculated—the low estimate includes only recalcitrant C and the high estimate includes both recalcitrant C as well as avoided emissions from energy production). A separate study concluded that when biochar was utilized in the field, fertilizer use was reduced, and thus farmer expenditures for fertilizer were reduced which improved the profitability of a maize farm in Western Kenya by 25% (Crane-Droesch and Clare 2012).

Biochar, Fertilizers, and Soil Fertility

Field studies of biochar have examined its effects on soil fertility through chemical changes, interactions with the soil when combined with fertilizers, and effects on the plants themselves. For a study on corn production, there was no substantial evidence of higher N immobilization with biochar application at any level (Gaskin et al. 2010). In a study on rice, utilization of biochar as an amendment to fields increased the soil pH, soil organic C, total N, and decreased the soil bulk density (Zhang et al. 2010). A trial with wheat production found that banding in the crop-row zone places the biochar where early plant root development occurs, which mitigates topsoil disturbance and loss through wind erosion (Blackwell et al. 2010). In another study of corn and grass in Wales, a wood-based biochar shifted the soil pH 0.32 units in year 2 (Jones et al. 2011). Electrical conductivity, moisture content, total N, substrate-induced respiration, soluble C, soluble N, available P, exchangeable sodium (Na), exchangeable calcium (Ca), and bulk density were not significantly affected by biochar additions compared to the control plot.

Another study found that fertilizer overtook biochar's impact on soil fertility after the first year because biochar was only applied once during the first year of the trial, while the fertilizer was added annually (Petter et al. 2012).

In terms of nutrient uptake, in one trial in Western Kenya, plant N concentrations were higher irrespective of soil degradation (on plots where maize had been grown for up to 85 years) when biochar was added to the soil (Kimetu et al. 2008). Phosphorus, K, Ca, and magnesium (Mg) concentrations were not affected or decreased on plots with the longest continuous cropping history where organic amendments, including biochar, were utilized. In a separate field study examining both pine chip and peanut hull biochars, the most significant effect of either type of biochar was the addition of base cations in the peanut hull biochar plots, which had a short-term effect on soil pH and increased the K, Ca, and Mg available in the soil (Gaskin et al. 2010). Addition of peanut hull biochar also showed an increase in K in the corn tissue.

Another study in Llanos Orientales, Colombia found that the availability of Ca and Mg was augmented in the biochar plots, and crop tissue analysis demonstrated that in plots with a biochar application rate of 20 tons/ha, maize leaves showed higher levels of Ca and Mg over maize leaves from the control plots (Major et al. 2010). Availability of Ca and Mg in the soil was increased by 77 – 320% in biochar plots over the control. Soil pH was also increased by biochar, which contributed to improved crop yields because it made the acidic tropical soil more alkaline. In the Husk and Major (2011) study on forage plants and soybeans in Quebec, Canada the authors observed increased plant nutrient uptake in biochar-amended soils. In the forage plants (ryegrass, red clover, timothy, and oats), "protein, fat, starch, total minerals and energy – measured as Total Digestible Nutrients (TDN) – were all greater in the forage plants from the biochar-amended plot. The plant fibre content with biochar was lower" (Husk and Major 2011).

In Abergyngregyn, Wales, a grass crop had significantly increased its foliar N due to one biochar addition to the soil applied in the first year, with the change in foliar N observed the second year of the experiment compared to the control (Jones et al. 2011). Biochar had no effect on dissolved organic C (DOC) and N (DON). After three years in the field, the alkalinity of biochar was fully neutralized and it had lost most of its K, Na, and Ca cations. Biochar had no significant effect on nutrition quality of crops in terms of C:N ratio, C, P, K, Na, or Ca content compared to the control. However, in year two there was an increase in the exchangeable K in the biochar-amended plots.

Charcoal residue in one field experiment in Ejura, Ghana increased soil pH, base saturation, electrical conductivity, exchangeable Ca, Mg, K, Na, and P in the soil at the kiln sites over adjacent soils (Oguntunde et al. 2004). Soil texture of charcoal site soils became sandier and contained less clay. The study postulates that increased nutrient availability due to charcoal residues (biochar) could have resulted in improvement of maize grain and biomass yield: 91% and 44% respectively over control without charcoal. In Solaiman et al. (2010), biochar amended soils showed early nutrient uptake, which was in part due to the presence of larger quantities of biomass, and higher tissue concentrations on average. Additional nutrient supply may have been due to the higher application rate of biochar at 6 t/ha, a factor that could explain the crop yield increase (Solaiman et al. 2010).

One study found that biochar application elevated the level of available P, exchangeable K, Mg, and Ca compared to the control, which was equivalent to the changes observed with the application of cattle manure (Sukartono et al. 2011). Another found increased cation exchange capacity in soils with biochar application improved nutrient retention (Castaldi et al. 2011). Increased uptake of P and K by grape vines were observed in plots with biochar application, while Ca was probably slightly absorbed by the biochar and consequently lowered its uptake by the grape vines (Niggli and Schmidt 2012). A separate study observed soil pH, soil organic C, and total N were increased in plots with biochar compared to the control (Zhang et al. 2012).

Some researchers (Sun et al. 2012) found that the total C content of soil significantly increased commensurate with biochar application rate (rates went from 0 kg per hectometer to 6,000 kg per hectometer). The total N content of soil slightly increased towards the end of the study, while changes in total P and K were not obvious. Available N and pH increased with biochar application compared to the control. During the first year of a different study, soils amended with biochar also had markedly increased availability of Ca, P, aluminum (Al), pH, and total organic C (Petter et al. 2012). The increased depth of the organic C in the soil profile improved the K availability deeper in the soil. Liu et al. 2012 found that increasing biochar additions tended to increase the total organic C, but only the highest biochar addition (at 20 Mg/ha) caused a statistically significant increase.

Water Uptake and Availability

In some field studies, water uptake and availability to crops was affected by the application of biochar. A study by Asai et al. (2009) in northern Laos found that higher biochar application rates improved soil water permeability and holding capacity, which improved the overall plant water availability. Liu et al. (2012) found that a biochar-compost application to soils in NE Germany had a more positive effect on water availability than pure compost application, especially regarding water retention. Blackwell et al. (2010) observed low biochar application rates (about 1 t/ha by banding) improved crop yield due to better crop water supply.

Mycorrhizal Fungi Colonization and Microbial Activity

Several sources independently corroborate the positive effects of biochar on mychorrhizal root colonization and beneficial microbial activity in the soil. The addition of biochar, combined with inoculated mineral fertilizers, to the soil for wheat production in Australia allowed more mycorrhizal colonization during the latter half of the growing season (Solaiman et al. 2010). The study found that evidence exists to suggest additional fungal hyphae mass from arbuscular mychorrhiza (AM) colonization could contribute to wheat tolerance of drought stress and bolster yield. Biochar directly encouraged mycorrhizal root colonization, which had positive growth and yield effects on grains in the conditions of the experiment. AM hyphae may have improved water supply, which mitigated drought stress and improved survival of grain.

Furthermore, greater crop water supply was available in plots where biochar was utilized due to augmented AM fungal colonization during dry seasons and in low phosphate soils (Blackwell et al. 2010). A third study evaluating the effects of biochar on maize production in Western Kenya concluded that one possible explanation for increased productivity from biochar amendments was the effect on plant-available soil water and microbial populations and dynamics (Kimetu et al. 2008). In a field study in Abergyngregyn, Wales, there was an increase in the fungal and bacterial rate of growth during the second year after the biochar application in the prior year (Jones et al. 2011). Furthermore, by the third year, a microbial community was fully established.

Several more recent studies have had mixed results regarding microbial activity and fungal growth in soils amended with biochar. One study found that microbial growth rates increased significantly with the application of biochar, while another observed little difference in microbial activity in the biochar amended soil compared to the control (Jones et al. 2011, Castaldi et al. 2011). A third study found that bacteria increased in abundance more than actinomycetes, but fungal abundance dropped marginally in soils amended with biochar (Sun et al. 2012). While investigation should continue into this line of inquiry, preliminary analyses and results are promising.

Greenhouse Gas Flux

Analyses of greenhouse gas emissions related to biochar utilization in these agriculture field studies reveal uncertainty in biochar's impact on the soils' ability to reduce greenhouse gas emissions. Some of the uncertainty and conflicting evidence may be due to a lack of data on the composition of the biochar utilized in the field trials. One assessment of the effect of a biochar amendment to soil on the soil-atmosphere exchange of greenhouse gases (N_2O, CH_4, and CO_2) in an intensive subtropical pasture in northeastern New South Wales, Australia observed significant N_2O and CO_2 emission increases, while a net reduction of CH_4 occurred compared to the control (Scheer et al. 2011). N_2O emissions were episodic; in particular there was one major pulse that followed a period of heavy rain. Overall, there was no significant difference in the net flow of greenhouse gases from biochar and non-biochar-amended plots.

A biochar amendment applied at a rate of 40 t/ha was found to significantly increase CH_4 emissions from paddy soil when cultivating rice compared to control plots, both with and without N fertilization (Zhang et al. 2010). However, dramatic reductions in direct N_2O emissions and indirect CO_2 emissions occurred because biochar reduced the need for N fertilizer application. This trial concluded that there was an increased overall CO_2e emission intensity from CH_4 and N_2O, and that further study was required to determine the best and most cost-effective environmental management strategy with regard to rice cultivation. In another study in Abergyngregyn, Wales, an increased soil respiration and fungal/bacterial growth rate coincided with a transition to a decomposer community primarily of bacteria, suggesting a decline in the potential for C sequestration mediated by microbial life (Jones et al. 2011).

Several more recent studies have released their findings regarding greenhouse gas flux. The authors of a biochar field trial observed an increase in stable soil organic C in biochar treated soils, which implies its potential as a source of soil C sequestration (Sukartono et al. 2011). A different trial found that biochar application led to minimal changes in greenhouse gas fluxes after the first 14 months compared to the control plots (Castaldi et al. 2011). While soil N_2O fluxes were reduced in biochar plots, the results were not significant due to high spatial variability. A two year study on rice and biochar found that biochar application decreased N_2O emissions and increased CH_4 emissions during the growing cycle for both years of the trial compared to the control, with no significant difference in the C intensity of rice between biochar application rates of 10 t/ha and 40 t/ha (Zhang et al. 2012). In a study of soil albedo and biochar, biochar application to soil decreased surface albedo by up to 40% relative to controls over the entire crop season, which increased soil temperature (Genesio et al. 2012). The results of one study in Cambodia projected a net C abatement with rice husk biochar was 0.86 tonnes CO_2 per tonne of biochar compared to status quo resource utilization for fuel and soil amendment (Shackley et al. 2012).

Conclusions

It is clear that different biochars have different effects in different soils and climates; this is, in part, because biochar feedstocks come from a spectrum of materials and biochar materials are created under different pyrolysis conditions (Lehmann and Joseph 2009). Future research should strive to delineate and identify what characteristics can be attributed to different impacts and outcomes; the *IBI Biochar Standards* can serve as a guide. There is a dearth in trials comparing the effects of plant-based and manure biochars in the field; combined biochar/bokashi compost trials and the effects of biochar on the production of fruits and vegetables are lacking in the literature. Currently there are only a few published large-scale field trials spanning several growing seasons, but there are some studies in the pipeline that will likely have results published within the next year.

References

Asai, H., B. Samson, H. Stephan, K. Songyikhangsuthor, K. Homma, Y. Kiyono, Y. Inoue, T. Shiraiwa, and T. Horie. "Biochar Amendment Techniques for Upland Rice Production in Northern Laos. Soil Physical Properties, Leaf SPAD and Grain Yield." *Field Crops Research* 111.1-2 (2009): 81-84.

Blackwell, Paul, Evelyn Krull, Greg Butler, Allan Herbert, and Zakaria Solaiman. "Effect of Banded Biochar on Dryland Wheat Production and Fertiliser Use in South-Western Australia: An Agronomic and Economic Perspective." *Australian Journal of Soil Research* 48.7 (2010): 531-45. Print.

Castaldi, S., M. Riondino, S. Baronti, F.r. Esposito, R. Marzaioli, F.a. Rutigliano, F.p. Vaccari, and F. Miglietta. "Impact of Biochar Application to a Mediterranean Wheat Crop on Soil Microbial Activity and Greenhouse Gas Fluxes." *Chemosphere* 85 (2011): 1464-471.

Crane-Droesch, Andrew, and Abigail Clare. "Biochar Increases Maize Yields and Smallholder Profitability: Evidence From Western Kenya." *University of California, Berkeley*. In Review (2012). http://andrewcd.berkeley.edu/ACD_AJC_SS_Kenya_WorkingPaper.pdf.

Gaskin, Julia W., R. A. Speir, Keith Harris, K. C. Das, R. D. Lee, Lawrence A. Morris, and Dwight S. Fisher. "Effect of Peanut Hull and Pine Chip Biochar on Soil Nutrients, Corn Nutrient Status, and Yield." *Agronomy Journal* 102.2 (2010): 623-33.

Genesio, L., F. Miglietta, E. Lugato, S. Baronti, M. Pieri, and F. P. Vaccari. "Surface Albedo Following Biochar Application in Durum Wheat." *Environmental Research Letters* (2012): 1-8. *IOP Science*. http://iopscience.iop.org/1748-9326/7/1/014025.

Hammond, Jim, Shackley Simon, Prendergast-Miller Miranda, Cook Jason, Buckingham Sarah, and Pappa Valentini A. "Biochar field testing in the UK: outcomes and implications for use". *Carbon Management*. Volume 4 Issue 2. (2013).

Husk, Barry, and Julie Major. "Biochar Commercial Agriculture Field Trial in Québec, Canada – Year Three: Effects of Biochar on Forage Plant Biomass Quantity, Quality and Milk Production." (2011). Print.

Islami, Titiek, Bambang Guritno, Nur Basuki, and Agus Suryanto. "Maize Yield and Associated Soil Quality Changes in Cassava + Maize Intercropping System After 3 Years of Biochar Application." *Journal of Agriculture and Food Technology* 1.7 (2011): 112-15. http://www.textroad.com/pdf/JAFT/J.%20Agric.%20Food.%20Tech.,%201(7)%20112-115,%202011.pdf.

Jeffery, S., F.G.A. Verheijen, M. van der Velde, A.C. Bastos. "A quantitative review of the effects of biochar application to soils on crop productivity using met-analysis." *Agriculture, Ecosystems and Environment* 144 (2011): 175-187.

Jones DL, Rousk J, Edwards-Jones G, DeLuca TH, Murphy DV. "Biochar-mediated changes in soil quality and plant growth in a three year field trial." *Environment Centre Wales*, Bangor, UK. (2011)

Kimetu, Joseph M., Johannes Lehmann, Solomon O. Ngoze, Daniel N. Mugendi, James M. Kinyangi, Susan Riha, Lou Verchot, John W. Recha, and Alice N. Pell. "Reversibility of Soil Productivity Decline with Organic Matter of Differing Quality Along a Degradation Gradient." *Ecosystems* 11.5 (2008): 726-39. Print.

Laird, David A. "Field Study Research Summary." Message to the author. 29 July 2011. E-mail.

Lehmann, Johannes, and Stephen Joseph. *Biochar for Environmental Management: Science and Technology*. London: Earthscan, (2009). Print.

Liu, Jie, Hardy Schulz, Susanne Brandl, Herbert Miehtke, Bernd Huwe, and Bruno Glaser. "Short-term effect of biochar and compost on soil fertility and water status of a Dystric Cambisol in NE Germany under field conditions." *J. Plant Nutr. Soil Sci.* (2012): 1–10.

Major, Julie. "Field Study Research Summary." Message to the author. 8 Aug. 2011. E-mail.

Major, Julie, Marco Rondon, Diego Molina, Susan J. Riha, and Johannes Lehmann. "Maize Yield and Nutrition During 4 Years After Biochar Application to a Colombian Savanna Oxisol." *Plant Soil* 333 (2010): 117-28. Print.

Natural Resources Conservation Service. "Saturated Hydraulic Conductivity: Water Movement Concepts and Class History." USDA. Web 2011. http://soils.usda.gov/technical/technotes/note6.html.

Niggli, Claudio, and Hans-Peter Schmidt. "Biochar in European Viticulture: Results of the 2011 Season." *Ithaka Journal* (2012): n. pag. *Ithaka Journal*. Delinat Institut, www.ithaka-journal.net/druckversionen/e022012-bc-viticulture.pdf.

Oguntunde, Philip G., Matthias Fosu, Ayodele E. Ajayi, and Nick Van De Giesen. "Effects of Charcoal Production on Maize Yield, Chemical Properties and Texture of Soil." *Biology and Fertility of Soils* 39.4 (2004): 295-99.

Petter, Fabiano A., Beata E. Madari, Mellissa A. Soler Da Silva, Marco Carneiro, Marcia T. De Melo Carvalho, Ben Junior, and Leandro P. Pacheco. "Soil Fertility and Upland Rice Yield after Biochar Application in the Cerrado." *Pesquisa Agropecuária Brasileira* 47.5 (2012): 699-706. http://www.scielo.br/scielo.php?pid=S0100-204X2012000500010&script=sci_arttext.

Roberts, Kelli G., Brent A. Gloy, Stephen Joseph, Norman R. Scott, and Johannes Lehmann. "Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential." *Environmental Science & Technology* 44.2 (2010): 827-33. Print.

Scheer, Clemens, Peter R. Grace, David W. Rowlings, Stephen Kimber, and Lukas V. Zwieten. "Effect of Biochar Amendment on the Soil-Atmosphere Exchange of Greenhouse Gases from an Intensive Subtropical Pasture in Northern New South Wales, Australia." *Plant Soil* (2011). Springer Science.

Shackley, Simon, Sarah Carter, Tony Knowles, Erik Middelink, Stephan Haefele, and Stuart Haszeldine. "Sustainable Gasification–Biochar Systems? A Case-Study of Rice-Husk Gasification in Cambodia, Part II: Field Trial Results, Carbon Abatement, Economic Assessment and Conclusions." *Energy Policy* 41 (2012): 618-23.

Solaiman, Zakaria M., Paul Blackwell, Lynette K. Abbott, and Paul Storer. "Direct and Residual Effect of Biochar Application on Mycorrhizal Root Colonisation, Growth and Nutrition of Wheat." *Australian Journal of Soil Research* 48.7 (2010): 546-54. Print.

Sovu, Mulualem Tigabu, Patrice Savadogo, and Per Christer Oden. "Facilitation of Forest Landscape Restoration on Abandoned Swidden Fallows in Laos Using Mixed-Species Planting and Biochar Application." *Silva Fennica* 46.1 (2012): 39-51. http://www.metla.fi/silvafennica/full/sf46/sf461039.pdf.

Sukartono, W. H. Utomo, Z. Kusuma, and W. H. Nugroho. "Soil Fertility Status, Nutrient Uptake, and Maize (Zea Mays L.) Yield Following Biochar and Cattle Manure Application on Sandy Soils of Lombok, Indonesia." *Journal of Tropical Agriculture* 49.1-2 (2011): 47-52. *Journal of Tropical Agriculture*. http://www.jtropag.in/index.php/ojs/article/viewFile/1036/263.

Sun, Daquan, Meng Jun, Weiming Zhang, Xuechao Guan, Yuwei Huang, Yu Lan, Jiping Gao, and Wenfu Chen. "Implication of Temporal Dynamics of Microbial Abundance and Nutrients to Soil Fertility under Biochar Application – Field Experiments Conducted in a Brown Soil Cultivated with Soybean, North China." *Advanced Research Materials* 518-523 (2012): 384-94. http://www.scientific.net/AMR.518-523.384.

Van Zwieten L, Kimber S, Orr L, Morris S, Downie A, Sinclair K, Joseph SD, Chan KY. "Agro-economic valuation of biochar using field-derived data." Proc 1st Asia Pacific Biochar Conference, Gold Coast Australia May 17-20. (2009) ISBN 978 0 7347 1973 7.

Zhang, Afeng, Liqiang Cui, Gengxing Pan, Lianqing Li, Qaiser Hussain, Xuhui Zhang, Jinwei Zheng, and David Crowley. "Effect of Biochar Amendment on Yield and Methane and Nitrous Oxide Emissions from a Rice Paddy from Tai Lake Plain, China." *Agriculture, Ecosystems & Environment* 139.4 (2010): 469-75.

Zhang, Afeng, Rongjun Bian, Genxing Pan, Liqiang Cui, Qaiser Hussain, Lianqing Li, Jinwei Zheng, Jufeng Zheng, Xuhui Zhang, Xiaojun Han, and Xinyan Yu. "Effects of Biochar Amendment on Soil Quality, Crop Yield and Greenhouse Gas Emission in a Chinese Rice Paddy: A Field Study of 2 Consecutive Rice Growing Cycles." *Field Crops Research* 127 (2012): 153-60. http://journals.ohiolink.edu/ejc/article.cgi?issn=03784290&issue=v127inone_c&article=153_eobaoso2crgc