

## **THE POTENTIAL USES OF BIOCHAR: A REVIEW**

Biochar is a compound created using organic materials in a minimally oxygenated, high temperature environment. This publication focuses on the uses of biochar, including as a soil amendment and for climate mitigation, and the influences on its efficacy towards such purposes.



# **THE POTENTIAL USES OF BIOCHAR: A REVIEW**

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## Introduction

In the late 1800's, Herbert Smith, an explorer, wrote about the "terra preta" or dark earth of the Amazon, and how it produced robust crops (Marris, 2006). Recently, researchers have again focused their attention on this dark earth, finding that it may hold answers to certain environmental issues of today including climate change, sustainable agricultural practices, and viable renewable energy sources (Atkinson, Fitzgerald, & Hipps, 2010; Barrow, 2012). Terra preta and terra mulata (brown earths) are man-made altered soils created thousands of years ago by inhabitants of the Amazon and were generated by burning natural organic contents such as crop residue, leaving a compound high in carbon (Barrow, 2012). Today, researchers are exploring a similar soil amendment, calling it biochar. Akin to coal, biochar is a material created through the decomposition of organic material in the absence of oxygen using heat, a process known as pyrolysis (United States Department of Agriculture, 2010).

This University Center for Economic Development technical report provides a review of current biochar research, assessing biochar's viability for agriculture, soil reclamation and climate mitigation. It addresses the conditions under which biochar might be most useful towards these pursuits. This publication focuses on field trials that have been undertaken in order to inform an ongoing field trial taking place in Eureka County, Nevada. Part of the Eureka County field trial's objective is to reclaim tailing piles at the Ruby Hill mine site by applying biochar (generated from Pinyon Juniper) to a minimum of one-acre of the tailings pile in an effort to increase long-term vegetation cover. This will be monitored over the course of the next few years and it is one of the largest field trials known to be conducted in the Western United States and the first of its kind in Nevada. An extensive literature review on biochar research is presented with an annotated bibliography

provided in appendix one, and a listing of key terms that are used in this article in appendix two. This synthesis will inform the upcoming field trial, which will in turn provide new insight into biochar's possibilities, especially in more arid climates.

## Creating Biochar

Biochar is created through pyrolysis, a decomposition of organic material in a non- or reduced-oxygenated, enclosed environment with heat. This process usually occurs in one of two forms: 1) fast (taking no more than a few seconds) or 2) slow (which can take hours)<sup>1</sup>.

Pyrolysis typically takes place at temperatures between 350 and 500 degrees Celsius (°C) (Laird, et al., 2009; Spokas, Baker, and Reicosky, 2010; Winsley, 2007; Wolfe, et al., 2010) and its product yields, by mass, are typically 50 percent to 70 percent bio-oil, 10 percent to 30 percent biochar, and 15 percent to 20 percent biogas (e.g., Demirbas, 2008; Laird, et al., 2009; Maraseni, 2010; Mullen, et al., 2010; Sohi, Lopez-Capel, & Bol, 2010). Variation in end-product percentages is dependent on the temperature and type of pyrolysis as well as the organic input. Estimates place the amount of biochar produced using low temperature pyrolysis to be at about a 50 percent conversion of biomass carbon, with another 33 percent converted to biofuel (either bio-oil or syngas) (Lee, Hawkins, Day, & Reicosky, 2010). Ideally, it will be possible to capture all three pyrolysis byproducts helping to make the system profitable (Demirbas, 2008; Lee, et al., 2010).

Biochar itself is a carbon-rich, highly porous material containing polycyclic aromatic hydrocarbons (Atkinson, et al., 2009; Preston and Schmidt 2006; Schmidt and Noack 2000; Sohi, Lopez-Capel, Krull, & Bol, 2009; Trompowsky, et al., 2005) and having a

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<sup>1</sup> Laird et al (2009) note that two other forms also exist – flash pyrolysis and gasification.

molecular structure that is highly chemically and microbially stable (Cheng, Lehmann, & Engelhard, 2008). Many types of biomass are suitable for biochar production and several studies have considered a wide range of materials (e.g. Balat & Balat, 2009; Demirbas, 2004; Demirbas, Pehlivan, & Altun, 2005; Özçimen & Ersoy-Meriçboyu, 2010; Spokas, et al., 2010)<sup>2</sup>.

Acknowledging the possibilities inherent in biochar, research has been occurring in both the public and private sectors. Some research is focused on input materials (called biomass, organic materials, feedstock, or even agricultural residue) and how their structure and composition affect soil performance, crop productivity, and water retention. Other studies are focused more on outcomes rather than inputs, while others are interested in understanding the interactions between the pyrolysis temperatures, feedstock, and outcomes. Additionally, there has been consideration of the ability of biochar to assist in greenhouse gas reduction.

### Variation in Biochar Production

Due to the potential for anything that is organic to be used to generate biochar, it is not surprising that input materials vary dramatically in lab and field studies, yielding biochars with dramatically different physical properties, such as porosity, total pore volume, and BET surface area (Özçimen and Ersoy-Meriçboyu 2010). Often, the choice of biomass is determined based on what is most abundant in a given area.

Biomass used in several studies includes the use of green waste, such as plant pruning and grass clippings (Chen, Phillips, Condron,

Goloran, & Chan, 2013; Park, Choppola, Bolan, Chung, & Chuasavathi, 2011), pine needles (Chen & Yuan, 2011), tea waste (Demirbas, 2004), switchgrass (Ippolito, Novak, Busscher, Ahmedna, Rehrah, & Watts, 2012), and chicken manure (Park, Choppola, Bolan, Chung, & Chuasavathi, 2011). Table 1 provides a listing of research papers and feedstocks.

### Biomass Decomposition Temperature

Not only does the composition of the original biomass affect the type of biochar produced, the temperature at which the biomass is decomposed into biochar also plays a role in its stability and benefits. In one study, pecan shells were ground and pyrolyzed in a Lindberg box programmable furnace beginning at 40°C and then gradually increasing to 170°C and finally to 700°C. When analyzed, the biochar lacked alkyl C, and had a single-ring aromatic with some heterocyclic compounds, which previous researchers (e.g., Rutherford, Wershaw, & Cox, 2004) determined occurs when cellulose and lignin char at high temperatures (Novak, et al., 2009). Novak et al. (2009) conclude that the structure of the biochar produced at high temperatures, with its “recalcitrant nature,” can be beneficial if the goal of the biochar is storing carbon (p.111). But if biochar is to be used as a soil amendment, a lower temperature pyrolysis would allow for more “oxidizable structural groups and a low C:N ratio” (Novak, et al., p. 111). Similarly, Ippolito, et al. (2012) found that pyrolysis at 500°C rather than 250°C led to switchgrass biochar having a larger surface area, increased pH, and increased ash content.

Demirbas (2004) also explored the effect of temperature on biomass, using agricultural residues including olive husks, corncobs, and tea waste, selecting six temperature at which to pyrolyze the biomass, including 470°K (197°C), 550°K, 650°K, 750°K, 850°K, 950°K and 1,050°K (777°C). Demirbas found that

<sup>2</sup> Each of these conducted studies using multiple types of biomass. Atkinson, Fitzgerald, and Hipps (2009) and Jeffrey et al (2011) offer excellent tables cross-referencing researchers and the type(s) of biomass used in their studies.

biomass pyrolyzed at under 575°K (302°C) degraded cellulose to a stable anhydrocellulose form, yielding more biochar, while temperatures exceeding 575°K resulted in more volatiles and cellulose depolymerization. Additionally, carbon increased with increasing pyrolysis temperature, while hydrogen and oxygen decreased.

Similarly, Chen & Yuan (2011) studied pine needle biochar produced under 100°C, 300°C, 400°C and 700°C pyrolysis temperatures, finding that sorption rate improved and became nonlinear between 300 and 700°C. In response to these differences, Ogawa, Okimori, and Takahashi (2006) suggest classifying biochar based on pH, ash content, water holding capacity, pore volume, specific surface area, volatile content, and bulk density. Such a classification system could potentially aid in synthesizing existing and future biochar research.

### **Physical Properties of Biomass**

Researchers have discovered that the shape and nutrients within the biomass affect characteristics of the biochar created and their subsequent benefits to soil, crops, and so forth. For instance, Özçimen and Ersoy-Meriçboyu (2010) found calorific values, hydrocarbon distributions, ash content, total pore volume, and BET surface area to vary between apricot stone, hazlenut shell, grapeseed, and chestnut shell organic matter. They conclude that these variations among biochar feedstocks make the feedstocks conducive to producing various carbon materials, including activated carbon, carbon fibers, and carbon nanotubes, all of which increase the utility of biochar as a soil amendment.

Additionally, it has been found that the introduction of biochar to soil can have multiple positive effects on soil. These include an increase in the ability of soil to immobilize harmful heavy metals, such as cadmium (Cd),

copper (Cu), and lead (Pb), all of which can be toxic to plants (Park et al 2011; Uchimiya et al 2010; Yu et al 2009). Park, et al. (2011) discovered chicken manure-derived and green waste-derived biochars to be particularly effective at immobilizing metal contaminants. More specifically, they found that concentrations of cadmium, copper, and lead in the roots and shoots of Indian mustard plants were significantly reduced for plants grown in soil amended with chicken manure-derived biochar (compared to plants grown in unamended soil). The concentrations of these heavy metals were also reduced, though to a lesser extent, for plants grown in soil amended with green waste-derived biochar.

Moreover, the addition of biochar can also significantly increase plant nutrient uptake. Park et al (2011) found significantly increased concentrations of potassium (K) and phosphorus (P) in the roots of Indian mustard plants grown in soil amended with chicken manure-derived and green waste-derived biochar (compared to concentrations found in plants grown in unamended soil). Finally, biochar yield is impacted by the particle size of the organic compound and the amount of lignin, with larger particles and more lignin producing larger amounts of biochar (Demirbas, 2004).

### **Crop Productivity from Biochar**

Although biochar varies based on the input used and the temperature at which it is converted, controlling for various factors and with the addition of varying amounts of biochar both in lab studies (Chan, Zwieter, Meszaros, Downie, & Joseph, 2007; Jeffery, Verheijen, van der Velde, & Bastos, 2011; Park, et al., 2011; Rondon, Lehmann, Ramirez, & Hurtado, 2007; Solaiman, Murphy, & Abbott, 2012) and field trials (Vaccari, et al., 2011; Yamato, Okimori, Wibowo, Anshori, & Ogawa, 2006), researchers have generally found that biochar has the potential to increase crop productivity .

Lab studies have tested the reaction of various plants to biochar amended soil in pot trials. Chan, et al. (2007) studied greenwaste biochar on radish yield using an Alfisol soil. The researchers concluded that the results were no different from the control when biochar was used alone. When Nitrogen was added to varying levels of biochar and amended to the soil, the results were very positive with regard to higher radish yield particularly at higher levels of biochar<sup>3</sup> and the interaction between biochar and Nitrogen provided better results than Nitrogen alone. Additional benefits to the soil were also realized with the biochar and Nitrogen combination, with pH, organic Carbon, and exchangeable cations all increasing while tensile strength decreased. Similarly, Rondon, et al. (2007) examined the effect of varying levels of biochar on two types of common beans using an innately infertile soil. Bean yield was 46 percent higher than the control at 90 g kg<sup>-1</sup> bio-char added; however Nitrogen soil uptake decreased by 50 percent at this same rate (C/N ratio increased at lower levels of biochar application). Moderate levels of biochar tend to be most beneficial for nitrogen fixation, a concern especially in weathered or acid soil conditions.

Park, et al. (2011) also found benefits to the addition of greenwaste and chicken manure biochar on Indian mustard growth, using heavily metal-contaminated soils. The researchers determined that the addition of biochar helped to immobilize the heavy metals and reduced their contamination of Indian mustard. Differential effects were found on growth based on biochar type. With the addition of 1.0 percent biochar, a 353.0 percent and 572.0 percent increase in roots and shoots respectively was gained. Greenwaste biochar only achieved those numbers when approximately 15 percent was added to the soil. There may be better returns on investment

in crop productivity depending on the biochar used.

Solaiman, et al. (2012) focused on seed germination in a lab setting, finding that using petri dishes with different types of biochar only can help to identify whether certain types of seeds would benefit or be harmed by the application of biochar since the effects were comparable to those grown in a soil with a biochar amendment. Due to the many variables that can hurt or harm the effectiveness of biochar on crop productivity, this seems like a useful first step before conducting a field trial.

There have been field trials to test biochar's effect on crop productivity. Vaccari, et al. (2011) used copiced woodland biochar, sowing 450 seeds of durum wheat per square meter in a silty loam soil with a 5.2 pH over two seasons. A control, biochar application rate of 30t ha<sup>-1</sup> (B30) and 60 t ha<sup>-1</sup> (B60) were sectioned off for the first growing season. Residual biochar effects were studied by growing wheat during the second season in the same plots without biochar, and a separate area was chosen to replicate the first season's block layout. More than 45 inches of rain fell at the trial site per year. The researchers found that both levels of biochar increased crop yield, and this increase was maintained in the second season even without the addition of more biochar in the original plots.

Yamato, et al. (2006) conducted a field trial using woodwaste biochar to amend an infertile soil growing maize, cowpea, and peanut crops. The researchers found gains in crop growth for maize and peanut after the application of fertilizer to the soil. The soil itself was found to contain more arbuscular mycorrhizal (AM) fungi when maize was grown, and pH, total N available, and exchangeable cations were all increased using the biochar and fertilizer combination.

Both lab and field trials support that crop productivity tends to increase with the

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<sup>3</sup> At 10 t/ha the biochar/nitrogen compound was used a significantly reduced radish yield was found, but the cause is unclear.

application of biochar, although it is evident that the level of germination and crop productivity are dependent on the type of biochar (Solaiman, et al., 2012), type of soil, addition of other elements such as fertilizers, and the type of plant being grown.

### **Water Retention and Adsorption of Other Elements**

Soil studies have found that when biochar is used as a soil amendment, it can alter the porosity of the soil and the soil's surface area which can in turn result in increased water retention capacity (Laird, et al., 2010). Additionally, biochar amendment also increased soil moisture content by 4 percent and 5 percent, respectively, (using a 5 percent biochar and 95 percent compost mixture compared to the control) at an 8-inch depth in an outdoor field trial (Clarke, 2014).

Research has also found that the amended soil has an increased capacity to adsorb water when alkali is added (Liu, et al., 2012) as well as an increased capacity to adsorb common herbicides (Spokas, Koskinen, Baker, & Reicosky, 2009). It can also reduce harmful elements including cadmium, zinc, copper and lead (Beesley & Marmioli, 2011; Park, et al., 2011), and polycyclic aromatic hydrocarbons (Chen & Yuan, 2011), and provides other heavy metal immobilization (Park, et al., 2011), which in turn allows for healthier plants to be grown, although this effect may be mediated by the soil's pH level (Chen, et al., 2013). Indeed, Enders, et al (2012) found that woody biomass feedstock was the most versatile with regard to soil pH but hazard that the temperature of the pyrolysis and the biomass characteristics will interact with soil characteristics, potentially altering crop production and other soil benefits.

This potential of biochar to enhance the ability of soil to retain water has great significance for Nevada, which is experiencing an extended period of drought (National Drought Mitigation Center, 2014). All 17 Nevada counties have

been designated a drought emergency since 2012 (Wolterbeek, 2014). During the five-year period from March 2009 to February 2014, the National Climatic Data Center of the National Oceanic and Atmospheric Administration recorded annual rainfall in Nevada to be 4.45 inches below average. The addition of biochar to soil in Nevada may help to attenuate the impact of this drought on crop production.

### **Micro-Organism Benefits**

Due to its composition, biochar can provide shelter to soil organisms like mycorrhizal fungi (Warnock, Lehmann, Kuyper, & Rillig, 2007), which play a key role in crop productivity and overall soil health. The pH level of the soil, which can affect the survivability of microorganisms, has also been found to change with the application of biochar (see Jeffery, et al., 2011 for meta-analysis discussing this) and biochar can provide nitrogen to plants through ammonia (NH<sub>3</sub>) adsorption (Taghizadeh-Toosi, Clough, Sherlock, & Condon, 2012).

Spokas, et al. (2010) suggest biochar might be a nitrification inhibitor, which is why there are differences in plant and microbial responses to its application. The increased porosity of the soil and large surface area of some biochar allows for increased adsorption of chemicals and nutrients from both gases and liquids (Demirbas, 2004, 2008; Liu, et al., 2012; McHenry, 2009; van Zwiiten et al., 2010; Vaccari et al., 2011).

Mullen et al. (2010) found porosity to be positively related to the ability of biochar to remove metal ions from soil, while some studies suggest that increased soil porosity caused by the addition of biochar may improve overall soil drainage (Maraseni, 2010). It has also been suggested that soil porosity impacts microbial activity and that soils with higher porosity provide more favorable environments for micro-organisms (Laird, Brown, Amonette, & Lehmann, 2009; Atkinson, et al., 2010).



## Climate Change and Carbon Sequestration

In addition to its potential soil benefits, biochar has also been studied for its potential climate change mitigation benefits through the use of biochar, bio-oil, and biogas (e.g., Ippolito, Laird, & Busscher, 2012; Laird, 2008; Lee et al., 2010; Woolf et al., 2010). One of the most widely considered of these is the potential of biochar and the byproducts of its production to reduce greenhouse gas emissions. Utilizing biogas and bio-oil can aid in avoiding carbon dioxide emissions produced by burning fossil fuels and the conversion of biomass into biochar, bio-oil, and biogas also avoids the methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions produced through the natural decay of biomass (Woolf et al., 2010). Woolf et al. (2010) found that the use of biochar and its production byproducts has the potential to offset as much as 12 percent of the current anthropogenic carbon sequestered from carbon dioxide emitted (CO<sub>2</sub>-C) equivalent emissions, a total of 1.8 pictograms of total carbon sequestered from overall carbon dioxide emissions (Pg CO<sub>2</sub>-C<sub>e</sub>) per year. Over the course of a century, this is a net offset of 130 Pg CO<sub>2</sub>-C<sub>e</sub> of anthropogenic emissions. The application of biochar as a soil amendment may also act as a carbon sequestration mechanism (Chen & Yuan, 2011; Glaser, Lehmann, & Zech, 2002; Lehmann, Gaunt, & Rondon, 2006; Oguntunde, Fosu, Ajayi, & van de Giesen, 2004; Ogawa, et al., 2006; Wang, Zhang, Xiong, Liu, & Pan, 2011) and has also been found to depress the amount of nitrous oxide emitted from crop cultivation (Wang, et al., 2011).

## Application in Large Scale Tests

Despite the breadth of biochar research that has taken place, there is still a need for further work. There has been comparably little large-scale testing of the biochar-to-soil amendment system. Ongoing larger projects span the globe, from Western Australia, to Indonesia, to Japan. In Western Australia, salinity

management led to the planting of mallee in a semi-arid region during the 1990s (McHenry, 2009). What began with 20,000 trees planted in the first year continued to increase over time, to over two million in 2007 using 1,018 hectares (URS Australia Pty Ltd, 2009). Although there were environmental benefits, there was a need for this project to be financially beneficial and push towards becoming a major industry in the region. Among other byproducts such as eucalyptus oil and wood pellets, Verve Energy constructed a trial that included an integrated wood processing plant to generate biochar from the wood fraction of the mallees (McHenry, 2009; URS Australia Pty Ltd, 2009). This pilot program was profitable and the company is looking for investment to construct a larger plant (URS Australia Pty Ltd, 2009).

In Sumatra, Indonesia biochar is generated using harvested tree trunks as wood residue and remainders from a nearby pulp mill. The biochar is then used as a soil amendment and for water purification, with estimates of annual total biochar production in 2003 at 18,739 MG-bdw year (Ogawa, et al., 2006). A similar project was conducted in Japan using wood waste from sawmills, construction sites and tree thinnings as biochar inputs, with the resulting biochar used for a myriad of uses including water purification and livestock deodorization (Ogawa, et al., 2006).

Closer to Nevada, a coal basin reclamation project, including the use of biochar as a soil amendment, began in 2012 in western Colorado (Clark, 2014). Erosion from 50 years of coal mining, leading to sedimentation issues in the Crystal River, spurred a pilot reclamation program that considered, among other restoration techniques, the application of a biochar and compost mixture. Over 1.5 acres of soil in different parts of the reclamation area were treated with a compost, biochar and compost mixture, and a control (no treatment) to study soil density, water retention, and soil nutrients. The biochar compost ratio was 5 percent biochar and 95 percent compost by

volume, with three inches of the soil amendment laid down (B. McMullen, personal communication, March 6, 2014). Results so far indicate increased plant growth and soil moisture content (4 percent to 5 percent measured at 8-inch depth) in areas with the biochar and compost mixture compared to controls (Clarke, 2014). More recently, this biochar and compost mixture was used in a gas pad reclamation and a uranium mine reclamation project also in Colorado, although results of the application are pending (B. McMullen, personal communication, March 6, 2014).

Although field trials are ongoing throughout the world, documentation and detailed results of these trials is much harder to find or access. Subsequently, there is still much unknown with regard to how biochar works under real world conditions. It is unknown as to how long biochar once amended to soil will last, and whether it will begin depreciating in its value to the soil and to carbon sequestration over time. Vaccari, et al. (2011) found that there was no change to crop yield after two years of biochar soil amendment, while Laird, et al. (2010) found a much greater impact of biochar compared to manure on soil quality after 500 days, and Koide, Petprakob, and Peoples (2011) found no significant difference between biochar mixed into soil for 15 months versus biochar never combined with soil. Although it seems based on these studies that there is some consistent benefit of biochar over time, none of these trials were longer than two years leaving much unknown about the long-term benefit of biochar to soil.

## Conclusion

Some of the major challenges to synthesizing existing biochar research and allowing for conclusions include the interactions between type of feedstock, pyrolysis temperature, biochar characteristics, soil characteristics, and crop types, especially in light of the absence of large-scale field studies, and long-term studies,

not always in controlled environments, in order to determine what does and does not produce optimal results.

There are many concerns that have yet to be fully dealt with regarding biochar. First, it is unknown whether biochar will truly be economically feasible, with success relying on feedstock cost, transportation costs, energy conversion costs and the efficiency of pyrolysis methods. In a research note to the USDA, the Rocky Mountain Research Station writes, "In the western United States, the cost of biomass removal often exceeds its value, despite increasing interest in forest biomass utilization. Burgeoning interest in using woody biomass for heat or bioenergy is a result of rising fuel costs, greenhouse gas emissions from fossil fuels, and the threat of stand replacing wildfires; however, the collection and transportation of woody debris and harvesting waste from forests are among many economic impediments to woody biomass utilization" (McElligott, Page-Dumroese, & Coleman, 2011, p. 1). In addition to worries over economic sustainability, there are also concerns over how to properly store and apply the biochar (in a safe way so the small particles are not breathed in), especially with less stable biochars which have the potential to catch on fire due to friction (Brick, 2010).

Although there are many unknowns, the real benefits of biochar as a soil amendment for agricultural and reclamation purposes maybe found in its use on a large scale and over a long period of time outside of a lab. Thus, the current project being undertaken in Eureka County, Nevada. has the potential to be greatly informative in determining how successful the application of biochar is for mining reclamation and more broadly its effect on soil over time, especially in arid environments where water is at a premium. Additionally, drought-management must be addressed in a comprehensive fashion, and biochar may be one tool to apply to this issue.

## References

- Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review." *Plant Soil*, 337, 1-18.
- Balat, M., & Balat, H. (2009). Recent trends in global production and utilization of bio-ethanol fuel. *Applied Energy*, 86, 2273-2282.
- Barrow, C.J. (2012). Biochar: Potential for countering land degradation and for improving agriculture. *Applied Geography*, 34, 21-28.
- Beesley, L., & Marmiroli, M. (2011). The immobilisation and retention of soluble arsenic, cadmium and zinc by biochar. *Environmental Pollution*, 159, 474-480.
- Brick, S. (2010). Biochar: Assessing the promise and risks to guide U.S. policy." *National Resources Defense Council Issue Paper*. Retrieved from [www.nrdc.org/energy/files/biochar\\_paper.pdf](http://www.nrdc.org/energy/files/biochar_paper.pdf).
- Chan, K. Y., Zwieten, L. V., Meszaros, I., Downie, A., & Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research*, 45, 629-634.
- Chen, B., & Yuan, M. (2011). Enhanced sorption of polycyclic aromatic hydrocarbons by soil amended with biochar. *Journal of Soils and Sediments*, 11, 62-71.
- Chen, C. R., Phillips, I. R., Condon, L. M., Goloran, J., Xu, Z. H., & Chan, K. Y. (2013). Impacts of greenwaste biochar on ammonia volatilisation from bauxite processing residue sand. *Plant Soil*, 367, 301-312.
- Cheng, C. H., Lehmann, J., & Engelhard, M. H. (2008). Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence. *Geochimica et Cosmochimica Acta*, 72, 1598-1610.
- Clarke, S. (2014). CWCB watershed restoration project annual report. *Report of the Roaring Fork Conservancy*. Retrieved from <http://www.roaringfork.org/sitepages/pid397.php>
- Demirbas, A. (2004). Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues. *Journal of Analytical and Applied Pyrolysis*, 72, 243-248.
- Demirbas, A. (2008). Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. *Energy Conversion and Measurement*, 49, 2106-2116.
- Demirbas, A., Pehlivan, E., & Altun, T. (2006). Potential evolution of Turkish agricultural residues as bio-gas, bio-char, and bio-oil sources. *International Journal of Hydrogen Energy*, 31, 613-620.
- Enders, A., Hanley, K., Whitman, T., Joseph, S. & Lehmann, J. (2012). Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresource Technology*, 114, 644-653.
- Glaser, B., Lehmann, J., & Lech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal- a review. *Biol Fertil Soils*, 35, 219-230. doi: 10.1007/s00374-002-0466-4
- Ippolito, J. A., Laird, D. A., & Busscher, W. J. (2012). Environmental benefits of biochar. *Journal of Environmental Quality*, 41, 967-972.
- Ippolito, J.A., Novak, J. M., Busscher, W. J., Ahmedna, M., Rehrh, D., & Watts, D. W. (2012). Switchgrass biochar affects two aridisols. *Journal of Environmental Quality*, 41, 1123-1130.
- Jeffery, S., Verheijen, F. G. A., van der Velde, M., Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis.

*Agriculture, Ecosystems and Environment*, 144, 175-187.

Koide, R. T., Petprakob, K., & Peoples, M. (2011). Quantitative analysis of biochar in field soil. *Soil Biology & Biochemistry*, 43, 1563-1568.

Laird, D. A. (2008). The charcoal vision: A win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal*, 100(1), 178-181.

Laird, D. A., Brown, R. C., Amonette, J. E., & Lehmann, J. (2009). Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels, bioproducts, & Biorefining*, 3, 547-562.

Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., & Karlen, D.L. (2010). Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma*, 158, 443-449.

Lee, J. W., Hawkins, B., Day, D. M., & Reicosky, D. C. (2010). Sustainability: The capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration. *Energy & Environmental Science*, 3(11), 1695 – 1705.

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems- A review. *Mitigation and Adaptation Strategies for Global Changes*, 11, 403-427.

Liu, P., Wu-Jun, L., Jiang, H., Chen, J., Li, W., & Yu- H. (2012). Modification of bio-char derived from fast pyrolysis of biomass and its application in removal of tetracycline from aqueous solution. *Bioresource Technology*, 121, 235-240.

Madari, B. E., Pimenta, A. S., Hockaday, W. C., & Hatcher, P. G. (2005). Characterization of humic like substances obtained by chemical

oxidation of eucalyptus charcoal. *Organic Geochemistry*, 36(11), 1480-1489.

Maraseni, T. N. (2010). Biochar: Maximising the benefits." *International Journal of Environmental Studies*, 67(3), 319-327.

Marris, Emma. (2006). "Black is the New Green." *Nature*. 442: 624-626.

McElligott, K., Page-Dumroese, D., & Coleman, M. (2011). Bioenergy production systems and biochar application in forests: Potential for renewable energy, soil enhancement, and carbon sequestration." *Rocky Mountain Research Station. Research Note to the United States Department of Agriculture*. RMRS-RN-46, 1-14. Retrieved from [www.fs.fed.us/rm/pubs/rmrs\\_rn046.pdf](http://www.fs.fed.us/rm/pubs/rmrs_rn046.pdf).

McHenry, M. P. (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.

Mullen, C. A., Boateng, A. A., Goldberg, N. M., Lima, I. M., Laird, D. A., & Hicks, K. B. (2010). Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. *Biomass and Bioenergy*, 34, 67-74.

National Climatic Data Center of the National Oceanic. (2014.) National Oceanic and Atmospheric Administration. <http://www.ncdc.noaa.gov/temp-and-precip/climatological-rankings/index.php?periods%5B%5D=12&periods%5B%5D=24&periods%5B%5D=48&periods%5B%5D=60&parameter=pcp&state=26&div=0&year=2014&month=2#ranks-form>. accessed 6 May 2014.

National Drought Mitigation Center. (2014.) University of Nebraska, Lincoln. <http://drought.unl.edu/DroughtBasics/WhatisDrought.aspx>. accessed 6 May 2014.

Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W., & Niandou, M. A. S. (2009). Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil Science*, 174, 105-112.

Ogawa, M., Okimori, Y., & Takahashi, F. (2006). Carbon sequestration by carbonization of biomass and forestation: Three case studies. *Mitigation and Adaptation Strategies for Global Change*, 11, 429-444.

Oguntunde, P. G., Fosu, M., Ajayi, A. E., & van de Giesen, N. (2004). Effects of charcoal production on maize yield, chemical properties and texture of soil. *Biol Fertil Soils*, 39, 295-299. doi: 10.1007/s00374-003-0707-1

Özcimen, D., Ersoy-Mericboyu, A. (2010). Characterization of biochar and bio-oil samples obtained from carbonization of various biomass materials. *Renewable Energy*, 35, 1319-1324.

Park, J. H., Choppola, G. K., Bolan, N. S., Chung, J. W., & Chuasavathi, T. (2011). Biochar reduces the bioavailability and phytotoxicity of heavy metals. *Plant Soil*, 348, 439-451.

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

Rutherford, D.W., Wershaw, R.L., & Cox, L.G. (2004). Changes in composition and porosity occurring during the thermal degradation of wood and wood components. *U.S. Geological Survey Scientific Investigations Report 2004-5292*, 78 p. (Also online at [http://pubs.usgs.gov/sir/2004/5292/.](http://pubs.usgs.gov/sir/2004/5292/))

Sohi, S. P., Lopez-Capel, E., & Bol, R. (2010). A review of biochar and its use and function in soil." *Advances in Agronomy*, 105, 47-82.

Sohi, S., Lopez-Capel, E., Krull, E., & Bol, R. (2009). Biochar, climate change and soil: A

review to guide future research. *CSIRO Land and Water Science Report 05/09*, 1-64.

Solaiman, Z.M., Murphy, D.V., & Abbott, L.K. (2012). Biochars influence seed germination and early growth of seedlings." *Plant Soil*, 353, 273-287.

Spokas, K. A., Baker, J. M., & Reicosky, D. C. (2010). Ethylene: Potential key for biochar amendment impacts. *Plant Soil*, 333, 443-452.

Spokas, K.A., Koskinen, W.C., Baker, J.A., & Reicosky, D.C. (2009). Impacts of woodchips biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. *Chemosphere*, 77, 547-581.

Taghizadeh-Toosi, A., Clough, T. J., Sherlock, R. R., & Condron, L. M. (2012). Biochar adsorbed ammonia is bioavailable. *Plant Soil*, 350, 57-69.

Uchimiya, M. Lima, I.M., Klasson, T., Chang, S., Wartelle, L.H., and Rodgers, J.E. (2010). Immobilization of heavy metal ions (CuII, CdII, NiII, and PbII) by broiler litter-derived biochars in water and soil. *Journal of Agricultural and Food Chemistry*, 58, 5538-5544.

United States Department of Agriculture. (April, 2010). *What is pyrolysis?* Retrieved from Biomass Pyrolysis Research at the Eastern Regional Research Center website: <http://www.ars.usda.gov/Main/docs.htm?docid=19898>

United States Drought Monitor. (2014.) United States Department of Agriculture. <http://droughtmonitor.unl.edu>. accessed 6 May 2014.

URS Australia Pty Ltd. (2009, July). *Oil mallee industry development plan for Western Australia*. Retrieved from the Forest Products Commission website: [http://www.fpc.wa.gov.au/content\\_migration/](http://www.fpc.wa.gov.au/content_migration/)

[ssets/documents/plantations/industry\\_plans/oil\\_mallee\\_idp.pdf](#).

Vaccari, F.P., Baronita, S., Lugator, E., Genesio, L., Castaldi, S., Fornasier, F., & Miglietta, F. (2011). Biochar as a strategy to sequester carbon and increase yield in durum wheat. *European Journal of Agronomy*, *34*, 231-238.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., Joseph, S., & Cowie, A. (2010) Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant Soil*, *327*, 235-246.

Wang, J., Zhang, M., Xiong, Z., Liu, P., & Pan, G. (2011). Effects of biochar addition on N<sub>2</sub>O and CO<sub>2</sub> emissions from two paddy soils. *Biology and Fertility of Soils*, *47*, 887-896.

Warnock, D.D., Lehmann, J., Kuyper, T. W. & Rillig, M. C. (2007). Mycorrhizal responses to biochar in soil – Concepts and mechanisms.” *Plant Soil*, *300*, 9-20.

Winsley, P. (2007). Biochar and bioenergy production for climate change mitigation. *New Zealand Science Review*, *64*(1), 5-10.

Wolterbeek, Mike. (2014.) “University research informs public, agencies on drought rezones: Rangeland, soil, forest, water and megadrought expertise helps Nevada, western U.S.” Nevada Today.  
<http://www.unr.edu/nevada-today/news/2014/university-drought-expertise>.  
accessed 6 May 2014.

Wolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *56*, 1-9.

Yamato, M., Okimori, Y., Wibowo, I.F., Anshori, S., & Ogawa, M. (2006). Effects of the application of charred bark in *Acacia mangium* on the yield of maize, cowpea, peanut and soil

chemical properties in south Sumatra, Indonesia. *Soil Science and Plant Nutrition*, *52*, 489-495.

Yu, X.Y., Ying, G.G., Kookana, R.S. (2009). Nitric acid digestion and multi-element analysis of plant material by inductively coupled plasma spectrometry. *Communications in Soil Science and Plant Analysis*, *18*, 131-146.



**Table 1: Biomass Feedstock Used in Research Studies**

<b>Authors &amp; Year</b>	<b>Pyrolysis Temperature</b>	<b>Biomass</b>
Beesley, L., & Marmioli, M. (2011)	400°C	Oak, common ash, sycamore, birch, cherry
Beesley, L., Moreno- Jiménez, E., & Gomez-Eyles, J. L. (2010)	Not specified	Hardwood (not further specified)
Chan, K. Y., Zwieten, L. V., Meszaros, I., Downie, A., & Joseph, S. (2007)	450°C	Greenwaste (plant pruning, grass clippings, cotton trash)
Chen, B., & Yuan, M. (2011)	100°C, 300°C, 400°C, 700°C, 1000°C	Pine Needles
Chen, C. R., Phillips, I. R., Condrón, L. M., Goloran, J., Xu, Z. H., & Chan, K. Y. (2013)	450°C	Greenwaste
Demirbas, A. (2004)	470°K, 550°K, 650°K, 750°K, 850°K, 950°K, 1,050°K	Olive husk, Corn cob, Tea Waste
Enders, A., Hanley, K., Whitman, T., Joseph, S. & Lehmann, J. (2012).	300°C to 600°C at 50°C increments	Bull manure, Corn stover, Dairy manure with rice hulls, Hazlenut shells, Oak wood, Pine wood, Poultry manure with sawdust, Grass clippings, Leaves, Brush (winter yard waste), Food waste, White paper mill sludge, Switchgrass, Soybean, Peanut, Kuikui. (varying types of some of these)
Ippolito, J.A., Novak, J. M., Busscher, W. J., Ahmedna, M., Rehrah, D., & Watts, D. W. (2012)	250°C and 500°C	Switchgrass
Koide, R. T., Petprakob, K., & Peoples, M. (2011)	Not specified	Domestic Hardwood (Brookville, PA)
Kwapinski, W., Byrne, C. M. P., Kryachko, E., Wolfram, P., Adley, C., Leahy, J. J., Novotny, E. H., & Hayes, M. H. B. (2010)	400°C to 600°C	Miscanthus, Pine, & Willow chips
Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., & Karlen, D. L. (2010)	Not specified	Mixed Hardwood (primarily Oak & Hickory)
Lin, Y., Munroe, P., Joseph, S., Kimber, S., & Zwieten, L. V. (2012)	550°C	Chicken Manure, Paper Sludge
Liu, P., Wu-Jun, L., Jiang, H., Chen, J., Li, W., & Yu- H. (2012)	723°K to 773°K	Rice Husk
Mullen, C. A., Boateng, A. A.,	500°C	Corn Cobs & Corn Stovers

Goldberg, N. M., Lima, I. M., Laird, D. A., & Hicks, K. B. (2010)		(stalks, leaves & husks- no cobs)
Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W., & Niandou, M. A. S. (2009)	170°C up to 700°C for 1 hour	Pecan Shells
Özcimen, D., Ersoy-Mericboyu, A. (2010)	Not Specified	Apricot Stone, Hazlenut Shell, Grapeseed, Chestnut Shell
Park, J. H., Choppola, G. K., Bolan, N. S., Chung, J. W., & Chuasavathi, T. (2011)	550°C	Chicken Manure, Green Waste
Quayle, W. C. (2010)	500°C to 650°C	Grapevine prunings, Orange tree prunings, Grape marc, Orange peel
Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010)	Not specified	Corn Stover, Yard Waste, Switchgrass Feedstocks
Smith, J.L., Collins, H.P., & Bailey, V.L. (2010)	500°C	Switchgrass
Solaiman, Z.M., Murphy, D.V., & Abbott, L.K. (2012)	Not specified	Oil Mallee, Rice Husks, New Jarrah, Old Jarrah, Wheat Chaff
Spokas, K.A., Baker, J.M., & Reicosky, D. C. (2010)	350°C, 400°C, 450°C, 500°C	Activated coconut charcoal, Hardwood sawdust, Macadamia nut, Dried distillers grain, Corn cobs, Mixed wood waste, Wood pellets, Peanut hulls
Spokas, K.A., Koskinen, W.C., Baker, J.A., & Reicosky, D.C. (2009)	500°C	Mixed Sawdust
Steinbeiss, S., Gleixner, G., & Antonietti, M. (2009)	Not specified	Glucose, Yeast
Taghizadeh-Toosi, A., Clough, T.J., Sherlock, R.R., & Condron, L.M. (2012)	300°C, 350°C, 500°C	Monterey Pine Wood Chips
Vaccari, F.P., Baronita, S., Lugator, E., Genesio, L., Castaldi, S., Fornasier, F., & Miglietta, F. (2011)	500°C	Coppiced woodlands (Beech, Hazel, Oak & Birch)
Wang, J., Zhang, M., Xiong, Z., Liu, P., & Pan, G. (2011)	350°C to 500°C	Rice Husks
Zimmerman, A.R., B. Gao, and M.Y. Ahn. (2011)	Not specified	Oak, Pine, Bubinga, Eastern gamma grass, Bagasse



# Appendix A

## Literature Review Summary

**\*note: most of the information contained here is taken directly from the articles referenced. All abstracts are taken directly from the articles referenced. Spellings reflect US English.**

Atkinson, Christopher J. and Jean D. Fitzgerald. 2010. "Potential Mechanisms for Achieving Agricultural Benefits from Biochar Application to Temperate Soils: A Review." *Plant Soil*. 337: 1-18.

**Abstract:** Natural organic biomass burning creates black carbon, which forms a considerable proportion of the soil's organic carbon. Due to black carbon's aromatic structure it is recalcitrant and has the potential for long-term carbon sequestration in soil. Soils within the Amazon-basin contain numerous sites where the 'dark earth of the Indians' (Terra preta de Indio, or Amazonian Dark Earths (ADE)) exist and are composed of variable quantities of highly stable organic black carbon waste ('biochar'). The apparent high agronomic fertility of these sites, relative to tropical soils in general, has attracted interest. Biochars can be produced by 'baking' organic matter under low oxygen ('pyrolysis'). The quantities of key mineral elements within these biochars can be directly related to the levels of these components in the feedstock prior to burning. Their incorporation in soils influences soil structure, texture, porosity, particle size distribution and density. The molecular structure of biochars shows a high degree of chemical and microbial stability. A key physical feature of most biochars is their highly porous structure and large surface area. This structure can provide refugia for beneficial soil micro-organisms such as mycorrhizae and bacteria, and influences the binding of important nutritive cations and anions. This binding can enhance the availability of macro-nutrients such as N and P. Other biochar soil changes include alkalization of soil pH and increases in electrical conductivity (EC) and cation exchange capacity (CEC). Ammonium leaching has been shown to be reduced, along with N<sub>2</sub>O soil emissions. There may also be reductions in soil mechanical impedance. Terra preta soils contain a higher number of 'operational taxonomic units' and have highly distinctive microbial communities relative to neighboring soils. The potential importance of biochar soil incorporation on mycorrhizal fungi has also been noted with biochar providing a physical niche devoid of fungal grazers. Improvements in soil field capacity have been recorded upon biochar additions. Evidence shows that bioavailability and plant uptake of key nutrients increases in response to biochar application, particularly when in the presence of added nutrients. Depending on the quantity of biochar added to soil significant improvements in plant productivity have been achieved, but these reports derive predominantly from studies in the tropics. As yet there is limited critical analysis of possible agricultural impacts of biochar application in temperate regions, nor on the likelihood of utilizing such soils as long-term sites for carbon sequestration. This review aims to determine the extent to which inferences of experience mostly from tropical regions could be extrapolated to temperate soils and to suggest areas requiring study.

**Theory:** review of literature

**Basic Hypothesis/Goal:** How well we can extrapolate tropical region biochar research to temperate soils and areas for future research?

**Biomass Used:** This is not detailed. However, it is noted that the physical and chemical properties of a biochar, along with method of pyrolysis, can largely influence its application on soil.

**Type of Study:** review

**Land/Agricultural Use:** Biochar in sandy soil enhanced in surface area (Liang et al, 2006). Porous nature of biochar creates a refuge for organisms and may also help with nutrient retention capacity. Biochar can induce soil alkalization, which in turn can increase soil nitrification (p. 7)

**Conclusions:** More research on temperate zones to determine stability of biochar in those soils is required. Biochar physical structure determines porosity and provides refuge for soil organisms like fungi and bacteria, which can improve soil health. Incorporating a biochar into a soil alters the soil's physical structure, chemistry, and biology.

Balat, Mustafa and Havva Balat. 2009. "Recent Trends in Global Production and Utilization of Bio-ethanol Fuel." *Applied Energy*. 86: 2273-2282.

**Abstract:** Bio-fuels are important because they replace petroleum fuels. A number of environmental and economic benefits are claimed for bio-fuels. Bio-ethanol is by far the most widely used bio-fuel for transportation worldwide. Production of bio-ethanol from biomass is one way to reduce both consumption of crude oil and environmental pollution. Using bio-ethanol blended gasoline fuel for automobiles can significantly reduce petroleum use and exhaust greenhouse gas emission. Bio-ethanol can be produced from different kinds of raw materials. These raw materials are classified into three categories of agricultural raw materials: simple sugars, starch, and lignocellulose. Bio-ethanol from sugar cane, produced under the proper conditions, is essentially a clean fuel and has several clear advantages over petroleum-derived gasoline in reducing greenhouse gas emissions and improving air quality in metropolitan areas. Conversion technologies for producing bio-ethanol from cellulosic biomass resources such as forest materials, agricultural residues and urban wastes are under development and have not yet been demonstrated commercially.

**Theory:** This article offers a review of literature as well as future thinking.

**Basic Hypothesis/Goal:** The goal of this article is examining trends of bioethanol/biofuel.

**Biomass Used:** This article discusses biomass as part of larger bio-ethanol options. 1) Sucrose-containing feedstock, 2) starchy materials, and 3) lignocellulosic biomass (wood, straw, grasses) are considered.

**Process:** Bioconversion of lignocellosics to bio-ethanol is difficult because the 1) resistant nature of biomass to breakdown, 2) the variety of sugars released when hemicellulose and cellulose polymers are broken resulting in the need to find or genetically engineer organisms to ferment sugars, and 3) the cost for collection/storage of low density lignocellulosic feedstocks. In order to process these feedstocks, 1) pretreatment, 2) hydrolysis, 3) fermentation, and 4) product separation/distillation is required. Refer to Table 6 p. 2278 for biomass compositions.

**Economics:** See table 3 for cost levels and comparisons of bio-ethanol yield from different energy crops. Table 4 includes land use as well. Agricultural residues (corn stover, wheat straw), wood, and energy crops are the most abundant reproducible resource on earth and such biomass could produce up to 442 billion liters/ per year of bio-ethanol.

**Conclusions:** Biochar is popular in part due to policies but popularity is also linked to potential future demand. Many countries are currently in various research stages. Biomass from lignocellulose is especially attractive in areas where cultivating energy crops would be hard and because it has the potential to also reduce food-versus-fuel concerns.

Barrow, C.J. 2012. "Biochar: Potential for Countering Land Degradation and for Improving Agriculture." *Applied Geography*. 34: 21-28.

**Abstract:** Biochar is attracting attention as a means for sequestering carbon and as a potentially valuable input for agriculture to improve soil fertility, aid sustainable production and reduce contamination of streams and groundwater. This study reviews biochar potential and problems and argues for adequate research before hasty application leads to environmental and socio-economic damage and discourages application. There is also a need for broad overview because research is conducted by a diversity of specialist fields including soil chemistry, archaeology, farming extension and so forth. Research on biochar-rich Amazonian dark earths may help identify the best raw materials (feedstock) and ways for producing biochar for agricultural use and countering land degradation.

**Theory:** This article considers the historical root of biochar via an interdisciplinary approach.

**Basic Hypothesis/Goal:** This article is mainly an overview of biochar and its possibilities.

**Biomass Used:** A wide variety from many regions/cultures are discussed.

**Conclusions:** Biochar may be viable, but we also must be wary of "ad hoc, sometimes not very scientific trials... [T]here is a need for broader interdisciplinary study" (p. 26)

Beesley, Luke and Marta Marmioli. 2011. "The Immobilization and Retention of Soluble Arsenic, Cadmium and Zinc by Biochar." *Environmental Pollution*. 159: 464-480.

**Abstract:** Water-soluble inorganic pollutants may constitute an environmental toxicity problem if their movement through soils and potential transfer to plants or groundwater is not arrested. The capability of biochar to immobilize and retain arsenic (As), cadmium (Cd), and zinc (Zn) from a multi-element contaminated sediment-derived soil was explored by a column leaching experiment and scanning electron microanalysis (SEM/EDX). Sorption of Cd and Zn to biochar's surfaces assisted a 300 and 45-fold reduction in their leachate concentrations, respectively. Retention of both metals was not affected by considerable leaching of water-soluble carbon from biochar, and could not be reversed following subsequent leaching of the sorbant biochar with water at pH 5.5. Weakly water-soluble As was also retained on biochar's surface but leachate concentrations did not duly decline. It is concluded that biochar can rapidly reduce the mobility of selected contaminants in this polluted soil system, with especially encouraging results for Cd.

**Theory:** The article considers column leaching and utilizes scanning electron microanalysis

**Basic Hypothesis/Goal:** The article evaluates efficacy and permanence of element retention by biochar of arsenic, cadmium and zinc.

**Biomass Used:** Oak, common ash, sycamore, birch, and cherry

**Process:** Soil from a canal bank in Kidsgrove, Staffordshire, UK, which has excessive levels of pollutants. Three (3) samples of 500 grams each were taken by hand and mixed together for use in column leaching tests. Samples were pre-treated with hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) to remove organic matter. Biochar was created at 400°C in steel ring furnaces, using six glass columns. Two of these had 400g of soil, while the other four were filled three-quarters full with biochar (the equivalent length of 400g of soil). Columns leached upwards at a 0.4ml per min flow rate. Two of the biochar amendments were linked to two soil columns to allow biochar to intercept contaminated eluate directly leached from the soil columns. The two other biochars were used as controls. After leaching, the samples were ground to a fine powder and then a scanning electron microscope with an Oxford X-ray detector was used to compare what remained.

**Statistics:** ANOVA

**Land/Agricultural Use:** Biochar rapidly and significantly reduced concentrations of cadmium and zinc (but not arsenic). Cadmium may have been reduced because the addition of biochar increased pH via increased alkalinity of eluate from soil. Testing three weeks later suggested the removal not easily reversed

**Conclusions:** Biochar can effectively reduce high concentrations of soluble cadmium and zinc from contaminated soil and these effects seem resilient to change even three weeks later.

Beesley, Luke, Eduardo Moreno-Jiménez, and Jose L. Gomez-Eyles. 2010. "Effects of Biochar and Greenwaste Compost Amendments on Mobility, Bioavailability and Toxicity of Inorganic and Organic Contaminants in a Multi-Element Polluted Soil." *Environmental Pollution*. 158: 2282-2287.

**Abstract:** Applying amendments to multi-element contaminated soils can have contradictory effects on the mobility, bioavailability and toxicity of specific elements, depending on the amendment. Trace elements and PAHs [polycyclic aromatic hydrocarbons] were monitored in a contaminated soil amended with biochar and greenwaste compost over 60 days field exposure, after which phytotoxicity was assessed by a simple bio-indicator test. Copper and As [Arsenic] concentrations in soil pore water increased more than 30 fold after adding both amendments, associated with significant increases in dissolved organic carbon and pH, whereas Zn and Cd significantly decreased. Biochar was most effective, resulting in a 10-fold decrease of Cd in pore water and a resultant reduction in phytotoxicity. Concentrations of PAHs were also reduced by biochar, with greater than 50% decreases of the heavier, more toxicologically relevant PAHs. The results highlight the potential of biochar for contaminated land remediation.

**Theory:** Biochar and greenwaste help reduce polluted soil

**Basic Hypothesis/Goal:** Is biochar more effective than greenwaste compost at reducing mobile and potentially bioavailable fractions of trace metals and As, and total the bioavailable fraction of PAHs in multi-element contaminated soil?

**Biomass Used:** Hardwood-derived by Bodfari charcoal in Denbigh, UK

**Process:** Soil was collected from a canal bank in Kidsgrove, Staffordshire UK with high trace metal content. Four treatment conditions were carried out in triplicate. The first was: 600ml soil per pot. The second was: Soil + Compost – 400 ml soil, 200ml compost. The third was: Soil + Biochar – 400ml soil, 200ml biochar. The fourth was: Soil + Biochar + Compost – 200ml of each. Pots were placed outdoors in Liverpool for 60 days with pore water being collected. These were analyzed with cyclodextrin extractions as well as a shoot emergence test.

**Statistics:** ANOVA

**Land/Agricultural Use:** Shoot emergence was increased; PAH, cadmium, zinc were reduced.

**Conclusions:** Both biochar and greenwaste compost reduced acidity significantly with the combination of the two having the greatest pH increase. Biochar had no effect on water-soluble nitrogen and concentrations of DTN in pore water. Water extractable trace metals were significantly affected by amendments. Amendments reduced water extractable cadmium but enhanced water extractable As and Cu. Biochar treatment most effective for reducing concentrations of total and bioavailable PAH groups. Both increase shoot emergence (from 61% to 78%). "Biochar has greater potential to beneficially reduce bioavailability of both organic and inorganic contaminants than greenwaste compost in this multi-element contaminated soil, being especially effective at reducing phytotoxic concentrations of water-soluble Cd and Zn as well as heavier PAH groups" (p. 2286).

Brick, Stephen. 2010. "Biochar: Assessing the Promise and Risks to Guide U.S. Policy." *National Resources Defense Council Issue Paper*.

**Abstract:** In this report, we describe biochar production pathways, energy co-products resulting from biochar production and their potential uses, assess the key environmental risks associated with biochar production and utilization systems, discuss estimates of global technical and economic potential for biochar production and carbon sequestration, and give a brief overview of existing domestic and international policies on biochar.

**Basic Hypothesis/Goal:** This article is an overview of biochar production technologies and the potential environmental concerns associated with production and use of biochar.

**Biomass Used:** The biomass used was separated into two categories: 1) produced biomass grown for purpose of being used as a bioenergy or char and 2) waste biomass. See TABLE 2 for a list of feedstocks in recent studies with sources

**Pyrolysis Facility Details:** This article considers three biochar conversion systems: 1) small, mobile systems for char production; 2) larger-scale pyrolysis and gasification units; and 3) hydrothermal Char can be produced with this chemical process at low temperatures (200°C) and fairly short processing times. SEE TABLE 4 for nice table on ISSUES ASSOCIATED WITH BIOCHAR PROCESSES

**Economics:** The article suggests that there is a need to consider cost and emissions from producing biomass for biochar. Using bio-wastes could be the better option and may reduce the disposal cost incurred by producers, however the price currently for disposal of biomass is either unpriced or underpriced.

**Climate Change:** This may depend on the type of biomass used. Switchgrass was found to be greenhouse-gas positive depending on how land-use change is accounted for (Roberts et al, 2010). It is suggested that the role in mitigating global climate change depends on: 1) the answer to what portion of the sustainably produced biomass resource is assumed to be devoted to biochar systems (many promising biomass technologies that will compete for the same resources); 2) what are the comparative economics of competing products produced from biomass (transportation fuels, bio-based chemicals, etc.); 3) what is the market price for carbon; 4) how stable is the carbon market; and 5) how high are hurdles for claiming carbon credits. Development has been challenged because only the energy output can be priced with relative accuracy out of the many biochar proposed benefits. Harvesting would be required of some residual biomass like forestry and crop residue, so the best option might be sewage sludge and animal manure, which already need to be disposed of properly because of toxic threat to water and air.

**Emissions Reduction:** This article estimates carbon mitigation from biochar systems at twelve percent of global emissions (1.8 billion tons/yr), assuming high percentages of sustainably produced biomass are used in biochar conversion systems not accounting for economic, social or cultural barriers against adoption. Other competing bioenergy systems would yield ten percent mitigation.

**Environmental Concerns:** First is the direct effect when land converted from forest, pasture, conservatory to produce energy crops. A chain reaction caused when land use in one nation changes agriculture internationally and spurs conversion somewhere else is also a potential indirect effect. Additionally, the loss of biodiversity through cultivating energy crops is a concern. See Table 1 (p 3) for a list of biomass feedstocks with energetic and environmental issues. There are also concerns associated with the collection and transportation of emissions including what happens if some is lost or breathed in, or if there is a diversion of crop residues from soil. During conversion, particulate emissions (especially in small units), climate relevant black carbon components, human health, and supplemental energy use also all pose concern.

Within application, loss of biochar during transport and application, soil carbon loss due to biochar incorporation, phytotoxicity, and recalcitrance of bio-char based soil carbon pose concern.

**Other Concerns with Biochar Production and Utilization:** There are a number of these: 1) shortage of pilot/commercial-scale BPUs, especially slow pyrolysis; 2) critical shortage biochar for field testing; 3) inadequate characterization of production-related emissions; 4) fugitive loss of biochar during transport and application; 5) evidence that biochar can be lost during transportation and, if airborne, can be a climate forcer; 6) carbon loss from soil disturbance during biochar; and 7) monitoring and verification of terrestrial offsets from biochar application

**Conclusions:** More research and some larger field trials, which would cost between \$100 - \$150 million, are required to get better baseline data on production systems and provide a good, large source of biochar nationally



Chan, K.Y., et al. 2007. "Agronomic Values of Greenwaste Biochar as a Soil Amendment." *Australian Journal of Soil Research*. 45: 629-634.

**Abstract:** A pot trial was carried out to investigate the effect of biochar produced from greenwaste by pyrolysis on the yield of radish (*Raphanus sativus* var. Long Scarlet) and the soil quality of an Alfisol. Three rates of biochar (10, 50 and 100 t/ha) with and without additional nitrogen application (100 kg N/ha) were investigated. The soil used in the pot trial was a hardsetting Alfisol (Chromosol) (0–0.1 m) with a long history of cropping. In the absence of N fertiliser, application of biochar to the soil did not increase radish yield even at the highest rate of 100 t/ha. However, a significant biochar × nitrogen fertiliser interaction was observed, in that higher yield increases were observed with increasing rates of biochar application in the presence of N fertiliser, highlighting the role of biochar in improving N fertiliser use efficiency of the plant. For example, additional increase in DM of radish in the presence of N fertiliser varied from 95% in the nil biochar control to 266% in the 100 t/ha biochar-amended soils. A slight but significant reduction in dry matter production of radish was observed when biochar was applied at 10 t/ha but the cause is unclear and requires further investigation. Significant changes in soil quality including increases in pH, organic carbon, and exchangeable cations as well as reduction in tensile strength were observed at higher rates of biochar application (>50 t/ha). Particularly interesting are the improvements in soil physical properties of this hardsetting soil in terms of reduction in tensile strength and increases in field capacity.

**Basic Hypothesis/Goal:** The goal is to determine the effect of biochar from greenwaste by pyrolysis on yield of radish and soil quality of an Alfisol.

**Biomass Used:** greenwaste (plant pruning, grass clippings & cotton trash)

**Process:** Soil was collected from the Flat Paddock Centre for Recycled Organic in Agriculture site. The soil had a low organic carbon concentration, was acidic with a pH of 4.5. The biochar was alkaline in nature, high in total carbon but low in total nitrogen (1.3g/kg) with C/N of 200 and low mineral nitrogen (<.5 mg/kg). The study was conducted in a temperature-controlled greenhouse with a factorial randomized block design with five replications. Four biochar rates (0, 10, 50, 100 t/ha, respectively) combined with two nitrogen fertilizer rates (0, 100 kg/ha, respectively) were used. Air-dried soil and biochar-amended soils were packed into pots and watered with de-ionized water. Ten radish seeds were planted in each pot and thinned to five seedlings. After six weeks the whole radish plants were harvested, washed with de-ionised water, and oven dried at 70°C to weigh. The soil was then air-dried and ground to pass through a 2mm sieve for analysis of pH, total carbon, total nitrogen, extractable phosphorus, and exchangeable cations. Soil hardsetting-ness was also measured.

**Statistics:** 2 way anovas,  $p < .05$

**Crop Detail:** Without nitrogen fertilizer, radish production was lower than the nil biochar control. When nitrogen was included, a significant radish yield was observed in all treatments (including nil biochar control), and a significant interaction between biochar application and the nitrogen fertilizer addition was seen. The amount of radish with nitrogen addition was much higher in biochar amended soils; magnitude of yield increased with the application rate of biochar. The amount of radish due to N fertilizer varied from 95% in the control to 266% in the 100t/ha biochar amended soil. There was an additional yield increase as a result of increased biochar application for rates [greater than] 20 t/ha which could not solely be attributed to addition of nitrogen fertilizer. The radishes had significantly higher levels of nitrogen when the nitrogen fertilizer was applied. Biochar application increased P, K, and Ca but not Mg concentration in the plants and significant differences only in 50 or 100 t/ha when no N applied.

**Pyrolysis Facility Details:** 450°C temperature pyrolysis plant by BEST Energies Australia.

**Fertilizer Efficiency:** Fertilizer was found to be most efficient when combined with higher levels of biochar.

**Soil Details:** Soil properties changed with biochar application. Level of pH, organic carbon, exchangeable Na, K, and Ca, as well as extractable P were increased, but amount exchangeable Al was decreased. Changes were roughly proportional in magnitude to application of biochar, but statistical difference was only evident at higher levels, 50 and 100 t/ha. Tensile strength of hardsetting decreased with biochar application but was again only significant at higher rates of application. The same was noted regarding field capacity. The highest microbial content occurred in the control. When N was applied, FDA was higher in biochar amended than the nil biochar control soil, except for 10 t/ha treatment.

**Conclusions:** Greenwaste biochar had potential in increasing nitrogen fertilizer use efficiency. There was also improvement in the physical conditions after biochar amendment - tensile strength was reduced and field capacity water content was increased. Only the combination of N fertilizer and biochar improved soil and increased yield. Soil quality also increased pH, organic carbon, and exchangeable cations, as well as reduced tensile strength at higher rates of biochar application.

Chen, Baoliang and Miaoxin Yuan. 2011. "Enhanced Sorption of Polycyclic Aromatic Hydrocarbons by Soil Amended with Biochar." *Journal of Soil Sentiments*. 11: 62-71.

**Abstract:** *Purpose:* Polycyclic aromatic hydrocarbon (PAHs) are ubiquitous pollutants in agricultural soils in China. Biochar is the charred product of biomass pyrolysis, which is widely applied to soils to sequester atmospheric carbon dioxide and guarantees a long-term benefit for soil fertility. Knowledge about the impacts of various biochars on soil sorption affinity remains obscure. In this study, we evaluated the effects of various biochars on PAHs sorption to biochar-amended agricultural soil.

*Materials and methods:* Biochar of pine needle were produced under different pyrolytic temperatures (100°C, 300°C, 400°C, and 700°C, referred as P100-P700) and inputted into a paddy soil with various content. A batch equilibration method was used to determine sorption of PAHs (naphthalene, phenanthrene, and pyrene) in biochar amendment treated and untreated soil. The effects of biochar on PAHs sorption in biochar-amended soil were discussed.

*Results and discussion:* Biochars impose different effects on PAHs sorption by biochar-amended soil. P100 added to soil increased the linearity of sorption isotherm due to the linear-type isotherm of P100. While the nonlinearity of sorption isotherm for P300, P400, and P700 amended soil were increased with the increase of biochar content in soil. Biochar produced under high pyrolytic temperature demonstrated high efficiency in improving the sorption affinity of biochar-amended soil, and the total sorption were largely controlled by biochar when P300 content was larger than 0.5%, and P400 and P700 content above 0.1%. The predicted sorption of soil amended with P100 and P300 was consistent with their experimental values. However, for P400 and P700 amended soil, the actual sorption was lower than the predicted.

*Conclusions:* The results show that added biochar into soil may enhance the sorption of PAHs to soil, thus provide a theoretical reference to apply biochar to mitigating the PAHs-contaminated soils through transferring PAHs from soil to biochar.

**Basic Hypothesis/Goal:** The goal of this article is to determine the effect of various biochars on PAHs sorption to biochar-amended soil.

**Biomass Used:** Pine needle.

**Amount of Dry Biomass:** The biochar used was produced under different pyrolytic temperatures (100°C, 300°C, 400°C, and 700°C). Biochar content was set to 0.1, 0.5, 1, 2, and 5wt% for P100, P300, P400 samples, while 0.1, 0.2, 0.5, 1, and 2 wt% for P700.

**Type of Study:** lab

**Process:** Paddy soil was collected from a Chinese campus presumed to have minimal biochar levels. This was dried and passed through a 0.154mm sieve. A biochar sample also sent through a sieve of the same size. Biochar was mixed with soil for two days for uniformity. Biochar was amended at 0.1, 0.5, 1, 2, and 4 wt.% for P100, 300 and 400 samples, and 0.1, 0.2, 0.5, 1 and 2 wt% for P700. Naphthalene, phenanthrene, and pyrene were chosen as PAHs because they are widely distributed in contaminated soil and a sorption experiment was conducted for all biochar-amended soils.

**Statistics:** Regression

**Pyrolysis Facility Details:** Facility on Huajiachi campus, Zhejiang University, China?? Biochars were produced via pyrolyzing pine needle at various temperatures (100 C, 300 C, 400C, 700 C)

**Soil Details:** The paddy soil used in this study was collected from the Huajiachi campus, Zhejiang University, China. The soil, without records of crop residue burning and industrial input, was presumed to contain minimal levels of biochar. The soil was dried and passed through a 0.154 mm sieve.

**Economics:** Cost still needs to be studied. The results provide a theoretical reference to apply biochar to mitigating PAH-contaminated soils through increasing soil sorption and capacity, but more studies about the cost, social implications, and legal requirements (related to clean up levels) are needed to implement biochar-based mitigation technologies.

**Land/Agricultural Use:** Application of biochar to soil may enhance the sequestration of atmospheric carbon dioxide and guarantees a long-term benefit for soil fertility. In addition, biochar-mimicking BC offers a critical binding phase for organic pollutants in the environment because of its high sorption affinity and recalcitrance to microbial decomposition.

**Conclusions:** Sorption of PAHs in soil was significantly enhanced by the biochar amendment, which was dependent on the biochar structure, content, and the sorbate concentration. Absorption with P100 was linear although soil amended with P300-P700 had enhanced sorption that was nonlinear, and the nonlinearity increased with increasing biochar content. There was an attenuation effect for the P400 and P700 amended soil, which was especially evident in low sorbate concentrations, hypothesized to be a result of soil native organic compounds competing or blocking the adsorption sites of the biochar.

Chen, C.R., et al. 2013. "Impacts of Greenwaste Biochar on Ammonia Volatilisation from Bauxite Processing Residue Sand." *Plant Soil*. 367: 301-312.

**Abstract: Background and Aims:** The objective of this study was to test the suitability of greenwaste biochar to aid nitrogen (N) retention in rehabilitated bauxite-processing residue sand (BRS).

**Methods:** Bauxite residue sand was collected from the Alcoa of Australia Pinjarra refinery. The pH of BRS was adjusted to values of 5, 7, 8 and 9 and subsequently amended with different rates (1, 5, 10 and 20%, w/w) of greenwaste biochar. The loss of N via  $\text{NH}_3$  volatilization following addition of di-ammonium phosphate (DAP) was determined using an acid trapping method.

**Results:** At low pH (5), increasing pH rather than adsorption capacity, resulting from biochar addition, caused greater losses of N through volatilization from BRS. In BRS with medium pH (7, 8), increasing adsorption capacity, induced by biochar addition, played the more dominant role in enhancing adsorption of  $\text{NH}_4\text{-N}/\text{NH}_3\text{-N}$  and lowering  $\text{NH}_3$  volatilization. In the BRS with high pH (9), the majority of  $\text{NH}_4\text{-N}/\text{NH}_3\text{-N}$  pools was lost via  $\text{NH}_3$  volatilization due to the strong acid-base reaction at this pH. **Conclusions:** It is concluded that the interaction of changes in pH and adsorption capacity induced by greenwaste biochar addition affects the availability and dynamics of  $\text{NH}_4\text{-N}/\text{NH}_3\text{-N}$  in BRS amended with DAP.

**Basic Hypothesis/Goal:** The goal of this article was to test the suitability of greenwaste biochar to aid nitrogen retention in rehabilitated bauxite-processing residue sand.

**Biomass Used:** greenwaste (plant pruning, grass clippings & cotton trash)

**Type of Study:** lab

**Process:** Soil was taken from an area after bauxite refinement, which had high alkalinity, high salinity, poor nutrient availability, high hydraulic conductivity, and low nutrient retention capacity. Greenwaste biochar had a high total C, Colwell P, and pH, but a low total of N, low ammonium nitrate, low  $\text{NO}_3\text{-N}$  and CEC and exchangeable Na. One percent calcium sulphate was added to the soil sample and the pH was adjusted to 5.2, 7.1, 8.1, or 9.1. Distilled water was adjusted to a 55% water holding capacity after adjusting for di-ammonium phosphate added.  $\text{NH}_3$  (ammonia) volatilization was measured multiple times. Biochar at rates of 0, 1, 5, 10 and 20% of BRS was applied.

**Statistics:** two-way ANOVA

**Pyrolysis Facility Details:** Pyrolysis was conducted at a 450°C temperature pyrolysis plant by BEST Energies Australia.

**Land/Agricultural Use:** If mining bauxite, depending on the pH in the Bauxite residue sand, biochar may enhance adsorption of  $\text{NH}_4\text{-N}/\text{NH}_3\text{-N}$  and lower ammonia volatilization.

**Conclusions:** Significant interactions between pH and biochar addition for cumulative  $\text{NH}_3$  volatilization, extractable  $\text{NH}_4\text{-N}$ , N recovery percentage and un-extracted N.  $\text{NH}_3$  volatilization from BRS of different pH values (5, 7, 8, 9) respond differently to biochar addition. At pH-5,  $\text{NH}_3$  volatilization increased due to biochar's increasing of the pH (rather than adsorption capacity), leading to lower availability of  $\text{NH}_4\text{-N}$  for adsorption. In BRS with medium pH, increasing adsorption did play a role through biochar addition (over that of pH) in enhancing adsorption of  $\text{NH}_4\text{-N}/\text{NH}_3\text{-N}$  and lowering  $\text{NH}_3$  volatilization. At the highest pH level (9), most of the  $\text{NH}_4\text{-N}/\text{NH}_3\text{-N}$  pools were lost through  $\text{NH}_3$  volatilization due to strong acid-base reaction at this pH.

Demirbas, Ayhan, Erol Pehlivan, and Turkan Altun. 2006. "Potential Evolution of Turkish Agricultural Residues as Bio-Gas, Bio-Char and Bio-Oil Sources." *International Journal of Hydrogen Energy*. 31: 613-620.

**Abstract:** A study has been conducted to evaluate the potential power production from the pyrolysis for bio-oil and bio-char, and anaerobic digestion (for bio-gas), of agricultural residues in Turkey. Agricultural residues are potential renewable energy resources such as bio-gas from anaerobic digestion, bio-oil from pyrolysis, and bio-char from carbonization and slow pyrolysis processes. Anaerobic bio-gas production is an effective process for conversion of a broad variety of agricultural biomass to methane to substitute natural gas and medium calorific value gases. When the pyrolysis temperature increased the bio-char yield decreased. The bio-char yield increased with increasing particle size of the sample. Thermochemical conversion processes of biomass are the most common and convenient methods for conversion into energy. Among the processes of energy production from biomass, pyrolysis is the most popular thermal conversion process.

**Basic Hypothesis/Goal:** The goal of this study was to evaluate the potential power production from the pyrolysis for bio-oil and bio-char and anaerobic digestion for bio-gas of agricultural residues in Turkey.

**Biomass Used:** walnut shell, hazelnut shell, tea waste, almond shell, corncob, corn stover, cotton stalk, wheat straw, olive husk, rice straw, sunflower shell, sugarcane bagasse, rapeseed cake

**Type of Study:** lab

**Process:** The experiment process in this study began with manure/straw mix digestion. During the 30-day digestion period, 80-85% of bio-gas was found to be produced in the first 15-18 days. The study also considered effects of different biomass on biochar production. The presence of moisture can increase char yield between 660-730<sup>o</sup>K especially with kraft lignin. Bio-oil can be produced with flash pyrolysis but poor thermal stability and corrosivity of the oil are problematic in the conversion process.

**Biofuel Advantages:** Biomass firing (compared to coal) helps reduce total emissions per unit energy produced.

**Conclusions:** Anaerobic bio-methane production is effective to convert a broad variety of agricultural residues to methane to substitute natural gas and medium calorific value gases. Biochar requires lower temperatures and larger particle sizes

Demirbas, Ayhan. 2004. "Effects of Temperature and Particle Size on Bio-Char Yield from Pyrolysis of Agricultural Residues." *Journal of Analytical and Applied Pyrolysis*. 74: 243-248.

**Abstract:** This article deals with slow pyrolysis of agricultural residues such as olive husk, corncob and tea waste at high temperature (950–1250 K) in a cylindrical reactor batch reactor. The aim of this study was to experimentally investigate how different residues utilizing strategies affect the treatment conditions such as temperature, particle size, and lignin and inorganic matter contents on bio-char yield and reactivity. When the pyrolysis temperature is increased, the bio-char yield decreases. The bio-char yield increased with increasing particle size of the sample. A high temperature and smaller particles increase the heating rate resulting in a decreased bio-char yield. The higher lignin content in olive husk results in a higher bio-char yield comparison with corncob. Bio-char from olive husk was more reactive in gasification than bio-char from corncob because of the higher ash content.

**Basic Hypothesis/Goal:** The goal of this article was to study the effect of the treatment conditions such as temperature, particle size, and lignin and inorganic matter contents on bio-char yield.

**Biomass Used:** olive husk, corncob, and tea waste from the Black Sea region in Turkey

**Type of Study:** lab

**Process:** The process used heated samples at different temps: 470, 550, 650, 750, 850, 950 and 1050K. Chemical analysis on the residue was performed (see Table 2). Corncob had the highest volatile matter content. Generally biochar yield quickly decreases as temperature of pyrolysis increased. Temperatures under 575K gave higher biochar yield through degradation of cellulose to more stable anhydrocellulose. Above that temperature, cellulose depolymerizes and creates volatiles. So the effect of heating rate is stronger in pyrolysis of biomass than in coal.

**Pyrolysis Facility Details:** The pyrolysis facility used a cylindrical reactor of height 95.1mm, i.d 17.0mm, and o.d. 19.0mm heated externally by an electric furnace with temperature controlled by a thermocouple inside the reactor. Temperature of 450-1250K was reached at a 10K per second heating rate to get the bio-char

**Conclusions:** The authors argue that it is the higher cellulose content of biomass compared to coal for why there is a stronger effect of heating rate during pyrolysis. Carbon increases with pyrolysis temperature, while hydrogen and oxygen decrease. Lignin (higher in olive husk) gives a higher yield compared to oak wood and what straw. For high char production, low temperature and a low heating rate process would be chosen. Biochar yield also increased with increasing particle size of the sample.



Demirbas, Ayhan. 2008. "Biofuels Sources, Biofuel Policy, Biofuel Economy and Global Biofuel Projections." *Energy Conversion and Measurement*. 49: 2106-2116.

**Abstract:** The term biofuel is referred to liquid, gas and solid fuels predominantly produced from biomass. Biofuels include energy security reasons, environmental concerns, foreign exchange savings, and socioeconomic issues related to the rural sector. Biofuels include bioethanol, biomethanol, vegetable oils, biodiesel, biogas, bio-synthetic gas (bio-syngas), bio-oil, bio-char, Fischer-Tropsch liquids, and biohydrogen. Most traditional biofuels, such as ethanol from corn, wheat, or sugar beets, and biodiesel from oil seeds, are produced from classic agricultural food crops that require high-quality agricultural land for growth. Bioethanol is a petrol additive/substitute. Biomethanol can be produced from biomass using bio-syngas obtained from steam reforming process of biomass. Biomethanol is considerably easier to recover than the bioethanol from biomass. Ethanol forms a azeotrope with water so it is expensive to purify the ethanol during recovery. Methanol recycles easier because it does not form an azeotrope. Biodiesel is an environmentally friendly alternative liquid fuel that can be used in any diesel engine without modification. There has been renewed interest in the use of vegetable oils for making biodiesel due to its less polluting and renewable nature as against the conventional petroleum diesel fuel. Due to its environmental merits, the share of biofuel in the automotive fuel market will grow fast in the next decade. There are several reasons for biofuels to be considered as relevant technologies by both developing and industrialized countries. Biofuels include energy security reasons, environmental concerns, foreign exchange savings, and socioeconomic issues related to the rural sector. The biofuel economy will grow rapidly during the 21st century. Its economy development is based on agricultural production and most people live in the rural areas. In the most biomass-intensive scenario, modernized biomass energy contributes by 2050 about one half of total energy demand in developing countries

**Basic Hypothesis/Goal:** Why use biomass?

**Process:** Biomass compared to other renewable energy sources can provide solid, liquid, and gas fuels that can be stored, transported, and used globally. Bio-oil is mainly a liquid fuel made from biomass materials as a by-product of thermochemical process. Pyrolysis can be used to create it and is in the pilot stage. Pyrolysis produces high fuel-to-feed ratios and is thus the most efficient process for biomass conversion.

**Economics:** The article discusses projections for how much need there will be in the future, in part based on policies.

**Alternative Biomass Uses:** The article discusses many in depth.

**Conclusions:** Biofuel may be a very useful, possibly inexhaustible source of energy.



Demirbas, Ayhan. 2009. "Political, Economic and Environmental Impacts of Biofuels: A Review." *Applied Energy*. 86: 5108-5117.

**Abstract:** Current energy policies address environmental issues including environmentally friendly technologies to increase energy supplies and encourage cleaner, more efficient energy use, and address air pollution, greenhouse effect, global warming, and climate change. The biofuel policy aims to promote the use in transport of fuels made from biomass, as well as other renewable fuels. Biofuels provide the prospect of new economic opportunities for people in rural areas in oil importer and developing countries. The central policy of biofuel concerns job creation, greater efficiency in the general business environment, and protection of the environment. Projections are important tools for long-term planning and policy settings. Renewable energy sources that use indigenous resources have the potential to provide energy services with zero or almost zero emissions of both air pollutants and greenhouse gases. Biofuels are expected to reduce dependence on imported petroleum with associated political and economic vulnerability, reduce greenhouse gas emissions and other pollutants, and revitalize the economy by increasing demand and prices for agricultural products.

**Basic Hypothesis/Goal:** Biofuels can be a more sustainable energy source.

**Biomass Used:** See table 6 for list with cost per ton.

**Economics:** See Table 1. The article considers sustainability, fuel diversity, increased number of rural manufacturing jobs, increased income taxes, increased investments in plant and equipment, agricultural development, international competitiveness, and reduced dependency on imported petroleum. Costs for biodiesel production include capital cost, plant capacity, process technology, raw material cost, and chemical cost. Feedstock is about 75-80% of the total operating cost, in addition to labor, methanol, and catalyst (added to feedstock).

**Biofuel Advantages:** 1) easily available from common biomass sources; 2) represents the carbon dioxide-cycle in combustion; 3) considerable environmentally friendly potential; 4) benefits to the environment, economy, and consumers in using them; and 5) they are biodegradable and contribute to sustainability

**Conclusions:** Biofuel can be an excellent option in a world of increased cost and decreased supply of petroleum. Costs for production vary widely depending on feedstock, conversion process, scale of production, and region. Europe has sustainability and biodiversity criteria related to biofuel.

Ippolito, James A., David A. Laird, and Warren J. Busscher. 2012. "Environmental Benefits of Biochar." *Journal of Environmental Quality*. 41: 967-972.

**Abstract:** Understanding and improving environmental quality by reducing soil nutrient leaching losses, reducing bioavailability of environmental contaminants, sequestering C, reducing greenhouse gas emissions, and enhancing crop productivity in highly weathered or degraded soils, has been the goal of agro-ecosystem researchers and producers for years. Biochar, produced by pyrolysis of biomass, may help attain these goals. The desire to advance understanding of the environmental and agronomic implication of biochar utilization led to the organization of the 2010 American Society of Agronomy–Soil Science Society of America Environmental Quality Division session titled "Biochar Effects on the Environment and Agricultural Productivity." This specialized session and sessions from other biochar conferences, such as the 2010 U.S. Biochar Initiative and the Biochar Symposium 2010 are the sources for this special manuscript collection. Individual contributions address improvement of the biochar knowledge base, current information gaps, and future biochar research needs. The prospect of biochar utilization is promising, as biochars may be customized for specific environmental applications.

**Climate Change:** The author believes biochar is an effective sequestering agent of C in soils, however net greenhouse gas (GHG) impact to biochar application also depends on crop productivity, increases in efficiency of residue mineralization or humification, soil organic matter cycling, and emissions of methane and nitrous oxide. This is all in addition to biochar production, transport, and soil application

**Other Concerns with Biochar Production and Utilization:** Placing biochars where they could intercept runoff or groundwater with other nutrients or contaminants could be more beneficial than uniformly spreading it on fields. All impacts considered are short-term.

**Conclusions:** The type of feedstock, pyrolytic process, and pyrolytic conditions influence biochar in turn influencing environment and agronomic impacts of application. Ideally the authors would choose a biochar for a specific environment or agronomic application.

Ippolito, James A., et al. 2012. "Switchgrass Biochar Affects to Aridisols." *Journal of Environmental Quality*. 41: 1123-30.

**Basic Hypothesis/Goal:** The goal of this article is to identify changes in acidic soil fertility status and nutrient leaching with a low pH biochar produced at relatively low temperatures as compared with a high pH biochar produced at high temperatures

**Biomass Used:** Air-dried switchgrass from a field in 4th year growing at Clemson University, South Carolina.

**Type of Study:** lab

**Process:** A Delco series of soil was taken from Aberdeen, Idaho where field crops were grown under irrigation with a 3 year barley, wheat, and potato rotation. A Warden series was also collected from a depth of 0 - 20cm in Prosser, Washington where crops were grown on a 3 year rotation of alfalfa, corn, and wheat. Biochar was mixed at 2% (w/w) into the Declo or Warden soil at a rate equivalent to 24 Mg ha<sup>-1</sup> assuming a 10cm application depth and bulk density of 1.2 g cm<sup>3</sup> (there was also a control). 450g soil mixtures were potted with each treatment replicated three times. Soil moisture was held at 15% throughout the experiment and all pots were kept at room temperature throughout the experiment. Each pot was leached on Days 34, 62, 92, and 127 using 1.2 to 1.3 pore volumes of de-ionized water.

**Statistics:** ANOVA using Proc GLM in SAS (significance level of p<0.05)

**Pyrolysis Facility Details:** Used slow pyrolysis (1-3 hrs) under N<sub>2</sub> gas stream at 250 or 500C. Ground down to pass through a 1-2 mm sieve.

**Findings:** There was a decrease in leachate Ca and Mg content under 250C switchgrass biochar – low-temperature biochars may have more surface functional groups to act as nutrient retention sites. Leachate K increased at both temperatures for the Declo soil and at 500C for the Warden soil. Leachate P content increased two to three times with the 500°C biochar compared to 250°C biochar or the control.

**Soil Details:** Arid soil in this study was compared with a less arid soil at two different biochar temperatures.

**Potential Relevance for Arid Soils:** This study looks at Aridisols (which is a desert soil classification).

**Conclusions:** 250°C switchgrass biochar application decreased Ca and Mg leaching, increased K leaching, and increased Mn and Ni soil-extractable concentrations (likely due to greater total negative surface charge at the 250°C temperature favoring divalent cation sorption). NO<sub>3</sub>-N leaching and soil concentrations reduced at the 250°C temperature also likely due to microbial immobilization. It seems like the switchgrass biochar at the 250°C temperature helped improve Aridisol soil nutrient status while reducing leaching losses that could adversely affect environmental quality.

Jeffrey, S., et al. 2011. "A Quantitative Review of the Effects of Biochar Application to Soils on Crop Productivity Using Meta-Analysis." *Agriculture, Ecosystems and Environment*. 144: 175-187.

**Biomass Used:** Significant positive effects were found for wood, paper pulp, wood chips and poultry litter (at 450°C and 550°C). There was also a negative effect on crop production for bio-solids. Other biomass used yielded no statistically significant effect on crop production.

**Process:** The various pH levels were collapsed into three categories: very acidic (pH<5), neutral (5<pH<6), and acidid pH>6. Three soil textures (fine, medium, coarse) were utilized.

**Statistics:** This analysis performed a meta-analysis of other studies had a control defined as identical to experimental but did not have biochar. It also focused on studies that considered biochar and crop productivity or crop production or crop yield before March 1, 2010. Both pot and experimental studies were used as long as quantitative results were reported. Data normalized by square root transformation and effect size was calculated using MetaWin vers 2.

**Findings:** An application rate of any t/ha-1 was found to significantly increase crop productivity compared to the control. A significant increase in crop productivity occurred when biochar was added to acidic or neutral soil (though not with very acidic soil). Crop productivity was found to be significantly better with biochar when soil was medium or coarse in texture; no difference was found for fine-textured soil. Increased crop productivity was significant for radish and soybean when biochar was added, while the opposite was true for rye-grass. Other crops yielded no statistically significant results. Both pot and field trials had a significant positive effect, with crop productivity in the pot trials three times greater than field trials.

**Fertilizer Efficiency:** No statistically significant effect of biochar application to soil was found between groups (as grouped by fertilizer addition) regardless of whether fertilizer was applied concurrently or whether organic or inorganic fertilizer was used.

**Potential Relevance for Arid Soils:** Five studies were in the neutral pH category, which arid soils tend to have

**Climate Change:** This article posited that since residence time of carbon reactive protein residue is only decades, while the residue of biochar would remain for hundreds to thousands of years, CO<sub>2</sub> released back into the atmosphere would be decreased via the use of biochar. This depends, however, on whether other greenhouse gas emissions from soils are elevated when biochar is applied and we must also take into account the fact that production and transport of biochar and feedstock don't offset sequestered C. (Roberts et al, 2010). The feedstock required to convert to biochar is dependent on the C retention (ratio of C in biochar over C in initial dry biomass feedstock). Via slow pyrolysis, 49% carbon retention was achieved at atmospheric pressure. Higher C retention resulted in less stable biochar (with a residence time of 4-29 years) (Woolf et al, 2010).

**Other Concerns with Biochar Production and Utilization:** Over 90% of studies in the meta-analysis showed results over only 1 growing season. Additionally, field trials pose a concern because one cannot truly anticipate, account for, or control all environmental variables in an experimental design such as meteorological factors and annual or inter-annual variability. These limitations reduce our ability to extrapolate from the available field trial studies and thus reduce our ability to make future predictions.

**Biofuel Advantages:** The biofuel advantages suggested by this article are: 1) the potential to mitigate climate change; 2) the provision of a method for organic waste disposal; and 3) the potential to help achieve food security as the world population increases to a predicted 9.2 billion in 2050.

**Conclusions:** The grand mean over all the presented figures shows a statistically significant positive effect on crop production of about 10% in response to biochar application. The greatest positive effects were realized with biochar application rates of 100 t ha-1 (39%), as well as in

acidic (14%) and neutral pH (13%) soils and soils with coarse (10%) or medium (13%) texture. Yield improvement mechanisms may limit the observed effect and the influence on water holding capacity.

Jha, Pramod, et al. 2010. "Biochar in Agriculture – Prospects and Related Implications." *Current Science*. 99(9): 1218-25.

**Abstract:** Sequestration of atmospheric carbon to the soil is a challenging task for the scientific community to mitigate the rising concentration of atmospheric carbon dioxide (CO<sub>2</sub>). Biochar, due to its aromatic structure and long mean residence time in the soil (more than 100 years) has the potential for long-term carbon sequestration in the soil. The trend obtained from the meager published literature raised our hopes of achieving the goal of enhancing the productivity of different crops along with environmental sustainability. According to an estimate, global production of black carbon has been reported between 50 and 270 Tg yr<sup>-1</sup>, with as much as 80% of this remaining as residues in the soil. Biochar decomposition rate is slow in the soil, which indicates that it could be the possible answer to mitigation of elevated atmospheric CO<sub>2</sub>. It is reported that black carbon can produce significant benefits when applied to agricultural soils in combination with some fertilizers. Increase in crop yield to the tune of 45–250% has been reported by application of biochar along with chemical fertilizers. Soil water retention properties, saturated hydraulic conductivity and nutrients availability increased with the application of biochar. Biochar application reduced CO<sub>2</sub> respiration, nitrous oxide and methane production, and decreased dissipation rate of herbicide in the soil.

**Basic Hypothesis/Goal:** This article looks positively at biochar as a possible soil amendment and way to mitigate CO<sub>2</sub> emissions.

**Biomass Used:** See Table 1

**Crop Detail:** See table 2 for the effect of biochar application on crop yield. (It should be noted, however, that all are short-term so it is unknown whether growth would be sustained over the long-term with the addition of biochar.)

**Findings:** This article found that the water regime on carbon loss and potential CEC (CEC<sub>p</sub> at pH7) significantly depended on biomass type.

**Environmental Concerns:** Does biochar production involve large scale fossil-fuel burning? The article notes that CO<sub>2</sub> for production of biochar should be considerably less than carbon sequestered in charcoal.

**Other Concerns with Biochar Production and Utilization:** The article notes a series of other concerns regarding biochar production and utilization: 1) How will soil microbial community (especially soil heterotrophs) behave with non-degrading a carbon source?; 2) What is the mechanism by which nutrients are released and become available?; 3) What will be the enzymatic activity under the influence of a non-degrading substrate?; 4) What is the optimal rate of application for biochar?; 5) What is the impact of long-term application of biochar on crop yield and soil quality?; 6) Is there proven technology for large-scale production of biochar on a small farm scale?; and 7) What will be the effect of biochar on problematic soil?

**Conclusions:** The article concludes that biochar is promising but there are still many questions.

Koide, Roger T., Krittika Petprakob, and Matthew Peoples. 2011. "Quantitative Analysis of Biochar in Field Soil." *Soil Biology & Biochemistry*. 43: 1563-1568.

**Abstract:** Biochar is used with increasing frequency as a soil amendment because of its potentially beneficial effects on soil carbon sequestration, crop yield, nutrient leaching and greenhouse gas emissions. Simple methods for the analysis of biochar in soil, however, are currently unavailable. Therefore, we have adapted the "loss on ignition" method for this purpose. The technique requires knowledge of the proportions of both biochar and biochar-free soil that are lost on ignition. One can use values determined prior to the amendment of the soil with biochar, assuming that the values do not change after biochar is incorporated in the soil. We tested these assumptions. Over the course of 15 months, the assumptions proved to be valid under our test conditions. The technique accurately determined a wide range of biochar concentrations in field soil.

**Basic Hypothesis/Goal:** The goal of this article was to come up with a more straightforward way to analyze biochar in soil, aiming to adapt the "loss on ignition" method.

**Biomass Used:** The biomass utilized in this study was domestic hardwood from Humphrey Charcoal in Brookville, PA. The particle size of the biochar was measured via mesh size # 6 (smaller than 3.4 mm) and then mesh size #10 (smaller than 1.7mm).

**Type of Study:** field

**Process:** A portion of field formerly growing corn on it with a Hagerstown soil- fine, mixed, semiactive, mesic Typic Hapludalfs was rototilled at 25cm. The field was noted as having a silt loam surface with silty clay loam and silty clay subsurface. The study used four plots each one square meter in size in each of the three blocks. Two plots in each block were treated with biochar while two plots served as controls (the treatment and control plots were separated by two meters). Each biochar plot received 12.5 pounds of biochar (about 56.8 tonne ha<sup>-1</sup>). After 15 months of biochar being on the ground with corn and soybeans growing samples were taken from a depth of 15cm. Two cores were taken from each of the control plots; four cores were taken from each biochar plot. The biochar was then separated from the soil using a 5mm sieve. The study then compared the samples never containing biochar, the pure biochar separated from soil plots, the pure soil separated from biochar soil plots, and the biochar never added to soil. The biochar was heated in muffle furnace at 550 degrees Celsius for four hours.

**Statistics:** ANOVA. The study tested actual and calculated biochar contents of 5g samples from field soil.

**Crop Detail:** Sweet Corn (Delectable, Rupp Seeds Wauseon, OH, USA); soybeans (FS H535A90, Growmark, Bloomington, IL).

**Pyrolysis Facility Details:** conventional, slow pyrolysis

**Conclusions:** No significant effect was detected after 15 months of biochar being on the ground compared to biochar never added to soil when using this method to analyze biochar in soil. This result suggests this method is a good alternative to more laborious or instrument-intensive techniques.



Laird, David A. 2008. "The Charcoal Vision: A Win-Win-Win Scenario for Simultaneously Producing Bioenergy, Permanently Sequestering Carbon, while Improving Soil and Water Quality." *Agronomy Journal*. 100(1): 178-181.

**Abstract:** Processing biomass through a distributed network of fast pyrolyzers may be a sustainable platform for producing energy from biomass. Fast pyrolyzers thermally transform biomass into bio-oil, syngas, and charcoal. The syngas could provide the energy needs of the pyrolyzer.

Bio-oil is an energy raw material ( $\sim 17 \text{ MJ kg}^{-1}$ ) that can be burned to generate heat or shipped to a refinery for processing into transportation fuels. Charcoal could also be used to generate energy; however, application of the charcoal co-product to soils may be key to sustainability. Application of charcoal to soils is hypothesized to increase bioavailable water, build soil organic matter, enhance nutrient cycling, lower bulk density, act as a liming agent, and reduce leaching of pesticides and nutrients to surface and ground water. The half-life of C in soil charcoal is in excess of 1000 yr. Hence, soil-applied charcoal will make both a lasting contribution to soil quality and C in the charcoal will be removed from the atmosphere and sequestered for millennia. Assuming the United States can annually produce  $1.1 \times 10^9 \text{ Mg}$  of biomass from harvestable forest and crop lands, national implementation of The Charcoal Vision would generate enough bio-oil to displace 1.91 billion barrels of fossil fuel oil per year or about 25% of the current U.S. annual oil consumption. The combined C credit for fossil fuel displacement and permanent sequestration, 363 Tg per year, is 10% of the average annual U.S. emissions of  $\text{CO}_2\text{-C}$ .

**Basic Hypothesis/Goal:** A national system of pyrolyzers for processing biomass into bio-oil and charcoal could reduce US demand for fossil oil by 25%, C emissions by 10%, enhance soil and water quality, and increase agricultural productivity and strengthen rural economies

**Economics:** If an energy company only paid by volume of fuel delivered, no incentive would exist to convert any biomass to charcoal.

**Other Concerns with Biochar Production and Utilization:** Technology needed to handle, spread, and incorporate charcoal into soils must be considered. Proper engineering of pyrolyzers to ensure no emissions of NO, CO, etc, must be ensured.

**Biofuel Advantages:** Pyrolyzers can be scaled to match biomass size and source. Pyrolyzers can also process diverse sources of biomass.

**Conclusions:** The use of biochar could be a win-win-win situation



Laird, David A., et al. 2009. "Review of the Pyrolysis Platform for Coproducing Bio-Oil and Biochar." *Biofuels, Bioproducts, and Biorefining*. 3: 547-562.

**Economics:** The cost of bio-oil could be as low as \$26/barrel (in a 550 ton per day plant).

**Other Concerns with Biochar Production and Utilization:** Biochar is flammable as a solid and powders may spontaneously combust if exposed to moisture and oxygen during storage. A large concentration of biochar dust in an enclosed area is potentially explosive. (These concerns can be mitigated if bio-oil is pelletized or prepared in a slurry with water or liquid waste, but this increases cost.)

Laird, David A., et al. 2010. "Impact of Biochar Amendments on the Quality of a Typical Midwestern Agricultural Soil." *Geoderma*. 158: 443-449.

**Abstract:** Biochar, a co-product of thermochemical conversion of lignocellulosic materials into advanced biofuels, may be used as a soil amendment to enhance the sustainability of biomass harvesting. We investigated the impact of biochar amendments (0, 5, 10, and 20 g-biochar kg<sup>-1</sup> soil) on the quality of a Clarion soil (Mesic Typic Hapludolls), collected (0–15 cm) in Boone County, Iowa. Repacked soil columns were incubated for 500 days at 25 °C and 80% relative humidity. On week 12, 5 g of dried and ground swine manure was incorporated into the upper 3 cm of soil for half of the columns. Once each week, all columns were leached with 200 mL of 0.001 M CaCl<sub>2</sub>. Soil bulk density increased with time for all columns and was significantly lower for biochar-amended soils relative to the un-amended soils. The biochar amended soils retained more water at gravity drained equilibrium (up to 15%), had greater water retention at -1 and -5 bars soil water matric potential, (13 and 10% greater, respectively), larger specific surface areas (up to 18%), higher cation exchange capacities (up to 20%), and pH values (up to 1 pH unit) relative to the un-amended controls. No effect of biochar on saturated hydraulic conductivity was detected. The biochar amendments significantly increased total N (up to 7%), organic C (up to 69%), and Mehlich III extractable P, K, Mg and Ca but had no effect on Mehlich III extractable S, Cu, and Zn. The results indicate that biochar amendments have the potential to substantially improve the quality and fertility status of Midwestern agricultural soils.

**Basic Hypothesis/Goal:** Soil biochar amendments will enhance the quality of a typical Midwestern Mollison by quantifying the impact of biochar and manure amendments on various soil quality indicators using a soil column leaching/incubation study.

**Biomass Used:** Mixed hardwood (primarily oak and hickory)

**Type of Study:** lab. Four biochar rates and two manure treatments over six replications for 48 columns were performed

**Process:** Soil was tumbled in a rotary cement mixer for twenty minutes. Biochar was slowly added in different amounts - 0, 5, 10, or 20 g kg<sup>-1</sup>. Soil columns were created and packed to a bulk density of 1.1 g cm<sup>-3</sup>. Constant temperature of 25 Celsius and 80% relative humidity was maintained. At week 12, 5g of dried and ground swine manure was added to half the columns.

**Statistics:** The authors used three-way ANOVA to determine the significance of the overall model. Measures of biochar, manure, depth, and interaction terms for total C, N, ECEC, pH, and Mehlich three extractable nutrients were included. Two-way ANOVA was performed for gravity drained equilibrium water content and bulk density. One-way ANOVA was performed for biochar treatment effects on moisture retention and specific surface.

**Pyrolysis Facility Details:** Biochar was obtained from a commercial producer using traditional kilns (slow pyrolysis).

**Findings:** There was no detectable loss of C in biochar during the 500 days of incubation. However, when manure added, less than 20% of manure C was recovered. C in the biochar was relatively stable, while C in the manure was subject to fairly rapid mineralization in the soil environments. Nitrogen content in the soil was significantly increased with biochar treatments. The manure treated soil only showed 2% higher N (which was not statistically significant). Leachate N decreased significantly when biochar was added to manure. Thus, biochar seems to have helped stabilize some of the N added with the manure. The amount of water retained in the soil in the columns was higher in biochar than in the control. Manure treatment showed no significant water retention. The starting pH of the biochar was 8.2 in deionized water. After 500 days, it was almost 1 pH unit higher in the 20g kg<sup>-1</sup> biochar treatment. (A weak liming agent may be the amount of ash is lower because of the type of biochar used). Bulk density

was lower for the biochar columns, which serves as confirmation that it is an effective soil conditioner. Specific surface area increased with the biochar treatment. P, K, Ca, and Mn all increased with the biochar added. No significant effect was detected on Mehlich 3 extractable Mg, Cu, and Zn. P was not statistically significant for biochar x manure but was for biochar x manure x depth. Biochar increased P retention in the 0 - 3cm depth increment. B and S both decreased with increasing levels of biochar.

**Soil Details:** Iowa State University from Boone County, Iowa. Clarion, fine-loamy, mixed, superactive, Mesic Typic Hapludolls

**Conclusions:** In non-tropical, Clarion loam, biochar addition significantly reduced bulk density increases due to soil compaction, while it increased water holding capacity, cation exchange capacity, specific surface area, pH, and retention of P and other plant nutrients. Soil quality indicators were all positive except for B. The manure amendment did not have an effect on water retention at gravity drain equilibrium or ECEC, and had relatively small C, N and C:N ratio effects. Overall, the effect of biochar was much more evident after 500 days than the effect of the manure on soil quality.

Lee, James Weifu, et al. 2010. "Sustainability: The Capacity of Smokeless Biomass Pyrolysis for Energy Production, Global Carbon Capture and Sequestration." *Energy & Environmental Science*. 3(11): 1609-1812.

**Basic Hypothesis/Goal:** Biomass can be used to offset climate change and provide a carbon-negative energy source.

**Economics:** The US can harvest 1.3 gigatons of dry biomass per year (1 Gt from croplands, .3 Gt from forestlands). Using low-temperature pyrolysis, assuming 50% conversion of biomass C to stable biochar and 33% to biofuels (syngas and bio-oils), it could produce .325 GtC y<sup>-1</sup> biochar and biofuels (the equivalent of 1.3 billion barrels of crude oil). This could be a significant step toward energy independence but it depends on a cost-effective biofuel-refinery technology to convert syngas/bio-oils from biomass into a liquid fuel. Based on a life-cycle assessment, biochar producing biomass pyrolysis tech could be profitable when CO<sub>2</sub> reductions are valued at or above about \$60/ton of CO<sub>2</sub> equivalent emissions.

**Energy:** The heating value of bio-oil is 40-50% of that for petroleum-based fuels but has a higher energy density to make up for the lower heating value.

**Land/Agricultural Use:** This article suggests that biochar from 400 degrees Celsius rather than 900 because it seems better in soil application. It also suggests inclusion of other fertilizers like NH<sub>4</sub>HCO<sub>3</sub>.

**Potential Relevance for Arid Soils:** The article notes biochar with a pH above 8 because of alkaline ash content, so addition could make alkaline soil pH worse for plant growth. NH<sub>4</sub>HCO<sub>3</sub> can act as a pH buffer.

**Climate Change:** The article calculates the maximum theoretical biochar sequestration capacity to be 303.8 ton C per hectare (or 123 ton C per acre) in a 30 cm soil layer alone, based on the calculation that 70% of biochar from 400°C pyrolysis weight is C and that bulk soil density is generally 1.3 tons per cubic meter. It further notes that 51.6 GtC of biochar particles could be sequestered in this first 30 cm layer. If world land areas could contribute an average of 303.8 ton C per hectare, global capacity for soil biochar carbon sequestration would be 3950 GtC, about sufficient to mitigate the additional 4000Gt expected to be released from burning remaining fossil fuel resources. However, only about 30% of world lands could be considered for this purpose, reducing total global capacity to 1166GtC.

**Emissions Reduction:** The article notes the importance of the idea of a smokeless (clean and effective) technology for biomass pyrolysis if it is to be used for a large-scale operation.

**Conclusions:** The authors advocate a push in research and development within the area of smokeless biomass pyrolysis as well as more effective syngas/bio-oil collection.

Lehmann, Johannes, John Guant, and Marco Rondon. 2006. "Bio-Char Sequestration in Terrestrial Ecosystems – A Review." *Mitigation and Adaptation Strategies for Global Changes*. 11: 403-427.

**Basic Hypothesis/Goal:** How can biomass be used to offset climate change?

**Climate Change:** See tables for details on change from slash and burn to kiln. Complete combustion of more than 90% of C in organic matter is oxidized creating CO<sub>2</sub>, whereas using a biochar production only 45-48% of organic C is oxidized to CO<sub>2</sub>. When utilizing feedstock for biochar production, 420-450kg C emissions per ton of C used would be avoided. Avoided emissions are currently tradable, but biochar offers other benefits as well including allowing for long-term storage of carbon.

**Alternative Biomass Uses:** Use of charcoal as a fuel replacing wood leads to lower levels of indoor pollution and reduced mortality.

**Conclusions:** There is definitely the potential for carbon sequestration but there are also challenges.

Lin, Yun, et al. 2012. "Nanoscale Organo-Mineral Reactions of Biochars in Ferrosol: An Investigation Using Microscopy." *Plant Soil*. 357: 369-380.

**Abstract:** Aims In this study, a chicken manure biochar (CM biochar) and a paper sludge biochar (PS biochar), prepared under similar treatment conditions, were amended into ferrosol as part of an agronomic field trial. The aim of this study is to investigate interactions between these biochars and the soil after a 3-month trial. Methods Soil samples following field trials were taken and biochar was separated from the soil, and studied for both surface oxidation and the degree of interaction with surrounding soil by X-ray photoelectron spectroscopy (XPS), SEM and TEM equipped with EDS for elemental analysis. Results Following incubation in field soil, both biochars showed that soil mineral incorporation on to their surfaces occurred within the first year, although the attachment was localized at specific sites on the surface. A relatively high concentration of Al was found at the interface between the biochar and mineral phases in both aged biochars, indicating a binding role of Al. For the CM biochar, a soil-iron redox reaction may be associated with the formation of biochar mineral complexes due to the relatively higher labile carbon content and higher pH value of this biochar. Conclusions Soil mineral attachment may occur directly on to the biochar surface because of the formation of carboxylic and phenolic functional groups on the aged CM biochar surface by an oxidation reaction. For the PS biochar, adsorption of organic matter from the soil facilitated interactions between the biochar and mineral phases in the soil. Calcium is believed to be important in this process.

**Basic Hypothesis/Goal:** What are the interactions between biochars and soil?

**Biomass Used:** The study uses chicken manure (CM) (included sawdust) and paper sludge (PS) (woodchip was secondary constituent).

**Amount of Dry Biomass:** One ton of chicken manure biochar; five tons of paper sludge biochar

**Type of Study:** field trial

**Process:** Biochar was incorporated at rate of 10 tha<sup>-1</sup> to a depth of 100mm using a rotary hoe. A randomized block design with controls was utilized. Plots were 4m x 5m. Sweet corn was sown right after biochar was added in December. The corn was harvested three months later and soil samples were taken. Biochar was then extracted from the samples. Two dry biochar particles were tested for each fresh biochar and aged biochar for the XPS. For SEM analysis, the biochar particles were further dried and more than 10 particles for each of the two biochars were sputter-coated with chromium.

**Crop Detail:** Corn was planted in an Australian ferrosol where sweet corn (*Zea maize*) has previously been planted.

**Pyrolysis Facility Details:** Biochar was produced by BEST Energies via continuous slow pyrolysis process. Pyrolysis took place at 550°C for 30 minutes, and was then activated in a separate chamber at 550°C with a maximum residence time of 60 minutes with steam and air introduced to provide more oxygenated functional groups. Chicken manure was measured at 30% moisture while paper sludge was measured at 50% moisture.

**Findings:** Using XPS, the authors found carbon for fresh PS was at 80% and CM had not only C and O but also trace amounts of Al, Si, Na, Cl, and small concentrations of Ca, K, N, and P (presumably from the chicken manure used as feedstock). After soil exposure, the carbon content decreased by over 15%. Total oxygen as well as oxygen bound to carbon increased. Al/Si ratios and N content increased. Iron was also detected in low levels. In aged CM, Ca content decreased to less than 1%, and no Na, K, P, and Cl was detected. Aged PS had a higher surface carbon concentration (about 60%), and lower Fe, Al, and Si contents than aged CM biochar. (This implies less soil mineral attachment compared to CM). Some ammonium-N dissolution occurred during soil application. Using SEM analysis, coverage of mineral phases for aged CM biochar were found to be higher and attached mineral grains were coarser than

for aged PS biochar. In aged PS biochar, mineral aggregates attached in localized regions and had fine grains. Fewer mineral phases adhered to carbon-rich regions on aged PS.

**Soil Details:** The soil utilized was highly weathered acidic ferrosol derived from basalt in a subtropical environment with average rainfall in the area of 1800 mm per year and a pH of 4.3 in  $\text{CaCl}_2$ .

**Conclusions:** Soil mineral incorporation on biochar surfaces happens within the first few months of incubation within field soil. Relatively high concentrations of Aluminum were present at the interface between biochar and mineral phases suggesting a binding role of Al. For CM biochar, soil minerals attachment may happen directly on the biochar surface but for PS biochar, adsorption of SOM via a cation bridge ( $\text{Ca}_2+$  and  $\text{Al}_3+$ ) first and then interaction of adsorbed SOM with mineral colloids may be the dominant mechanism.

Liu, Pei, et al. 2012. "Modification of Bio-Char Derived from Fast Pyrolysis of Biomass and its Application in Removal of Tetracycline from Aqueous Solution." *Bioresource Technology*. 121: 235-240.

**Abstract:** In this work, bio-char, a mass productive by-product of biomass fast pyrolysis, was adopted as an adsorbent to remove tetracycline (TC) from aqueous solution. To enhance the adsorption capacity, a simple modification of bio-char with acid and alkali was carried out. Bio-char samples were characterized by Fourier transform infrared (FTIR), X-ray photoelectron spectroscopy (XPS), and nitrogen adsorption–desorption isotherm. The results show that the alkali treated bio-char possesses larger surface area than those of raw and acid treated bio-chars, and accordingly exhibits a more excellent adsorption performance (58.8 mg/g) than the other two bio-chars and other adsorbents reported previously. The graphite-like structure of bio-char facilitates the formation of  $\pi$ - $\pi$  interactions between ring structure in tetracycline molecule and graphite-like sheets. The surface area showed significant effects on TC adsorption as well as O-containing functional groups, whereas the initial pH of solution has small effects on TC adsorption under the experimental conditions.

**Basic Hypothesis/Goal:** This study seeks to determine the effectiveness of biochar as an adsorbent to remove tetracycline from water.

**Biomass Used:** rice-husk

**Type of Study:** lab

**Process:** Twenty grams of raw biochar was added to 200mL of a 10%  $H_2SO_4$  solution or a 3 mol/L KOH solution and stirred for 1 hr at 333-343K. The biochar was then rinsed with de-ionized water until the pH of the elution liquid was 7.0. The biochar was then dried and prepared via two treatment methods to achieve an acid biochar and an alkali biochar.

**Pyrolysis Facility Details:** Biochar was obtained from a pilot-scale industry (1 ton per hour from Anhui Yineng Bioenergy Co. Ltd) using a fast pyrolysis system.

**Findings:** The chemical state of hydroxyl groups significantly changed after the acid treatment. Surface area of the alkali biochar was two to three times that of the acidic biochar and the raw biochar. The alkali biochar also contained more C and O than other two and had greater porosity. Adsorption of TC by the biochars was very slow. Maximum adsorption capacities of the raw, acidic, and alkali biochars were as follows: 16.95, 23.26, and 58.82 mg/g respectively. The alkali biochar exhibited excellent adsorption compared to other adsorbents considered in the literature.

**Conclusions:** Alkali bio-char possesses excellent adsorption capacity thanks to its large surface area and porous structure.



Maraseni, Tek Narayan. 2010. "Biochar: Maximising the Benefits." *International Journal of Environmental Studies*. 67(3): 319-327.

**Abstract:** There have been many studies on the benefits of producing biochar (black carbon) from organic wastes. Incorporating biochar into soils provides numerous environmental and financial benefits, which this paper examines. Nevertheless, there is no policy yet to apply biochar at farm level in Australia. This article discusses nine critical factors that need to be considered for maximizing the environmental and financial farm benefits from the use of biochar.

**Basic Hypothesis/Goal:** The goal of this study was to determine the factors needed in order to maximize environmental and financial farm benefits of biochar.

**Land/Agricultural Use:** The authors suggest that the application of biochar with seeds or fertilizer will be optimal because no extra machinery would be needed.

**Potential Relevance for Arid Soils:** The article notes that, in sandy soils, biochar's surface area can improve water-holding properties.

**Environmental Concerns:** Biochar application in carbon rich soils can actually offset GHG benefits (according to research by Wardle, Nilsson & Zachrisson (2008)).

**Biofuel Advantages:** The article notes a number of potential advantages from the use of biochar: 1) reduction of soil nutrient leaching; 2) enhancement of nutrient availability for plants; 3) ability to increase quality of water runoff; 4) reduction of dependency on artificial fertilizers; 5) reduction of toxicity of aluminum to plant roots and microbiota; 6) ability to increase soil structure and pH, reducing need for lime; 7) reduction of bioavailability of heavy metals, working as bioremediation; and 8) ability to decrease N<sub>2</sub>O and CH<sub>4</sub> emissions from soils, thus further the reduction of GHG emissions.

**Conclusions:** This article suggest a systematic approach to biochar from temperature of pyrolysis to soil carbon, soil rate, biochar application rate, soil pH, and contamination levels of land where application will be in order to maximize the benefit.

Marris, Emma. 2006. "Black is the New Green." *Nature*. 442: 624-626.

**Basic Hypothesis/Goal:** Could biochar be the key to the new green revolution?

**Climate Change:** According to Glaser, a hectare of meter-deep terra preta can contain 250 tonnes of carbon (compared to 100 tonnes in unimproved soils from similar parent materials). Lehmann is hoping the process will fit under the Kyoto Protocol's Clean Development Mechanism, where rich countries sponsor green projects in poor countries and get credit for reduced emissions.

**Other Concerns with Biochar Production and Utilization:** Can this be done in a no till way?

Matovic, Darko. 2011. "Biochar as a Viable Carbon Sequestration Option: Global and Canadian Perspective." *Energy*. 36: 2011-2016.

**Abstract:** Biochar production and mixing in soil are seen as the best options for atmospheric carbon sequestration, providing simultaneous benefits to soil and opportunities for distributed energy generation. The proximity of biomass source and biochar dispersal greatly reduces the energy and emissions footprint of the whole process. The viability of the whole biochar process is examined from two boundary points: is there enough biomass around to have significant impact on the atmospheric CO<sub>2</sub> levels and is there enough soil area for biochar dispersal. The answers are soundly positive, both for the world as a whole and for Canada, for which a more detailed analysis was done. However, the massive adoption of biochar solution is critically dependent on proper recognition of its carbon sequestration impact its soil improvement potentials. To that extent the International Biochar Initiative, together with national chapters, including recently formed Canadian Biochar Initiative, are actively promoting biochar related research and policy framework. This paper addresses the questions of availability of sources and sites that would benefit from its dispersal.

**Basic Hypothesis/Goal:** Can we offset annual CO<sub>2</sub> increases using biochar? How much carbon can be sequestered worldwide and in Canada specifically? Is there enough soil for dispersal?

**Economics:** See table 2 for carbon offset in Canada

**Climate Change:** There are four ways to mitigate carbon dioxide emissions: 1) CO<sub>2</sub> production reduction via phasing out fossil fuels; 2) CO<sub>2</sub> capturing and storage from the source; 3) CO<sub>2</sub> capturing and storage from the air; and 4) natural capture via the terrestrial carbon cycle. Carbon capture from the air using closed-cycle sodium hydroxide absorption costs \$500/tC (USD). Combining biomass with carbon capturing and sequestering can be done at half that cost. There is significant cost associated with compressing carbon dioxide and pumping it into the ground (both in energy and finance). Biochar does not have that cost. Based on Kurth et al's study of soils from forest fires, it is estimated here that there is a 3% level of charcoal in the top 30cm of soil. Table 1 outlines an overall carbon budget, assuming biomass available for conversion is 10% of the net primary production (estimated at 60.6 Gt/yr), which would be more than sufficient to offset the entire annual CO<sub>2</sub> increase in the atmosphere.

**Conclusions:** It can be feasible to use biochar to sequester carbon. More research is needed to maximize the benefit of biochar to soils and also restricted by the amount of agricultural land.

McHenry, Mark P. 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.

**Abstract:** Reducing the vulnerability of agriculture to climate change while increasing primary productivity requires mitigation and adaptation activities to generate profitable co-benefits to farms. The conversion of woody-wastes by pyrolysis to produce bio-char (biologically derived charcoal) is one potential option that can enhance natural rates of carbon sequestration in soils, reduce farm waste, and substitute renewable energy sources for fossil-derived fuel inputs. Biochar has the potential to increase conventional agricultural productivity and enhance the ability of farmers to participate in carbon markets beyond traditional approach by directly applying carbon into soil. This paper provides an overview of the pyrolysis process and products and quantifies the amount of renewable energy generation and net carbon sequestration possible when using farm bio-waste to produce bio-char as a primary product. While this research provides approximate biochar and energy production yields, costs, uses and risks, there is a need for additional research on the value of biochar in conventional crop yields and adaptation and mitigation options.

**Basic Hypothesis/Goal:** This article aims to reduce investment uncertainty for agriculturalists looking to diversify into converting biomass to biochar and energy, with a special focus on experiences in western Australia.

**Pyrolysis Facility Details:** As an example: A 1MWe demonstration Plant in W. Australia in Narrogin with an annual output of 7500MWh of electricity, 690 t of activated carbon, and 210 t of eucalyptus oil (they planted mallee). A 5 MWe integrated tree processing plant costs \$28.4 million with an expected operating cost of \$7.9 million annually including feedstock purchases. Annual production is expected to be 40,000 MWh of electricity, 1050t of eucalyptus oil, 2720 t of granular activated carbon, 1090 t of pelletized activated carbon, and 294 t of powdered activated carbon. Intermediate biochar output is 7240t y-1, before conversion to activated carbon. After tax, there is an IRR of 18.8% and NPV of \$7.8 million, with a discount rate of 12.5% over 15 year project.

**Findings:** The article hypothesizes that farmers could benefit from entering the carbon market in a number of ways: 1) via compensation for carbon sequestration based on quantity and market price of carbon; 2) via benefit from gains in productivity associated with adoption of carbon sequestering practices; and 3) via owning a share in biochar and renewable energy production facilities that would produce net benefits from the investment.

**Economics:** Transport costs have been reduced for waste disposal since biochar mass is 70-80% less than original wood waste (Lehmann, 2007). Estimated gate prices for granular activated carbon and CSIRO activated wood pellets are around 3000 Australian dollars/ton , powdered activated carbon approximately 1000 Australian dollars/ton (Enecon, 2001). Biomass production for biochar alone is not likely to be economically feasible because of high production costs, so there is a need for an integrated stream of production.

**Conclusions:** Investment in biochar depends on government policy, emission accounting frameworks, carbon market design, and the enduring price carbon credits may achieve over the long term.

Mullen, Charles A. et al. 2010. "Bio-Oil and Bio-Char Production from corn Cobs and Stover by Fast Pyrolysis." *Biomass and Bioenergy*. 34: 67-74.

**Abstract:** Bio-oil and biochar were produced from corncobs and corn stover (stalks, leaves and husks) by fast pyrolysis using a pilot scale fluidized bed reactor. Yields of 60% (mass/mass) bio-oil (high heating values are  $w_{20}$  MJ kg<sup>-1</sup>, and densities  $>1.0$  Mg m<sup>-3</sup>) were realized from both corncobs and from corn stover. The high energy density of bio-oil,  $w_{20}$ –32 times on a per unit volume basis over the raw corn residues, offers potentially significant savings in transportation costs particularly for a distributed "farm scale" bio-refinery system. Biochar yield was 18.9% and 17.0% (mass/mass) from corncobs and corn stover, respectively. Deploying the biochar co-product, which contains most of the nutrient minerals from the corn residues, as well as a significant amount of carbon, to the land can enhance soil quality, sequester carbon, and alleviate environmental problems associated with removal of crop residues from fields.

**Basic Hypothesis/Goal:** The article aims determine the similarities and differences of corncobs and corn stover as biochars and bio oils.

**Biomass Used:** corncobs and corn stovers (stalks, leaves and husks with no cobs)

**Type of Study:** pilot/lab

**Process:** This study conducted elemental analysis on both types of biofuel. HPLC analysis of bio-oils was also conducted. Bio-oil water content was determined with Karl-Fischer titration using 3:1 methanol:chloroform as solvent. Elemental analysis took place and physical properties were determined. Biochar analysis and XRF elemental analysis were performed as well as SEM analysis. Surface area measurements were obtained from nitrogen adsorption isotherms at 77K using a Nova 2000 Surface Area Analyzer. Metal Ion adsorption was determined from labs and the pH of slurry was recorded at beginning and end of the experiment.

**Pyrolysis Facility Details:** Pyrolysis was achieved via a bubbling fluidized bed of quartz sand at temperatures of about 500 degrees Celsius in a 7.62cm diameter fluidized reactor section, using two cyclones in series for biochar separation followed by four condensing canisters cooled by circulating water jackets maintained at about 4°C and a series of three electrostatic precipitators collect largest fraction of pyrolysis oil produced. Actual feed rate varied between 1 and 1.6kg h<sup>-1</sup>.

**Findings:** Moisture content of feedstocks were 6.8% for corn cobs and 2.5% for stover. Similar elemental analysis was recorded for each. K was the most abundant element in corncobs and Si was most abundant in corn stover (2.8wt%). Phosphorous levels similar in each, while Ca and Mg were more highly concentrated in corn stover. Lignin measured at 3.3% for dry material corn cobs and 6.3% for stover. Cellulose was 29.8% of corn cobs, and 47.5% of stover. Hemicellulose was 38.3% cobs, and 28.6% stover. Non-fiber carbohydrates (such as starch, sugar, pectin) were 23.7 and 5.3% respectively. Gross heating value was similar, with cobs HHV of 17.8MJ kg<sup>-1</sup> and stover at 18.3 MJ kg<sup>-1</sup>. Energy density was estimated at .7-1.4 GJ m<sup>-3</sup> for corn crop residue. Bio-oil recovery was 41% on average for corncob and 58% for stover. Biochar yields were 19 and 17% respectively, and NCG production was 15% and 5% respectively. Biomass remained in tubing/piping and was not recovered at rates of 26% for cobs and 19% for stover. There was 55-62% of feedstock carbon found in bio-oil, 20-30% in biochar, and 15-18% found in NCG. (see Fig 3). Non-condensable gas (NCG) consisted mainly of CO and CO<sub>2</sub> with small amounts of CH<sub>4</sub> and H<sub>2</sub>. Corn stover contained less non-combustible CO<sub>2</sub>, making it a slightly higher quality fuel gas than corncobs. Overall, about 49% of input energy is covered in bio-oil from corncobs and 55% from stover. Oil and char constitute 70% for both feedstocks. Overall energy efficiency of 75% was determined. Balance of energy was attributed to reactor heat loss and energy lost in the condenser train.

**Soil Details:** Chars from plant or animal waste typically yield higher pH biochars reflecting the presence of ash admixed with the biochar. In soil environments, biochar will first act as a liming agent raising the pH by dissolving the ash and releasing the base cations to the soil solution. Subsequent oxidation of the biochar surfaces will create carboxylate groups such that the biochar becomes a weak acid. Biochar at lower temps of creation may have higher yield recoveries and contain more C=O and C-H functional groups that can serve as nutrient exchange sites after oxidation

**Land/Agricultural Use:** The detrimental effects of removing crop residue like corncobs and stover from fields can be mitigated by applying biochar to the soil because it replaces carbon, nitrogen, and most of the plant nutrients that are removed from the soil with the biomass.

**Alternative Biomass Uses:** Corn stover biochars removed more metal ions in general than corncob biochars. Biochar was most effective at removing copper, then zinc, cadmium, and nickel.

**Conclusions:** Bio-oil yield was about 6% from corn crop residue feedstocks. Bio-oils have 20-32 times the energy density of biomass feedstock on a volume basis making transportation of bio-oil more cost effective than biomass. Biochar yields 17-19% on a mass basis.

Novak, Jeffrey M., et al. 2009. "Impact of Biochar Amendment on Fertility of a Southeastern Coastal Plain Soil." *Soil Science*. 174(2): 105-112.

**Basic Hypothesis/Goal:** The goal of this article was to determine the impact of pecan shell-based biochar additions on soil-fertility characteristics and water leachate chemistry for a Norfolk loamy sand.

**Biomass Used:** pecan shells

**Amount of Dry Biomass:** Approximately 1000 - 2000g of shells in a crucible inserted into a Lindberg box programmable furnace

**Type of Study:** lab

**Process:** Pecan shells were ground to pass through a 2mm sieve and pyrolyzed. These were then ground to pass through .25mm sieve. Moisture percent (wt/wt) was measured as well as pH. Ash content was also measured. Elemental analysis of C, H, N, S, and O was performed, along with determination of concentrations of Ca, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Si, Zn. Open top PVC columns were created with .25mm sieved biochar mixed into 750 g of air dried 2 mm sieved AP horizon soil for 0, .5, 1.0 and 2.0% (wt/wt) biochar treatments. Each treatment was conducted in triplicate. On days 25 and 67 columns were leached with 1.2 to 1.4 pore volumes of de-ionized water and leachate was collected and weighed. Samples of biochar-treated Norfolk AP soil were collected on incubation days 0 and 67 for analysis of plant available nutrients.

**Statistics:** ANOVA with  $p < 0.05$ .

**Pyrolysis Facility Details:** Pyrolysis was conducted via a Lindberg box programmable furnace equipped with an airtight retort. The furnace heated to 40°C then 170°C at 5°C per min<sup>-1</sup> and maintained for 30 minutes. Heating continued to 700°C at 5°C per min<sup>-1</sup> and maintained for one hour.

**Findings:** Most of the biochar was distributed in aromatic structures (58%) with reduced amounts of C having single O bonds (29%) and in carboxyl (13%) groups. Pecan-shell based biochar was composed of a mix of organic structural groups reflecting the chemistry of the feedstock and reactions during and after pyrolysis on exposure to water and oxygen. Biochar enriched with C, Ca, K, Mg, N and Si. Soil was enriched with Al, Fe, Na, and Si. Pyrolysis at higher temperatures increased concentration of C but reduced O and H due to evaporation of absorbed H<sub>2</sub>O and driving off of the -OH functional group. The soil treatment with 1 and 2% biochar on day 0 had significantly greater mean SOC content than the control. This increased to between 5.1 and 14.2 g kg<sup>-1</sup>. No significant loss of biochar C occurred during incubation. Adding 2% biochar significantly increased soil mean TCN content (but not at lower % of biochar). The C:N ratio of biochar was 244:1. Soil CEC increase was negligible even at 2%. There was a decrease in concentration of multivalent cations in the leachates with increasing levels of biochar addition. See Table 5 for details on soil change. The pH of the soil was more basic after biochar added.

**Conclusions:** Biochar increased SOC content but didn't significantly improve soil N status. No detectable SOC loss occurred during the 67 day incubation. Soil pH and Ca, K, and P concentrations increased after applying biochar. Water leaching showed K enrichment but net sorption of P and most multivalent cations. The type of biochar, pecan shells, pyrolyzed at a high temp of 700°C would be useful for sequestering C, but if the goal is to improve fertility in soil and also C sequestration, having more readily oxidizable structural groups and a low C:N ratio could be more appropriate.



Ogawa, Makota, Yasuyuki Okimori, and Fumio Takahashi. 2006. "Carbon Sequestration by Carbonization of Biomass and Forestation: Three Case Studies." *Mitigation and Adaptation Strategies for Global Change*. 11: 429-444.

**Abstract:** We proposed the carbon sink project called "Carbon Sequestration by Forestation and Carbonization (CFC)," which involves biomass utilization and land conservation by incorporating the products of biomass carbonization into the agents for soil improvement, water purification, etc. Our purpose was to demonstrate the potential of the CFC scheme for carbon sequestration, particularly carbon storage in soil. Case studies were conducted in both developing and developed countries. 1. In southern Sumatra, Indonesia, 88,369 Mg-C year<sup>-1</sup> of wood residue from a plantation forest and excess bark from a pulp mill would be converted into 15,571 Mg-C year<sup>-1</sup> of the net carbon sink by biochar\* for soil improvement. The fixed carbon recovery of the system is 21.0%. 2. In a semiarid region in western Australia, the carbonization of wood residue was incorporated with multipurpose projects of a mallee eucalyptus plantation that involved the function of salinity prevention. During the project period of 35 years, the total carbon sink would reach 1,035,450 Mg-C with 14.0% by aboveground biomass, 33.1% by belowground biomass and 52.8% by biochar in soil. 3. In southern Kyushu, Japan, the study was focused on the effective use of surplus heat from a garbage incinerator for carbonizing woody materials. Sawdust of 936.0 Mg-C year<sup>-1</sup> would be converted into the net carbon sink of 298.5 Mg-C year<sup>-1</sup> by carbonization, with the fixed carbon recovery of the system being 31.9%. Consequently, the CFC project could encourage the creation of a carbon sink in soil. However, we recognize that the quality standard of biochar, the stability of biochar in soil, and the methods for monitoring biochar utilization must be clarified before incorporating biochar carbon into the carbon credit system.

**Basic Hypothesis/Goal:** The goal of this article was to investigate the feasibility of the Carbon Sequestration by Forestation and Carbonization scheme as a measure for carbon sequestration in three countries with different natural and economic conditions.

**Type of Study:** Case Study

**Process:** The first case study took place in Sumatra, Indonesia in cooperation with a tree plantation planting a fast growing tree species, "Acacia mangium," and harvesting the trunks leaving massive wood residue. Logs were transported to a pulp mill where bark is discharged. The wood residue in the forest and excess bark in the pulp mill are used as fuelwood for carbonization with the biochar then used for soil improvement. The second case study took place in western Australia using the Mallee Eucalyptus plantation, which was multipurpose involving salinity prevention. The Eucalyptus oil is harvested and the wood waste is used for power generation or as material for activated carbon. The third case study took place in Japan in an urban area. This study included wood waste generated by sawmills, tree thinning, and at building construction sites. A fourth study was took place in Kyushu, Japan and considers wood waste from sawmills and excrement from livestock industry.

**Pyrolysis Facility Details:** In Indonesia, a drum kiln, a Hume pipe kiln, and a brick kiln were used. In Australia the furnace was mobile with internal-heating rotary system with a planned temp of 500-600°C. In Japan, an internal-heating rotary kiln with a fuelwood charge of 1.20 Mg-bdw hour<sup>-1</sup> and annual total of 1,872 Mg-bdw was utilized for carbonization at a planned temperature of 500-600°C.

**Findings:** In Indonesia, the estimated total recovery of fixed carbon from fuelwood to biochar is 21% and the net amount of carbon sequestered would be 15,571Mg-C year<sup>-1</sup>. In Australia the estimated carbon sequestration was 1,035,450 (Mg-C). In Japan, carbon recovery from wood waste was estimated at approximately 31.9% by carbonization project.



**Conclusions:** This article suggests that biochar be classified into several groups based on quality and factors such as pH, volatile content, ash content, water-holding capacity, bulk density, pore volume, and specific surface area. It also suggests there should be a monitoring method to accurately supervise the course of biochar production from biomass to end-use.

Özçimen, Didem and Aysegül Ersoy-Meriçboyu. 2010. "Characterization of Biochar and Bio-Oil Samples Obtained from Carbonization of Various Biomass Materials." *Renewable Energy*. 35: 1319-1324.

**Abstract:** Apricot stone, hazelnut shell, grapeseed, and chestnut shell are important biomass residues obtained from the food processing industry in Turkey and they have a great importance as being a source of energy. In this study, the characteristics of bio-oil and biochar samples obtained from the carbonization of apricot stone, hazelnut shell, grapeseed and chestnut shell were investigated. It was found that the biochar products can be characterized as carbon rich, high heating value and relatively pollution-free potential solid biofuels. The bio-oil products were also presented as environmentally friendly green biofuel candidates.

**Basic Hypothesis/Goal:** The goal of this study was to test the feasibility of a variety of ample food byproducts for their use as alternative energy to fossil fuels.

**Biomass Used:** apricot stone, hazelnut shell, grapeseed, chestnut shell

**Process:** Calorific value of samples of each type of biomass was measured by ASTM bomb calorimeter method. Porosity, total pore volume, and surface area were also measured. Fourier Transform Infrared spectroscopic analysis was performed.

**Pyrolysis Facility Details:** The study used a Jenkner-type retort with a length of 270mm and an inner diameter of 130mm. This was heated externally with an isolated electrical furnace where temperature was measured by an Ni-Cr-Ni thermocouple inside the bed. Before heating, the system was flushed with dry nitrogen for 30 minutes to remove all oxygen traces. After carbonization, the final weight of samples was calculated to obtain biochar yields.

**Findings:** Grapeseed oil had the highest gross calorific value and chestnut shell had the lowest. The highest gross calorific values for biochar and bio-oil samples was found as 30.76MJ/kg for apricot stone biochar and 29.76Mj/kg for grapeseed bio oil. Chestnut shell had the highest amount of fixed carbon, while apricot stone had the lowest. Grapeseed had the highest ash content, while apricot stone had the lowest. The total pore volume and BET surface area values were higher than biomass samples except for chestnut shell. Most abundant hydrocarbon distribution in the C5-C19 chain structure was found in both apricot stone and hazelnut shell bio-oils and peak intensity were the same. The most abundant hydrocarbon distribution was observed in the range of C7-C30 in grapeseed bio-oil. Peak intensity was noted in C30. The most abundant hydrocarbon distribution was observed in the range of C5-C28 in chestnut shell bio oil, with a peak intensity of C16.

**Biofuel Advantages:** Unlike solar, hydroelectric, and wind, biomass energy systems can be located almost anywhere.

**Conclusions:** Biochars can replace conventional fossil fuels due to high fixed carbon content and high calorific value. They can also be used as a carbon source for various carbon materials. Bio-oil can only be used as an alternative fuel after modifications such as Fischer-Tropsch synthesis, cracking, hydrogenation, etc.

Park, Jin Hee, et al. 2011. "Biochar Reduces the Bioavailability and Phytotoxicity of Heavy Metal." *Plant Soil*. 348: 439-451.

**Abstract:** *Background and aims:* Biochar has attracted research interest due to its ability to increase the soil carbon pool and improve crop productivity. The objective of this study was to evaluate the metal immobilizing impact of chicken manure- and green waste-derived biochars, and their effectiveness in promoting plant growth.

*Methods:* The immobilization and phytoavailability of Cd, Cu and Pb was examined using naturally contaminated shooting range and spiked soils. Biochar samples prepared from chicken manure and green waste were used as soil amendments. Results Application of biochar significantly reduced  $\text{NH}_4\text{NO}_3$  extractable Cd, Cu and Pb concentrations of soils, indicating the immobilization of these metals. Chicken manure-derived biochar increased plant dry biomass by 353 and 572% for shoot and root, respectively with 1% of biochar addition. This might be attributed to reduced toxicity of metals and increased availability of nutrients such as P and K. Both biochars significantly reduced Cd, Cu and Pb accumulation by Indian mustard (*Brassica juncea*), and the reduction increased with increasing amount of biochar application except Cu concentration. Metal sequential fractionation data indicated that biochar treatments substantially modified the partitioning of Cd, Cu and Pb from the easily exchangeable phase to less bioavailable organic bound fraction.

*Conclusions:* The results clearly showed that biochar application was effective in metal immobilization, thereby reducing the bioavailability and phytotoxicity of heavy metals.

**Basic Hypothesis/Goal:** The goal of this article was to examine the effect of chicken manure and green waste-derived biochars on immobilization of heavy metals in soil and biochars on plant growth and metal mobility.

**Biomass Used:** Chicken manure and green waste

**Process:** Metal spiked and naturally metal-contaminated soils were used. Spiking soil was collected from Adelaide Hills, South Australia spiked with Cd, Cu, and Pb at concentration of 5, 160 and 1,000 mg kg<sup>-1</sup>, respectively. Two naturally contaminated soils were used (Cd and Pb contaminated shooting range soil from South Korea and a Cu contaminated mine soil from Kapunda, South Australia). Biochar was analyzed for pH, nitrogen, carbon, hydrogen, and sulfur composition, cation exchange capacity, surface area, and pore size. Different soils were amended with 5g of CM and GW and moisture content was kept at 60% water holding capacity. Control sample without biochar treatment as well. 14 days of incubation at 25C. Plant growth experiment- plastic pots filled with 300g of the spiked soil and amended with 1, 5 or 15% of CM or GW. Ten Indian mustard (*Brassica juncea*) seeds were sown per pot. Rhizon samplers per pot were placed horizontally at 2cm. Each treatment was carried out in triplicate. Seedlings were thinned to five per pot four days after germination then grown for five weeks. Pore water samples were collected each week. Plant material was analyzed for metal content after harvest.

**Statistics:** Used SPSS. Duncan's multiple range test used to compare means of treatments,  $p < .05$  statistically significant

**Pyrolysis Facility Details:** The study utilized a low temperature pyrolysis plant (550°C) operated by Pacific Pyrolysis at Somersby, New South Wales.

**Findings:** Surface area of the chicken manure (CM) biochar was slightly higher than GW (green waste biochar). Adding both biochars significantly reduced  $\text{NH}_4\text{NO}_3$  and the extractable Cd concentration of spiked and naturally contaminated shooting range soil. CM dramatically reduced extractable Cd and Pb concentrations. When Cu concentration was low (spiked soil and AH) the extractable Cu concentration increased in CM amended soil. When soil had high Cu concentration (like the mining soil) a significant decrease in  $\text{NH}_4\text{NO}_3$  extractable Cu

concentration. GW biochar immobilized Cd, Cu, and Pb by 30.3, 22.9 and 36.8% respectively for spiked soil, and by 42.7, 0.901 and 72.9% for naturally contaminated soil. CM at 1% increased dry biomass by 353 and 572% shoot and root respectively. GW at 15% increased dry biomass by 252 and 527% respectively. No difference in biomass dry weight was seen when the highest amounts of biochar were applied except for 15% GW. Both CM and GW effective in reducing Cd and Pb concentrations of Indian mustard shoots. CM significantly decreased these with increasing level of application: 74.7, 79.6 and 88% for Cd, 76.1, 82.2, and 96.3% for Pb (at 1, 5 and 15%). GW was most effective when 15% of biochar was added with 67.2 and 81.6% reduction in Cd and Pb, respectively. Cadmium concentration in roots was not significantly influenced by biochar addition. Copper concentration in roots was decreased by 53, 67.40, and 69.1% for CM, and 28.7, 54.0, and 65.6% for GW. This was more pronounced for Pb with 60.6, 84.2 and 88.7% decreases. With GW, Pb reduction in roots was 14.6, 29.1 and 63.1% respectively. CM increased K in shoots by 74.1 and 100% (5 and 15% biochar application). Phosphorous uptake was more pronounced with CM application, 257, 452 and 636% increase. GW also significantly increased P uptake – 23.4, 119 and 216%. Potassium concentration of roots was significantly increased by 386, 1403 and 1516% with CM. Soil pH base was 5.11. Soil respiration was highest at 15% CM. GW didn't affect soil microbial activity.

**Conclusions:** Metal immobilization by biochar might occur by specific and nonspecific adsorption. Biochars are effective at immobilizing heavy metals, but this effectiveness varies depending on the type of biochar. Mechanisms for heavy metal immobilization are: 1) formation of metal (hydr)oxide, carbonate, or phosphate precipitates; 2) electrostatic interactions between metal cations, and the activated functional groups by increase pH as shown in the Ft-IR spectra; and 3) surface chemisorption between d-electrons of metal and delocalized pi-electrons of char. Soil pH increased. In situ remediation by immobilizing metals, thereby reducing metal availability to plants. Nutrient availability and microbial activity was also increased (CM was more effective in both metal immobilization and increase plant growth).

Quayle, Wendy C. 2010. "Biochar Potential for Soil Improvement and Soil Fertility." *IREC Farmers' Newsletter*. 182: 22-24.

**Abstract:** Biochar is a form of charcoal resulting from the burning of organic materials at high temperatures under low oxygen conditions. There is great interest in biochar production as a means of carbon storage of material that would otherwise be dealt with as waste (and most likely burnt). A research project has commenced at CSIRO Griffith to investigate the potential use of local agricultural waste products to produce biochar, and the potential use of the resulting biochar as a soil amendment.

**Biomass Used:** grapevine prunings, orange tree prunings, grape marc from winery waste, and orange peel from juicing waste

**Amount of Dry Biomass:** 30kg

**Type of Study:** field trial

**Process:** Each biomass was run through pyrolysis, with about 21-25% by mass remaining with little ash. Biochars are 67-85% carbon, a 34-83% carbon increase over biomass material burnt as feedstock. There was a 166-250% nitrogen increase (though final nitrogen levels were at most 3%). The biochars were then added to a Hanwood Loam soil to determine the effects on sweetcorn production and soil properties at three rates ( 0, 45, and 90 t/ha) combined by two nitrogen phosphorous fertilizer rates (0 N:P and 30kg N/ha: 40kg P/ha). This trial is still continuing.

**Crop Detail:** sweetcorn

**Pyrolysis Facility Details:** Pyrolysis took place in a 50L can inverted inside a 500L drum. Pine chips were used as combustion fuel lit from above at various points. Maximum temperature was 500-650°C and it took up to 24 hours to convert the biomass to biochar.

**Conclusions:** Constructing a small-scale biochar plant was fairly straightforward but did not collect gases and particulate organic matter emissions during pyrolysis process.

Reijnders, L. 2009. "Are Forestation, Bio-Char and Landfilled Biomass Adequate Offsets for the Climate Effects of Burning Fossil Fuels?" *Energy Policy*. 37: 2839-2841.

**Abstract:** Forestation and landfilling purpose-grown biomass are not adequate offsets for the CO<sub>2</sub> emission from burning fossil fuels. Their permanence is insufficiently guaranteed and landfilling purpose-grown biomass may even be counterproductive. As to permanence, bio-char may do better than forests or landfilled biomass, but there are major uncertainties about net greenhouse gas emissions linked to the bio-char lifecycle, which necessitate suspension of judgment about the adequacy of bio-char addition to soils as an offset for CO<sub>2</sub> emissions from burning fossil fuels

**Basic Hypothesis/Goal:** This article considers whether carbon-offsetting schemes can completely offset the CO<sub>2</sub> emissions linked to burning fossil fuels.

**Climate Change:** Carbon offsetting by forestation is only guaranteed for 100 years, which is too short a time to remove all fossil fuel-derived CO<sub>2</sub> from the atmosphere. The effect of production of biochar and its amendment to soil on carbon offsetting depends on persistence of biochar in soils, the effect of biochar on other types of soil carbon, net emissions of greenhouse gases from soils, and the seed-to-biochar emission of greenhouse gases. Unfortunately, these have only been studied in a limited capacity. There is evidence that biochar may remain in soil for thousands of years with other lab studies finding degradation depending on production procedure.

**Conclusions:** Biochar may be better with regard to permanence in dealing with greenhouse gas emissions. However, there are still major uncertainties regarding net greenhouse gas emissions so one cannot say whether biochar would be adequate to offset CO<sub>2</sub> produced from burning fuels.

Roberts, Kelli G., et al. 2010. "Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential." *Environmental Science Technology*. 44: 827-833.

**Basic Hypothesis/Goal:** The goal of this article is to examine the life-cycle impact of biochar pyrolysis systems in order to estimate their energy and climate change impacts.

**Biomass Used:** corn stover, yard waste, and switchgrass feedstocks

**Amount of Dry Biomass:** 1 ton

**Process:** Biomass was collected and transported to the pyrolysis facility, reduced in size, and dried. Slow pyrolysis was utilized. Syngas and bio-oils were combusted for heat applications. Biochar was then transported to a farm and applied to crop fields. (Production of transportation vehicles not included) (Water consumption NOT included in LCA).

**Crop Detail:** LCA of corn stover by Kim, Dale, & Jenkins was measured in late and early harvest (moisture content 15% and 30%). For switchgrass feedstock, two models were used. Model 1: Lifecycle Emissions Model for land-use, fertilizer, and cultivation-related emissions of switchgrass production, net GHG of +406.8 kg CO<sub>2</sub>e t<sup>-1</sup> dry switchgrass. Model 2: comprehensive worldwide agricultural model for land-use change from Searchinger et al. Both account for the cropland diversion effect from annual crops to perennial grass energy crop (direct land-use change) and land conversion to cropland to replace lost crops to bioenergy crops (indirect land-use change). In model two, the net GHG emissions were +886.0 kg CO<sub>2</sub>e t<sup>-1</sup>. Yard waste biomass was diverted from industrial scale composting so no environmental burden was attached.

**Fertilizer Efficiency:** The most consistent and greatest yields in crop performance were found in highly degraded soils. N consideration of crop yield increased in this study, but improved fertilizer use efficiency was also considered with the goal of reducing commercial chemical fertilizers. There was 7.2% difference between biochar and the control.

**Economics:** Feedstock collection and pyrolysis both present costs. Smaller costs are presented by feedstock transport, biochar transport, and biochar application. Energy production and tipping fees for yard waste present revenue sources. Biochar value lies in P and K content, improved fertilizer efficiency, and GHG emission reduction. This study uses life cycle C emission reduction to calculate GHG offset with values of \$20 and \$80 t<sup>-1</sup> CO<sub>2</sub>e used depending on the value of CO<sub>2</sub>e. There is high revenue potential for late stover (+\$35) and moderate potential for economic viability. Overall profitability is hindered by cost of feedstock collection and pyrolysis. (see p 831). Transportation has significant cost ramifications as well.

**Conclusions:** Biochar presents a possibility of carbon sequestration, GHG emission reduction, renewable energy creation, and economic viability but these are highly dependent on the feedstock chosen.



Rondon, Marco A., et al. 2007. "Biological Nitrogen Fixation by Common Beans (*Phaseolus vulgaris* L.) Increases with Bio-Char Additions." *Biology and Fertility of Soils*. 43: 699-708.

**Abstract:** This study examines the potential, magnitude, and causes of enhanced biological N<sub>2</sub> fixation (BNF) by common beans (*Phaseolus vulgaris* L.) through bio-char additions (charcoal, biomass-derived black carbon). Biochar was added at 0, 30, 60, and 90 g kg<sup>-1</sup> soil, and BNF was determined using the isotope dilution method after adding 15N-enriched ammonium sulfate to a Typic Haplustox cropped to a potentially nodulating bean variety (CIAT BAT 477) in comparison to its non-nodulating isolate (BAT 477NN), both inoculated with effective *Rhizobium* strains. The proportion of fixed N increased from 50% without biochar additions to 72% with 90 g kg<sup>-1</sup> bio-char added. While total N derived from the atmosphere (NdfA) significantly increased by 49 and 78% with 30 and 60 g kg<sup>-1</sup> bio-char added to soil, respectively, NdfA decreased to 30% above the control with 90 g kg<sup>-1</sup> due to low total biomass production and N uptake. The primary reason for the higher BNF with bio-char additions was the greater B and Mo availability, whereas greater K, Ca, and P availability, as well as higher pH and lower N availability and Al saturation, may have contributed to a lesser extent. Enhanced mycorrhizal infections of roots were not found to contribute to better nutrient uptake and BNF. Bean yield increased by 46% and biomass production by 39% over the control at 90 and 60 g kg<sup>-1</sup> bio-char, respectively. However, biomass production and total N uptake decreased when biochar applications were increased to 90 g kg<sup>-1</sup>. Soil N uptake by N-fixing beans decreased by 14, 17, and 50% when 30, 60, and 90 g kg<sup>-1</sup> bio-char were added to soil, whereas the C/N ratios increased from 16 to 23.7, 28, and 35, respectively. Results demonstrate the potential of biochar applications to improve N input into agroecosystems while pointing out the needs for long-term field studies to better understand the effects of bio-char on BNF.

**Basic Hypothesis/Goal:** The goal of this article is to determine the influence of various levels of biochar additions on BNF of common beans on acid Oxisol and BNF soil nutrient availability and mycorrhizal infection.

**Type of Study:** lab (greenhouse)

**Process:** The experiment in this study took place in a greenhouse with an average daily temperature of 25°C and relative humidity of 60-70%. Soil received a basal dose of fertilizer - 300kg ha<sup>-1</sup> of lime, 20 kg P ha<sup>-1</sup>, and 20 kg N ha<sup>-1</sup>. Biochar was added to pots at 0, 30, 60 and 90 g of biochar per kilogram of soil. Soil reaction was determined, cation exchange capacity was determined, and Morgan extraction on the final soil sample as well as plasma atomic emission spectroscopy was performed. Leaves were tested for chlorophyll levels. Roots were analyzed for mycorrhizal infection level count.

**Statistics:** ANOVA  $p < 0.05$

**Crop Detail:** Two common bean varieties were planted.

**Pyrolysis Facility Details:** Pyrolysis took place in a large, temperature-controlled kiln at 350°C with oxygen level regulated at 15%. Charring time was 1 hour for 20 kg of air-dried logs cut into .2m long pieces.

**Findings:** The biomass production of N-fixing beans was significantly higher than non-N-fixing isolate. The increased biomass came mostly from the leaves. The proportion of N derived from biological N fixation significantly increased from 50% without biochar to 72% with 90g kg with biochar. Total N from BNF peaked at 60 g/kg of biochar application. N concentration in plant tissue was significantly lower in non-N-fixing than N-fixing bean. P, K, Ca, Mg, and B concentrations significantly increased with bio-char applications, while S, Zn, Cu, and Mn did not change and Fe and Al significantly decreased. Mo levels were detectable and significantly increased with biochar additions. Extractable mineral N was not significantly affected by



biochar addition but was significantly lower in soil under N-fixing plants. Mineral N significantly decreased an average of 51% throughout the experiment.

**Soil Details:** Soil was collected from the top .2m of a clay-loam oxisol (typic Haplustox) from the Matazul research site at the Colombian Eastern Plains (Llanos). This soil has very low inherent fertility.

**Conclusions:** Nitrogen fixation was significantly improved by moderate biochar additions. There is potential for increasing N input by BNF into agro-ecosystems in highly weathered and acid soils via biochar application.

Singh, Balwant, Bhupinder Pal Singh, and Annette L. Cowie. 2010. "Characterisation and Evaluation of Biochars for their Application as a Soil Amendment." *Australian Journal of Soil Research*. 48: 516-525.

**Abstract:** Biochar properties can be significantly influenced by feedstock source and pyrolysis conditions; this warrants detailed characterization of biochars for their application to improve soil fertility and sequester carbon. We characterized 11 biochars, made from 5 feedstocks [Eucalyptus saligna wood (at 4008C and 5508C both with and without steam activation); E. saligna leaves (at 4008C and 5508C with activation); papermill sludge (at 5508C with activation); poultry litter and cow manure (each at 4008C without activation and at 5508C with activation)] using standard or modified soil chemical procedures. Biochar pH values varied from near neutral to highly alkaline. In general, wood biochars had higher total C, lower ash content, lower total N, P, K, S, Ca, Mg, Al, Na, and Cu contents, and lower potential cation exchange capacity (CEC) and exchangeable cations than the manure-based biochars, and the leaf biochars were generally in-between. Papermill sludge biochar had the highest total and exchangeable Ca, CaCO<sub>3</sub> equivalence, total Cu, and potential CEC, and the lowest total and exchangeable K. Water-soluble salts were higher in the manure-based biochars, followed by leaf, papermill sludge, and wood biochars. Total As, Cd, Pb, and polycyclic aromatic hydrocarbons in the biochars were either very low or below detection limits. In general, increase in pyrolysis temperature increased the ash content, pH, and surface basicity and decreased surface acidity. The activation treatment had a little effect on most of the biochar properties. X-ray diffraction analysis showed the presence of whewellite in E. saligna biochars produced at 4008C, and the whewellite was converted to calcite in biochars formed at 5508C. Papermill sludge biochar contained the largest amount of calcite. Water-soluble salts and calcite interfered with surface charge measurements and should be removed before the surface charge measurements of biochar. The biochars used in the study ranged from C-rich to nutrient-rich to lime-rich soil amendment, and these properties could be optimized through feedstock formulation and pyrolysis temperature for tailored soil application.

Smith, Jeffrey L., Harold P. Collins, and Vanessa L. Bailey. "The Effect of Young Biochar on Soil Respiration." *Soil Biology & Biochemistry*. 42: 2345-2347.

**Abstract:** The low temperature pyrolysis of organic material produces biochar, a charcoal like substance. Biochar is being promoted as a soil amendment to enhance soil quality, it is also seen as a mechanism of long-term sequestration of carbon. Our experiments tested the hypothesis that biochar is inert in soil. However, we measured an increase in CO<sub>2</sub> production from soils after biochar amendment, which increased with increasing rates of biochar. The  $\delta^{13}\text{C}$  signature of the CO<sub>2</sub> evolved in the first several days of the incubation was the same as the  $\delta^{13}\text{C}$  signature of the biochar, confirming that biochar contributed to the CO<sub>2</sub> flux. This effect diminished by day 6 of the incubation suggesting that most of the biochar C is slowly decomposing. Thus, aside from this short-term mineralization increasing soil C with young biochar may indeed be a long-term C storage mechanism.

**Basic Hypothesis/Goal:** Biochar is not completely inert in soil and thus contributes to CO<sub>2</sub> flux when added to soil.

**Biomass Used:** switchgrass

**Type of Study:** lab

**Process:** Soil samples were collected from a Shano silt loam and a Walla Walla silt loam (both in WA state) from the 0-5cm depth, put through a 2 mm sieve, and used field moist (adjusted to 0.03 MPa where needed). For each soil, 25g aliquots were amended with biochar at rates equivalent to 0, 11.2, 22.4 and 44.8 Mg/ha. Biochar plus sand was used as a secondary control. The amended soils were incubated at 0.03 MPa moisture potential in closed containers with a 1 N-NaOH trap for collecting CO<sub>2</sub>. Total CO<sub>2</sub> was determined by titration of these traps at 2, 6, 10, 17, 28, 35, 42, 49 days. Before the titration, trapped CO<sub>2</sub> was precipitated with SrCl<sub>2</sub> to form a precipitate that combusts at a temperature less than 1100 degrees C. The residual Sr<sub>13</sub>CO<sub>3</sub> left after the titration was dried and the  $\delta^{13}\text{C}$  of the Sr<sub>13</sub>CO<sub>2</sub> evolved was determined by isotope ratio mass spectrometry (IRMS).

**Pyrolysis Facility Details:** processed feedstock at 500°C for two hours

**Findings:** Both soils showed an increase in CO<sub>2</sub> production with increased biochar additions. The Walla Walla soil experienced larger increases. CO<sub>2</sub> production in the Shano soil did not differ significantly at the two intermediate rates of biochar addition. In contrast, these biochar amendment rates in the Walla Walla soil did generate significantly different rates of CO<sub>2</sub> evolution, and the lowest rate was not significantly different than the control. However, in both soils the increases were mostly during the first few days of incubation, thereafter the rates of CO<sub>2</sub> production were similar.

**Soil Details:** The Shano silt loam has a pH of 5.4, 0.64% C, 0.08% N and a  $\delta^{13}\text{C}$  of 21.4%. The Walla Walla silt loam has a pH of 7.1, 1.27% C, 0.12% N and a  $\delta^{13}\text{C}$  of 21.2%.

**Emissions Reduction:** After two days the CO<sub>2</sub> evolved from the highest biochar addition had a similar signature to that of pure biochar, approximately 13%. After four days both soils continued to show a significant biochar influence in the CO<sub>2</sub> evolved from decomposition. By day six there was no significant difference in the CO<sub>2</sub> signature between the control soil (0 biochar additions) and the other three biochar soil additions. This was consistent from day 6 to day 50 of the incubation.

**Conclusions:** We conclude that there is a distinct labile C pool associated with young biochar that may be significant in the short-term. It is likely that a fraction of the condensates from the bio-oil formed during pyrolysis absorbed to the biochar during cooling. These condensates are likely the source of the labile C pool and thus do not originate from the stable carbonized components of the biochar. Since only about 10-20% of the soluble component is mineralized to CO<sub>2</sub> it is probable that the aromatic and aliphatic compounds may precipitate forming larger

more complex molecules. In the long-term, we suggest these materials would be resistant to decomposition and would become part of the slow to resistant C pools in soils. Thus the claims in the literature and popular press that the greenhouse effect of increased CO<sub>2</sub> could be reduced by converting organic material to biochar and used as a soil amendment may have merit.

Sohi, S.P., et al. 2010. "A Review of Biochar and its Use and Function in Soil." *Advances in Agronomy*. 105: 47-82.

**Abstract:** Agricultural activities and soils release greenhouse gases, and additional emissions occur in the conversion of land from other uses. Unlike natural lands, active management offers the possibility to increase terrestrial stores of carbon in various forms in soil. The potential to sequester carbon as thermally stabilized (charred) biomass using existing organic resource is estimated to be at least 1 Gt yr<sup>-1</sup> and "biochar," defined by its useful application to soil, is expected to provide a benefit from enduring physical and chemical properties. Studies of charcoal tend to suggest stability in the order of 1000 years in the natural environment, and various analytical techniques inform quantification and an understanding of turnover processes. Other types of biochar, such as those produced under zero-oxygen conditions have been studied less, but costs associated with logistics and opportunity costs from diversion from energy or an active form in soil demand certainty and predictability of the agronomic return, especially until eligibility for carbon credits has been established. The mechanisms of biochar function in soil, which appear to be sensitive to the conditions prevailing during its formation or manufacture, are also affected by the material from which it is produced. Proposed mechanisms and some experimental evidence point to added environmental function in the mitigation of diffuse pollution and emissions of trace gases from soil; precluding the possibility of contaminants accumulating in soil from the incorporation of biochar is important to ensure safety and regulatory compliance.

**Basic Hypothesis/Goal:** The purpose of this article to explain biochar generally.

Solaiman, Zakaria M., Daniel V. Murphy, and Lynette K. Abbott. 2012. "Biochars Influence Seed Germination and Early Growth of Seedlings." *Plant Soil*. 353: 273-287.

**Abstract:** *Background and aims:* Biochar can be produced from a wide range of organic sources with varying nutrient and metal concentrations. Before making irreversible applications of biochar to soil, a preliminary ecotoxicological assessment is desirable.

*Methods:* First, we determined the effect of biochar type and rate on early growth of wheat in a soilless Petri dish bioassay. Second, we investigated the effect of the same biochars on seed germination and early growth of wheat in ten soils with varying texture using a glasshouse bioassay. Finally, we investigated whether these biochars had similar effects on three plant species when grown in one soil.

*Results:* Biochar type and application rate influenced wheat seed germination and seedling growth in a similar manner in both the soil-less Petri dish and soil-based bioassay.

Germination and early root growth of mung bean and subterranean clover differed from that of wheat in response to the five biochars.

*Conclusions:* We recommend use of the soil-less Petri dish bioassay as a rapid and simple preliminary test to identify potential toxicity of biochars on seed germination and early plant growth prior to biochar application to soil.

**Basic Hypothesis/Goal:** preliminary ecotoxicological assessment

**Biomass Used:** Oil Mallee, Rice Husks, New Jarrah, Old Jarrah, and Wheat Chaff

**Amount of Dry Biomass:** amounts equaling 0, 10 (1%), and 100 (10%) t/ha (calculated as soil volume to 10 cm soil depth), mixed with 500mL of soil for each soil tested

**Type of Study:** lab

**Process:** 3 experiments:

*1<sup>st</sup>:* Fifty wheat seeds were sown in Petri dishes on a layer of filter paper moistened with 20mL of de-ionized water. Each of five biochar types was added at rates of 0, 0.5, 1.0, 2.5, 5.0 g/Petri dish with three replicates. All Petri dishes were covered with lids and incubated in the dark at 25°C for 72 hours when germination percentage and root length were assessed. Root length of germinated seeds was measured in fresh roots using a ruler, and summed for each Petri dish (m/Petri dish).

*2<sup>nd</sup>:* Fifty wheat seeds were sown in 500mL soil in a plastic container for each of ten soils following the OECD guidelines for terrestrial plant growth. Each biochar was mixed separately with each soil at the rates 0, 10 (1%) and 100 (10%) t/ha (calculated as soil volume to 10 cm soil depth). Pots were placed randomly on a glasshouse bench, immersed with water and allowed to drain for 24 hours before weighing to measure water-holding capacity (WHC). During the experiment, the pots were weighed and water was added daily to maintain the soil at 80% WHC. Germination percentage was recorded daily from the fifth to twelfth day after sowing. Data are presented only for the 9th day of sowing, the day of peak germination. On the twelfth day after sowing, roots were washed free of soil, wiped with a paper towel and root lengths were measured using a gridline intercept method and estimated as m/pot. Shoot and root dry weights (DW) were recorded after oven-drying at 60°C for at least 72 hours at the end of the experiment.

*3<sup>rd</sup>:* Fifty seeds of wheat, mung bean, and subterranean clover were sown into soil in germination trays together (2L of soil with or without biochar) with three replications. Trays were filled with either soil or soil-biochar mixtures, placed on glasshouse benches randomly, saturated and drained prior to measuring WHC before sowing of seeds. Trays were watered daily to 80% WHC by spraying to a constant weight. Germination percentage was recorded between days five and ten after sowing. Data are presented only for the seventh day of sowing

corresponding to peak germination. On the tenth day after sowing, roots were sampled and assessed as for the wheat bioassay conducted in the ten soils.

**Statistics:** ANOVA

**Crop Detail:** 50 Calingiri wheat seeds were sown into Petri dishes for experiment 1; 50 Calingiri wheat seeds sown into germination trays in experiment 2; 50 seeds of Calingiri wheat, R. Wilczak mung bean, and Seaton Park subterranean clover were sown into germination trays in experiment 3

**Findings:** *Experiment 1:* In the soil-less Petri dish bioassay, biochar type and rate of application significantly affected wheat seed germination ( $p < 0.001$ ). Biochar generally increased wheat seed germination at the lower rates of biochar application (10–50 t/ha) and decreased or had no effect at higher rates of application. Both biochar type and rate of application generally increased root length of the seedlings in the Petri dish bioassay, especially at the first three rates of application ( $p < 0.001$ ).

*Experiment 2:* There was significant variation in wheat seed germination among soils in the presence of biochar ( $p < 0.001$ ). Seed germination with 10 t/ha biochar was increased by 9% for OM, 8% for WC and 4% for RH ( $p < 0.05$ ) but not for OJ and NJ biochars ( $p > 0.05$ ). In contrast, there was an inhibitive main effect on seed germination at the higher rate (100 t/ha) of application of all biochars ( $p < 0.001$ ).

*Experiment 3:* Biochar application rate significantly altered seed germination of clover ( $p < 0.001$ ); it decreased significantly with the increased rate of biochar application for all five biochars. As for subterranean clover, both biochar type and rate of application altered seed germination of mung bean seed ( $p < 0.001$ ). Wheat seed germination was increased with 10 t/ha biochar application for most of the biochar sources used such as OM, WC and OJ ( $p < 0.05$ ).

**Soil Details:** see table 2 within the article

**Conclusions:** recommend use of the soil-less Petri dish bioassay as a rapid and simple preliminary test to identify potential toxicity of biochars on seed germination and early plant growth prior to biochar application to soil. The effect of biochars on seed germination and seedling growth varied with soil properties. The five biochar types used in this study generally increased wheat seed germination at rates of application  $< 50$  t/ha and three of them tended to inhibit germination at the highest rate of application under the bioassay conditions. Wheat chaff biochar (WC) had the greatest inhibitory effect on seed germination among the biochars compared when applied at higher rates. Based on the comparison of the effects of biochar on plant growth in a glasshouse experiment with three agricultural plant species.

Spokas, Kurt A., John M. Baker, and Donal C. Reicosky. 2010. "Ethylene: Potential Key for Biochar Amendment Impacts." *Plant Soil*. 333: 443-452.

**Abstract:** Significant increases in root density, crop growth and productivity have been observed following soil additions of biochar, which is a solid product from the pyrolysis of biomass. In addition, alterations in the soil microbial dynamics have been observed following biochar amendments, with decreased carbon dioxide (CO<sub>2</sub>) respiration, suppression of methane (CH<sub>4</sub>) oxidation and reduction of nitrous oxide (N<sub>2</sub>O) production. However, there has not been a full elucidation of the mechanisms behind these effects. Here we show data on ethylene production that was observed from biochar and biochar-amended soil. Ethylene is an important plant hormone as well as an inhibitor for soil microbial processes. Our current hypothesis is that the ethylene is biochar derived, with a majority of biochars exhibiting ethylene production even without soil or microbial inoculums. There was increased ethylene production from non-sterile compared to sterile soil (215%), indicating a role of soil microbes in the observed ethylene production. Production varied with different biomass sources and production conditions. These observations provide a tantalizing insight into a potential mechanism behind the biochar effects observed, particularly in light of the important role ethylene plays in plant and microbial processes.

**Basic Hypothesis/Goal:** Ethylene could be an additional potential mechanism for the soil and plant responses observed from biochar amendments

**Biomass Used:** activated coconut charcoal (steam activated; water rinsed); hardwood sawdust; macadamia nut; dried distillers grain (pyrolysis at 350°C); dried distillers grain (pyrolysis at 400°C); corn cobs (pyrolysis at 350°C); corn cobs (pyrolysis at 400°C); mixed wood waste (pyrolysis at 400°C); mixed wood waste (pyrolysis at 450°C); wood pellets; mixed wood waste (updraft gasifier pyrolysis at 400-500°C); peanut hulls

**Amount of Dry Biomass:** respectively (in m<sup>2</sup>/g): 976.2; 10.4; 6.9; 66.3; 0.28; 0.28; <0.10; <0.10; 3.5; 26.8; 1.8; 33.5; 1.0

**Type of Study:** sealed aerobic lab incubations

**Process:** Three replicates each of three sets of incubations were established. The first set was performed on all twelve biochar types, the second only using the macadamia nut biochar, the third without biochar addition. (see document for specification of incubation sets)

**Pyrolysis Facility Details:** Biochars were produced by the following suppliers, respectively: Willinger Brothers; Dynamotive, Biochar Brokers, Best Energies, ISTC; ISTC; ISTC; ISTC; ISTC; ISTC; Chip Energy; Chip Energy; EPRIDA

**Findings:** Soil without biochar amendments did not produce any detectable ethylene at field capacity and the production at saturated conditions (1:1 slurry) was just slightly above the detection limit. When the biochar was mixed with soil, six out of the twelve biochar-amended soil samples exhibited increased ethylene production compared to the unamended soil at field capacity. The highest ethylene-producing soil-biochar combination (BC-2; macadamia nut biochar) was also evaluated with different oxygen concentrations and with soil sterilization. Soil was also incubated in the presence of ethylene to observe the impact on soil greenhouse gas production potentials (Fig. 1). As seen in the figure, there were no statistically significant differences in the three greenhouse gases for the pre-ethylene injection. However, following ethylene injections, the presence of ethylene caused significant reductions in N<sub>2</sub>O production and CH<sub>4</sub> oxidation correlated with increasing levels of ethylene (Fig. 1a and c). On the other hand, there was no significant alteration in CO<sub>2</sub> production as a function of ethylene concentrations (Fig. 1b). CO<sub>2</sub> production rates were statistically decreased at some ethylene concentrations, but were not impacted at the highest ethylene concentration evaluated (275 μL L<sup>-1</sup>). In addition, ethylene additions caused a decrease in the available nitrate and an increase



in the available ammonium as a function of the ethylene headspace concentration at the end of the thirty-day incubation (Fig. 2). These inhibitory effects did diminish with time as the ethylene was oxidized, particularly at the lower ethylene levels.

**Soil Details:** Soil for the laboratory studies was collected at the University of Minnesota's Research and Outreach Station in Rosemount, MN (44°45' N, 93°04' W). Soil at the site is a Waukegan silt loam (fine-silty over skeletal mixed, super active, mesic Typic Hapludoll) containing approximately 22% sand, 55% silt, and 23% clay with a pH (1:1 H<sub>2</sub>O) of 6.3–6.6, 2.6% organic carbon and a slope < 2%. This site was farmed in a conventionally tilled (moldboard plow) corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation for the last 8+ years. The soil was sampled following corn harvest. Surface soil (0–5 cm) was collected, sieved to <2 mm and homogenized for the incubation study.

**Land/Agricultural Use:** Findings that ethylene production was increased with the use of biochar could have a positive impact on soil fertility

**Emissions Reduction:** Ethylene could contribute to GHG reductions that have been previously observed following soil biochar additions (e.g. Spokas and Reicosky 2009; Spokas et al. 2009; Yanai et al. 2007; Van Zwieten et al. 2009).

**Conclusions:** The observed production of ethylene could be a contributing factor to the observations from biochar amended soils, both for microbial and plant processes. The more important implication of this finding is the potential utilization of biochar as a nitrification inhibitor. However, biochar use as a nitrification inhibitor still requires further investigations into the durations and temporal trends of these observed effects. While we are not suggesting that ethylene is the sole mechanism of biochar impacts, this observed production offers a potential explanation for some of the contrasting effects that have been observed in plant and microbial responses to biochar amendments, particularly for plant growth, microbial activities and fungi colonization.

Spokas, Kurt A., et al. 2009. "Impacts of Woodchips Biochar Additions on Greenhouse Gas Production and Sorption/Degradation of Two Herbicides in a Minnesota Soil." *Chemosphere*. 77: 547-581.

**Abstract:** A potential abatement to increasing levels of carbon dioxide (CO<sub>2</sub>) in the atmosphere is the use of pyrolysis to convert vegetative biomass into a more stable form of carbon (biochar) that could then be applied to the soil. However, the impacts of pyrolysis biochar on the soil system need to be assessed before initiating large-scale biochar applications to agricultural fields. We compared CO<sub>2</sub> respiration, nitrous oxide (N<sub>2</sub>O) production, methane (CH<sub>4</sub>) oxidation and herbicide retention and transformation through laboratory incubations at field capacity in a Minnesota soil (Waukegan silt loam) with and without added biochar. CO<sub>2</sub> originating from the biochar needs to be subtracted from the soil–biochar combination in order to elucidate the impact of biochar on soil respiration. After this correction, biochar amendments reduced CO<sub>2</sub> production for all amendment levels tested (2, 5, 10, 20, 40 and 60% w/w; corresponding to 24–720 t ha<sup>-1</sup> field application rates). In addition, biochar additions suppressed N<sub>2</sub>O production at all levels. However, these reductions were only significant at biochar amendment levels >20% w/w. Biochar additions also significantly suppressed ambient CH<sub>4</sub> oxidation at all levels compared to unamended soil. The addition of biochar (5% w/w) to soil increased the sorption of atrazine and acetochlor compared to non-amended soils, resulting in decreased dissipation rates of these herbicides. The recalcitrance of the biochar suggests that it could be a viable carbon sequestration strategy, and might provide substantial net greenhouse gas benefits if the reductions in N<sub>2</sub>O production are lasting.

**Basic Hypothesis/Goal:** The purpose of this study was to document the impact of biochar application to a Minnesota agricultural soil on CO<sub>2</sub> and N<sub>2</sub>O production, CH<sub>4</sub> oxidation potentials and alterations in sorption/degradation characteristics for two common herbicides (atrazine and acetochlor).

**Biomass Used:** mixed sawdust

**Amount of Dry Biomass:** surface area: 1.6m<sup>2</sup>g<sup>-1</sup>; bulk density: 225 kgm<sup>-3</sup>

**Type of Study:** lab

**Process:** Soil was collected at the University of Minnesota's Research and Outreach Station in Rosemount, MN. CQuest biochar produced by Dynamotive Energy Systems from a fast pyrolysis process of mixed sawdust optimized for the production of liquid bio-fuel. Seven incubations of combinations of biochar, soil, and water were conducted at field capacity (-33kPa).

**Statistics:** linear regression analysis for CH<sub>4</sub> oxidation rate; ANOVA for data analysis

**Pyrolysis Facility Details:** CQuest produced by Dynamotive Energy Systems (Vancouver) from a fast pyrolysis process (500°C) of mixed sawdust optimized for the production of liquid bio-fuel, with yields of 60-75 wt% oil, 15-20 wt% biochar and 10-20 wt% gases

**Findings:** There was observable CO<sub>2</sub> accumulation in the biochar + water incubations...At first inspection, it would appear that the biochar amendments increased CO<sub>2</sub> production. However, an important factor that needs to be accounted with analyzing CO<sub>2</sub> production of biochar + soil combinations is to account for the CO<sub>2</sub> production from biochar alone.

**Soil Details:** Soil for the laboratory studies was collected at the University of Minnesota's Research and Outreach Station in Rosemount, MN (44°45'N, 93°04'W). Soil at the site is a Waukegan silt loam (fine- silty over skeletal mixed, super active, mesic Typic Hapludoll) containing approximately 22% sand, 55% silt and 23% clay with a pH (1:1 H<sub>2</sub>O) of 6.3–6.6, 2.6% organic carbon and a slope <2%. This site was farmed in a conventionally tilled (moldboard plow) corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation. The soil was sampled following corn harvest. Surface soil (0–5 cm) was collected, sieved to <2 mm and homogenized for the

incubation study. Soil was collected within 1 month of initiating the soil incubations to reduce the impacts of storage on the microbial assessments

**Conclusions:** These results confirm that biochar is resistant to microbial degradation, and hence may be an effective mode of carbon sequestration. Furthermore, there appears to be a positive greenhouse gas benefit, primarily due to the reduction in  $N_2O$  production as a consequence of the sawdust biochar addition. This reduction in observed  $N_2O$  production could easily offset the 60% reduction in  $CH_4$  oxidation activity with 10% w/w biochar additions in the net greenhouse gas balance. Biochar also increased the sorption of two common herbicides, reducing the likelihood of leaching and runoff losses, but also reducing bioavailability, perhaps necessitating higher application rates. However, additional field scale trials are necessary to further investigate the impacts of biochar amendments. In addition, it is important to note that the impacts observed in these laboratory incubations were the initial effects and the long-term impacts of the biochar amendments still need to be assessed. These initial observations could be influenced by absorbed organics that will dissipate with time. Therefore, aged biochar could cause entirely different impacts than those observed here with freshly produced biochar.

Steinbeiss, S., G. Gleixner, and M. Antonietti. 2009. "Effect of Biochar Amendment on Soil Carbon Balance and Soil Microbial Activity." *Soil Biology & Biochemistry*. 41: 1301-1310.

**Abstract:** We investigated the behavior of biochars in arable and forest soil in a greenhouse experiment in order to prove that these amendments can increase carbon storage in soils. Two qualities of biochar were produced by hydrothermal pyrolysis from  $^{13}\text{C}$  labeled glucose (0% N) and yeast (5% N), respectively. We quantified respiratory losses of soil and biochar carbon and calculated mean residence times of the biochars using the isotopic label. Extraction of phospholipid fatty acids from soil at the beginning and after 4 months of incubation was used to quantify changes in microbial biomass and to identify microbial groups utilizing the biochars. Mean residence times varied between 4 and 29 years, depending on soil type and quality of biochar. Yeast-derived biochar promoted fungi in the soil, while glucose-derived biochar was utilized by Gram-negative bacteria. Our results suggest that residence times of biochar in soils can be manipulated with the aim to "design" the best possible biochar for a given soil type.

**Basic Hypothesis/Goal:** 1) How stable are biochars produced by this method in different soils? 2) How do inherited soil microorganisms react on the addition of such biochars? 3) Is the stability of these biochars tunable by varying the condensation grade and chemical composition of the biochar?

**Biomass Used:** Biochars were produced by hydrothermal pyrolysis using glucose (signature G) and yeast (signature Y) as parent material, respectively. A  $^{13}\text{C}$  label was introduced to both biochars adding uniformly  $^{13}\text{C}$  labeled glucose (99 atom%, Sigma Aldrich) to the parent materials prior to biochar synthesis.

**Type of Study:** lab

**Process:** Soil columns were filled with 150g of soil (dry weight); 15 columns were filled with arable soil (signature A) and 15 columns were filled with forest soil (signature F). The soil of six columns of each soil type was mixed with glucose-derived biochar (signatures AG and FG) and further six columns of each soil type were mixed with yeast-derived biochar (signatures AY and FY). Three columns of each soil type were left as control without biochar (signatures A and F). The amount of biochar added to the soil was calculated to correspond to a carbon addition of 30% of the initial soil organic carbon content. Initial soil properties including PLFA analyses were determined from soil samples without incubation (signatures AI and FI) with triple replicates. Soil columns were incubated at 25 degrees C during the day and 20 degrees C during the night. No artificial lighting was applied. Soil moisture was adjusted every three to four days in all columns. No water leached out from the columns. Soil respiration was measured using a carbon dioxide probe from week 1 to week 25 with a temporal resolution of 1 week in the beginning (up to week 7) and 2–3 weeks afterwards. The respired gas was collected in weeks 7, 12, 15, 17, 20, 23 and 26 using 2.3 l gas flasks connected via a capillary to the soil columns (filling time 4 hours per sample). Sample air was dried chemically using magnesium perchlorate. Each time two flasks were filled the same way with greenhouse air to correct ambient  $\text{CO}_2$  concentration and isotope ratios of the treatments ( $\delta^{13}\text{C}$  treatment, korr). Gas  $\text{CO}_2$  concentration was measured by GC-FID and stable carbon isotope ratios were determined by isotope ratio mass spectrometry

**Statistics:** t-tests for direct comparison of treatments; ANOVA

**Findings:** Glucose-derived biochar was highly carbonized and thus thermally stable. The degree of condensation in the yeast-derived biochar was much lower than that of the glucose-derived biochar, indicated by a total mass loss of 72%, which is only 10% less than that of the parent material, yeast, under the same conditions. Initial respiration rates differed strongly between the treatments (Fig. 3) but did not correlate to the initial carbon content. In arable soil, both biochar treatments (AG, AY) showed similar respiration rates to the control despite the carbon

addition ( $p=0.64$  and  $0.50$ , respectively). Measured respiration rates reflect temporary carbon losses and varied over time due to temperature and soil moisture variability. Addition of glucose-derived biochar to both soil types caused a significant reduction of microbial biomass ( $p<0.001$ ) during incubation. In contrast, yeast-derived biochar addition did not change the PLFA content in the soils ( $p=0.39$ ), which still was as high as before incubation in both soil types. We found no interaction between soil type and biochar type ( $p=0.15$ ).

**Soil Details:** Soils used for the greenhouse experiment were sampled at the continued arable plot of the Jena Experiment and at the old growth forest field site of the Hainich National Park, respectively. The soil of the Jena Experiment was classified as Eutric Fluvisol and had a texture of 23% clay, 64% silt and 13% sand. The soil of the Hainich field site was a fertile Cambisol containing 40% clay, 56% silt and 4% sand. In September 2007 the top 5 cm of soil were sampled at both field sites, passed through a sieve with a mesh size of 2 mm and partitioned for PLFA extraction (fresh soil), for soil column filling and for chemical analyses (dried at 40 degrees C), respectively.

**Conclusions:** Answering "Goal" questions respectively: 1) Biochars produced by hydrothermal pyrolysis would add to the decadal soil carbon pool. 2) Inherited soil microorganisms adapted to the new carbon source and utilized both types of biochar. The biochar type determined, which group of microorganisms were involved in the decomposition process. Yeast-derived biochar strongly promoted fungi, while glucose-derived biochar primarily was utilized by Gram-negative bacteria. 3) Our results clearly show that the type of biochar, i.e. condensation grade and chemical structure, is the main driver for all differences observed between our treatments. All patterns observed for the biochar types were the same in both soils. We thus conclude that the condensation grade and the chemical structure of biochars produced by this method could serve as "tuning parameter" to design biochars that act as fertilizers but simultaneously add to the soil carbon pool on a decadal time scale.

Taghizadeh-Toosi, Arezoo, et al. 2012. "Biochar Adsorbed Ammonia is Bioavailable." *Plant Soil*. 350: 57-69.

**Abstract:** Abstract Biochar is produced as a by-product of the low temperature pyrolysis of biomass during bioenergy extraction and its incorporation into soil is of global interest as a potential carbon sequestration tool. Biochar influences soil nitrogen transformations and its capacity to take up ammonia is well recognized. Anthropogenic emissions of ammonia need to be mitigated due to negative environmental impacts and economic losses. Here we use an isotope of nitrogen to show that ammonia-N adsorbed by biochar is stable in ambient air, but readily bio-available when placed in the soil. When biochars, containing adsorbed  $^{15}\text{N}$  labeled ammonia, were incorporated into soil the  $^{15}\text{N}$  recovery by roots averaged 6.8% but ranged from 26.1% to 10.9% in leaf tissue due to differing biochar properties with plant  $^{15}\text{N}$  recovery greater when acidic biochars were used to capture ammonia. Recovery of  $^{15}\text{N}$  as total soil nitrogen (organic + inorganic) ranged from 45% to 29% of  $^{15}\text{N}$  applied. We provide a proof of concept for a synergistic mitigation option where anthropogenic ammonia emissions could be captured using biochar, and made bio-available in soils, thus leading to nitrogen capture by crops, while simultaneously sequestering carbon in soils.

**Biomass Used:** 4 biochar materials (BC1-4) of Monterey Pine wood chips pyrolyzed at 300, 300, 350, and 500 degrees C, respectively, and characterized for: cation exchange capacity using a 1 g biochar (sieved < 2 mm): 50 ml silver thiourea extraction ratio and analysis by ICP- OES

**Type of Study:** lab

**Process:** Petri dishes containing sieved (< 2 mm) oven-dried ( $105^\circ\text{C}$ ) biochar (1.5 g) were placed in Mason jars (0.5 l) above the NaOH solution (55 ml). Gas-tight lids, fitted with septa, were put on to the jars prior to injecting 25 ml of the  $^{15}\text{N}$  enriched  $(\text{NH}_4)_2\text{SO}_4$  solution into the NaOH solution contained by the jars. Jars were left sealed for 1 week. No measure of aerobic status was made over this time since generation of  $\text{NH}_3$  neither consumes oxygen nor produces  $\text{CO}_2$ , and microbial activity on the biochar was considered negligible. After 1 week excess 0.1M sulfuric acid was injected to neutralize the solution in the jars and to allow any remaining  $\text{NH}_3$  gas to be absorbed by the acid solution. The jars were then left for a further 2 hours. All the  $^{15}\text{N}$  enriched biochar materials were stored in sealed glass vials prior to analysis. Both non-enriched (BC) and enriched (eBC) biochar materials were analyzed for total N and  $^{15}\text{N}$  enrichment 3 days after  $^{15}\text{N}$  labelling using continuous flow isotope ratio mass spectrometry (CFIRMS; 20–20 Sercon Ltd). Subsamples of the eBC1 biochar were taken every other day and analysed, using CFIRMS, for total N content and  $^{15}\text{N}$  enrichment. Ten treatments were monitors: soil alone, soil with ryegrass, soil + ryegrass + unenriched biochar (BC1-4), and soil + ryegrass +  $^{15}\text{N}$ -enriched biochar (eBC1-4).

**Statistics:** linear regression

**Crop Detail:** perennial ryegrass (*Lolium perenne* L.)

**Findings:** The uptake of  $^{15}\text{N}$  labeled  $\text{NH}_3$  by the biochar materials was higher than in previously summarized studies where rates of the order of 0.2 to 1.8 mg g<sup>-1</sup> of biochar were noted, and this may be a function of biomass used, biochar pyrolysis conditions and/or the  $\text{NH}_3$  concentration the biochars were exposed to. The close relationship observed here between both the biochar pH and surface acidity and the amount of  $\text{NH}_3\text{-N}$  taken up supports this idea, along with the increase in pH following exposure to  $\text{NH}_3$  of the eBC materials.

**Soil Details:** A Temuka silt loam soil of adequate fertility to grow ryegrass was sampled (0–7.5 cm depth) from a grazed pasture site ( $43^\circ 38' 58''\text{S}$ ,  $172^\circ 27' 53''\text{E}$ ), air-dried, and sieved to 2 mm.

**Conclusions:** The use of  $^{15}\text{N}$  stable isotope unequivocally demonstrates that  $\text{NH}_3$  adsorbed onto biochar can provide a source of N for plants when the biochar- $\text{NH}_3$  complex is placed in the

soil-plant matrix. [The study] demonstrates a proof of concept for dramatically reducing the leakage of N from agricultural systems and its recycling by using biochar to capture NH<sub>3</sub> emissions.



Vaccari, F.P., et al. 2011. "Biochar as a Strategy to Sequester Carbon and Increase Yield in Durum Wheat." *European Journal of Agronomy*. 34: 231-238.

**Abstract:** Carbon sequestration in agricultural soils is a climate change mitigation option since most of cultivated soils are depleted of soil organic carbon and far from saturation. The management practices, most frequently suggested to increase soil organic carbon content have variable effects depending on pedo-climatic conditions and have to be applied for a long time periods to maintain their sink capacity. Biochar (BC), a carbon rich product obtained through carbonization of biomass, can be used for carbon sequestration by applying large amounts of carbon very resistant to decomposition. The BC remains into soil for a long time and there is evidence that the BC stores atmospheric carbon from centennial, to millennial timescales. However most of the agronomic studies on BC application have been made in tropical and sub-tropical climates, while there is a substantial lack of studies at mid-latitudes and in temperate climates. This paper presents the results on an investigation of large volume application of BC (30 and 60 t ha<sup>-1</sup>) on durum wheat in the Mediterranean climate condition, showing the viability of BC application for carbon sequestration on this crop. BC application also has positive effects up to 30% on biomass production and yield, with no differences in grain nitrogen content. Moreover no significant differences between the two BC treatments were detected, suggesting that even very high BC application rates promote plant growth and are, certainly, not detrimental. The effect of the biochar on durum wheat was sustained for two consecutive seasons when BC application was not repeated in the second year.

**Basic Hypothesis/Goal:** Field experiment where a large volume of biochar was applied to durum wheat crop for two consecutive seasons in a Mediterranean climate.

**Biomass Used:** a commercial horticultural charcoal provided by Lakeland Coppice Products (England) obtained from coppiced woodlands (beech, hazel, oak and birch)

**Type of Study:** field experiment

**Process:** Biochar was manually applied, before sowing operation in 2009 and in 2010 and partially buried with a rotary hoeing tillage. Wheat was sown on 16th January 2009 (experiment 2008/2009) and on 14th December 2009 (experiment 2009/2010) in rows with a sowing rate of 450 germinable seeds per square meter. Nitrogen-phosphate and phosphorous fertilizer were distributed at sowing (22 kg ha<sup>-1</sup> of N and 50 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub>) and a second fertilization was made on April using ammonium nitrate fertilizer at a rate of 100 kg N ha<sup>-1</sup> for both experiments. During the wheat-growing season, three destructive biomass samples were done at Zadoks scale of (Zadoks et al., 1974): 32 (stem elongation or jointing, 2nd node detectable), 50 (heading, first spikelet of head visible) and 91 (ripening, kernel hard difficult to separate by fingernail). The plots were manually harvested on 25th June 2009 and on 4th July 2010 by selecting three subplots of 0.25 m<sup>2</sup> in the central part of each plot to avoid the edge effects. Total above ground biomass (AGB) was oven-dried and weighted. Wheat ears were then separated from the straw and the grains were separated from the ears using a laboratory thresher (LD 350, Wintersteiger, Ried, Austria); nitrogen (N) grain concentration was determined using a Near-Infrared Spectroscopy (NIR Analyzer, Carlo Erba, MI, Italy). During the 2008/2009 experimental season the soil temperature was monitored at five different dates (January 15th, 29th; February 20th, 24th and March 24th) at 5 cm of soil depth, using a soil temperature probe (STP-1, PPSystems, Hitchin, UK). Moreover, the number of durum wheat plants along a row (1 m length) was counted in each plot at Zadoks scale 12 (2nd leaves unfolded) and the weed productions were harvested by selecting three subplots of 0.25 m<sup>2</sup> on each plot at durum wheat harvest (25th June) and at 16th October 2009. Soil pH was measured in 1:2.5 (soil:water) suspension adding CaCl<sub>2</sub> (0.01 M), sampling the soil before and after (end of June) BC application, in 2009.



**Statistics:** one-way ANOVA performed separately in each growing season to compare the three treatments (C0, B30, and B60). Moreover, the residual effect of BC in 2009/2010 (treatments C0w, B30w and B60w) was evaluated including in the analysis the new treatments with BC application in the same year. Prior to ANOVA, Bartlett's test was used on the data to test the homogeneity of variance. Student–Newman–Keuls test at 0.05 significance level was used as means multiple comparison test.

**Crop Detail:** The field experiment was made over two consecutive seasons in 2008/2009 and 2009/2010 near Pistoia (Toscana, Lat. 43° 56' N, Long. 10° 54' E, 65 m a.s.l.), using the durum wheat (*Triticum durum* L.) cultivar Neolatino. Meteorological parameters were collected by an automatic weather station, installed close to the experimental field. During the period September–July of 2008/2009 and 2009/2010, total rainfall was 1159 and 1222.8 mm respectively and the mean air temperature was 13.9 and 15.1°C (Fig. 1). The soil was a silty-loam (USDA, 2005) with a sub-acid pH of 5.2 (Table 1). In the first experimental season (2008/2009), a randomized block experiment with four replicates was set up in plots of 25 m<sup>2</sup>, considering three treatments: Control (C0), biochar at a rate of 30 t ha<sup>-1</sup> (B30) and 60 t ha<sup>-1</sup> (B60). In order to evaluate the potential residual effect of BC application on wheat yield, the same plots (thereinafter called C0w, B30w and B60w) were cultivated without BC application in the following growing season (2009/2010). In 2009/2010, new plots with BC application were added in the experimental site, maintaining the same layout of the previous year (C0, B30 and B60).

**Pyrolysis Facility Details:** The BC applied in both field experiments was a commercial horticultural charcoal provided by Lakeland Coppice Products (England) obtained from coppiced woodlands (beech, hazel, oak and birch). BC has been obtained at pyrolysis temperatures of 500°C in a transportable ring kiln (2.15 m in diameter and holding around 2 t of hardwood). The BC was crushed into particles smaller than 1 cm before application into soil in order to increase the area/volume ratio and to enhance its expected effects on soil properties.

**Findings:** Found the addition of biochar to increase crop yield. Two years of field experiments supported the view, that the addition of large quantities of BC to sequester atmospheric CO<sub>2</sub> is a viable option for durum wheat crops, at least for the typical conditions of Southern Europe, where this species is commonly cultivated.

**Soil Details:** Sand (g kg<sup>-1</sup>) a 2mm >> 0.05mm: 501 | Silt (g kg<sup>-1</sup>) 0.05 mm >> 0.002 mm: 433 | Clay (g kg<sup>-1</sup>) < 0.002 mm: 67 | Bulk density (Mg m<sup>-3</sup>): 1.2 | OC (g kg<sup>-1</sup>) b: 21 | N (g kg<sup>-1</sup>) c: 1.2 | CEC (mequiv./100 g) d: 18 | pHe: 5.2

**Potential Relevance for Arid Soils:** possibly more relevant than other trials but the area used receives considerably more rain than NV (the authors documented rainfall over the two growing seasons exceeding 45 inches per year)

**Climate Change:** This experiment provided evidence that such important carbon sequestration potential may be realized without any negative consequence on crop yield.

**Conclusions:** The results presented and discussed in this paper provide important evidence that BC can be successfully used to sequester atmospheric CO<sub>2</sub> in durum wheat crops. Large BC applications had no harmful effects on yield and yield quality over two consecutive years and also did not interfere with the execution of conventional agricultural management. The results presented and discussed in this paper provide important evidence that BC can be successfully used to sequester atmospheric CO<sub>2</sub> in durum wheat crops. Large BC applications had no harmful effects on yield and yield quality over two consecutive years and also did not interfere with the execution of conventional agricultural management. Lower bulk density in BC-treated plots has the potential to reduce the tensile strength of mineral soils eventually leading to reduced tillage costs.

Wang, Jinyang, et al. 2011. "Effects of Biochar Addition on N<sub>2</sub>O and CO<sub>2</sub> Emissions from Two Paddy Soils." *Biology and Fertility of Soils*. 47: 887-896.

**Abstract:** Impacts of biochar addition on nitrous oxide (N<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>) emissions from paddy soils are not well documented. Here, we have hypothesized that N<sub>2</sub>O emissions from paddy soils could be depressed by biochar incorporation during the upland crop season without any effect on CO<sub>2</sub> emissions. Therefore, we have carried out the 60-day aerobic incubation experiment to investigate the influences of rice husk biochar incorporation (50 tha<sup>-1</sup>) into two typical paddy soils with or without nitrogen (N) fertilizer on N<sub>2</sub>O and CO<sub>2</sub> evolution from soil. Biochar addition significantly decreased N<sub>2</sub>O emissions during the 60-day period by 73.1% as an average value while the inhibition ranged from 51.4% to 93.5% ( $P < 0.05$ – $0.01$ ) in terms of cumulative emissions. Significant interactions were observed between biochar, N fertilizer, and soil type indicating that the effect of biochar addition on N<sub>2</sub>O emissions was influenced by soil type. Moreover, biochar addition did not increase CO<sub>2</sub> emissions from both paddy soils ( $P > 0.05$ ) in terms of cumulative emissions. Therefore, biochar can be added to paddy fields during the upland crop-growing season to mitigate N<sub>2</sub>O evolution and thus global warming.

**Theory:** The addition of biochar to soil can help to mitigate global warming by mitigating N<sub>2</sub>O evolution

**Basic Hypothesis/Goal:** The aim of this study is to give an insight into the effect of biochar addition on N<sub>2</sub>O and CO<sub>2</sub> emissions during the upland crop season as influenced by paddy soil type and N fertilizer.

**Biomass Used:** produced from rice husks through thermal decomposition (350-500 degrees C) from a local (Chinese) company and ground to pass through a 2-mm stainless steel sieve

**Type of Study:** lab

**Process:** Soil samples were collected from ChangShu (CS) agro-ecological experimental station in the Jiangsu province and LiuYang (LY) agro-technical experimental field station in the Hunan province in China, typical for single rice–upland crop rotation and double rice agriculture, respectively. Three to four soil cores (30 × 30 cm) were taken randomly and mixed homogeneously at each site. Soil samples were air-dried, ground to pass through a 2-mm stainless steel sieve, and then stored at 4°C. The following treatments were established with four replicates: control (ck), soil + biochar (B), soil + urea N (N), and soil + urea N + biochar (BN). The aerobic incubation method was modified after Huang et al. (2004). Soil (90 g on oven-dry weight basis) was added to an Erlenmeyer flask (250 ml) and treated with distilled water to achieve the desired moisture content of 40% water holding capacity (WHC). Then the flasks were incubated at 25 ± 1°C in the dark for 7 days to stabilize microbial activity. During the following 60-day incubations, soil water content was brought to 60% WHC by adding distilled water; every 2 or 3 days, water was added to compensate water losses. Urea was evenly applied after pre-incubation at 200 mg Nkg<sup>-1</sup> soil and biochar rate was 26.67 gkg<sup>-1</sup> soil equivalent to a field application rate of 50 tha<sup>-1</sup>, by considering incorporation into the 0–15 cm soil layer and a soil bulk density of 1.25 gcm<sup>-3</sup>.

**Statistics:** MANOVA was used to test B, N, and their interaction on N<sub>2</sub>O and CO<sub>2</sub> emissions from two paddy soils for each incubation period. Both results were separately analyzed for each paddy soil since significant interactions between biochar, N fertilizer, and soil were detected. Then, a three-way analysis of variance (ANOVA) was applied to determine cumulative N<sub>2</sub>O and CO<sub>2</sub> emissions affected by biochar, N fertilizer, soil, and their interactions. An ANOVA with F test linearly related the total variation of CO<sub>2</sub> emissions with the changes of DOC content and also gave the part not explained by the relationship. Comparisons of cumulative N<sub>2</sub>O and CO<sub>2</sub>

emissions from each paddy soil affected by biochar and N fertilizer were made using Tukey's honestly significant difference tests based on least square means.

**Conclusions:** The aerobic incubation study showed that N<sub>2</sub>O emissions from paddy soils can be substantially reduced via biochar incorporation, due to reduction of soil NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N concentration. In terms of cumulative CO<sub>2</sub> emissions and DOC changes, biochar addition did not enhance soil C cycling in both paddy soils. Thus, biochar addition during the upland crop season (non-rice season) has a great potential to depress N<sub>2</sub>O emissions and to counteract global warming.

Whitman, Thea and Johannes Lehmann. 2009. "Biochar – One Way Forward for Soil Carbon in Offset Mechanisms in Africa?" *Environmental Science & Policy*. 12: 1024-1027.

**Abstract:** The Kyoto Protocol's Clean Development Mechanism (CDM) has had relatively little success in Africa due to a number of factors. Increases in agricultural soil carbon have strong benefits for soil health as well as potential for carbon sequestration, but such projects are currently excluded from the CDM and other offset mechanisms. Small-scale biochar systems with net emission reductions may hold a key for Africa to engage with the international offset mechanisms and open the door to soil carbon sequestration projects.

**Basic Hypothesis/Goal:** Small-scale biochar systems with net emission reductions may hold a key for Africa to engage with the international offset mechanisms and open the door to soil carbon sequestration projects.

**Amount of Dry Biomass:** It is suggested that it should be limited to the amount needed for cooking and not the amount of biomass that can be accessed.

**Type of Study:** review

**Conclusions:** Biochar could very well be Africa's key to the doors that the CDM was supposed to open toward sustainable development and climate change mitigation. Significant field-level research is needed first, but biochar could lead the way for other soil carbon management strategies to improve soil health and provide tangible local benefits while addressing global warming, making it a strong candidate for future incarnations of the CDM and other offset mechanisms in Africa.

Winsley, Peter. 2007. "Biochar and Bioenergy Production for Climate Change Mitigation." *New Zealand Science Review*. 64(1): 5-10.

**Abstract:** The world will increasingly depend on renewable energy with low or zero net greenhouse gas (GHG) emissions. This paper explores how science and the economic 'rules of the game' might realize the potential for the pyrolysis co-production of biochar and bio-oil to mitigate net GHG emissions while achieving other economic and environmental benefits. This pyrolysis process produces a high carbon biochar that can be sequestered almost permanently in soil, and energy that substitutes for fossil fuels. It is 'carbon negative', that is, it allows an ever-increasing carbon sink to be built up in soil. Biochar can reduce emissions of nitrous oxide and leaching of nitrates into water. It can also lift agricultural productivity through its effect on soil structure, micro-biota and nutrient availability.

**Theory:** Biochar and bio-energy can be increase agricultural yields and help mitigate climate change

**Basic Hypothesis/Goal:** The goal of this article is to demonstrate multiple positive effects of using biochar.

**Climate Change:** can reduce nitrogen fertilizer requirements and nitrous oxide emissions; bio-oil can be used as a fuel alternative

Woolf, Dominic, et al. 2010. "Sustainable Biochar to Mitigate Global Climate Change." *Nature Communications*. 56: 1-9.

**Abstract:** Production of biochar (the carbon (C)-rich solid formed by pyrolysis of biomass) and its storage in soils have been suggested as a means of abating climate change by sequestering carbon, while simultaneously providing energy and increasing crop yields. Substantial uncertainties exist, however, regarding the impact, capacity and sustainability of biochar at the global level. In this paper we estimate the maximum sustainable technical potential of biochar to mitigate climate change. Annual net emissions of carbon dioxide (CO<sub>2</sub>), methane and nitrous oxide could be reduced by a maximum of 1.8 Pg CO<sub>2</sub>-C equivalent (CO<sub>2</sub>-Ce) per year (12% of current anthropogenic CO<sub>2</sub>-Ce emissions; 1Pg=1Gt), and total net emissions over the course of a century by 130 Pg CO<sub>2</sub>-Ce, without endangering food security, habitat or soil conservation. Biochar has a larger climate-change mitigation potential than combustion of the same sustainably procured biomass for bioenergy, except when fertile soils are amended while coal is the fuel being offset.

**Theory:** Biochar can be a means of mitigating climate change through carbon sequestration, projection of a cleaner energy alternative, and allowing for larger crop yields.

**Basic Hypothesis/Goal:** Estimate of the maximum potential of biochar to mitigate climate change

**Biomass Used:** Estimates are provided for: rice, other cereal grains, sugar cane, manures, biomass crops, forestry residues, agro-forestry, and green/wood waste.

**Amount of Dry Biomass:** Varies. Estimates of the actual annual yield/availability for each type of biomass are provided.

**Type of Study:** lab

**Process:** used a statistical "model (BGRAM version 1.1) to calculate the net avoided GHG emissions attributed to sustainable biochar production as a function of time" and applied it to three scenarios (each uses a different percentage [an alpha, beta, and maximum sustainable technical potential] of the available amount of each source)

**Statistics:** own model (BGRAM version 1.1) plus sensitivity and Monte Carlo analyses

**Crop Detail:** -statistical analysis of available biomass from various sources; no crop detail-

**Climate Change:** "Our analysis demonstrates that sustainable biochar production (with addition to soils) has the technical potential to make a sustainable contribution to mitigating climate change. Maximum avoided emissions of the order to 1.8Pg CO<sub>2</sub>-Ce annually, and of 130 Pg CO<sub>2</sub>-Ce over the course of a century, are possible at current levels of feedstock availability, while preserving biodiversity, ecosystem stability, and food security."

**Emissions Reduction:** "Maximum avoided emissions of the order to 1.8Pg CO<sub>2</sub>-Ce annually, and of 130 Pg CO<sub>2</sub>-Ce over the course of a century, are possible at current levels of feedstock availability, while preserving biodiversity, ecosystem stability, and food security."

**Comment:** Useful graphics of the impacts of pyrolysis and the pyrolysis emissions cycle. Would be useful to see the supplemental documents

Zimmerman, Andrew R., Bin Gao, and Mi-Youn Ahn. 2011. "Positive and Negative Carbon Mineralization Priming Effects Among a Variety of Biochar-Amended Soils." *Soil Biology & Biochemistry*. 43: 1169-1179.

**Theory:** Assessment of the effect of biochar amendment on soil

**Basic Hypothesis/Goal:** Explanation of the seeming confusion over the short and long-term effect of biochar amendment on soil; explanation of why some studies show a positive priming effect while others show a negative priming effect.

**Biomass Used:** oak, pine, bubinga, Eastern gamma grass, bagasse

**Amount of Dry Biomass:** biochar alone: 200mg quartz sand and 20mg biochar; soil alone: 1g; soil-biochar mix: 1g and 100mg, respectively -- "This soil-biochar mixture, or 10% biochar by weight, corresponds to 90 ton/ha application rate (10 cm tillage) which is in the upper end of application rates currently employed"

**Type of Study:**

**Process:** "A microbial inoculate consisting of a forest soil extract (from within the same watershed) and an NPK nutrient solution similar to that of the soils [60 g of  $(\text{NH}_4)_2\text{SO}_4$  # 6 g of  $\text{KH}_2\text{PO}_4$  L1] was added to the biochar-alone incubations, whereas only distilled water was added to the soils, in each case to bring the soil or soil-biochar mixture to 50% water holding capacity (0.4e0.7 ml) was added to the soil-alone and soil # biochar incubations. Tubes were incubated in the dark at 32 C. Oxidation of biochar-C was determined every two weeks during the first three months and monthly thereafter by measuring  $\text{CO}_2$  evolution into the vial headspace using an automated  $\text{CO}_2$  coulometer (UIC Inc., Joliet, IL). Headspace  $\text{CO}_2$  was carried with  $\text{CO}_2$ -free air into the coulometer during a 5 min flushing time, leaving the vials refilled with  $\text{CO}_2$ -free air for re-incubation. The analytical detection limit for  $\text{CO}_2$  is 0.1 mg C and systems blanks, empty tubes, yielded  $\text{CO}_2$  measurements of less than 2mg for any given time period. Assuming 1:1  $\text{CO}_2$  production to oxygen consumption,  $\text{O}_2$  was always in excess."

**Conclusions:** the biochar type, the soil type, and the period over which measurements are made, can strongly influence the direction and magnitude of priming effect recorded. While both positive and negative priming effects were observed in these incubations of biochar and soil, it is negative priming, that is, the enhanced storage of both biochar-C and SOC, which is expected to endure into the future.

# **Appendix B**

## **Key Terms Defined**



**alkyl C:** in chemistry, a carbon atom that is free of a larger molecule

**anhydrocellulose:** the chief component of plant cell walls prior to the addition of water

**BET:** short for “Brunauer, Emmett, and Teller,” a common method used to describe specific surface area. The BET equation is:

$$\frac{1}{W((P_0/P)-1)} = \frac{1}{W_m C} + \frac{C-1}{W_m C} \left( \frac{P}{P_0} \right)$$

where  $W$  is the weight of gas adsorbed;  $P/P_0$  is relative pressure;  $W_m$  is the weight of the adsorbate as a monolayer, and  $C$  is the BET constant

**biochar:** a charcoal-like product produced through the pyrolysis of plant matter

**depolymerization:** the process of converting a large molecule into a small molecule, or a number of small molecules

**green waste:** biodegradable wastes such as grass cuttings, flower cuttings, hedge trimmings, etc

**heterocyclic compound:** a compound having at least two different elements making up the rings in its atomic structure

**lignin:** a substance that, in conjunction with cellulose, forms the woody cell walls of plants

**nitrification:** the process of oxidation of ammonia with oxygen, forming ammonium, then nitrite, then nitrate

**polycyclic aromatic hydrocarbons:** any of a number of chemicals frequently found together in groups of two or more (per the US Environmental Protection Agency)

**pyrolysis:** a process of thermo-chemical decomposition

**single-ring aromatic hydrocarbon:** an organic compound consisting entirely of carbon and hydrogen having only a single ring of alternating double and single bonds between the atoms in the compound's structure

**sorption:** the physical and chemical process during which one substance becomes attached to another

**syngas:** short for “synthetic gas,” a gaseous fuel mixture typically consisting of primarily hydrogen, carbon monoxide, and frequently some carbon dioxide

**terra mulata:** literally, “brown earth”

**terra preta:** literally, “dark earth”

**Frequently Used Abbreviations**

C – Carbon

CO<sub>2</sub>-C – carbon sequestered from carbon dioxide emitted

CO<sub>2</sub>-C<sub>e</sub> – total carbon sequestered from carbon dioxide emitted

K – Kelvin temperature scale

N – Nitrogen

NH<sub>3</sub> – Ammonia

Pg – Picograms

USDA – United States Department of Agriculture