Institute for Governance & Sustainable Development

Significant Climate Mitigation Is Available from Biochar

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Biochar has the potential to be an efficient carbon sink while providing strong co-benefits

Biochar can sequester massive amounts of carbon in the soil for hundreds to thousands of years.[1] Pre-Columbian Amazonian Indians used it to enhance soil productivity and made it by smoldering agricultural waste.[2] They called it "*Terra Preta de Indio*."[3] Its modern equivalent is being developed using pyrolysis to heat biomass in the absence of oxygen in kilns.[4]

Modern biochar production can be combined with biofuel production in a process that is energy-positive—producing 3-9 time more energy than invested, and carbon-negative—withdrawing CO_2 from the atmosphere and rebuilding geological carbon sinks.[5] With temperature thresholds, or "tipping points", as close as ten years away for abrupt and irreversible climate changes, including catastrophic sea-level rise,[6] the need for carbon negative energy sources is paramount.[7]

Biochar (also known as "agri-char") is a high-carbon, fine-grained residue which can be produced either by smoldering biomass utilizing centuries-old techniques (i.e., covering burning biomass with soil and letting it smolder) or through modern pyrolysis processes. Pyrolysis is the direct thermal decomposition of biomass in the absence of oxygen to obtain an array of solid (biochar), liquid (bio-oil) and gas (syngas) products. The specific yield from the pyrolysis is dependent on process conditions, and can be optimized to produce either energy or biochar.[8] Even when optimized to produce char rather than energy, the energy produced per unit energy input is higher than for corn ethanol.[9]

In addition to its potential for carbon sequestration, biochar has numerous co-benefits when added to soil. It can prevent the leaching of nutrients out of the soil,[10] increase the available nutrients for plant growth,[11] increase water retention,[12] and reduce the amount of fertilizer required. Additionally, it has been shown to decrease N_20 and CH_4 emissions from soil, thus further reducing GHG emissions.[13] Biochar can be utilized in many applications as a replacement for or coterminous strategy with other bio-energy production strategies. One is

For further information please contact Durwood Zaelke, President, Institute for Governance & Sustainable Development, at dzaelke@igsd.org (black carbon), Elise Stull at estull@igsd.org (tipping points), Pete Grabiel at pgrabiel@igsd.org (Montreal Protocol), or Eric Meltzer at emeltzer@igsd.org (biochar). **For COP14 attendees**, please visit the side event on fast-track mitigation strategies to avoid tipping points, hosted by Sweden and the Federated States of Micronesia, on 9 Dec 08 at 19:30 in the Aesculapian Snake room, Hall 14B (light refreshments provided).

switching from “slash-and-burn” to “slash-and-char” to prevent the rapid deforestation and subsequent degradation of soils.

“Biochar sequestration does not require a fundamental scientific advance and the underlying production technology is robust and simple, making it appropriate for many regions of the world.”[14] Johannes Lehmann, of Cornell University, estimates that pyrolysis will be cost feasible when the cost of a CO_2 ton reaches \$37[15] (as of the end of June 2008, CO_2 is trading at ~\$45/ton on the ECX) – so using pyrolysis for bio-energy production is feasible, even though it may be more expensive than fossil fuels at the moment.

Pyrolysis of biomass as a carbon sink (biochar)

Biochar can be used to sequester carbon on centurial or even millennial time scales. Plant matter absorbs CO_2 from the atmosphere while growing. In the natural carbon cycle, plant matter decomposes rapidly after the plant dies, which emits CO_2. Instead of allowing the plant matter to decompose, pyrolysis can be used to sequester the carbon in a much more stable form. Biochar thus removes circulating CO_2 from the atmosphere and stores it in virtually permanent soil carbon pools, making it a truly carbon-negative process. In places like the Rocky Mountains, where beetles have been killing of vast swathes of pine trees, the utilization of pyrolysis to char the trees instead of letting them decompose into the atmosphere would offset substantial amounts of CO_2 emissions. Although some organic matter is necessary for agricultural soil to maintain its productivity, much of the agricultural waste can be turned directly into biochar, bio-oil, and syngas.[16] The use of pyrolysis also provides an opportunity for the processing of municipal waste into useful clean energy rather than increased problems with land space for storage.[17]

Biochar is believed to have long mean residence times in the soil. While the methods by which biochar mineralizes (turns into CO_2) are not completely known,[18] evidence from soil samples in the Amazon shows large concentrations of black carbon (biochar) remaining after they were abandoned thousands of years ago.[19] The amount of time the biochar will remain in the soil depends on the feedstock material, how charred the material is, the surface:volume ratio of the particles, and the conditions of the soil the biochar is placed in.[20] Estimates for the residence time range from 100 to 10,000 yrs, with 5,000 being a common estimate.[21] Lab experiments confirm a decrease in carbon mineralization with increasing temperature, so carefully controlled charring of plant matter can increase the soil residence time of the biochar C.[22]

Under some circumstances, the addition of biochar to the soil has been found to accelerate the mineralization of the existing soil organic matter,[23] but this would only reduce the net benefit gained by sequestering carbon in the soil by this method. Furthermore, the suggested soil conditions for the integration of biochar are in heavily degraded tropical soils used for agriculture, not organic matter rich boreal forest soils (as tested in the above reference).

Production of biochar

The yield of products from pyrolysis varies heavily with temperature. The lower the temperature, the more char is created per unit biomass.[24] High temperature pyrolysis is also known as gasification, and produces primarily syngas from the biomass.[25] The two main methods of pyrolysis are "fast" pyrolysis and "slow" pyrolysis. Fast pyrolysis yields 60% bio-oil, 20% biochar, and 20% syngas, and can be done in seconds, whereas slow pyrolysis can be optimized to produce substantially more char (~50%), but takes on the order of hours to complete. For typical inputs, the energy required to run a "fast" pyrolyzer is approximately 15% of the energy that it outputs.[26] Modern pyrolysis plants can be run entirely off of the syngas created by the pyrolysis process and thus output 3-9 times the amount of energy required to run.[27]

The ancient method for producing biochar as a soil additive was the "pit" or "trench" method, which created *terra preta*, or dark soil.[28] While this method is still a potential to produce biochar in rural areas, it does not allow the harvest of either the bio-oil or syngas, and releases a large amount of CO2, BC (black carbon), and other GHGs (and potentially, toxins) into the air. Modern companies are producing commercial-scale systems to process agricultural waste, paper byproducts, and even municipal waste.

There are three primary methods for deploying a pyrolysis system. The first is a centralized system where all biomass in the region would be brought to a pyrolysis plant for processing. A second system would effectively mean a lower-tech pyrolysis kiln for each farmer or small group of farmers. A third system is a mobile system where a truck equipped with a pyrolyzer would be driven around to pyrolyze biomass. It would be powered using the syngas stream, return the biochar to the earth, and transport the bio-oil to a refinery or storage site. Whether a centralized system, a distributed system, or a mobile system is preferred is heavily dependent on the specific region. The cost of transportation of the liquid and solid byproducts, the amount of material to be processed in a region, and the ability to feed directly into the power grid are all factors to be considered when deciding on a specific implementation.

Unless crops are going to be dedicated to biochar production, the residue-to-product ratio (RPR) for the feedstock material is a useful gauge of the approximate amount of feedstock that can be obtained for pyrolysis after the primary product is harvested and the waste remains. The amount of crop residue available to be used for pyrolysis can be determined by using the RPR, and the collection factor (the percent of the residue not used for other things). For instance, Brazil harvests approximately 460Mt of sugar cane annually[29], with an RPR of 0.30, and a collection factor (CF) of 0.70 for the sugar cane tops, which are normally burned on the field.[30] This translates into approximately 100Mt of residue which can be pyrolyzed to create energy and soil additives annually. Adding in the bagasse (sugar cane waste) (RPR=0.29 CF=1.0) which is currently burned inefficiently in boilers, raises the total to 230 Mt of pyrolysis feedstock just from sugar cane residues. Some plant residue, however, must remain on the soil to avoid heavily increased costs and emissions from nitrogen fertilizers.[31]

Co-benefits of pyrolysis

Biochar can be used as a soil amendment to increase plant growth yield,[32] improve water quality, reduce soil emissions of GHGs, reduce leaching of nutrients, reduce soil acidity, and reduce irrigation and fertilizer requirements.[33] These properties are very dependent on the properties of the biochar, [34] and may depend on regional conditions including soil type, condition (depleted or healthy), temperature, and humidity.[35] Modest additions of biochar to soil were found to reduce N_2O emissions by up to 80% and completely suppress methane emissions.[36]

Switching from slash-and-burn to slash-and-char techniques in Brazil can both decrease deforestation of the Amazon and increase the crop yield. Under the current method of slash-and-burn, only 3% of the carbon from the organic material is left in the soil.[37] Switching to slash-and-char can sequester up to 50% of the carbon in a highly stable form.[38] Adding the biochar back into the soil rather than removing it all for energy production is necessary to avoid heavy increases in the cost and emissions from more required nitrogen fertilizers.[39] Additionally, by improving the soil tilth, fertility, and productivity, the biochar enhanced soils can sustain agricultural production, whereas non-amended soils quickly become depleted of nutrients, and the fields are abandoned, leading to a continuous slash-and-burn cycle and the continued loss of tropical rainforest.

Using pyrolysis to produce bio-energy also has the added benefit of not requiring infrastructure changes the way processing biomass for cellulosic ethanol does. Additionally, the biochar produced can be applied by the currently used tillage machinery or equipment used to apply fertilizer.[40]

Pyrolysis for the production of energy (Biochar, Bio-oil, Syngas)

Bio-oil can be used as a replacement for numerous applications where fuel oil is used, including fueling space heaters, furnaces, and boilers.[41] Additionally, it can be used to fuel some combustion turbines and reciprocating engines, and as a source to create several chemicals.[42] If bio-oil is used without modification, care must be taken to prevent emissions of black carbon and other particulates. Syngas and bio-oil can also be "upgraded" to transportation fuels like biodiesel and gasoline substitutes.[43] If biochar is used for the production of energy rather than as a soil amendment, it can be directly substituted for any application that uses coal. Pyrolysis also may be the most cost-effective way of producing electrical energy from biomaterial.[44] Syngas can be burned directly, used as a fuel for gas engines and gas turbines, or potentially used in the production of methanol and hydrogen.[45]

Bio-oil has a much higher energy density than the raw biomass material.[46] Mobile pyrolysis units can be used to lower the costs of transportation of the biomass itself if the biochar is returned to the soil and the syngas stream is used to power the process.[47] Bio-oil contains organic acids which are corrosive to steel containers, has a high water vapor content which is detrimental to ignition, and contains some biochar in the liquid which can block injectors.[48]

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[*] Institute for Governance & Sustainable Development, http://www.igsd.org; International Network for Environmental Compliance & Enforcement, http://www.inece.org.

[1] *See* Lehmann, Johannes, *Terra Preta de Indio*, SOIL BIOGEOCHEMISTRY *available at* http://www.css.cornell.edu/faculty/lehmann/terra_preta/TerraPretahome.htm (internal citations omitted); *see also* Winsley, Peter, *Biochar and Bioenergy Production for Climate Change Mitigation*, 64 NEW ZEALAND SCI. REV. 5, 5 (2007) *available at* http://www.biochar-international.org/images/NZSR64_1_Winsley.pdf; Kern, Dirse C., *New Dark Earth Experiment in the Tailandia City – Para-Brazil: The Dream of Wim Sombroek*, 18th World Congress of Soil Science (9-15 July 2006). Not only do biochar enriched soils contain more carbon, 150gC/kg compared to 20-30gC/kg in surrounding soils, but biochar enriched soils are, on average, more than twice as deep as surrounding soils. Therefore, the total carbon stored in these soils can be one order of magnitude higher than adjacent soils. *See id.*

[2] Solomon, Dawit, Johannes Lehmann, Janice Thies, Thorsten Schafer, Biqing Liang, James Kinyangi, Eduardo Neves, James Petersen, Flavio Luizao, and Jan Skjemstad, *Molecular signature and sources of biochemical recalcitrance of organic C in Amazonian Dark Earths*, 71 GEOCHEMICA ET COSMOCHEMICA ACTA 2285, 2286 (2007) *available at* http://www.css.cornell.edu/faculty/lehmann/publ/GeochimCosmochimActa%2071,%202285-2298,%202007%20Solomon.pdf. ("Amazonian Dark Earths (ADE) are a unique type of soils apparently developed between 500 and 9000 years B.P. through intense anthropogenic activities such as biomass-burning and high-intensity nutrient depositions on pre-Columbian Amerindian settlements that transformed the original soils into Fimic Anthrosols throughout the Brazilian Amazon Basin.") (internal citations omitted)

[3] Glaser, Bruno, Johannes Lehmann, and Wolfgang Zech, *Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review*, 35 BIOLOGY AND FERTILITY SOILS 219, 220 (2002) *available at* http://www.nt.gov.au/dcm/legislation/climatechange/docs/submissions/14b.pdf. ("These so called Terra Preta do Indio (Terra Preta) characterize the settlements of pre-Columbian Indios. In Terra Preta soils large amounts of black C indicate a high and prolonged input of carbonized organic matter probably due to the production of charcoal in hearths, whereas only low amounts of charcoal are added to soils as a result of forest fires and slash-and-burn techniques.") (internal citations omitted)

[4] Lehmann, Johannes, *A handful of carbon*, 447 NATURE 143, 143 (2007) *available at* http://www.grainlegumes.com/fckeditor/aepfiles/File/Job%20opportunities/Lehmann_Nature2007.pdf.

[5] Lehmann, Johannes, *Bio-energy in the black*, 5 Front Ecol Environ 381, 385 (2007) *available at* http://www.css.cornell.edu/faculty/lehmann/publ/FrontiersEcolEnv%205,%20381-387,%202007%20Lehmann.pdf. ("pyrolysis produces 3–9 times more energy than is invested in generating the energy. At the same time, about half of the carbon can be sequestered in soil. Such a carbon-negative technology would lead to a net withdrawal of CO2 from the atmosphere, while producing and consuming energy.")

[6] Abrupt climate change refers to the passing of a point beyond which no further inputs are required for the climate system to amplify itself irreversibly out of control on human time-scales. Timothy Lenton, Hermann Held, Elmar Kriegler, Jim Hall, Wolfgang Lucht, Stefan Rahmstorf, and Hans Joachim Schellnhuber, *Tipping elements in the Earth's climate system*, 105 PROC. OF THE NAT'L ACAD. OF SCI. 6 (12 Feb 2008) *available at* http://www.pik-potsdam.de/~stefan/Publications/Journals/lenton_etal_PNAS_2008.pdf. (The palaeoclimate records show that past climate changes have included both steady linear changes, as well as abrupt non-linear changes where small increases in warming produced large and irreversible impacts once a tipping point was passed, including rapid loss of ice causing significant sea-level rise. Abrupt climate changes also are possible in the future. Tipping points for ice-melt in the Arctic and ice-melt and disintegration of the Greenland Ice Sheet are considered to be among the most sensitive. The tipping point for the loss of the West Antarctic Ice Sheet is considered less sensitive, though with large uncertainty. Other tipping points may apply to the Atlantic thermohaline circulation, the Amazon rainforest and boreal forests, the El Niño phenomenon, and the West African monsoon.); *see also* James Hansen, *Scientific reticence and sea level rise***,** Environ. Res. Lett. 2 (2007); James Hansen, *Climate Catastrophe*, NEW SCIENTIST (28 July 2007); Committee on Abrupt Climate Change, *Abrupt Climate Change: Inevitable Surprises*, National Academy Press, Washington, D.C., 2003 (the "available evidence suggests that abrupt climate changes are not only possible, but likely in the future, potentially with large impacts on ecosystems and societies"); *See also* Peter Schwartz & Doug Randall, *An Abrupt Climate Change Scenario and Its Implications for United States National Security* (2003) (warning that result of abrupt climate change without adequate preparation "could be a significant drop in the human carrying capacity of the Earth's environment", including shortages of food and fresh water, drought, and flooding, which could lead to geopolitical de-stabilization and "skirmishes, battles, and even war."), *available at* http://www.gbn.com/ArticleDisplayServlet.srv?aid=26231; and Chris Abbott, Paul Rogers, and

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John Slobada, *Global Responses to Global Threats: Sustainable Security for the 21st Century,* Oxford Research Group, June 2006, http://www.oxfordresearchgroup.org.uk/publications/briefing_papers/globalthreats.php.

[7] James Hansen recently estimated that the concentration beyond which the CO_2 level in the atmosphere is potentially catastrophic is 350ppm, a point which has already been passed. James Hansen, *Target Atmospheric CO2: Where Should Humanity Aim?,* Open Atmospheric Science Journal (forthcoming 2008) (manuscript at 11, *available at* http://arxiv.org/ftp/arxiv/papers/0804/0804.1126.pdf) ("Equilibrium sea level rise for today's 385 ppm CO2 is at least several meters, judging from paleoclimate history. Accelerating mass losses from Greenland and West Antarctica heighten concerns about ice sheet stability. An initial CO2 target of 350 ppm, to be reassessed as the effect on ice sheet mass balance is observed, is suggested.") (internal citations omitted); *see also* James Hansen, *Why We Can't Wait*, THE NATION (7 May 2007) ("The Energy Department says that we're going to continue to put more and more CO_2 in the atmosphere each year--not just additional CO_2 but more than we put in the year before. If we do follow that path, *even for another ten years*, it guarantees that we will have dramatic climate changes that produce what I would call a different planet--one without sea ice in the Arctic; with worldwide, repeated coastal tragedies associated with storms and a continuously rising sea level; and with regional disruptions due to freshwater shortages and shifting climatic zones.").

[8] Gaunt, John L. and Johannes Lehmann, *Energy Balance and Emissions Associated with Biochar Sequestration and Pyrolysis Bioenergy Production*, 42 ENVTL. SCI. & TECH. 4152, 4155 (2008) *available at* http://www.css.cornell.edu/faculty/lehmann/publ/ES&T%2042,%204152-4158,%202008%20Gaunt.pdf. ("Assuming that the energy in syngas is converted to electricity with an efficiency of 35%, the recovery in the life cycle energy balance ranges from 92 to 274 kg CO2 MW-1 of electricity generated where the pyrolysis process is optimized for energy and 120 to 360 kg CO2 MW-1 where biochar is applied to land. This compares to emissions of 600–900 kgCO2MW-1 for fossil-fuel-based technologies.)

[9] *Id.* at 4152 ("Despite a reduction in energy output of approximately 30% where the slow pyrolysis technology is optimized to produce biochar for land application, the energy produced per unit energy input at 2–7 MJ/MJ is greater than that of comparable technologies such as ethanol from corn.")

[10] Steiner, Christoph, Wenceslau G. Teixeira, Johannes Lehmann, Thomas Nehls, Jeferson Luis, Vasconcelos de Macêdo, Winfried E. H. Blum, Wolfgang Zech, *Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil*, 291 PLANT & SOIL 275, 287 (2007) *available at* http://www.css.cornell.edu/faculty/lehmann/publ/PlantSoil,%20online,%202007,%20 Steiner.pdf. ("The application of charcoal significantly reduced leaching of applied mineral fertilizer N. The increased ratio of uptake to leaching due to charcoal application indicates a high efficiency of nutrients applied with charcoal.")

[11] *Id.* ("The increased ratio of uptake to leaching due to charcoal application indicates a high efficiency of nutrients applied with charcoal. In this study, we were not able to statistically prove increased availability of soil nutrient contents but in spite of significantly higher nutrient export by means of yield withdrawal, the available nutrient contents remained as high or higher in soils receiving charcoal than only mineral fertilized soils (Fig. 4).")

[12] Glaser, *supra* note 3 at 223 ("[S]oil water retention increased by 18% upon addition of 45% (by volume) charcoal to a sandy soil. Glaser et al. (2002b) reported that charcoal-rich Anthrosols whose surface areas were 3 times higher than those of surrounding soils increased the field capacity by 18%. Tryon (1948) also studied the effect of charcoal on the percentage of available moisture in soils of different textures. Only in sandy soil did the addition of charcoal increase the available moisture (Table 3). In loamy soil, no changes were observed, and in clayey soil the available soil moisture even decreased with increasing coal additions, probably due to hydrophobicity of the charcoal. Therefore, improvements of soil water retention by charcoal additions may only be expected in coarse-textured soils or soils with large amounts of macropores") (internal citations omitted) (*citing* Tryon, EH, Effect of charcoal on certain physical, chemical, and biological properties of forest soils, 18 ECOLOGICAL MONOGRAPHS 81 (1948) *available at* http://www.jstor.org/pss/1948629.).

[13] Gaunt, *supra* note 8 at 4152. ("Rondon et al. found that CH4 emissions were completely suppressed and N2O emissions were reduced by 50% when biochar was applied to soil. Yanai et al. also found suppression of N2O when biochar was added to soil") (internal citations omitted).

[14] Lehmann, *supra* note 4 at 144 (2007).

[15] *Id.* ("We calculate that biochar sequestration in conjunction with bioenergy from pyrolysis becomes economically attractive, under one specific scenario, when the value of avoided carbon dioxide emissions reaches $37 per tonne.")

[16] The question scientists are debating is precisely how much can be removed. Adding the char back into the soil makes up for a large amount of the SOM needed, but it may not be sufficient in all cases.

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[17] Shinogi, Y., H. Yoshida, T. Koizumi, M. Yamaoka, and T. Saito, *Basic characteristics of low-temperature carbon products from waste sludge*, 7 Advances Envtl. Res. 661, (2003) (“The results showed there are not harmful levels (based on the Japanese standard) of heavy metals and harmful substances.”), *See also* Antal, M., Flash Carbonization, Hawaii Natural Energy Institute, *available at* http://www.hnei.hawaii.edu/bio.r3.asp#flashcarb (1 July 2008).

[18] Masiello, C.A., *New directions in black carbon organic geochemistry*, 92 Marine Chemistry 201, 202 (2004) (“We know little about BC loss processes and almost nothing about biotic or abiotic agents of BC decomposition.”)

[19] Lehmann, Johannes, John Gaunt, and Marco Rondon, *Biochar Sequestration In Terrestrial Ecosystems – A Review*, 11 Mitigation and Adaptation Strategies for Global Change 403, 404 (2006) *available at* http://www.css.cornell.edu/faculty/lehmann/publ/plantsoil%20300,%209-20%202007,%20Warnack.pdf. (“Large amounts of biochar derived C stocks remain in these soils today, hundreds and thousands of years after they were abandoned. The total C storage is as high as 250MgCha−1 m−1 compared to typical values of 100MgCha−1 m−1 in Amazonian soils derived from similar parent material.”) (internal citations omitted).

[20] Cheng, Chih-Hsin, Johannes Lehmann, and Mark H. Engelhard, *Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence*, 72 Geochimica et Cosmochemica Acta 1598, 1599 (2008) (“Biotic and abiotic processes, such as greater temperature and moisture, may facilitate BC oxidation, while aggregate protection of BC [decreased surface to volume ratio] promoted in fine-textured soils may reduce BC oxidation.”); *see also infra* note 17.

[21] Cheng, Chih-Hsin, Johannes Lehmann, Janice E. Thies, and Sarah D. Burton, *Stability of black carbon in soils across a climatic gradient*, 113 J. Geophysical Res. G02027, 8 (2008) (“the half-life of BC at a site with 10C MAT may be as high as 925 years. Due to systematic overestimation of long-term BC decay by short-term incubations, the true half-life of BC is ***most likely greater*** than calculated here. This agrees well with the C-14 ages of BC which have been reported to lie in the hundreds to thousands of years”) (emphasis added) (internal citations omitted); Warnock, Daniel D. & Johannes Lehmann, *Mycorrhizal responses to biochar in soil – concepts and mechanisms*, 300 Plant & Soil 9 (2007) (“Biochar is believed to have long mean residence times in soil, ranging from 1,000 to 10,000 years, with 5,000 years being a common estimate.”)

[22] Baldock and Smernik (2002) used red pine (Pinus resinosa) wood charred at different temperatures. After 120 days incubation in sand, 20% of C was mineralized from wood heated at 70 C (essentially unaltered). Carbon mineralization decreased to 13% for wood heated to 150 C, and to less than 2% for chars produced at 200–350 C, with increasing proportions of aromatic C.

[23] Wardle, David, Marie-Charlotte Nilsson, and Olle Zackrisson, *Fire-Derived Charcoal Causes Loss of Forest Humus*, 320 Science 1 (2 May 2008) (“Although several studies have recognized the potential of black C for enhancing ecosystem C sequestration, our results show that these effects can be ***partially*** offset by its capacity to stimulate loss of native soil C, ***at least*** for boreal forests.”) (emphasis added) (internal citations omitted).

[24] Winsley, Peter, *Biochar and bioenergy production for climate change mitigation*, 64 New Zealand Sci. Rev. 5 (2007) *available at* http://www.biochar-international.org/images/NZSR64_1_Winsley.pdf. (See Table 1 for differences in output for Fast, Intermediate, Slow, and Gasification).

[25] *Id.*

[26] Laird, David A., *The Charcoal Vision: A Win–Win–Win Scenario for Simultaneously Producing Bioenergy, Permanently Sequestering Carbon, while Improving Soil and Water Quality*, 100 Agronomy J. 178, 179 (2008) *available at* http://agron.scijournals.org/cgi/reprint/100/1/178. (“The energy required to operate a fast pyrolyzer is □15% of the total energy that can be derived from the dry biomass. Modern systems are designed to use the syngas generated by the pyrolyzer to provide all the energy needs of the pyrolyzer.”)

[27] Lehmann - Bioenergy in the Black, supra note 5.

[28] To date, scientists have been unable to completely reproduce the beneficial growth properties of *terra preta*. It is hypothesized that part of the benefit of *terra preta* may require the biochar to be aged so that it increases the cation exchange capacity of the soil. Lehmann, Bio-energy in the black, *supra* note 5 at 386 (“Only aged biochar shows high cation retention, as in Amazonian Dark Earths. At high temperatures (30–70°C), cation retention occurs within a few months. The production method that would attain high CEC in soil in cold climates is not currently known.”) (internal citations omitted).

[29] FAOSTAT 2006, *available at* http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567 (accessed 1 July 2008) (production quantity of sugar cane in Brazil in 2006).

[30] Perera, K.K.C.K., P.G. Rathnasiri, S.A.S. Senarath, A.G.T. Sugathapala, S.C. Bhattacharya, and P. Abdul Salam, *Assessment of sustainable energy potential of non-plantation biomass resources in Sri Lanka*, 29 Biomass &

BIOENERGY 199, 204 (2005) (showing RPRs for numerous plants, describing method for determining available agricultural waste for energy and char production).

[31] Laird, *supra* note 26 at 179 ("Much of the current scientific debate on the harvesting of biomass for bioenergy is focused on how much can be harvested without doing too much damage.")

[32] Lehmann, Johannes, and Jose Pereira da Silva Jr., Christoph Steiner, Thomas Nehls, Wolfgang Zech, & Bruno Glaser, *Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments*, 249 PLANT & SOIL 343, 355 (2003) *available at* http://www.css.cornell.edu/faculty/lehmann/publ/PlantSoil%20249,%20343-357,%202003%20Lehmann.pdf. ("The amounts of charcoal added were clearly critical for the effects on crop growth and nutrition. Already at charcoal additions of 10% (w/w) plant growth improved significantly and larger quantities added further increased biomass production.")

[33] *Supra* notes 10-13; Day, Danny, Robert J. Evans, James W. Lee, and Don Reicosky, *Economical CO2, SOx, and NOx capture from fossil-fuel utilization with combined renewable hydrogen production and large-scale carbon sequestration*, 30 ENERGY 2558, 2560 ("char also provides the ability to capture farm chemical runoff."); Winsley, supra note 24 at 6. ("The carbon in biochar . . . improves soil structure and water retention, enhances nutrient availability, lowers acidity, and reduces the toxicity of aluminium to plant roots and soil microbiota. Biochar may help reduce the bioavailability of heavy metals and endocrine disruptors in some production systems and may therefore have potential in bioremediation.")

[34] Glaser, *supra* note 3 at 224 ("Three main factors influence the properties of charcoal: (1) the type of organic matter used for charring, (2) the charring environment (e.g. temperature, air), and (3) additions during the charring process. The source of charcoal material strongly influences the direct effects of charcoal amendments on nutrient contents and availability.")

[35] Dr. Wardle points out that plant growth has been observed in tropical (depleted) soils by referencing Lehmann, but that in the boreal (high native SOM content) forest this experiment was run in, it accelerated the native soil organic matter loss. Wardle, *supra* note 23. ("Although several studies have recognized the potential of black C for enhancing ecosystem C sequestration, our results show that these effects can be partially offset by its capacity to stimulate loss of native soil C, ***at least*** for boreal forests.") (internal citations omitted) (emphasis added).

[36] Lehmann - Bioenergy in the Black, *supra* note 5 at 384. ("In greenhouse experiments, NOx emissions were reduced by 80% and methane emissions were completely suppressed with biochar additions of 20 g kg-1 to a forage grass stand.")

[37] Glaser, *supra* note 3 at 225 ("The published data average at about 3% charcoal formation of the original biomass C.")

[38] Lehmann – *Biochar sequestration in terrestrial ecosystems*, *supra* note 19 at 407 ("If this woody aboveground biomass were converted into biochar by means of simple kiln techniques and applied to soil, more than 50% of this C would be sequestered in a highly stable form.")

[39] Gaunt, *supra* note 3 at 4152 ("This results in increased crop yields in low-input agriculture and increased crop yield per unit of fertilizer applied (fertilizer efficiency) in high-input agriculture as well as reductions in off-site effects such as runoff, erosion, and gaseous losses.")

[40] Lehmann, *A handful of carbon*, *supra* note 4 at 143. ("It can be mixed with manures or fertilizers and included in no-tillage methods, without the need for additional equipment.")

[41] Badger, Phillip C. and Peter Fransham, *Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs—A preliminary assessment*, 30 BIOMASS & BIOENERGY 321, 322 (2006) ("including fueling space heaters, furnaces, and boilers (including cofiring in utility boilers); and fueling certain combustion turbines and reciprocating engines, as well as serving as a source of several chemicals.")

[42] *Id.*

[43] Laird, *supra* note 26 at 178.

[44] Bridgwater, A. V., A.J. Toft, and J.G. Brammer, *A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion*, 6 RENEWABLE & SUSTAINABLE ENERGY REV. 181, 231 ("the fast pyrolysis and diesel engine system is clearly the most economic of the novel systems at scales up to 15 MWe");

[45] McKendry, Peter, *Energy production from biomass (part 2): conversion technologies*, 83 BIORESOURCE TECH. 47, 48-49 (2002).

[46] Badger, *supra* note 41 at 323.

[47] *Id.* at 322.

[48] Yaman, Serdar, *Pyrolysis of biomass to produce fuels and chemical feedstocks*, 45 ENERGY CONVERSION & MGMT 651, 659 (2003).