Published as: Graber, E.R. (2009) Biochar for 21st century challenges: Carbon sink, energy source and soil conditioner. Conference Proceedings, Dahlia Gredinger International Symposium, Haifa, May 2009.

BIOCHAR FOR 21ST CENTURY CHALLENGES: CARBON SINK, ENERGY SOURCE AND SOIL CONDITIONER

Ellen R. Graber
Institute of Soil, Water and Environmental Sciences
POB 6 Bet Dagan 50250 Israel
ergraber@agri.gov.il

ABSTRACT

Biochar, a charcoal produced from biomass, can sequester carbon in soil for hundreds to thousands of years. Pre-Columbian Amazonian Indians used it to enhance soil productivity, and it is still found in large concentrations in Amazon soils abandoned thousands of years ago. Its modern equivalent is produced by pyrolysis, the direct thermal decomposition of biomass in the absence of oxygen to an array of solid (biochar), liquid (bio-oil) and gas (syngas) products. The specific yield from pyrolysis depends on process conditions, and can be optimized to produce either energy or biochar. Being an exothermic process, biochar production produces 3-9 times more energy than is invested, and is carbon-negative (withdraws CO_2 from the atmosphere). In addition, modest additions of biochar to soil have been found to reduce NO_x emissions by up to 80% and to completely suppress methane emissions, thus directly reducing agricultural greenhouse gas emissions. While some fresh organic matter is needed by agricultural soil to maintain its productivity, much agricultural waste (and other kinds of waste streams) can be turned directly into biochar, bio-oil, and syngas.

In addition to its potential for carbon sequestration and decreased greenhouse gas emissions from agriculture, biochar is reported to have numerous benefits as a soil amendment: increased plant growth yield, improved water quality, reduced leaching of nutrients, reduced soil acidity, increased water retention, and reduced irrigation and fertilizer requirements. The quality of biochar as a soil ameliorant depends on the character of the biochar and on regional conditions including soil type and condition (depleted or healthy), temperature, and humidity.

Estimates for biochar residence time in soil range from 100 to 10,000 years, with 5,000 years being a common estimate. Whilst the means by which biochar mineralizes are not completely known, it is apparent that mineralization rates depend on the feedstock material, the extent of charring, the surface:volume ratio of the particles, and the soil environment. Lab experiments confirm a decrease in carbon mineralization with increasing pyrolysis temperature, so careful control over the charring process can increase the soil residence time of the biochar C.

Bio-oil created in the pyrolysis process can be used as a replacement for numerous applications where fuel oil is used, as well as a feedstock for chemical production. Syngas and bio-oil can also be “upgraded” to transportation fuels like biodiesel and gasoline substitutes. 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. Syngas can be burned directly, used as a fuel for gas engines and gas turbines, or used in the production of methanol and hydrogen.

INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), the earth's temperature rose 0.6°C during the 20th century, and is projected to continue to rise between 1.5 to 4.5°C by the year 2100 (*1*). Man-made, anthropogenic greenhouse gas emissions are considered the dominant causal factor for these increasing temperatures which lead to other related changes in climate. Consequently, there is a world-wide drive to develop different strategies for reducing net greenhouse gas emissions, and part of that drive has brought us to the cusp of a paradigm shift from a "petroeconomy", fueled by fossil carbon, to a "bioeconomy", fueled by biomass created through photosynthesis (*2*). The petroeconomy is overwhelmingly carbon positive - contributing carbon to the already existing load. In contrast, the bioeconomy is conventionally considered to be carbon neutral, whereby the carbon emitted through biomass burning replaces the carbon absorbed during the growing of the crop (*2*). The reality of the bioeconomy as carbon neutral is currently the subject of intense debate, with detractors arguing that much of the biofuel production in temperate climates is almost entirely carbon positive due to the heavy inputs of fossil fuels for agricultural production and the use of fertilizers (*3-5*). However, this controversy could be entirely eliminated by producing carbon negative biofuels, in other words, fuels which remove more carbon from the atmosphere than they put back in through burning (*2*). This can be accomplished by treating biomass by pyrolysis, the direct thermal exothermic decomposition of biomass in the absence of oxygen to an array of solid (biochar), liquid (bio-oil) and gas (syngas) bioenergy products. Instead of burning the produced charcoal (biochar), it can be returned to the soil as a soil conditioner (*6*), where it remains in an essentially permanent form.

Soil amendment with biochar, a charcoal produced from biomass, can sequester carbon in soil for hundreds to thousands of years (*7*). Pre-Columbian Amazonian Indians used char to enhance soil productivity, and it is still found in large concentrations in fertile Amazon soils abandoned thousands of years ago. Modern biochar is produced by pyrolysis, the specific yield of which depends on both the process conditions and the feedstock. Pyrolysis can be optimized to produce syngas, bio-oil or biochar. Being an exothermic process, pyrolysis of biomass and biochar production produces 3-9 times more energy than is invested (*7*), and when the biochar is applied to soil, the whole process becomes carbon-negative (*9*). In addition, modest additions of biochar to soil have been found to reduce emissions of greenhouse gases from cultivated soils, for example, reducing N_2O emissions by up to 80% and completely suppressing methane emissions (*9-11*). While some fresh organic matter is needed by agricultural soil to maintain its productivity, much agricultural waste (and other kinds of organic waste streams) can be turned directly into biochar for reapplication to the soil and for creation of biofuels. For example, biochar production can utilize much urban, agricultural or forestry biomass residues, including and not limited to wood chips, corn stover, rice or peanut hulls, tree bark, paper mill sludge, animal manure, olive mill waste, municipal waste, municipal sludge, and recycled organics (*12*).

Consequently, biochar and bioenergy co-production from urban, agricultural and forestry biomass has been proposed to help combat global climate change in a number of ways: (i) by displacing fossil fuel use via production of energy from waste materials, (ii) by sequestering carbon in stable soil carbon pools, and (iii) by reducing soil emissions of nitrous oxides and methane, more potent greenhouse gases than carbon dioxide. Moreover, there is evidence that biochar applied to soil can increase crop yields and productivity, reduce soil acidity, and reduce water, chemical and fertilizer requirements (*13*). In the soil, biochar provides a habitat for soil organisms, but is not itself consumed by them to a great extent, such that most of the applied biochar can remain in the soil for several hundreds to thousands of years (*14, 15*). When used as a soil conditioner along with organic and inorganic fertilizers, biochar appears to significantly improve soil tilth, productivity, and nutrient retention and availability to plants via both direct slow-release fertilizing properties and indirect effects on improved water holding capacity, nutrient holding ability, and soil aggregate stability (*13*). Because biochar aids in soil retention of nutrients and agrochemicals for plant and crop utilization (*16, 17*), and is a good sorbent for organic and inorganic pollutants, it can be anticipated that chemical leaching to groundwater and run-off to surface waters will be reduced. As such, biochar systems may help in the fight against soil degradation, and can be a tool in the creation of sustainable food and fuel production in areas with severely depleted soils, scarce organic resources, and inadequate water and chemical fertilizer supplies.

AGRONOMIC VALUE OF BIOCHAR

Currently, very little biochar is utilized in agriculture, and its agronomic value in terms of crop response and soil health benefits still needs to be quantified. The few reports available show a general increase in crop yield and soil quality (*13*, *18-20*), but a review of the scant literature showed a wide range of biochar application rates (0.5 – 135 ton/ha), as well as a wide range of plant responses (-29 to 324% increase in dry matter) (*13*). More importantly, for the most part, properties of the biochar used in the investigations were not reported. Biochars can be produced from a vast array of organic materials and under different conditions (*12*), resulting in products with varying physical and chemical properties. For example, although biochar produced from greenwaste (mixture of grass clippings, cotton trash, plant prunings) and poultry litter had similar total N contents (1.8% and 2%, respectively), the greenwaste biochar had virtually no KCl-extractable N (<0.3 mg/kg), while the while poultry litter biochar had 2.4 mg/kg extractable N (*18*, *19*). Little research has been published elucidating the mechanisms responsible for the reported benefits of the biochars on crop growth, production and soil quality. Such understanding is essential for the development of agricultural markets for biochars and for the future development of technology for the production of biochar products with improved quality and value (*19*). What is clear from the limited research that has been performed is that the quality of biochar as a soil conditioner depends on the character of the biochar and on regional conditions including soil type and condition (depleted or healthy), temperature, and humidity (*13*, *18*, *19*).

In an early study, Iswaran et al. (*20*) reported that charcoal added to soil at 500 kg/ha increased the yield of moong, soybean and pea in a pot culture experiment by 22, 51 and 60%, respectively. The increases in yield upon charcoal amendment were only slightly less (9 to 25%) than increases in yield obtained upon soil inoculation with rhizobacterium. Later, Kishimoto and Sugiura (*21*) reported that five years after the application of 0.5 Mg charcoal/ha, the heights of sugi trees (*Cryptomeria japonica*) increased by a factor of about 1.3, and biomass production by a factor of 2.5 to 3.2. Crop yields of soybeans were also reported to increase by a factor of 1.5 after an application of 0.5 Mg charcoal/ha (*21*). However, yield declines were observed at much higher amendment rates (5 Mg and 15 Mg charcoal/ha) (*21*). A study of the effect of charcoal on birch and pine growth reported that birch shoot and root biomass was five times greater in charcoal-amended soil from a site dominated by shrub-released phenolic root exudates, an effect which was attributed to sorption and detoxification of allelopathic phenolic compounds (*22*).

More recently, studies from the group of Lehmann examined the effect of both ancient and recent biochar on soil fertility and nutrient leaching from highly leached tropical Ferralsols. Lehmann et al. (*23*) compared soil fertility and leaching losses of nutrients between an Anthrosol (relict soil from pre-Columbian settlements in the Amazon with high organic C and large proportions of black carbon), and an adjacent un-amended Ferralsol. The Anthrosol showed significantly higher P, Ca, Mn, and Zn availability than the Ferralsol, and an increased biomass of both cowpea and rice by 38–45% without fertilization. Despite the generally high nutrient availability in the Anthrosol, leaching was minimal. When charcoal was added to the Ferralsol, uptake of P, K, Ca, Zn, and Cu by the plants increased. Leaching of applied fertilizer N was significantly reduced by the charcoal amendment, and Ca and Mg leaching was delayed. Rondon et al. (*11*) studied the potential for enhanced biological N_2 fixation by common beans through biochar additions at 0, 30, 60, and 90 g biochar/kg soil on a Ferralsol. The proportion of fixed N increased from 50% without biochar additions to 72% with 90 g/kg biochar amendment. The primary reason for the enhanced biological N_2 fixation with biochar additions was greater B and Mo availability. In addition, biomass production and bean yield were significantly improved with biochar additions, with biomass maximized at a biochar application rate of 60 g/kg (increase in biomass by 39%) and yield increasing monotonically with increasing biochar loading (increase in yield of 46% at 90 g/kg). Soil N uptake by N-fixing beans decreased by 14, 17, and 50% when 30, 60, and 90 g/kg biochar were added to soil, respectively, whereas the C/N ratios increased from 16 to 23.7, 28, and 35, respectively. Results of a field trial testing the influence of charcoal, compost and fertilizer on a tropical Ferralsol on retention of N were also recently reported (*16*). The total N recovery in soil, crop residues, and grains was significantly higher on compost (16.5%), charcoal (18.1%), and charcoal plus compost treatments (17.4%) in comparison to mineral-fertilized plots (10.9%). One process in the increased retention of applied fertilizer N was found to be recycling of N taken up by the crop. Overall, results from this group demonstrate the potential of biochar applications to improve N input into agroecosystems, while pointing out the need for long-term field studies to better understand the effects of bio-char on nitrogen dynamics.

A pot trial was carried out to investigate the effect of biochar produced from greenwaste on the yield of radish in a hard-setting Chromosol (Alfisol) (*19*). Three rates of biochar (10, 50 and 100 t/ha) with and without additional nitrogen application (100 kg N/ha) were investigated. In the absence of N fertilizer, 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 fertilizer interaction was observed, in that higher yields were observed with increasing rates of biochar application in the presence of the N fertilizer. For instance, additional increase in dry matter of radish in the presence of N fertilizer varied from 95% in the nil biochar control to 266% in the 100 t/ha biochar-amended soils. The results of this trial contrast interestingly with the results of a similar trial utilizing biochars produced from poultry litter (*18*). In the latter study, two biochars produced from poultry litter under different conditions were tested in a pot trial with radish. Both poultry litter biochars produced increases in dry matter yield of radish without N fertilizer. The yield increase compared with the un-amended control rose from 42% at 10 t/ha to 96% at 50 t/ha of biochar application. The yield increases were attributed largely to the ability of the poultry litter biochars to increase N availability. Significant additional yield increases, in excess of that due to N fertilizer alone, were observed when N fertilizer was applied together with the biochars, highlighting the other beneficial effects of these biochars. These works emphasize the importance of feedstock and process conditions during pyrolysis on the properties and, hence, soil amendment values of biochars.

SOIL QUALITY CHANGES IN BIOCHAR-AMENDED SOILS

Charcoal has been argued to enhance soil physical properties, including soil water retention and aggregation, both of which may improve water availability to crops, as well as decrease erosion (*13*). Glaser et al (*24*) reported that charcoal-rich Anthrosols from the Amazon region, whose surface area was 3 times greater than that of surrounding soils, had 18% greater field capacity. In a much earlier study, Tyron (*25*) examined the effect of charcoal on percentage of available water in soils of different textures. In a sandy soil, there was a monotonic increase in the percentage of available moisture as a function of charcoal volumetric proportion, with an increase of about 6% in a soil amended with 15 volume % charcoal. The loamy soil showed no improvement in available moisture percentage under any amendment amount, while the available moisture percentage in the clay soil decreased by nearly 7% under a 15 volume % load of charcoal. Recent studies by Chan and colleagues (*18, 19*) reported a noteworthy improvement in texture and behavior of a hard-setting soil, with a significant reduction in tensile strength at higher rates of biochar application. Charcoal has also been reported to form complexes with minerals as a result of interactions between oxidized carboxylic acid groups at the surface of the charcoal particles and mineral grains (*13*), suggesting that charcoal amendments may improve in this way soil aggregate stability.

Important effects of charcoal on soil chemical properties have also been reported, most notably increases in pH (in acid soils), cation exchange capacity (CEC), base saturation and exchangeable bases, and organic carbon content, as well as decreases in Al saturation in acid soils (*13*). The pH of biochar depends on the pyrolysis temperature, increasing from a low of about 4 pH units to a pH of around 9 in the optimal biochar production temperature range of 400-550^{o}C (*7*). Applied to soils, there is ample evidence that biochar additions can increase the pH of amended soils by 0.4 to 1.2 pH units, with greater increases observed in sandy and loamy soils than in clayey soils (*25-27*). There is also evidence that charcoal additions to soil increase the amounts of exchangeable bases, the total N content, the available P, and the available K, Ca and Mg, with cation availability exceeding the CEC by a factor of 3 (*25*). This is apparently because cations contained in the ash portion of the charcoal are present as dissolvable salts, and therefore are readily available for plant uptake. On the basis of these results, Glaser et al. (*13*) conclude that the charcoal may be more than just a soil conditioner, but may act as a fertilizer itself, as seen also in the results of Chan et al.(*18*). Regarding this, Day et al. (*28*) suggested using biochar to scrub CO_2, SO_x, and NO_x from fossil-fuel power plant flue gases, and in the process, creating a slow release fertilizer which sequesters additional CO_2. In addition to the effect of biochar amendment on soil nutrient content, charcoal amendments have been reported to have a positive effect on nutrient retention, particularly in highly weathered soils with low ion-retention capacities (*13*).

Some of the positive agronomic and soil physical effects described above have been attributed to biochar promotion of mycorrhizal fungi, according to a comprehensive recent review (*29*). For example, it was reported that biochar applied at a rate of 800 g/m^3 to abandoned orchard soil resulted in an increase in mycorrhizae response of more than 600% (*30*), and a rate of biochar applied to soil at 1500 g/m^2 resulted in a 300% increase in mycorrhizae response in soybean fields (*31*). A few studies which reported decreases in mycorrhizal fungi upon biochar additions were attributed to nutrient limitations, and in particular, limitations in P availability in biochar-amended media (*29*). According to Warnock et al. (*29*), there are at least 4 mechanisms by which biochar can influence mycorrhizae abundance or activity in soils and plant roots: (i) by altering levels of nutrients or nutrient availability, or other soil physico-chemical characteristics that lead to changes in mycorrhizal response; (ii) by having beneficial or detrimental effects on other soil microbes, which cascade to effects on mycorrhizal response; (iii) by altering plant-mycorrhizal fungal signaling processes or allelochemical toxicity; and (iv) by providing a physical refuge for mycorrhizal fungi from hyphal grazers. Understanding the relative importance of any one of these mechanisms, or alternative ones, is in its infancy.

BIOCHAR FOR WASTE MANAGEMENT

The production of biochar from various waste streams (including biosolids such as sludge and manure) can mitigate many nuisances associated with those wastes, such as nitrogen and phosphorous run-off and leaching, odors and pathogens (*32*). Conventionally, energy recovery and nutrient reuse from biosolids has been achieved via anaerobic digestion/power generation with land application of the biosolids. By contrast, thermal processes such as pyrolysis have typically been used only for energy recovery. Bridle and Pritchard (*33*) showed that by treating biosolids with pyrolysis, all the energy in biosolids could be beneficially recovered and reused. Their results demonstrated that the phosphorus in the biosolids char was plant available, although the nitrogen was insoluble. Based on these results it appears that there is potential to use pyrolysis as an effective means to recover and reuse both the energy and the valuable phosphorus present in biosolids, without the odors and other negative connotations associated with biosolids direct application on land. Additional benefits of conversion of organic residues to biochar include the elimination of pathogens and the speciation of some heavy metal contaminants into forms with reduced levels of toxicity (*32*). Thus, the creation of energy from waste via pyrolysis also converts a nuisance into a renewable energy resource.

ENERGY RECOVERY FROM PYROLYSIS OF BIOMASS IN ISRAEL

Based on figures for energy and biochar production from fast pyrolysis of biomass at a temperature of 500°C given by Laird (*6*), enough bio-oil to displace $1.185 \cdot 10^6$ tons of fossil fuel oil per year could be generated from the total 5 million tons of organic residues available in Israel (*34*), representing 14% of Israel's yearly consumption of fossil fuel oil for the year 2006 ($8.31 \cdot 10^6$ tons; http://www.cbs.gov.il/energy/). According to data from the United Nations Statistics Division (http://indexmundi.com/israel/carbon-dioxide-emissions.html), CO_2 emissions from Israel in the year 2004 reached 71 Tg. Following the assumptions in Laird (*6*), the generation of biofuels and sequestering of biochar in the soil could maximally offset 1.185 Tg of fossil fuel emissions per year and sequester 0.63 Tg of C per year in the soil. Together these represent 8.5% of the average C emissions for Israel in the year 2004. More reasonable estimates for possible biomass utilization would be about 1/3 of these values (*34*). None of the estimates take into account biochar's potential to reduce N_2O and methane emissions from agriculture (*10*) or the possibility of using biochar as a scrubber for flue gases containing NO_X, SO_X and CO_2, followed by its application to the soil as a slow-release fertilizer (*28*).

POTENTIAL PITFALLS AND KNOWLEDGE GAPS IN THE USE OF BIOCHAR IN AGRICULTURE

Lehmann (*7*) discussed impediments to the adoption of biochar use in agriculture, first and foremost among them being the great variability in biochar characteristics as a function of feedstock and production conditions (such as temperature). Biochar produced at temperatures below 400°C may have low CEC and low surface area, making it less suitable as a soil conditioner than biochar produced between 400-550°C. Likewise, production conditions can have a dramatic effect on the stability of the char in the environment, affecting its utility as a long term carbon sink. The aging of biochar in soil tends to increase its CEC, but the factors involved in the development of CEC during aging are not well-defined. Understanding and optimizing these features require an organized research effort.

Additional aspects of biochar use in soil that need to be considered include the possible occurrence of phytotoxic compounds or leachable metals in the biochar (*32*). Levels of metal contaminants present in some feedstocks may limit the safe level of biochar application. For the most part, there is little information on contaminants present in different biochars, and more importantly, on their availability to plants and their potential for leaching to the environment. On the other hand, it should be borne in mind that carbon-based materials make excellent sorbents for many organic and inorganic pollutants, and the presence of biochar in a soil may help reduce pollutant leaching out of the soil zone.

A further challenge to the use of biochar in soil is the means of application (*32*), which will depend largely on the biochar physical properties and intended function. Tilling biochar into the soil can disturb soil structure and increase carbon turnover rates, as well as lead to dust and erosion problems. On the other hand, broadcasting the char on the soil surface may lead to runoff and erosion of the char, obviating its carbon sequestration potential.

REFERENCES

(1) IPCC *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment*
Report of the Intergovernmental Panel on Climate Change; Geneva, 2007; p 104.
(2) Mathews, J. A. Carbon-negative biofuels. *Energy Policy* **2008,** *36* (3), 940-945.
(3) Searchinger, T.; Heimlich, R.; Houghton, R. A.; Dong, F. X.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T. H. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **2008,** *319* (5867), 1238-1240.
(4) Bruun, S.; Luxhoi, J. Is biochar production really carbon-negative? *Environmental Science & Technology* **2008,** *42* (5), 1388-1388.
(5) Lal, R. World crop residues production and implications of its use as a biofuel. *Environment International* **2005,** *31* (4), 575-584.
(6) Laird, D. A. The charcoal vision: A win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal* **2008,** *100* (1), 178-181.
(7) Lehmann, J. Bio-energy in the black. *Frontiers in Ecology and the Environment* **2007,** *5* (7), 381-387.
(8) Gaunt, J. L.; Lehmann, J. Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environmental Science & Technology* **2008,** *42* (11), 4152-4158.
(9) Lehmann, J.; Gaunt, J.; Rondon, M. Bio-char sequestration in terrestrial ecosystems – a review. *Mitigation and Adaptation Strategies for Global Change* **2006,** *11*, 403-427.
(10) Yanai, Y.; Toyota, K.; Okazaki, M. Effects of charcoal addition on N_2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. *Soil Science and Plant Nutrition* **2007,** *53* (2), 181-188.

(11) Rondon, M. A.; Lehmann, J.; Ramirez, J.; Hurtado, M. Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions. *Biology and Fertility of Soils* **2007,** *43* (6), 699-708.
(12) Yaman, S. Pyrolysis of biomass to produce fuels and chemical feedstocks. *Energy Conversion and Management* **2004,** *45* (5), 651-671.
(13) Glaser, B.; Lehmann, J.; Zech, W. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. *Biology and Fertility of Soils* **2002,** *35* (4), 219-230.
(14) Pessenda, L. C. R.; Gouveia, S. E. M.; Aravena, R., Radiocarbon dating of total soil organic matter and humin fraction and its comparison with C-14 ages of fossil charcoal. In *17th International Radiocarbon Conference*, Jerusalem, Israel, 2000; pp 595-601.
(15) Schmidt, M. W. I.; Skjemstad, J. O.; Jager, C. Carbon isotope geochemistry and nanomorphology of soil black carbon: Black chernozemic soils in central Europe originate from ancient biomass burning. *Global Biogeochemical Cycles* **2002,** *16* (4).
(16) Steiner, C.; Glaser, B.; Teixeira, W. G.; Lehmann, J.; Blum, W. E. H.; Zech, W. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. *Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde* **2008,** *171* (6), 893-899.
(17) Steiner, C.; Teixeira, W. G.; Lehmann, J.; Nehls, T.; de Macedo, J. L. V.; Blum, W. E. H.; Zech, W. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and Soil* **2007,** *291* (1-2), 275-290.
(18) Chan, K. Y.; Van Zwieten, L.; Meszaros, I.; Downie, A.; Joseph, S. Using poultry litter biochars as soil amendments. *Australian Journal of Soil Research* **2008,** *46* (5), 437-444.
(19) Chan, K. Y.; Van Zwieten, L.; Meszaros, I.; Downie, A.; Joseph, S. Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research* **2007,** *45* (8), 629-634.
(20) Iswaran, V.; Jauhri, K. S.; Sen, A. Effect of charcoal, coal and peat on the yield of moong, soybean and pea. *Soil Biology & Biochemistry* **1980,** *12* (2), 191-192.
(21) Kishimoto, S.; Sugiura, G. Charcoal as a soil conditioner. *Int. Achieve. Future* **1985,** *5*, 12-23.
(22) Wardle, D. A.; Zackrisson, O.; Nilsson, M. C. The charcoal effect in Boreal forests: mechanisms and ecological consequences. *Oecologia* **1998,** *115* (3), 419-426.
(23) Lehmann, J.; Pereira da Silva Jr., J.; Steiner, C.; Nehls, T.; Zec, W.; Glaser, B. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil* **2003,** *249*, 343-357.
(24) Glaser, B.; Guggenberger, G.; Zech, W. Past anthropogenic influence on the present soil properties of anthropogenic dark earths (Terra Preta) in Amazonia (Brazil). *Geoarcheology* **2002**.
(25) Tyron, E. H. Effect of charcoal on certain physical, chemical and biological properties of forest soils. *Ecol Monograph* **1948,** *18*, 81-115.
(26) Kauffman, J. B.; Cummings, D. L.; Ward, D. E.; Babbitt, R. Fire in the Brazilian Amazon. 1. Biomass, nutrient pools, and losses in slashed primary forests. *Oecologia* **1995,** *104* (4), 397-408.
(27) Sanchez, P. A.; Villachica, J. H.; Bandy, D. E. Soil fertility dynamics after clearing a tropical rainforest in Peru. *Soil Science Society of America Journal* **1983,** *47* (6), 1171-1178.
(28) Day, D.; Evans, R. J.; Lee, J. W.; Reicosky, D. Economical CO_2, SO_x, and NO_x capture from fossil-fuel utilization with combined renewable hydrogen production and large-scale carbon sequestration. *Energy* **2005,** *30*, 2558-2579.
(29) Warnock, D. D.; Lehmann, J.; Kuyper, T. W.; Rillig, M. C. Mycorrhizal responses to biochar in soil - concepts and mechanisms. *Plant and Soil* **2007,** *300* (1-2), 9-20.
(30) Ishii, T.; Kadoya, K. Effects of charcoal as a soil conditioner on citrus growth and vesicular-arbuscular mycorrhizal development. *Journal of the Japanese Society of Horticultural Science* **1994,** *63*, 529-535.
(31) Saito, M. Charcoal as a micro habitat for VA mycorrhizal fungi, and its practical application. *Agriculture Ecosystems & Environment* **1990,** *29*, 341-344.

(32) McHenry, M. P. Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: Certainty, uncertainty and risk. *Agriculture Ecosystems & Environment* **2009,** *129* (1-3), 1-7.
(33) Bridle, T. R.; Pritchard, D. Energy and nutrient recovery from sewage sludge via pyrolysis. *Water Science and Technology* **2004,** *50* (9), 169-175.
(34) Chalamish, N.; Tal, A.; Ben-Nun, G.; Chen, Y.; Chefetz, B.; Lavie, D.; Attas, A. *Compost in Israel*; Ministry of Environmental Quality and Ministry of Agriculture: 2006; p 174 (in Hebrew).