academicJournals

Vol. 8(38), pp. 4726-4739, 3 October, 2013
DOI:10.5897/AJAR2013.7239
ISSN 1991-637X ©2013 Academic Journals
http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Review

Biochar-boon to soil health and crop production

Srinvasagam Krishnakumar*, Selvan Ramesh Kumar, Natarajan Mariappan and Karuppasamy Krishna Surendar

Vanavarayar Institute of Agriculture, Manakkadavu, Pollachi – 642103, Tamil Nadu, India.

Accepted 13 August, 2013

Soil health is defined as the capacity of a soil to function within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health. Primary functions of soil include sustaining biological productivity, regulating water flow, storing and cycling of nutrients, filtering, buffering, and transforming organic and inorganic materials. The decrease in biomass production, decrease in organic matter supply and increased decomposition rate are the primary factors to reduction in soil organic matter. Biochar is a stable carbon compound created when biomass is heated to temperatures between 300 and 1000°C, under low oxygen concentrations. Fire accelerates carbon cycle, but biochar decelerates it. It is commonly defined as charred organic matter, produced with the intent to deliberately sequester carbon and improve soil properties. Biochar is to abate the enhanced greenhouse effect by sequestering C in soils, while concurrently improving soil quality. Application of biochar is very imperative to increase soil fertility, enhance nutrient uptake, ameliorate Cr polluted soils and reduce the amount of carbon produced due to biomass burning. It has the potential to increase conventional agricultural productivity and mitigate green house gas emissions from agricultural soils. This has led to renewed interest of agricultural researchers to produce biochar from bio-residues and it is used as a soil amendment.

Key words: Biochar, Mycorrhiza, soil physico chemical properties, soil microbes, carbon sequestration, green house gas emission.

INTRODUCTION

As the science of agriculture developed, plant nutrients were identified as essential components of soil health, at least with respect to sustaining biological productivity. Soil is the most important natural resources, because it is a primary medium for the growth of food and fodder. Carbon plays an important role in the soil. It has the potential to influence physical and chemical processes in soil (DeLuca et al., 2006; Glaser et al., 2001). It has also been shown to affect soil productivity, quality and fertility and nutrient cycling, which all affect crop production (Skjemstad et al., 2002; Lal, 2004). Carbon plays an influential role in many soil properties; therefore understanding how the addition of carbon may influence the soil is essential. The products produced from pyrolysis include a gaseous material referred to as “syngas” and a carbon (C) rich, charcoal material known as biochar (Lehmann, 2007). The application of biochar made from corn stover to soils has the potential to reduce the need for nitrogen fertilizer, as well as enhance soil chemical and physical properties.

Professor Tim Flannery, author of The Weather Makes a Widely Read Book about Climate Change, has said:

"Biochar may represent the single most important

*Corresponding author. E-mail: drkrishnakumar76@gmail.com.

Table 1. The mean post-pyrolysis feedstock residues resulting from different temperatures and residence times (IEA, 2007).

Mode	Conditions	Liquid (%)	Biochar (%)	Syngas (%)
Fast pyrolysis	Moderate temperature, ~500°C, short hot vapour residence time of ~ 1 s	75	12	13
Intermediate pyrolysis	Moderate temperature ~500°C, moderate hot vapour residence time of 10 – 20 s	50	20	30
Slow pyrolysis (Carbonisation)	Low temperature ~400°C, very long solids residence time	30	35	35
Gasification	High temperature ~800°C, long vapour residence time	5	10	85

> initiative for humanity's environmental future. The biochar approach provides a uniquely powerful solution, for it allows us to address food security, fuel crisis and climate problem, in an immensely practical manner."

The long lasting benefits of biochar include the increased retention of nutrients by the soil and water which enhances crop growth. Less leaching of nutrients (such as calcium, potassium, magnesium, and nitrogen) means that more nutrients are available for plants' uptake (Lehmann et al., 2011). Although, biochar is not a fertilizer itself, it improves the overall soil health and quality.

Terra preta

Soils discovered in the Amazon River Basin known as Terra Preta de Indio have been said to have higher levels of charcoal, 70 times higher than the surrounding soils; they are more productive than surrounding soils and have been around for hundreds to thousands of years (Mann, 2002; Glaser et al., 2001, 2002; Lehmann, 2007). Terra Preta soils have been measured with as much as 150 g/kg organic matter which is higher than the surrounding soils (Petersen et al., 2001; Woods et al., 2000). These soils are also higher in essential nutrients including phosphorus, calcium, sulfur and nitrogen, cation exchange capacity (CEC) and have a more neutral pH than the typical acidic oxisol soils found around the Terra Preta soils (Mann, 2002; Lehmann et al., 2003; Lehmann, 2007). The improved chemical properties of the Terra Preta soils result in productive farm land where it typically did not exist.

PYROLYSIS

Pyrolysis is a thermo-chemical decomposition of organic material at elevated temperatures in the absence of oxygen (or any halogen). Pyrolysis is a type of thermolysis, and is most commonly observed in organic materials exposed to high temperatures. It is one of the processes involved in charring wood, starting at 200 to 300°C (390 to 570°F).

Table 1 shows that different pyrolysis conditions lead to different proportions of each end product (liquid, char or gas). This means that specific pyrolysis conditions can be tailored to each desired outcome. For example, the IEA report (2007) stated that fast pyrolysis was of particular interest as liquids can be stored and transported more easily and at lower cost than solid or gaseous biomass forms. However, with regard to the use of biochar as a soil amendment and for climate change mitigation, it is clear that slow pyrolysis would be preferable as this maximizes the yield of char, the most stable of the pyrolysis end products.

The process of pyrolysis transforming organic materials into three different components being gas, liquid or solid in different proportions depends upon both the feedstock and the pyrolysis conditions used. Gases which are produced are flammable, including methane and other hydrocarbons which can be cooled when they condense and form an oil/tar residue which generally contains small amounts of water (Figure 1). The gasses (either condenses or in gaseous form) and liquids can be upgraded and used as a fuel for combustion. The remaining solid component after pyrolysis is charcoal; it is referred to as biochar when it is produced with the intention of adding it to soil to improve it. The list of key term related to biochar is given in Table 2.

Biochar

Biochar is a stable form of charcoal made from heating natural organic materials (crop and other waste, woodchips, manure) in a high temperature and low oxygen process known as pyrolysis. Due to its molecular configuration, biochar is chemically and biologically in a more stable form than the original carbon form it comes

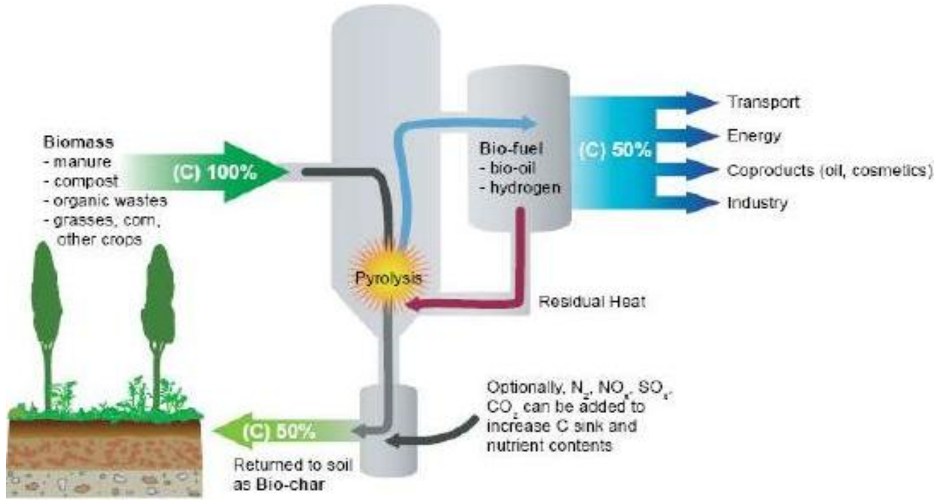

Figure 1. Biomass to biochar production, generation of bio-energy and sequestration of approximately 50% of the carbon from the biomass in soil (Lehmann, 2007).

Table 2. List of key terms.

Activated carbon	Noun: Charcoal produced to optimise its reactive surface area (e.g. by using steam during pyrolysis)
Anthrosol	Count noun: A soil that has been modified profoundly through human activities, such as addition of organic materials or household wastes, irrigation and cultivation (WRB, 2006)
Biochar	Material: Charcoal for application to soil Concept: “Charcoal (biomass that has been pyrolysed in a zero or low oxygen environment) for which, owing to its inherent properties, scientific consensus exists that application to soil at a specific site is expected to sustainably sequester carbon and concurrently improve soil functions (under current and future management), while avoiding short- and long-term detrimental effects to the wider environment as well as human and animal health."
Black carbon	Noun: All C-rich residues from fire or heat (including from coal, gas or petrol)
Black Earth	Mass noun: Term synonymous with Chernozem used (e.g. in Australia) to describe self-mulching black clays (SSSA, 2003)
Char	Mass noun: 1. Synonym of ‘charcoal’; 2. charred organic matter as a result of wildfire (Lehmann and Joseph, 2009) (verb) synonym of the term ‘pyrolyse’
Charcoal	Mass noun: charred organic matter
Chernozem	Count noun: A black soil rich in organic matter; from the Russian ‘chernij’ meaning ‘black’ and ‘zemlja’ meaning ‘earth’ or ‘land’ (WRB, 2006)
Coal	Mass noun: Combustible black or dark brown rock consisting chiefly of carbonized plant matter, found mainly in underground seams and used as fuel (OED, 2003)
Combustion	Mass noun: chemistry Rapid chemical combination of a substance with oxygen, involving the production of heat and light (OED, 2003)
Decline in soil organic matter (SOM)	soil threat: A negative imbalance between the build-up of SOM and rates of decomposition leading to an overall decline in SOM contents and/or quality, causing a deterioration or loss of one or more soil functions

Table 3. Total elemental composition and means of biochars from a variety of feedstocks (wood, green wastes, crop residues, sewage sludge, litter, nut shells) and pyrolysis conditions (350 to 500°C) used in various studies (Chan and Xu, 2009).

pH			C(g kg^{-1})	N (g kg^{-1})	N (NO_3^-+NH_4^+) (mg kg^{-1})	C:N	P(g kg^{-1})	Pa(g kg^{-1})	K(g kg^{-1})
Range	From	6.2	172	1.7	0.0	7	0.2	0.015	1.0
	To	9.6	905	78.2	2.0	500	73.0	11.6	58
Mean		8.1	543	22.3	-	61	23.7	-	24.3

from, making it more difficult to break down. This means that in some cases it can remain stable in soil for hundreds to thousands of years (Pessenda et al., 2001; Chmidt et al., 2002; Krull et al., 2006).

In order to differentiate biochar from charcoal formed in natural fire, activated carbon and other black carbon materials, the following list of terms aims to better define the different products. The differences, however, are relatively subtle since all products are obtained from the heating of carbon-rich material.

Char

Is the solid product arising from thermal decomposition of any natural or synthetic organic material. Examples are char from forest fire and soot resulting from the incomplete combustion of fossil hydrocarbon.

Charcoal

Charcoal is produced from the thermal decomposition of wood and related organic materials mainly for use as an urban fuel for heating and cooking, but also has traditional uses as soil amendment or control of odour (Okimori et al., 2003). Temperatures in traditional kilns approach 450 to 500°C, which is similar to that of industrial pyrolysis but with lower yields; conversion of feedstock dry mass may be as low as 10% compared to 35% using more formal production technology. Also, all heat as well as gaseous and liquid co-products are lost during the combustion process.

Activated carbon

Activated carbon is manufactured by heating carbonaceous material at a high temperature (above 500°C) and over long (>10 h) periods of time. The resulting material is characterized by a very high adsorptive capacity. It is not used as a soil amendment but has been applied for cleansing processes, such as water filtration and adsorption of gas, liquid or solid contaminants (Tomaszewski et al., 2007).

Black carbon

Black carbon is a general term that encompasses diverse and ubiquitous forms of refractory organic matter that originates from incomplete combustion (Baldock and Smernik, 2002). The diversity of burning conditions results in black carbon occupying a continuum of material. The review by Schmidt et al. (1999) provides a thorough account of the ‘black carbon’ continuum, its constituents and definitions. The total elemental composition (C, N, C:N, P, K, available P – *Pa* - and mineral N) and pH ranges of biochars (Table 3) from a variety of feedstocks (wood, green wastes, crop residues, sewage sludge, litter, nut shells) and pyrolysis conditions (350 to 500°C) were used in various studies (Brown, 2009). Total carbon content in biochar was found to range between 172 to 905 g kg^{-1}, although OC often accounts for < 500 g kg^{-1}, as reviewed by Chan and Xu (2009) for a variety of source materials. Total N varied between 1.8 and 56.4 g kg-1, depending on the feedstock. Despite being high, biochar total N content may not be necessarily beneficial to crops, since N is mostly present in an unavailable form (mineral N contents < 2 mg k^{-1}). Total P and total K in biochar were found to range broadly according to feedstock, with values between 2.7 to 480 and 1.0 to 58.0 g kg^{-1}, respectively (Chan and Xu, 2009).

Biochar application strategies

Biochar application strategies have been studied a little; the way biochar is applied to soils can have a substantial impact on soil processes and functioning. Biochar is most commonly incorporated into the soil. First, spread the desired amount onto the soil evenly, and then till it in with machine or by hand. The followings are the application strategies:

i. Topsoil incorporation,
ii. Depth application,
iii. Top-dressing.

Top soil incorporation

This is the incorporation of biochar on soil alone or combined with organic compost / organic manures. The homogenous mixture of biochar with organic compost/manure/slurry is essential for top soil application (in most arable soils from 0-15/30 cm depth). Moistening

Figure 2. Clockwise from top left: Biochar losses during handling, transportation to the field, application and incorporation in a field trial in Québec. Photos by B. Husk.

the biochar during soil application is very essential to minimize the loss of biochar from wind and water erosion.

Depth application

The placement of biochar to the soil is also a very significant approach to increase the efficiency of biochar on soil physic-chemical and biological properties. Depth application of biochar has been described mostly as ‘deep-banded’ application (Blackwell et al., 2007). Deep mould board ploughing essentially results in temporary ‘depth application’, although horizontally continuously. Subsequent mouldboard ploughing and cultivation will then further homogenize the biochar distribution through the topsoil.

Top-dressing

Top-dressing of biochar is the spreading of biochar (dust fraction mostly) to the soil surface and relying on natural processes for the incorporation of the biochar into the topsoil. This form of application is being considered mainly for those situations where mechanical incorporation is not possible, e.g. no-till systems, forests, and pastures. An obvious drawback is the risk of erosion by water and wind, as well as human health (inhalation) and impacts on other ecosystem components (e.g. surface water, leaf surfaces, etc.).

Both topsoil incorporation and top-dressing can be applied with a range of frequencies, that is, a ‘one-off’ application’, every few years, or every year. For specific effects on soil, e.g. nutrient availability (from a feedstock like poultry manure) or liming effect, a more frequent application may be more beneficial to the soil and/or less detrimental to the environment (nitrate leaching).

The sources of materials used to produce biochar and pyrolysis technique are the primary factors for the particle size distribution of biochar. Handling of biochar is very difficult especially due to the particle size distribution of biochar.

Problems of soil application

Wind loss

Applying of biochar to the soil is a tricky process due to wind or water losses. The large amount of biochar is lost through wind (Figure 2) and water during soil application for the purpose of soil carbon sequestration and crop production. The biochar field trial in Québec, Canada in

2008, Blue Leaf Inc. faced problem during the establishment of a biochar. Blue Leaf applied a fine grained biochar produced by fast pyrolysis, and estimated that 2% of the material was lost loading the spreader, 3% was lost during transport, and 25% was lost during spreading, leading to a total loss of approximately 30%. The biochar can be moistened to minimize the wind losses, however, it will increase the weight of the biochar materials and this will increase the transport cost. While water is usually added to biochar immediately after exiting the pyrolysis unit in order to quench it, more water could be applied to reduce dustiness prior to field application.

Minimizing wind loss

1. When winds are mild, apply biochar under the good weather conditions. The biochar dust is applied at mild rain conditions due to holding nature of biochar on the soil surface until biochar is incorporated into the soil by tillage,
2. Water can be applied to the biochar for the purpose of moistening to reduce the wind loss or it can be applied with moist manure,
3. Different formulation can be made by pelleting, prilling and mixing of biochar with compost or manure. Different biochar formulations will be best suited to different application methods, and very fine biochar may be described in certain cases, for example when applying as a slurry, by itself or mixed with manure (Blackwell et al., 2009).

Water erosion

Apart from wind loss, biochar can also be lost by water erosion. The factors such as heavy rain, sloping terrain, etc exacerbate this problem. Rumpel et al. (2006) found that surface-deposited biochar was eroded from steep slopes in Laos; they highlighted the need for soil incorporation especially when biochar is applied to sloping terrain. Major et al. (2010a) also observed significant losses of biochar incorporated into particularly flat terrain, in an area where intense rainfall events occur. Biochar can require some time for wetting soon after application, and may float away when a thick layer of standing water pool is over the soil and moves towards the bottom of the site’s slope.

Minimize erosion by water

Good management strategies were developed to incorporate biochar into soil especially on sloping terrain or where intense rainfall occurs. The method used for biochar incorporation must itself be chosen to minimize erosion losses.

Rate of biochar application

Biochar application rate in soil varies depending upon many factors including the type of biomass used, the degree of metal contamination in the biomass, the types and proportions of various nutrients, and also climatic and topographic factors of the land where the biochar is applied. Experiments have found that rates between 5 to 50 t/ha (0.5 to 5 kg/m^2) have often been used successfully. Rates around 1% by weight or less have been used successfully so far in field crops (Major, 2013). Winsley (2007) suggests that even low rates of biochar application can significantly increase crop productivity. Application to soils of higher amounts of biochar may increase the carbon credit benefit; but, in nitrogen-limiting soils, it could fail to assist crop productivity as a high C/N ratio leads to low N availability (Lehmann and Rondon, 2006). Chan et al. (2007) experiment shows that the case of piggery and poultry manure biochar, the biochar works both as organic fertilizer and soil conditioner with agronomic benefits observed at low application rate (10 t ha^{-1}). Biochar application rates also depend on the amount of dangerous metals present in the original biomass.

Interaction between biochar and soil

The interaction between biochar and soil is clearly shown in Figure 3. The biochar and its properties are taken under consideration using as amendments. The properties are viz., large surface area (SA) and presence of micropores (Mukherjee et al., 2011; Braida et al., 2003; Nguyen et al., 2004; Rutherford et al., 2004). The impact of biochar as an amendment depends on its properties. Key properties are those which contribute to the adsorptive properties of biochars and potentially alter soil’s SA, pore size distribution (PSD), bulk density (BD), water holding capacity (WHC) and penetration resistance (PR).

Biochar on soil physico-chemical properties

The application of biochar to the soil will change both the soil’s physical and chemical properties. The net effect on the soil physical properties will depend on the interaction of the biochar with the physico-chemical characteristics of the soil, and other determinant factors such as the weather conditions prevalent at the particular site, and the management of biochar application (Verheijen et al., 2010). Biochar application can reduce the bulk density (BD) of the different soils (Laird et al., 2010; Jones et al., 2010; Chen et al., 2011).

About 2% (w/w) rate of biochar amendment seems enough to decrease BD of amended soils (Table 4); however, in some instances BD can increase over time due to compaction during column leaching events

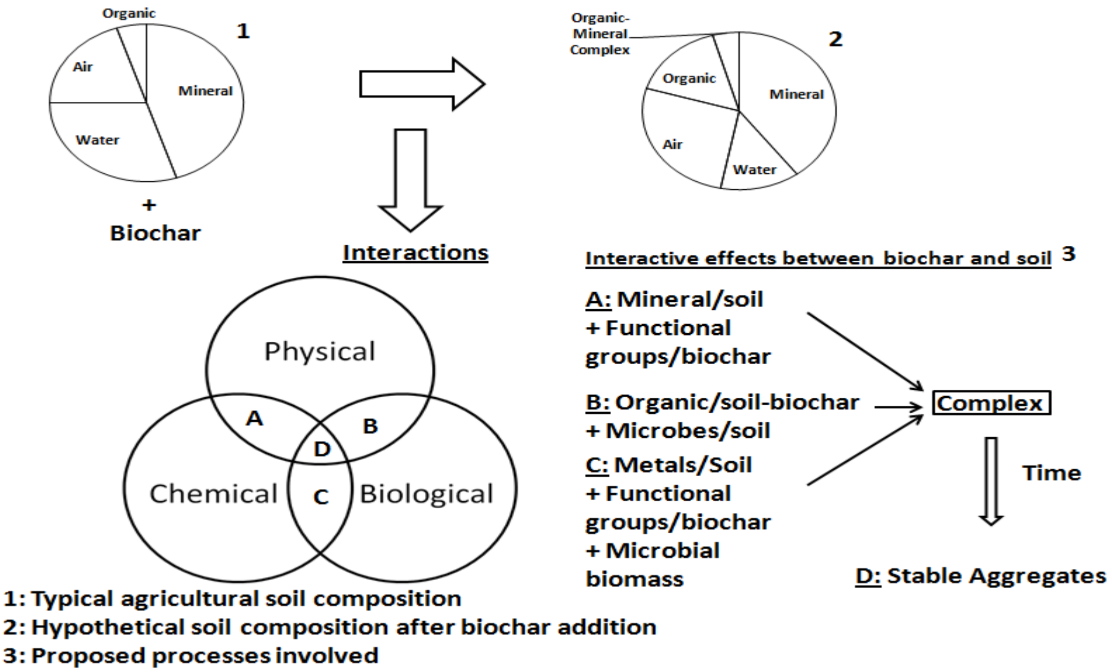

Figure 3. Schematic representation of interactions between biochar and soil (Mukherjee and Lal, 2013).

Table 4. Impact of biochar application on soil bulk density (Mukherjee and Lal, 2013).

Soil type	Biochar type	Study type (Scale)	Rate of biochar Application % (g g−1)	Bulk density (g cm^{-3})	References
Norfolk loamy sand: E	Pecan (*Carya illinoinensis*) shells, 700°C	Laboratory	0 2.1	1.52 1.45[1], 1.52[2]	Busscher et al. (2011)
Norfolk loamy sand: E and Bt			0 2.1	1.34 1.36[1], 1.34[2]	
Hydroagric stagnic anthrosol	Wheat (*Triticum* spp.) straw, 350 to 550°C	Field	0 1.1 2.2 4.4	0.99, 0.94[3] 0.96, 0.91[3] 0.91, 0.86[3] 0.89, 0.88[3]	Mankasingh et al. (2011)
Residue sand	Municipal green waste, 450°C	Laboratory	0 2.6 5.2	1.65 1.55 1.44	Jones et al. (2010)

[1]measured after 44 days; [2]measured after 94 days; [3]measured after one year.

(Rogovska et al., 2011). The soil BD decreased from 1.66 to 1.53 g cm^{-3} (Mankasingh et al., 2011), and another involving biochar amended soil columns showed significantly lower BD compared to no-biochar controls in a column incubation study (Laird et al., 2010). In a 3-year field study, application of biochar amendment decreased the BD of 0 to 7.5 cm soil layer by 4.5 and 6.0% for 0.23 kg m^{-2} and 0.45 kg m^{-2} application rate, respectively (Chen et al., 2011). A decrease in soil BD from biochar application rate of 9.4 (± 2.2%) was observed in another 2-year field study (Zhang et al., 2012).

The decrease in BD of biochar amended soil could be one of the indicators of enhancement of soil structure or aggregation, and aeration, and could be soil-specific. The higher the total porosity (micro- and macro-pores) the higher is soil physical quality because micropores are involved in molecular adsorption and transport while macropores affect aeration and hydrology (Atkinson et al., 2010).

Soil hydrological properties (that is, moisture content, WHC, water retention, hydraulic conductivity, water infiltration rate) are invariably related to SA, porosity, BD and aggregate stability. Several studies have reported alterations in WHC and water retention in biochar-amended

Table 5. Impact of biochar on water holding capacity (Mukherjee and Lal, 2013)

Soil type	Biochar type	Study type (Scale)	Rate of biochar application % (g g^{-1})	Water holding capacity (g cm^{-3})	References
Residue sand	Municipal green waste, 450°C	Laboratory	0 2.6 5.2	0.11 0.16 0.20	Jones et al. (2010)
Norfolk loamy sand Ap	Pecan shells, 700°C	Laboratory	0 0.5 1.0 2.0	0.64 0.59 0.60 0.66	Busscher et al. (2010)
Sandy loam	Ponderosa pine (*Pinus onderosa*), 450°C	Laboratory	0 0.5 1.0 5.0	11.9 12.4 13.0 18.8	Briggs et al. (2012)

Table 6. Effects of biomass derived char on percentage of available moisture in soils on a volume basis (Glaser et al., 2002).

Soil	0% biochar	15% biochar	30% biochar	45% biochar
Sand	6.7	7.1	7.5	7.9
Loam	10.6	10.6	10.6	10.6
Clay	17.8	16.6	15.4	14.2

Table 7. Impacts of different biochar on soil properties (Chan et al., 2007).

Feedstock	Activated	pH	EC (dS/m)	C (%)	Total (N %)	Total (P %)	Mineral (N) (mg/kg)	Extractable P (mg/kg)
Garden organic	Yes	9.4	3.2	36	0.18	0.07	<0.5	400
Poultry manure	Yes	13	14	33	0.9	3.6	2.5	1800
Poultry manure	No	9.9	5.6	38	2.0	2.5	2.4	11600

soils (Laird et al., 2010; Jones et al., 2010; Uzoma et al., 2011) with as low as 0.5% (g g^{-1}) biochar application rate sufficient to improve WHC (Table 5).

The biochar addition improved the water holding capacity as well as plant available moisture in sandy soils (Table 6). Because it is so porous, charcoal has a high surface area with increased micro-pores and improves the water holding properties of sandy soils. But, in loamy soils, no changes were observed; and in clayey soil, the available soil moisture decreased with increasing charcoal additions due to the hydrophobicity of charcoal (Glaser et al., 2002).

Chan et al. (2007) conducted an experiment related to biochar application to know the effect of different biochars on soil chemical properties. The results show that biochar produced from poultry manure had higher electrical conductivity, N, P and pH values than that from garden organic waste (Table 7). These analyses highlight the fact that the more nutrient-rich organic waste, the greater the benefits from the biochar.

Effect of biochar on soil microorganisms

The current knowledge about soil microbes is given in Table 8. Based on the experimental evidence, biochar has symbiotic relationship with the mycorrhizal system. The four mechanisms iby which bichar could improve mycorrhizal abundance (40%) and functioning are given by Warnock et al. (2007). The mechanisms are:

i. Alteration of soil physic-chemical properties,
ii. Indirect effects on mycorrhizae through effects on other soil microbes,
iii. Plant-fungus signaling interference, and
iv. Detoxification of allelochemicals on biochar.

There are 50 to 72% increases of soil biological nitrogen fixation (BNF) through biochar application (Lehman and Rondon, 2006). Biochar has positive effects on soil biology. It provides microbial habitat and refugia for microbes where they are protected from grazing. Both

Table 8. Summary of current state of knowledge regarding the influence of biochar amendments on soil biological properties.

Soil parameter	Current knowledge
Soil microbial population	i. Microbial biomass was 43 to 125% higher ($p<0.05$) overall in the ADE than the adjacent soils (Thies and Rillig, 2009). ii. Microbial activity of ADE is lower than neighbouring soils – lower CO_2 liberation (Thies and Rillig, 2009). iii. Biochar provides a source of chemi-sorption which effects the microbial community in soils.
Fungal diversity	i. Biochar interaction with mycorrhizal fungi is the one which has been studied the most (Thies and Rillig 2009).

bacteria and fungi are hypothesized to be better protected from grazers or competitors by exploring pore habitats in biochars (Ogawa, 1994; Ezawa et al., 2002; Saito and Marumoto, 2002; Thies and Rillig, 2009). Earthworms have been shown to prefer some soils amended with biochar to those soils alone. However, this is not true of all biochars, particularly at high application rates (Verheijen et al., 2010).

Soil carbon sequestration

The principle of using biochar for carbon (C) sequestration is related to the role of soils in the C-cycle. Biochar produced and added to the soil, in conjunction with bioenergy generation, can result in carbon sequestration (Lehmann, 2007). The stable form of organic carbon present in the biochar has significant effect on carbon sequestration and improves the soil condition. In photosynthesis, it converts light energy into the chemical energy of sugars and other organic compounds. This process consists of a series of chemical reactions that require carbon dioxide (CO_2) and water (H_2O) and store chemical energy in the form of sugar. The products of photosynthesis include carbohydrates in the form of sugars and starches as well as water and oxygen. The following equation summarizes photosynthesis:

$$6CO_2 + 6H_2O \xrightarrow{\text{Light}} \underset{\text{Sugar}}{6(CH_2O)} + 6O_2$$

In respiration, plants (and animals) convert the sugars (photosynthesis) back into energy for growth and other life processes (metabolic processes). The chemical equation for respiration shows that the photosynthesis combined with oxygen releases energy, carbon dioxide, and water. A simple chemical equation for respiration is given below. Notice that the equation for respiration is the opposite of that for photosynthesis.

$$\underset{\text{Sugar}}{6(CH_2O)} + 6O_2 \longrightarrow 6CO_2 + 6H_2O$$

Thus, the carbon cycle has a net carbon withdrawal from the atmosphere of 0%; or carbon neutrality as seen in Figure 4 (NASA, 2010). In a basic cycle eventually the plants decay, and this dead biomass begins to release captured carbon dioxide into the atmosphere yielding an ineffective natural cycle (Steiner, 2008). Organic biomass from decaying plant species or remnants of agriculture can be converted into a charcoal or biochar that can prevent global climate change by displacing fossil fuel use by sequestering carbon into soil carbon pools and by dramatically reducing emissions of nitrous oxides, a more potent greenhouse gas than carbon dioxide" (International Biochar Initiative [IBI], 2010). Biochar slows down the decaying and mineralization of the biological carbon cycle to establish a carbon sink and a net carbon withdrawal from the atmosphere of 20%, as seen in Figure 4. Additionally, calculations have shown that putting this biochar back into the soil can reduce emissions by 12 to 84% of current values; a positive form of sequestration that "offers the chance to turn bio-energy into a carbon negative industry" (Lehmann, 2007).

International Biochar Initiative (IBI) has already developed a model to predict the carbon removing potential of sustainable biochar utilizing system. Figure 5 shows the results of this preliminary model and gives a sense of what is possible counting only the impacts of biochar buried in soil; and without considering the displacement of energy from fossil fuels, we can conservatively offset one quarter of a gigaton of carbon annually by 2030. Optimistically, we could achieve one gigaton of offsets annually before 2050. Figure 6 highlights additional carbon offsets possible if energy from biochar production displaces fossil fuel energy, and if CCS (carbon capture and storage) is used. Sequestering 'biochar' in soil, which makes soil darker in colour, is a robust way to store carbon, as shown in Figure 7.

It has been well documented that biochar amendment to crop lands enhances crop productivity through

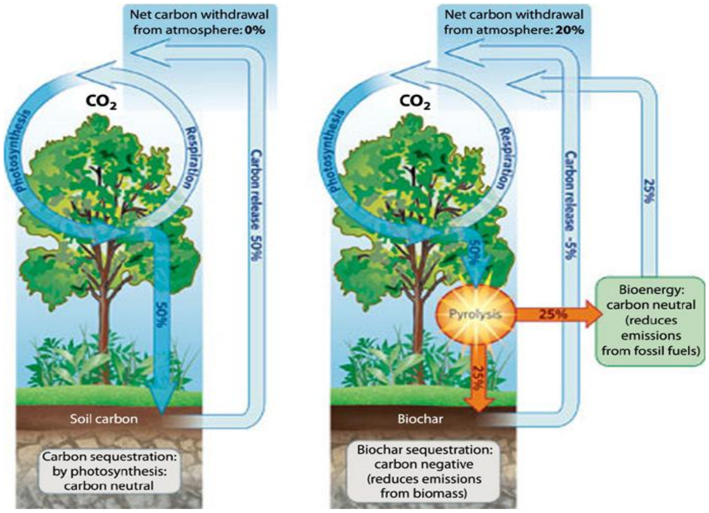

Figure 4. Comparison of normal and biochar carbon cycles (Lehmann, 2007).

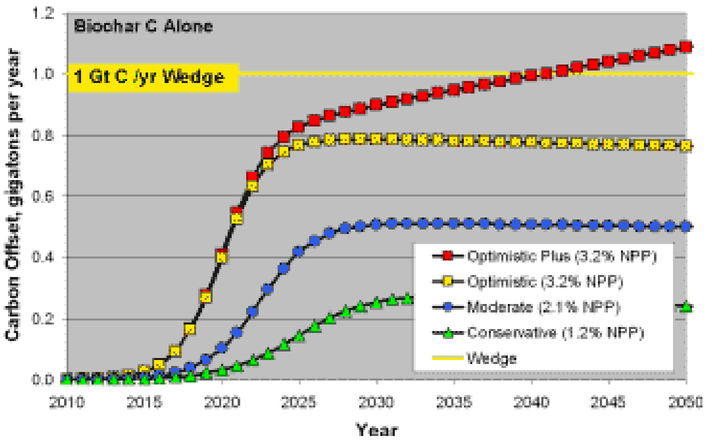

Figure 5. Four scenarious using carbon-negative biochar technology (cited in IBI website).

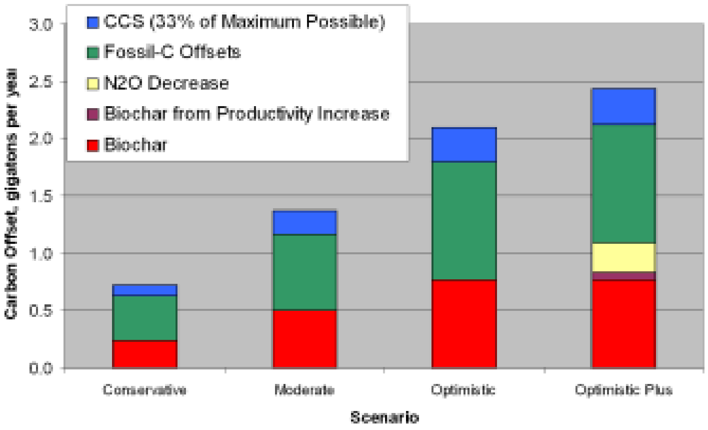

Figure 6. Annual contributions of components of sustainable biochar technology to carbon offsets (2050) (cited in IBI website).

Figure 7. Sequestering 'biochar' in soil, which makes soil darker in colour is a robust way to store carbon (Lehmann, 2007).

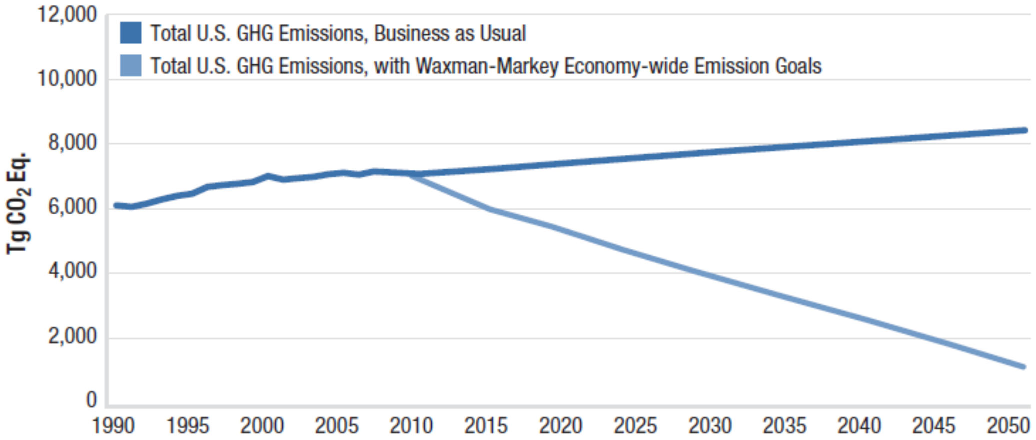

Figure 8. Projected U.S. GHG emissions meeting recently proposed goals (EPA, 2010).

improving soil quality (Asai et al., 2009; Major et al., 2010; Sohi et al., 2010; Zwieten et al., 2010; Gaskin et al., 2010; Haefele et al., 2011). The calculated biochar affects intensity (BEI) values for soil quality and crop productivity as well as GHGs emission. While there was positive effect in increasing soil pH (H_2O), SOC, total N and decreasing soil bulk density were observed in both rice cycles;1 the BEI (%) was observed less than 5% for pH (H_2O), and less than 10% for soil bulk density, −1.7 to 22.5% for total N, and 9.3 to 56% for soil organic carbon in both cycles (Zhanga et al., 2012).

Mitigation of greenhouse gas emissions

Every year, the amount of carbon dioxide in the atmosphere increased day by day and by the year 2020, the world will produce 33.8 billion metric tons up from 29.7 billion metric tons in 2007 (Figure 8). In recent years the use of surplus organic matter or biomass to create biochar has yielded promising results in the reduction of CO_2. Biochar is a carbon rich charcoal that is formed by the pyrolysis (thermal decomposition) of organic biomass. There are other environmental benefits that can be achieved by application of biochar in soils which will reduce emission of non-CO_2 green house gases (GHGs) by soil. N_2O and CO_2 gases are 23 and 298 times more potent than carbon dioxide as green house gases in the atmosphere (Srinivasarao et al., 2013). Biochar is reported to reduce N_2O emission that could be due to inhibition of either stage of nitrification and/or inhibition of denitrification, or promotion of the reduction of N_2O; and these impacts could occur simultaneously in a soil (Berglund et al., 2004; DeLuca et al., 2006).

Effect of biochar on crop yield

The forms of biochar *viz.*, dust, fine particles, coarse grain and the method of soil application *viz.*, surface

Table 9. Summary of experiments assessing the impact of biochar addition on crop yield (Srinivasarao et al., 2013).

Author	Study outline	Results summary
Glaser et al. (2002)	Cowpea on xanthic ferralsol	Char at 67 t/ha increased biomass by 150% Char at 135 t/ha increased biomass by 200%
Lehmann et al. (2003)	Soil fertility and nutrient retention. Cowpea was planted in pots and rice crops in lysimeters, Brazil	Biochar additions significantly increased biomass production by 38 to 45% (no yield reported)
Oguntunde et al. (2004)	Comparison of maize yields between disused charcoal production sites and adjacent fields, Ghana	Grain and biomass yield was 91 and 44% higher on charcoal site than control.
Yamamoto et al. (2006)	Maize, cowpea and peanut trial in area of low soil fertility	*Acacia* bark charcoal plus fertilizer increased maize and peanut yields (but not cowpea)
Chan et al. (2007)	Pot trial on radish yield in heavy soil using commercial green waste biochar (three rates) with and without N	Biochar at 100 t/ha increased yield x3; linear increase 10 to 50 t/ha, but no effect without added N

application, top dressing, drilling are the two main issues. These are all the important aspects to study the effect of biochar on soil health as well as crop productivity. Hill et al. (2007) clearly explained that even small quantities of biochar added to seed coatings may in some cases be sufficient for a beneficial effect. Effect of biochar on the different growing environments in rice viz., i) a double-cropped irrigated lowland, ii) a mono-cropped rain-fed upland, and iii) a monocropped rain-fed lowland are evaluated by Haefele (2008) and the grain yield variation between the sites was identified. Initially, the effect will be non-significant but significant improvement was shown in last three seasons. Lehmann et al. (2003) reported increasing crop yields with increasing biochar applications of up to 140 t C ha^{-1} on highly weathered soils in the humid tropics, and Rondon et al. (2007) found that the biomass growth of beans rose with biochar applications up to 60 t C ha^{-1}.

Scientists have reported that application of biochar on soil has significant effect on net primary crop production, grain yield and dry matter production (Chan et al., 2008; Chan and Xu, 2009; Major et al., 2009; Spokas et al., 2009). Purakayastha (2010) clearly explained that application of biochar prepared from wheat straw (1.9 t/ha) along with recommended doses of NPK at 180:80:80 kg ha^{-1} significantly increased the yield of maize in Inceptisol of IARI farm and this treatment was superior to either crop residue incorporation or 30 crop residue burning. Table 8 clearly shows the summary of experiments of biochar on crop yield. The summary of experiments assessing the impact of biochar addition on crop yield done by different scientists were shown in Table 9.

Biochar websites

www.css.cornell.edu/faculty/lehmann/,
www.biochar-international.org,
http://www.biochar.org/
www.bbc.co.uk › Science & Nature › TV & Radio Follow-up › Horizon, www.biochar-europe.org, biochar.bioenergylists.org,
biochar.bioenergylists.org/ubeyreuthde and http://biokohle.org/.

Conclusion

The soil health concept has increased awareness among agriculturist and horticulturist regarding the importance in maintaining soil fertility, crop productivity and environmental quality over a long term period. Biochar has positive effects on the physico-chemical and biological properties of soil, which means soil health directly and indirectly. The positive gains of biochar application in the soils include: retaining nutrients and cation exchange capacity, decreasing soil acidity, decreased uptake of soil toxins, improving soil structure, nutrient use efficiency, water holding capacity, decreasing release of non-CO_2 green house gases (CH_4, N_2O), increased number of beneficial soil microbes.

REFERENCES

Atkinson CJ, Fitzgerald JD, Hipps NA (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. Plant Soil 337:1-18.

Baldock JA, Smernik RJ (2002). Chemical composition and bioavailability of thermally altered Pinusresinosa (red pine) wood. Org. Geochem. 33:1093-1109.

Blackwell P, Shea S, Storer P, Kerkmans M, Stanley I (2007). Improving wheat production with deep banded oil mallee charcoal in Western Australia. Talk given at the International Agrichar Conference, April 27-May 2, 2007, Terrigal, NSW Australia.

Blackwell P, Riethmuller G, Collins M (2009). Biochar Application to Soil (Chapter 12), in: J. Lehmann and S. Joseph (Eds.), Biochar for Environmental Management: Science and Technology, Earthscan, London, UK. P. 207.

Braida WJ, Pignatello JJ, Lu Y, Ravikovitch PI, Neimark AV, Xing B (2003). Sorption hysteresis of benzene in charcoal particles. Environ. Sci. Technol. 37:409-417.

Briggs C, Breiner JM, Graham RC (2012). Physical and chemical properties of pinus ponderosa charcoal: Implications for soil modification. Soil Sci. 177:263-268.

Brown R (2009). Biochar Production Technology. In: Biochar for Environmental Management: Science and Technology (Eds. Lehmann, J. & Joseph, S.), Earthscan.

Busscher WJ, Novak JM, Ahmedna M (2011). Physical effects of organic matter amendment of asoutheastern us coastal loamy sand. Soil Sci. 176:661-667.

Busscher WJ, Novak JM, Evans DE, Watts DW, Niandou MAS, Ahmedna M (2010). Influence of pecan biochar on physical properties of a norfolk loamy sand. Soil Sci. 175:10-14.

Chan KY, Van Zwieten L, Meszaros I, Downie A, Joseph S (2007). Assessing the agronomic values of contrasting char materials on an Australian hard setting soil. Paper presented in International Agrichar Initiative (IAI) 2007 Conference, 27 April–2 May 2007, Terrigal, New South Wales, Australia.

Chan KY, Xu Z (2009). Biochar: nutrient properties and their enhancement. In: Biochar for environmental management (J. Lehmann and S. Joseph eds.), Science and Technology, Earthscan, London. pp. 67-84.

Chan Y, Van Zwieten, L, Meszaros I, Downie A, Joseph S (2008). Using poultry litterbiochars as soil amendments. Austr. J. Soil Res. 46:437-444.

Chen HX, Du ZL, Guo W, Zhang QZ (2011). Effects of biochar amendment on cropland soil bulk density, cation exchange capacity, and particulate organic matter content in the North Chinaplain. Yingyong Shengtai Xuebao. 22:2930-2934.

Chmidt MWI, Skjemstad JO, Jager C (2002). Carbon isotope geochemistry and nanomorphology of soil black carbon: Black chernozemic soils in central Europe originate from ancient biomass burning, Global Biogeochemical Cycles 16:1123, doi: 10.1029/2002GB001939.

DeLuca TH, MacKenzie MD, Gundale MJ, Holben WE (2006). Wildfire-produced charcoal directly influences nitrogen cycling in forest ecosystems. Soil Sci. Soc. Am. J. 70:448-453.

EPA (2010). EPA Outlook. Emissions.[Online] 2010.[Cited: January 25, 2011.]http://www.state.gov/documents/organization/140007.pdf.

Ezawa T, Yamamoto K, Yoshida S (2002). Enhancement of the effectiveness ofindigenous arbuscular mycorrhizal fungi by inorganic soil amendments. Soil Sci. Plant Nutr. 48:897-e900.

Gaskin JW, Speir RA, Harris K, Das KC, Lee RD, Morris LA (2010). Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status, and yield. Agron. J. 102:623-633.

Glaser B, Haumaier L, Guggenberge G, Zech W (2001). The 'Terra Preta'phenomenon: a model for sustainable agriculture in the humid tropics. Naturwissenschaften 88:37-41.

Glaser B, Lehmann J, Zech W (2002). Ameliorating physical and chemical propertiesof highly weathered soils in the tropics with charcoal – A review. Biol. Fertil. Soils 35:219-230.

Haefele MS, Konboon Y, Wongboon W, Amarante S, Maarifat AA, Pfeiffer ME, Knoblauch C (2011). Effects and fate of biochar from rice residues in rice-based systems. Field Crops Res. 121:430-440.

Haefele SM (2008). Biochar in rice-based systems: characteristics and agronomic effects. Biochar: Sustainability and security in a changing climate. Proceedings of the 2nd International Biochar Initiative Conference, Newcastle 2008.

Hill RA, Harris A, Stewart A, Bolstridge N, McLean KL, Blakeley R (2007). Charcoal and selected beneficial microorganisms: plant trials and SEM observations. Proceedings of the International Agrichar Conference, Terrigal NSW Australia May 2007.

International Biochar Initiative (2010). Biochar Can Help Renew the Earth. International Biochar Initiative [Online] [Cited: October 2, 2010.]www.biochar-international.org.

Jones BEH, Haynes RJ, Phillips IR (2010). Effect of amendment of bauxite processing sand with organic materials on its chemical, physical and microbial properties. J. Environ. Manag. 91:2281-2288.

Krull ES, Swanston CW, Skjemstad JO, McGowan JA (2006). Importance of charcoal in determining the age and chemistry of organic carbon in surface soils. J. Geophys. Res. P. 111 G04001, doi:10.1029/2006JG000194.

Laird DA, Fleming P, Davis DD, Horton R, Wang BQ, Karlen DL (2010). Impact of biochar amendments on the quality of a typical mid western agricultural soil. Geoderma. 158:443-449.

Lal R (2004). Soil carbon sequestration impacts on global climate change and food security. Science 304:1623-1627.

Lehmann J (2007). A handful of carbon. Nature 447:143-144.

Lehmann J (2007). Bio-energy in the black. Frontiers in Ecology and the Environment 5, doi: 10.1890/060133.

Lehmann J, Joseph S (2009). Biochar for Environmental Management: Science and Technology.Earthscan, London.

Lehmann J, Kern D, German L, McCann J, Martins G, Moreira A (2003). Soil fertility and production potential. In: Amazonian Dark Earths: Origin, Properties, Management (eds. Lehmann, J., Kern, D.C., Glaser, B., and Woods W.I) Kluwer Academic Publishers, Netherlands, pp. 105-124.

Lehmann J, Pereia da Silva Jr J, Steiner C, Nehls T, Zech W, Glaser B (2003). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plan Soil 249:343-357.

Lehmann J, Rondon M (2006). Biochar soil management on highly weathered soils in the humid tropics. In: Biological Approaches to Sustainable Soil Systems (N. Uphoff et al.eds), Boca Raton, FL: CRC Press. pp. 517-530.

Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D (2011). Biochar effects on soil biota: A review. Soil Biol. Biochem. 43:1812-1836.

Major J (2013). Practical aspects of biochar application to tree crops. IBI Technical Bulletin#102, International Biochar Initiative (Accessed online at http://www.biocharinternational.org/sites/default/files/Technical%20Bulletin%20Biochar%20Tree%20 Planting.pdf).

Major J, Rondon M, Molina D, Riha SJ, Lehmann J (2010a). Maize yield and nutrition after 4 years of doing biochar application to a Colombian savanna oxisol. Plant Soil 333:117-128.

Major J, Steiner C, Downie A, Lehmann J (2009). Biochar effects on nutrient leaching. In: Biochar for environmental management(J. Lehmann and S. Joseph eds.), Science and Technology, Earthscan, London. pp. 271-287.

Mankasingh U, Choi PC, Ragnarsdottir V (2011). Biochar application in a tropical, agricultural region: A plot scale study in Tamil Nadu, India. Appl. Geochem. 26:S218-S221.

Mann CC (2002). The real dirt on rainforest fertility. Science 297:920-923.

Mukherjee A, Lal R (2013). Biochar Impacts on Soil Physical Properties and Greenhouse Gas Emissions Agronomy. 3:313-339.

Mukherjee A, Zimmerman AR, Harris WG (2011). Surface chemistry variations among a series of laboratory-produced biochars. Geoderma 2011. 163:247-255.

NASA (2010). The Carbon Cycle. NASA Earth Observatory.[Online] [Cited: November 4, 2010.]http://earthobservatory.nasa.gov/Features/CarbonCycle/.

Nguyen TH, Brown RA, Ball WP (2004). An evaluation of thermal resistance as a measure of black carbon content in diesel soot, wood char, and sediment. Org. Geochem. pp. 217-234.

Ogawa M (1994). Symbiosis of people and nature in the tropics. III. Tropical agricultureusing charcoal. Farming Jpn. 28:21e35.

Oguntunde PG, Fosu M, Ajayi AE, Van de Giesen N (2004). Effects of charcoal production on maize yield, chemical properties and texture of soil. Biol. Fertil. Soils 39:295-299.

Okimori Y, Ogawa M, Takahashi F (2003). Potential of CO_2 emission reductions by carbonizing biomass waste from industrial tree plantation in South Sumatra, Indonesia. Mitigation Adapt. Strateg. Global Change 8(3):261-280.

Pessenda LCR, Gouveia SEM, Aravena R (2001). Radiocarbon dating of total soil organic matter and humin fraction and its comparison with 14C ages of fossil charcoal. Radiocarbon 43:595-601.

Petersen JB, Neves EG, Heckenberger MJ (2001). Gift from the past: Terra preta and prehistoric Amerindian occupation in Amazonia. *In* Unknown Amazonia. Ed. C. McEwan. pp. 86-105. British Museum, London, UK. As referenced in Lehmann et al, 2002.

Purakayastha TJ (2010). Effect of biochar on yield of different crops.IARI. Annual Report2010-11, Indian Agricultural Research Institute, New Delhi-110012, India. P. 55.

Rogovska N, Laird D, Cruse R, Fleming P, Parkin T, Meek D (2011). Impact of biochar on manure carbon stabilization and greenhouse gas emissions. Soil Sci. Soc. Am. J. 75:871-879.

Rondon M, Lehmann J, Ramirez J, Hurtado M (2007). Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with biochar additions. Biol. Fertil. Soils 43:688-708.

Rutherford DW, Wershaw RL, Cox LG (2004). Changes in Composition and Porosity Occurring during the Thermal Degradation of Wood and Wood Components; 2004-5292; U.S. Department of the Interior, U.S. Geological Survey: Denver, CO, USA, P. 88.

Saito M, Marumoto T (2002). Inoculation with arbuscular mycorrhizal fungi: thestatus quo in Japan and the future prospects. Plant Soil 244:273-e279.

Schmidt MWI, Skjemstad JO, Gehrt E, Kögel-Knabner I (1999). Charred organic carbon in German chernozemic soils. Eur. J. Soil Sci. 50(2):351-365.

Skjemstad JO, Reicosky DC, Wilts AR, McGowan JA (2002). Charcoal carbon in U.S. agricultural soils. Soil Sci. Soc. Am. J. 66:1249-1255.

Sohi S, Krull E, Lopez-Capel E, Bol R (2010). A review of biochar and its use and function in soil. Adv. Agron. 105:47-82.

Spokas KA, Koskinen WC, Baker JM, Reicosk DC (2009). Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. Chemosphere 77:574-581.

Srinivasarao Ch, Gopinath KA, Venkatesh G, Dubey AK, Harsha W, Purakayastha TJ, Pathak H, Pramod Jha, Lakaria BL, Rajkhowa DJ, Sandip M, Jeyaraman S, Venkateswarlu B, Sikka AK (2013). Use of biochar for soil health management and greenhouse gas mitigation in India: Potential and constraints, Central Research Institute for Dryland Agriculture, Hyderabad, Andhra Pradesh. P. 51.

Steiner C (2008). Biochar Carbon Sequestration. University of Georgia, Biorefining and Carbon Cycling Program, Athens, GA 30602, USA.

Thies JE, Rillig M (2009). Characteristics of biochar: biological properties. In: Lehmann J, Joseph S (Eds.), Biochar for Environmental Management: Science and Technology. Earthscan, London, pp. 85-e105.

Tomaszewski JE, Werner D, Luthy RG (2007). Activated carbon amendment as a treatment for residual DDT in sediment from a superfund site in San Francisco Bay, Richmond, California, USA. Environ. Toxicol. Chem. 26(10):2143-2150.

Uzoma KC, Inoue M, Andry H, Zahoor A, Nishihara E (2011). Influence of biochar application on sandy soil hydraulic properties and nutrient retention. J. Food Agric. Environ. 9:1137-1143.

Verheijen F, Jeffery S, Bastos AC, Van der Velde M, Diafas I (2010). Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions. JRC Scient. Technical reports. pp. 1-166.

Winsley P (2007). Biochar and bioenergy production for climate change mitigation. New Zealand Sci. Rev. 64:5-10.

Woods W, McCann JM, Meyer DW (2000). Amazonian dark earth analysis: State of knowledge and directions for future research. *In* Papers and Proceedings of Geography Conferences, 23 Eds. F.A. School master and J. Clark. pp. 114-121. Tampa, FL. As referenced in Lehmann et al. (2002).

Yamamoto M, Okimori Y, Wibowo IF, Anshori S, Ogawa M (2006). Effects of the application of charred bark of *Acacia mangium* on the yield of maize, cowpea and peanut, and soil chemical properties in South Sumatra, Indonesia. Soil Sci. Plant Nutr. 52:489-495.

Zhanga A, Biana R, Pana G, Cuia L, Hussaina Q, Li L, Zhenga J, Zhenga J, Zhanga X, Hana, X, Yua X (2012). Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: A field study of 2 consecutive rice growing cycles. Field Crops Res. 127:153-160.

Zwieten VL, Kimber S, Morris S, Chan YK, Downie A, Rust J, Joseph S, Cowie A (2010). Effect of biochar from slow pyrolysisi of papermill waste on agronomic performance and soil fertility. Plant. Soil 327:235-246.