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Biochar: Impact on Climate Change and Soil Health

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Carbon sequestration is a geoengineering technique for the long-term storage of carbon dioxide or other forms of carbon, for the mitigation of global warming caused by the green house gases released due to human interference with the nature. Biochar, a product of pyrolysis process, can sequester carbon in the soil for hundreds to thousands of years because of its aromatic structure and long mean residence time in soil. Biochar is of great importance as it is believed to store carbon in the soil for long time potentially leading to a significant reduction in atmospheric greenhouse gas (GHG) levels. It is reported that by the year 2050 biochar will be able to remove around 1 Gt carbon from atmosphere per year. According to an estimate, the maximum sustainable technical potential of biochar, to mitigate climate change is a maximum of 1.8 Gt of CO_2 equivalent (incorporating methane and nitrous oxide too) per year without endangering food security, habitat or soil conservation. This may annually sequester an amount of C equivalent to 12% of current anthropogenic CO_2 emissions and also improve soil physico-chemical properties, crop yield and decreased dissipation rate of herbicide in soil.

Key words: Biochar, carbon sequestration, crop yield, soil property.

There is a large imbalance between carbon release to the atmosphere and carbon uptake by other compartments that leads to a continued increase in atmospheric CO_2 equivalent to a rate of 4.1×10^9 tons of carbon per year (IPCC, 2007). Thus, it should be of utmost importance to develop new methods to retain carbon in a stable form that can be stored outside the atmosphere for longer time periods. Biochar has received increasing attention due to its potential in increasing soil carbon storage, improving soil fertility, as well as maintaining the balance of soil ecosystems, and it could act as a kind of soil fertilizer or amendment (Glasser *et al*., 2001; Marris, 2006) . From biomass to humus a considerable fraction of carbon is lost by respiratory processes and also from humus to resistant soil carbon. Around 2-20% of the carbon added as above ground residues and root biomass enters the soil organic carbon (SOC) pool by humification. The rest is converted to CO_2 due to oxidation and furthermore the SOC pool is not inert to oxidation (Lal, 2004). Soils can only sequester additional carbon until the maximum soil carbon capacity or soil carbon saturation, is achieved, which requires a steady input of biomass and careful management practices. In contrast, about 50% of the carbon can be captured if biomass is converted to biochar. Conversion of biomass C to biochar C leads to sequestration of about 50% of the initial C compared to the low amounts retained after burning (3%) and biological decomposition (<10–20% after 5–10 years) is shown in Figure-1. Biochar yields more stable soil C than burning or direct land application of biomass. This efficiency of C conversion of biomass to bio-char is highly dependent on the type of feedstock, but is not significantly affected by the pyrolysis temperature (within 350° C–500°C common for pyrolysis) (Lehmann *et al*., 2006) (Figure 2).

Biochar can be produced by incomplete combustion from any biomass and it is a byproduct of the pyrolysis technology used for biofuel and bioenergy production. Biochar offer an opportunity to carbon sequestration, soil restoration, renewable energy production and waste reutilization. The chemical composition of biochar provides the principal explanation for its generally high level of stability and its reflected in broad terms by its elemental composition; highly aromatic structure and with very high C content.

Impact of biochar on Greenhouse Gas (GHG) emission from soil

Tim Lenton (2009) suggests that biochar is one of the best technological solutions to reducing CO_2 levels arguing that biochar has the potential to sequester almost 400 billion tonnes of carbon by 2100 and to lower atmospheric carbon dioxide concentrations by 37 parts per million.

Carbon savings potentially come both from carbon sequestered in soils for the long term and from avoided emissions (from substituting fossil fuels and fertilizer and through suppression of methane and nitrous oxide emissions that would otherwise occur as biomass decomposes)

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(Shackley *et al.,* 2009; Gaunt *et al*., 2009). The avoided emissions of green house gases are between 2 and 5 times greater when biochar is applied to agricultural land than used solely for fossil energy offsets. The potential revenues from carbon trading alone can justify optimizing pyrolysis to produce biochar for application to land (Gaunt *et al*. 2008).

Long-term stability may depend on the conditions of pyrolysis (Shackley *et al*., 2009), on the nature of 'background' soils and other factors (Lehmann *et al*., 2009). Scientists consider the size of contribution to greenhouse gas reductions that carbon sequestered in soils through biochar could make. As Smolker (2010) notes, pro biochar organizations such as the IBI(International Biochar Initiative) have created their platforms around highly ambitious-soundbites: that as a 'climate geo engineering technology' biochar can sequester gigaton (Gt,10^{12} t) of carbon out of the atmosphere, or even 'absorb all of the carbon emissions from fossil fuel burning that has occurred in the past 50 years'. Worldwide, total soil organic carbon is about twice the size of the global atmospheric carbon pool (Denman *et al.,* 2007).

The global soc pool in the upper 1 m for the world's soils contains 1220 Gt carbon, 1.5 times the total for the standing biomass (Sombroek *et al*., 1993). The total soil carbon (organic and inorganic) is 3.3 times the size of the atmospheric carbon pool (Lal, 2004). As most agricultural soils have lost 50 to 70% of their original SOC pool (Lal, 2003) they represent a considerable carbon sink if efforts are made to restore SOC, but also a huge source of GHG if soil management and deforestation rates are not changed. There is high agreement and much evidence that with current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades (25-90% between 2000 and 2030) (IPCC ,2007).

Amonette *et al*. (2007) found that biochar will be able to remove around 1 Gt C/year by 2050 (Shackley *et al.* 2009). A recent study (Woolf *et al*.,2010) incorporating a set of aggregate sustainability criteria estimates the 'maximum sustainable technical potential' of biochar to mitigate climate change as a maximum of 1.8 Gt of CO_2 equivalent (incorporating also methane and nitrous oxide) per year without endangering food security, habitat or soil conservation. This is equivalent to 12% of current anthropogenic CO_2 emissions annually. 1 Gt C/year has been deemed a cut-off point for approaches to greenhouse gas abatement to be taken seriously.

However, Lehmann *et al*. (2006) calculated that a change in land use from slash-and-burn to a biochar system, could offset 0.21 Pg C annually, and the use of agricultural and forest wastes could add a conservatively estimated 0.16 Pg per year. To offset the CO_2 emissions of an average Finn, 5 Mg biochar had to be applied to soil annually. Additionally, the stored C in form of biochar is not only a passive sink, but it can support plant growth, and with that, also the active uptake of C from the atmosphere. Also, the soil release of methane (CH_4), which has a 25 times greater global warming potential than CO_2 , can be reduced. This is primarily because of better aeration through the low density of biochar and thus lesser anaerobic conditions in soils (Lehmann *et al*, 2006). In 2004, CH_4 constituted around 14% of global GHG emissions, counted in CO_2 equivalents (CO_2e), and while some soils, especially under anaerobic conditions emit CH_4 globally, soils consume 5% of the annual load of CH_4 to the atmosphere, and are therefore a net sink. Biochar application to soils could increase this sink (Lehmann, 2009).

The global warming potential (GWP) of CO_2 is 1.0; by comparison the GWP of nitrous oxide is 310 (U.S. Environmental Protection Agency, 2002). Under anaerobic conditions N_2O is emitted from soil through denitrification. Life cycle assessments quantifying the benefits of biochar-based strategies for energy depend quite heavily on a decrease in the emission of N_2O that frequently follows the addition of mineral nitrogen fertiliser. Accounting for this effect makes a great difference to the overall analysis of how a biochar to soil strategy impacts on net greenhouse gas balance (Gaunt *et al*., 2008). The expectation for this effect relates to the general impact of biochar on retention of N in the soil in a way that also enhances crop nutrition. If the latter effect is surface -mediated, it seems unlikely that biochar confines N to a physical location – such as very small pores – where it is inaccessible to denitrifying bacteria. It may be that, instead, biochar inhibits the process by sequestering dissolved mineral N. Published data demonstrating the effect of biochar on suppression of N_2O remains very limited. In the most widely cited study to date (Yanai *et al*., 2007) 'bio-waste' charcoal was applied during a re-wetting of a former grassland soil, high in organic matter, in laboratory incubation (25°C). Nine-tenths of N_2O was suppressed in five-day emission episodes after wetting of soils to 73% and 78% water filled pore space. At a slightly higher water filled pore space (83%), charcoal had the opposite effect, increasing N_2O emission. The rate of biochar addition used in the study equated to a relatively high application rate of 180 t ha^{-1} in topsoil. These results indicate that the effect of biochar additions to soils on the N cycle depend greatly on the associated changes in soil hydrology and that threshold of water content effects on N_2O production may be very important and would have to be studied for a variety of soil-biochar-climate conditions.

However, the authors were able to exclude the possibility that the alkalinity of their charcoal, or its nutrient content, were significant factors in their observations. In an arable soil with much lower C content (2.2% C), Sohi (2008) has studied the effect of willow charcoal at a much lower rate of 10 t C ha^{-1} which were assessed during 20°C incubation of wet (70% water holding capacity) and re-wetted (from 20% water holding capacity) soils, with and without simultaneous addition of small amounts of inorganic N (equivalent 75 kg N ha^{-1}). A more modest suppression of 15% was proportionally similar for all treatments where there was any response at all (the already-wet soil did not emit significant N_2O). After six months, available soil N would have been largely consumed and the soils thoroughly equilibrated. A second inorganic N addition (without new charcoal) at this time showed no difference in N_2O emissions between amended and control soils. If any correspondence exists between the two studies it appears that not only is effect of biochar on N_2O likely to be non-linear with respect to rate of application (and significant but not large at realistic rates) but as authors of both papers conclude – the effects are likely to reflect the impacts of biochar on soil physical properties, particularly modification of pore-size distribution (of which water holding capacity is not a sensitive measure).

Measurements of N_2O emission in the field environment are difficult due to the transient and spatially variable nature of denitrification. The availability of sample biochar in the quantities required to assess its many effects in true randomized plot designs presents a major challenge. In tropical environments field experiments have been established in Columbia and in Kenya. Results from the Columbian trials indicate 80% suppression of N_2O emissions (Renner, 2007). A reduction in N_2O emissions of 50% in soybean plantations and 80% in grass stands was also reported (Rondon *et al*. 2005) . The authors hypothesised that the mechanism leading to this reduction in N_2O emissions was due to slower N cycling, possibly as a result of an increase in the C:N ratio. It is also possible that the N that exists within the biochar is not bioavailable when introduced to the soil as it is bound up in heterocyclic form.

Longevity of biochar

The longevity of biochar in ecosystem is an important aspect since only a long half life will ensure a relevant sequestration. The stability and recalcitrance of biochar against biotic and abiotic oxidation is as volatile as the properties and origin of biochar itself as discussed for black C sources (Schmidt and Noack, 2000; Masiello, 2004). Stability of black Carbon critically depends on production procedure. Kawamoto *et al*. (2005) found greater stability of charcoal produced at 400°C than 1000°C against oxidation by ozone, despite the fact that aromaticity of biochar significantly increased for biochars produced at 200°C or higher, while aromatic structure determined by ^{13}C nuclear magnetic resonance (NMR) increased at 200°C or higher. Zimmerman (2010) reported oak-derived biochar longevity increased with charring temperature from 250°C to 650°C, with half-life increasing from hundreds to millions of years. Using labeled ^{14}C, Kuzyakov *et al*. (2009) determined that the mean residence time of charred perennial ryegrass at 400°C for 13 h was around 200 years under controlled optimum conditions (20°C, 70% water holding capacity). Kuzyakov *et al.* (2009) also reported that yield decreased with increasing charring duration; however, this effect has received little attention. Most research only considers one charring duration, for example, 1 h by Keiluweit *et al*. (2010), 6 h by Chun *et al*. (2004) and 72 h by Zimmerman (2010) indicated the wide ranges. They hypothesized that charring duration will result in different biochar properties and soil effects, even if precursor properties and charring temperatures are identical.

C mineralization and biochar

Zimmerman *et al.* studied the interaction of pyrogenic C, soil organic matter (OM) and biochars. CO_2 evolution was measured for more than a year. The interactive effects of biochar addition to soil on CO_2 evolution (priming) were evaluated by comparing the additive CO_2 release expected from separate incubations of soil and biochar with that actually measured from corresponding biochar and soil mixtures. Priming direction (positive or negative for C mineralization stimulation or suppression, respectively) and magnitude varied with soil and biochar type, ranging from 52 to 89 % at the end of 1 year. In general, C mineralization was greater than expected (positive priming) for soils combined with biochars produced at low temperatures (250°C and 400°C) and from grasses, particularly during the early incubation stage (first 90 days) and in soils of lower organic C content. It contrast, C mineralization was generally less than expected (negative priming) for soils combined with biochars produced at high temperatures (525°C and 650°C) and from hard woods, particularly during the later incubation stage (250–500 days). Measurements of the stable isotopic signature of respired CO_2 indicated that for grass biochars at least, it was predominantly pyrogenic C mineralization that was stimulated during early incubation and soil C mineralization that was suppressed during later incubation stages. It is hypothesized that the presence of soil OM stimulated the co-mineralization of the more labile components of biochar over the short term. The data strongly suggests that over the long term, biochar– soil interaction will enhance soil C storage via the processes of OM sorption to biochar and physical protection.

Biochar and nutrient availability

Biochar provides a unique opportunity to improve soil fertility and nutrient use efficiency using locally available and renewable materials in a sustainable way (Lehmann and Joseph, 2009). Gundale and De Luca, (2006) demonstrated that biochar addition can change the soil nutrient availability by affecting physico -chemical properties. Additions of biochar to soil have shown definite increases in the availability of major cations (Table 1) and phosphorus as well as in total nitrogen concentrations (Glaser *et al*., 2002; Lehmann *et al*., 2003). Both CEC and pH are also frequently increased through such applications, by up to 40% of initial CEC and by one pH unit, respectively (Tryon, 1948; Mikan and Abrams, 1995; Topoliantz *et al*., 2002) . Higher nutrient availability for plants is the result of both the direct nutrient additions by the biochar and greater nutrient retention (Lehmann *et al*., 2003), The immediate beneficial effects of biochar additions for nutrient availability are largely due to higher potassium, phosphorus, and zinc availability, and to a lesser extent, calcium and copper (Lehmann *et al.,* 2003). Long-term benefits for nutrient availability include a greater stabilization of organic matter, concurrent slower nutrient release from added organic matter, and better retention of all cations due to a greater cation exchange capacity. The nutrient contents of biochar depend on the biomass input and the pyrolysis process. The ranges of N and P contents cover wider ranges than that of other organic fertilizers, like compost, or fermentation sludges (Lehmann, 2009). Because of its high surface area, and CEC, it can store a large amount of plant available nutrients, and the usually high pH promotes microbial activity. All this reduces leaching ion of nutrients, especially from synthetic fertilizers and thus prevents accumulations in groundwater and surface water reservoirs, which can be harmful to water quality and biological balances (i.e. eutrophication). This also means that less fertilizer is necessary to maintain soil productivity.

Table 1. Effect of biochar on nutrient availability of Ferralsol (after rice)

Treatment	H (H_2O)	C ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	C/N	P ($mg\ kg^{-1}$)	K	Ca	Mg	Al	CEC
						($mmol_c\ kg^{-1}$)				
Ferralsol+(After rice)	5.14	39.7	3.17	12.6	8.1	28.1	14.8	8.8	2.3	54.0
Ferralsol+Manure+Fertilizers	5.80	39.5	3.09	12.8	21.0	189.3	36.1	22.5	0.0	247.8
Ferralsol+Charcoal(or bichar)	5.89	159.4	3.95	40.4	10.5	258.3	17.1	9.7	0.4	285.5

(Fertilizers with TSP, KCl and Lime, Manure- addition of chicken manure, Charcoal-application at 20% weight) (Source: Lehmann, 2003)

Effects of biochar on ease of tillage and mechanical disturbance

If, as proposed, natural soil movement influences the breakdown of biochar through its reduction in size, then the rate of breakdown would be expected to be further accelerated by tillage. This is important to consider since tillage is perhaps envisaged as the primary means to incorporate biochar into soil. Quénéa (2006) reported a 60% decrease in both the soot and charcoal content of sandy soil under temperate forest during 22 years after conversion to intensive agriculture with annual tillage. The loss of total soil carbon over the same period was 30%, suggesting that biochar and charcoal were relatively less resistant to degradation than bulk soil organic matter after disturbance. However, the analysis of the charcoal data was based on larger hand-picked fragments and it seems likely that particles broken down into very fine fractions might have led to an overestimate of the loss. The initial soot content was very low. In contrast, 50 years of cropping and cultivation had no measurable change in the aromatic aryl carbon, taken to reflect charcoal, whilst other fractions declined rather rapidly (Skjemstad *et al*., 2001). More research may enable likely rates of breakdown to be predicted. If, for example, tillage was a key factor, maximum longevity of biochar, targeted by application on land where minimum tillage is practised. In no -till systems, biochar could be sequestered into soil through a one-time addition at the time of conversion from a tilled system.

In a recent study (Gaskin, 2007), moisture release curves were determined using samples of loamy sand soil from a field experiment where biochar had been added at rates up to 88 t ha^{-1}. For soils where biochar was added at rates up to 22 t ha^{-1} there was no difference compared to non-amended soil, but at the highest rate the difference was significant at water potentials in the range 0.01– 0.20 MPa. At the highest potential the mean volumetric water content impact was doubled by the biochar addition

Effect of biochar on soil properties

It has been reported that biochar not only mitigate the GHG levels but also improve soil chemical properties (e.g. pH, CEC cation) [(Liang *et al*., 2006), (Zimmerman *et al*., 2011)], physical properties (e.g. Soil water retention, hydraulic conductivity) (Oguntunde *et al.*, 2008; Asai *et al.*, 2009) and crop yields (Van Zwiten *et al*., 2010). Peng *et al.* (2011) evaluated the effect of biochars on soil properties and plant growth. Rice straw-derived biochars were charred at temperatures from 250°C to 450°C for between 2 and 8 h. The increase of temperature caused smaller, less structured (as viewed by SEM) fragments to form with less O, H and aliphatic C functional groups, but more aromatic C as indicated by infrared spectroscopy. The mean residence time of biochars under controlled conditions (25°C, 40% field capacity) was estimated from 244 to 1700 years, generally increasing with charring temperature and duration. Amendment of 1%

biochar increased pH by 0.1–0.46 ($P < 0.01$) and CEC by 3.9–17.3% ($P < 0.05$), but had no effect on aggregate stability. In pot trials maize biomass was increased by 64% (without NPK) to 146% (with NPK) due to the biochar amendment. The study emphasizes that amendment with biochar can improve soil fertility at least in the short term. Future studies focusing on the persistence of biochar fertility in the field must explicitly take into account additional factors to transfer this technology.

Agusalim Masulili (2010) studied the characteristics of biochar made from rice husk and its potential as a soil amendment in acid soils. Biochar was produced by pyrolysis; after which it was applied as a soil amendment. The soil was incubated for 30 days, and then it was planted with rice. For comparison, soil was applied with: rice straw, rice husk, rice husk ash, *Chromolaena odorata* biomass, and no soil amendment. The characteristics of rice husk biochar and other soil amendments are presented in Table 2. Application of biochar decreased soil bulk density, soil strength, exchangeable Al and soluble Fe and increased porosity, available soil water content, C-organic, soil pH, available P, CEC, exchangeable K and Ca (Table 3). Out of these improvements, only soil carbon, phosphorus, exchangeable Al, soluble Fe, and soil strength significantly influenced rice biomass. Beside this, many workers have been reported that the presence of bichar not only improve the physico-chemical properties of soil but also it increased crop yield. The response of crops to biochar application is summarized in Table 4.

Table 2. The characteristics of rice husk biochar and four other soil amendments

Properties	Rice straw	Rice husk	Rice husk ash	Rice husk biochar	*Chromolaena odorata*
Water content (%)	12.2	11.26	6.74	4.96	13.3
BD (Mg m^{-1})	-	-	0.96	0.84	-
pH	-	-	8.4	8.7	-
C (%)	33.4	43.77	5.09	18.72	28.55
P (%)	0.1	0.07	0.06	0.12	0.13
CEC (cmol kg^{-1})	-	-	6.7	17.57	-
K (%)	0.1	0.12	0.16	0.2	0.1
Ca (%)	0.12	0.27	0.33	0.41	0.18
Mg (%)	0.18	0.16	0.21	0.42	0.15
Na (%)	0.42	0.6	1.26	1.4	0.67

Table 3. Effect of rice husk biochar and other amendments on the chemical properties of acid sulfate soil of West Kalimantan, Indonesia

Soil amendments	pH	C (%)	Total P (%)	CEC (Cmol kg^{-1})	K	Ca	Mg (%)	Na	Al (%)	Fe (%)
Before experiment	3.75	0.78	0.25	6.84	0.19	0.34	3.31	0.31	3.31	3.04
Control	3.36	0.54	0.21	6.64	0.20	0.24	3.55	0.2	3.84	3.61
Rice straw	3.68	3.58	0.30	7.32	0.22	0.23	3.45	0.24	3.42	3.34
Rice husk	3.96	3.73	0.31	7.20	0.34	0.45	3.43	0.22	3.47	3.22
Rice husk ash	3.98	2.78	0.27	7.79	0.43	0.44	3.56	0.25	3.57	3.34
Rice husk biochar	4.40	4.09	0.32	8.03	0.51	0.44	3.57	0.32	2.96	3.10
Chromolaena	44.06	3.22	0.29	7.15	0.25	0.22	3.45	0.27	3.31	3.28

(Source: Masulili, 2010)

Biochar and microbial dynamics

Biochar affects microbial population and soil biogeochemistry. Warnock *et al.* summarized the effect of biochar on mycorrhizal associations. According to them, mycorrhizal fungi use biochar as a habitat. They further reported that ubiquitous symbioses association between biochar and mycorrhizal in terrestrial ecosystems, are potentially important in various ecosystem services provided by soils, contributing to sustainable plant production, ecosystem restoration, soil-carbon sequestration and mitigation of global climate changes. After reviewing other works, the experimental evidence for such biochar effects on mycorrhizal associations, yeast-derived biochar strongly increased the proportion of fungi in both arable and forest soils, which consequently turned out as the microbial group that mostly utilized this type of biochar. Glucose-derived biochar was used as carbon source for the build up of bacterial biomass mainly utilized by the gram-negative bacteria (Steinbeiss, 2009). The effect of biochar application on biological nitrogen fixation was studied by Rondon *et al.* 2007. They studied the potential, magnitude and causes of enhanced biological N_2 fixation (BNF) by common beans (*Phaseolus vulgaris* L.) through biochar additions. Biochar was added at 0, 30, 60, and 90 g kg^{-1} soil, and Biological nitrogen fixation was determined using the isotope dilution method after adding 15N-enriched ammonium sulphate to a Typic Haplustox cropped to a potentially nodulating bean variety in comparison to its non-nodulating isoline, both inoculated with effective Rhizobium strains. The proportion of fixed N increased from 50% without biochar additions to 72% with 90 g kg^{-1} biochar added. Although total N derived from the atmosphere (NdfA) was significantly increased by 49% and 78%

Table 4. Effect of biochar application on crop yield

Crops	Soil type	Biochar rate ($t\ ha^{-1}$)	Fertilizer rate ($kg\ ha^{-1}$)	Yield /biomass increase over control (%)	Additional information	Workers
Wheat	Ferrosol	10	1.25 g nutricote per 250 g soil (nutricote contain 15.2% N, 4.7%P, and 8.9% K)	+250	Similar response was observed for biomass yield of Soyabean and radish.Calcarosol amended with fertilizer and biochar however gave varied crop responses.	Zwieten *et al*. 2007
Radish	Alfisol	100	N (100)	+266 (biomass)	In the absence of nitrogen fertilizer, application of biochar did not increase the dry matter production of radish even at higher rate (100t/ha)	Chan *et al*. 2007; Chan *et al.* 2008
Rice	Inceptisol	30	Nil	+294	Sole effect of biochar	Noguera *et al.* 2010
	Oxisol	88	Nil	+800	Interaction effect of earthworm and biochar	
	Oxisol	88	NilN(40), P(20), K(20)	-21	Interaction effect of earthworm and biochar	
Maize	Oxisol	20	N(156-170), P(30-43) K(83-138)	+28(1st year) +30 (2nd year) +140 (3rd year)	In the first year after biochar application, no significant effect on crop yield was observed.	Major *et al*.2010
Rice	Ferralsol	11	N(30), P(35), K (50)	+29 (stover) +73 (grain)	While charcoal addition alone did not affect crop production, a synergistic effect occurred when both charcoal and inorganic fertilizer were applied.	Steiner *et al*.2008

with 30 and 60 g kg^{-1} biochar added to soil respectively, NdfA decreased to 30% above the control with 90 g kg^{-1} due to low total biomass production and N uptake. It was reported that the higher BNF with biochar additions was due to greater B and Mo availability. Increase in K, Ca and P availability, as well as higher pH and lower N

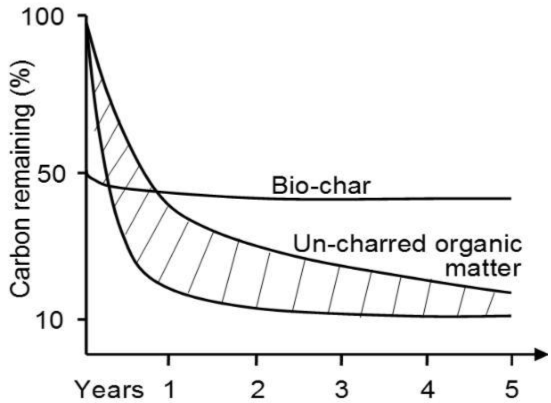

Fig 1. Carbon remaining after charring of organic matter in soil

availability and Al saturation, might also have contributed to a lesser extent. Enhanced mycorrhizal infections of roots did not contribute to better nutrient uptake and BNF. Bean yield increased by 46% and biomass production by 39% over the control at 30 and 60 g kg^{-1} biochar respectively. However, biomass production and total N uptake decreased when the biochar applications were increased to 90 g kg^{-1}. Results demonstrate the potential of biochar applications to improve N input into agro-ecosystems while pointing out the need for long-term field studies.

Impact of biochar on environment

Jones *et al*. (2011), evaluated the influence of biochar type, time after incorporation into soil, dose rate and particle size on the sorption, biodegradation and leaching of the herbicide simazine. Typical agronomic application rates of biochar (10– 100 t ha^{-1}) led to alterations in soil water herbicide concentrations, availability, transport and spatial heterogeneity. Overall, biochar suppressed simazine biodegradation and reduced simazine leaching. These responses were induced by a rapid and strong sorption of simazine to the biochar which limits its availability to microbial communities. Spatial imaging of ^{14}C-labeled simazine revealed concentrated hotspots of herbicide co-localized with biochar in the soil profile. The rate of simazine mineralization, amount of sorption and leaching was inversely correlated with biochar particle size. Biochar aged in the field for 2 years had the same effect as fresh biochar on the sorption and mineralization of simazine, suggesting that the effects of biochar on herbicide behavior may be long lasting. After reviewing other works they came to the conclusion, that biochar application to soil will reduce the dissipation of foliar applied pesticides decreasing the risk of environmental contamination and human exposure via transfer in the food chain, but may affect the efficacy of soil-applied herbicides.

Research Priorities and Future Challenges

Based on the results of this review, the following research priorities have been identified:

N Determine a predictive relationship for properties and qualities of biochar and its manufacture such that it can be optimised for use in soil.

Biochar performance currently, the predictive capacity for biochar ‘performance’ does not exist and how to best optimize the multiple useful characteristics as a function of feedstock has not been assessed. This is currently inhibiting the realization and application of this technology.

N Examine how the possibility of adverse impacts on the soil and atmosphere can be eliminated with certainty.

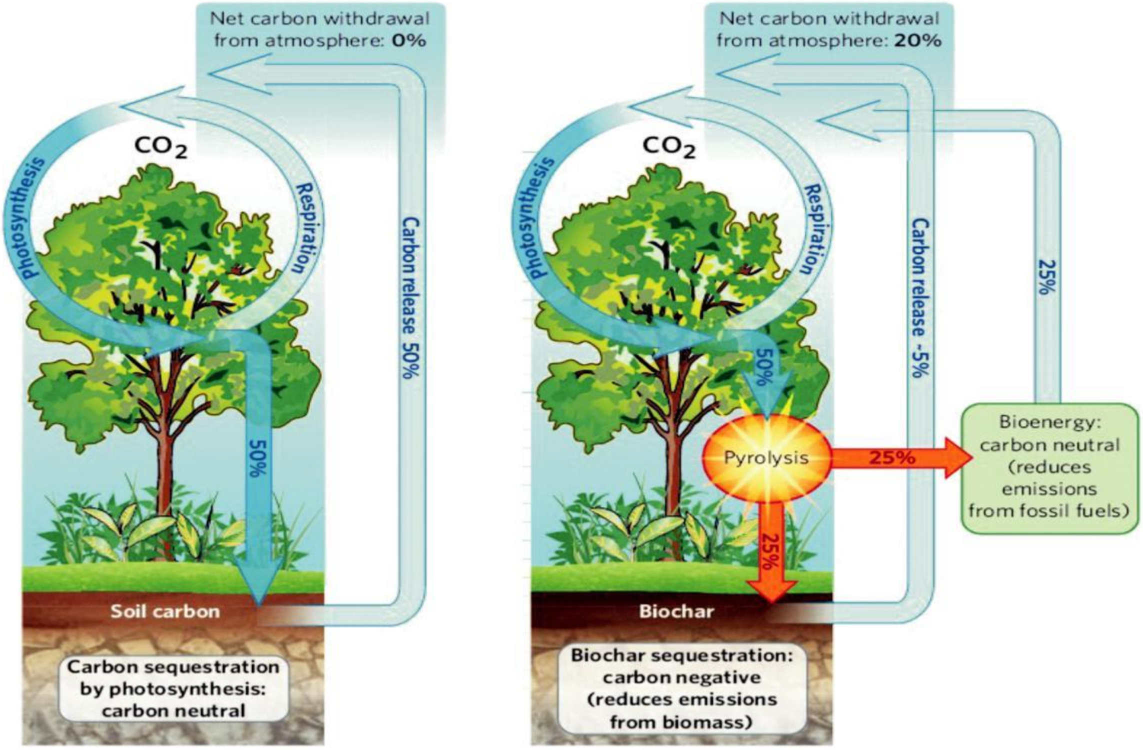

Fig. 2. Natural Carbon cycle (left) and carbon sequestration with Biochar (Right) (Source : Lehmann, 2007)

N Since the decomposition of biochar is extremely slow, what is the mechanism that operates for nutrients release/availability?

The physical, biological and chemical processes, that biochar may exert on microbial communities and their symbiotic interaction with plants, and possibly enhanced nutrient use efficiency, are not yet understood. The apparent contradiction between the high stability of biochar, soil organic matter accumulation and apparent enhancement of soil microbial activity needs to be resolved. Research in Japan and in Germany has indicated that biochar can complex the carbon from dead micro- organisms. Further research work is required to determine the conditions for such complex formation.

N What will be the impact of long-term application of biochar on crop yield and soil quality?

N Is there any proven technology for large-scale production of biochar?

N Model the impact of alternate bioenergy systems on the carbon cycle at the global scale,

N The optimal combination between different biochars and soils, the necessary feedstock and pyrolysis parameters to produce 'adequate' biochars,

N Classification for biochars, suitable soil application methods, and stability of biochar.

N Erosion, transport and fate

Conclusion

The stability of biochar in soils is relevant for GHG mitigation policies. So could the application to soils not only raise the income of farmers by increasing crop yields, but also by carbon trade. To make this possible, easy test methods for the biochar content in soils have to be developed. Of course, biochar had to be fully integrated into the carbon trade market, which is not only a scientific, but also a political effort. Since, there are contradictory reports on the beneficial use of biochar in agriculture, improve soil quality and climate change, research needs to provide answers that are applicable under diverse combinations of climate, agriculture and energy production systems. This requires a fundamental, mechanistic understanding of how biochar provides its unique functional characteristics, probably embodied in models, and would include its interactions with other living and nonliving components of soil. Besides this, to establish a large scale application for biochar, it is necessary to classify the product and there is need to monitor the changes in physical, chemical, hydrological and ecological settings of the soil under the long-term application of biochar. Also, the response of different crops to biochar application under the different agro-ecological regions must be ascertained

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