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Soil organic carbon, biochar, and applicable research results for increasing farm productivity in Western Australian agriculture

Mark P McHenry
School of Engineering and Energy
Murdoch University
90 South Street, Murdoch, Western Australia, 6150
+61 430 485 306
E-mail address: mpmchenry@gmail.com

Abstract
The conversion of vegetative biomass waste to biochar (biologically derived charcoal) is a source of carbon (C) that can be used to increase the level of soil organic carbon (SOC) in agricultural soils. This review collates available research into the effects of biologically derived C species with respect to the direct and indirect effects on agricultural productivity and their potential for use in Western Australian agricultural systems. There is a growing need to quantify the effect of biochar applications for agro-ecological purposes and to verify biosequestered C for climate change mitigation activities. This work provides quantitative assessment of safe biochar application rates and examines the present levels of scientific uncertainty surrounding the efficacy and reliability of applying biochar to soils in relation to crop productivity.

Keywords
Agriculture; biochar; carbon; soil; biosequestration.

Introduction
C in soil is known to have many benefits to the farmer in terms of increasing productivity and decreasing the need for some soil nutrient inputs (Bridle 2004; Lehmann et al. 2006). However, substantially increasing SOC levels by conventional agricultural management practices is a challenging and long-term undertaking, with no guarantee of success (Valzano et al. 2005). The maximum levels of SOC achievable in an agricultural region are known to
be heavily dependent on the previous land management practices, soil types and the climate (Grace et al. 2006). Biochar appears to be one promising source of C that farmers may use to increase the rate of SOC accrual, the final level of sequestered SOC, and the investment certainty of final SOC stocks in farm soils. Biochar structures range in complexity from graphite-like C to high molecular weight aromatic rings that persist in soil for thousands of years (Graetz and Skjemstad 2003; Ogawa 2007). Biochar can be produced from a variety of agricultural plant, animal and forestry wastes, or from dedicated sources of biomass (Ogawa 2007). Biochar is also a renewable product that can release significant amounts of useful gas and heat in its manufacture, and unlike fossil fuel energy generation and use, its proper production can result in virtually no ash waste or sulphur (S), nitrogen (N) and mercury (Hg) emissions (Antal and Gronli 2003). As plants remove atmospheric carbon dioxide (CO$_2$) through photosynthesis, the deliberate conversion of plants to long-lived C species may result in a new renewable energy industry while producing organic soil treatments, with a by-product of a long-term sink of atmospheric CO$_2$ (Graetz and Skjemstad 2003; Lehmann 2007) These considerable claims also come with equally sizable unknowns. There are large uncertainties surrounding the direct effects of biochar and other organic C species in soils and how they affect the surrounding ecology, their residence time in the soil, and whether it can be produced at a reasonable price. Utilising the agricultural industry’s technical capabilities and existing bodies of knowledge to sequester C can enable further research into developing a secure and verifiable C sink in agricultural land as another means to mitigate climate change in addition to increasing conventional primary production.

**Carbon, charcoal, char, black C and other soil C species**

C is continually in a state of flux between plants, animals, soils, microbial biomass, the atmosphere, rivers and oceans (Intergovernmental Panel on Climate Change 2000; Jones 2007). The amount of C stored within a living ecosystem is dependent on the climate, the quantity and quality of organic matter returned to the soil, and the soils ability to retain organic C (Grace et al. 2006). As around 80% of the terrestrial organic C stores are currently contained in soils, it seems reasonable that soil biosequestration receives significant attention (Intergovernmental Panel on Climate Change 2000). However, soil is not homogenous in its composition and exists as a mixture of plant and animal litter in various stages of decomposition, microbial biomass, its detritus, and biochar (Skjemstad et al. 1996; Skjemstad et al. 1998). To avoid confusion, this paper relates the nomenclature most commonly used for various C species.
Charcoal can be described as any black coloured plant derived solid material that has been produced by heating in a fire, which retains some recognisable structure of the parent material. Charcoal is commonly used to describe the mixture of residues including char, black carbon (BC) compounds that collectively contribute to the soil sink of biomass burning. The term “char”, is also used to refer to the diverse range of solid compounds formed when insufficient oxygen exists for fuels to completely combust (Jones et al. 1997; Glaser et al. 1998; Graetz and Skjemstad 2003). Ash, on the other hand is simply the mineral rich powdery residue remaining on site after complete combustion in a fire, while smoke contains visible gases, volatiles and particulates of variable structures that are released into the atmosphere. BC is a more general term used to describe a range of different C species and physical properties (Jones et al. 1997). More precise definitions of BC include references to aromatic and graphitic fractions, which are contained in charcoal, smoke and ash (Jones et al. 1997). Despite its variable definition, fractions described as BC are of interest to C modellers because of its chemistry and the graphite-like structures that confer low biodegradability (Glaser et al. 1998; Skjemstad et al. 1998; Graetz and Skjemstad 2003). Notwithstanding the remaining uncertainty about its longevity, BC has been found to be the oldest fraction of SOC, but its stability critically depends on its production procedure (Lehmann et al. 2006). For simplicity, the author will use the single term “biochar” to refer to charcoal, char and BC to distinguish between charcoal derived from living organisms, and charcoals produced from mineral or fossil fuels such as coal.

**Biosequestration and agricultural applications**

Across Australia soil C densities increase with increasing rainfall and decreasing temperature (Valzano et al. 2005). Organic C densities are determined by the balance of two biotic processes; the production of organic matter by land vegetation; and decomposition of organic matter by soil organisms. Each of these processes are strongly dependent on physical, chemical and biological factors such as the climate, soil water status, nutrient availability and plant growth patterns (Post et al. 2001). Biochar represents an average of approximately 25% of the total Australian SOC pool over all soil types. From the instant of formation, biochar is highly inert and newly formed biochar is a more stable C sink than other forms of newly formed soil C (Graetz and Skjemstad 2003). In all Australian soil types containing a large measurable inert pool of soil organic matter (SOM) over 1000 years of age, the pool is almost entirely biochar. While the turnover uncertainty of biochar will remain dependent on physical and chemical soil variables, for practical purposes, it is in the order of thousands of years, and thus can exert a large influence on the change in SOM.
Despite its predominantly high recalcitrance, biochar will eventually be mineralised to CO$_2$. (Skjemstad et al. 1998). Biochar particles are often very small and will migrate along with other soil particles during erosion events, or it can be blown away if it is not incorporated into the soil (Skjemstad et al. 1998; Marris 2006). At present, there is little scientific consensus on the stability of many of the biochar components under various oxidation and decomposition mechanisms, such as decomposition by micro-organisms and degradation by ultraviolet light (Graetz and Skjemstad 2003; Lehmann et al. 2006). Similarly, the half life of biochar is heavily dependent on the biomass used, the production conditions and the environment after pyrolysis (Lehmann 2007). There is also a scarcity of knowledge about the formation, movement, and oxidation of biochar in the soil environment, although the little information that is available has indicated that biochar concentrations are highest on alluvial deposits (Skjemstad et al. 1998). In the very near future, this information is likely to be available for assimilation into specific agricultural systems and soil types, with a confidence similar to existing soil amendment activities.

**Biochar application rates and safety concerns**

There are areas that contain extremely high levels of biochar residues and have excellent agricultural productivity. Certain “dark earths” in the Amazonian basin have received large amounts of charred materials as the result of humans burning biomass before the arrival of Europeans, with some areas containing 250 tonnes of carbon per hectare (tC ha$^{-1}$) per metre of depth. This far exceeds the potential for C sequestration even if bare soil could be restocked to primary forest containing about 110 tC ha$^{-1}$ in the same region (Sombroek et al. 2003). Less is known about the potential levels of biochar that can be safely and productively added to Australian soil types. The burning of biomass in Australia, whether measured by area or biomass consumed, is an integral part of contemporary and traditional land management (Graetz and Skjemstad 2003). However, the levels of metal contaminants derived from the biomass feedstock often limit the amount of biochar that can be safely applied to soils. The biochar application required to exceed the contaminant-limited
biosolids application rate of copper (Cu), (based on the maximum allowable solid contaminant concentrations) is in excess of 38 tonnes per hectare (t ha\(^{-1}\)) on a typical lateritic soil (Department of Agriculture Western Australia et al. 2002; Bridle 2004). Other metals of concern, such as Cadmium (Cd), would require a biochar application of 250 t ha\(^{-1}\). Other metals such as zinc (Zn), mercury (Hg), arsenic (As), lead (Pb) and nickel (Ni) require much larger applications (Bridle 2004). Based on a typical broad application rates to provide total phosphorus (P) loadings equivalent to 100 kg ha\(^{-1}\) of Superphosphate (i.e. 9 kg P ha\(^{-1}\)), land application rates of only 160 kg ha\(^{-1}\) of biochar would be required. This is well below the maximum allowable soil contaminant concentration loading (Bridle 2004). These approximate application rates suggest that there is comparably low risk in contaminating soils when applying biochar to pasture soils in a similar manner to conventional soil additives.

These application rates for soils shows the enormous potential for biosequestration, however, applying relatively large amounts of biochar to agricultural soils entails significant practical and technical barriers. One such barrier is the safe production and use of biochar for agricultural purposes. In terms of handling risk, some biochars contain toxic materials that are controlled by permissible exposure limit standards in some countries. The levels of these toxic materials in the biochar is highly dependent on both the biomass feedstock and its processing environment, so there is no straightforward “permissible exposure limit” available for biochar as yet (Blackwell et al. 2009). Other risks associated with biochar are related to its flammable characteristics. The dust of biochar can spontaneously combust and poses a minor risk when handled, stored or transported when in enclosed spaces. This risk is similar to other dusts that can become combustible hazards, such as some metals, foods, coal, plastics, and woods (Joseph 2007). The level of fire hazard is highly dependent on the content of volatiles in the biochar product, deriving from the temperature of pyrolysis, duration of pyrolysis, chemical characteristics of the original biomass, and many other parameters (Blackwell et al. 2009). The development of a secure and responsible biochar industry will require improvements in the low level of scientific certainty and awareness of safe methods of handling, storage and application of biochar. In addition to safety procedures and guidelines, producing or purchasing biochar to supplement or displace an equivalent amount of traditional soil additives will need to be justified economically and be suitable for application with existing agricultural technologies. Notwithstanding these issues, the greater scientific challenge is determining the efficacy of biochar C species in a range of specific agricultural production systems, in both the long and the short-term.
**Biochar farm soil nutrient levels and waste recovery**

The amount of SOC stored within an ecosystem is dependent on temperature, precipitation, the quality and quantity or organic matter returned to soil, and the soils ability to retain organic C (Grace et al. 2006). Changes in soil and vegetation management can also impact strongly on the rates of C accumulation and loss in soil, even over short periods of time (Post et al. 2001). At the farm-scale, soil C density is affected by the interaction of climate, soil type, tillage, stubble management and plant growth patterns. In Australia, highly productive pastures have the highest C densities at the 0-30 cm depth, followed by forest soils, grazed pastures and cropped soils (Valzano et al. 2005). Many agricultural systems that have been managed to enhance organic matter show less long-term yield variability and are less sensitive to drought that conventionally managed systems (Lotter et al. 2003; Lugato et al. 2007). The advantage of biochar over other forms of SOC in terms of increasing C density is that biochar storage levels are less dependent on soil management practices and soil properties (Lehmann 2007).

Biochar applications have the potential to absorb pollution by adsorbing ammonia to reduce ammonia volatilisation in agricultural soils (Lehmann et al. 2006). Biological immobilisation of inorganic N also aids in retaining N, adsors dissolved ammonium, nitrates, P, as well as hydrophobic organic pollutants such as polycyclic aromatic hydrocarbons (Beaton et al. 1960; Gustafsson et al. 1997; Accardi-Dey and Gschwend 2002; Lehmann et al. 2003; Bridle 2004; Mizuta et al. 2004). Little research exists at present weather this adsorption behaviour would translate into a significant reduction of widespread environmental pollution of ground and surface waters by fertilisers or other pollutants in agricultural catchments (Lehmann et al. 2006; Lehmann 2007). Nutrient research by Laird et al (2008) with soil amendments of 0, 5, 10 and 20 g of biochar kg$^{-1}$ of soil, in combination with dried pig manure (0, 5 g kg$^{-1}$ of soil), found higher amounts of NO$_3$ leached when amended with 20 g kg$^{-1}$ biochar relative to soils containing 0, 5, or 10 g kg$^{-1}$ biochar. This suggests that biochar enhances mineralisation of SOM. This was in contrast to soils with the manure that recorded 7 to 10% more NO$_3$ leaching from the 0 g kg$^{-1}$ biochar soils, than the 5, 10 or 20 g kg$^{-1}$ biochar emended soils. The researchers accounted for this result by suggesting the readily mineralisable N containing organic compounds in the manure was adsorbed and stabilised by the biochar. The research also found biochar additions also substantially reduced leaching of total P due to manure addition P adsorption (Laird et al. 2008).
In general, biochar applications are considered soil conditioners rather than fertilisers due to its often low-nutrient content (Steiner et al. 2007). Biochars act as soil conditioners to enhance plant growth by supplying and retaining nutrients and improving soil physical and biological properties. Nonetheless, biochar can be applied to agricultural soils as a form of fertiliser to improve yields on acid soils where nutrient resources are scarce. Biochar may also be returned to its place of origin to return nutrients, improve nutrient retention to assist the sustainability of agricultural systems (Lehmann et al. 2006). Improving the low nutrient content of most biochars is achieved by simply introducing nutrients or by producing the biochar using feedstocks with high nutrient contents, such as manures. Due to the recent price increases of inorganic fertilisers used in Western Australian agriculture, there has been movement towards using liquid and solid wastes to fertilise some crops. A report by Bridle (2004) on using pyrolysis to recover energy and nutrients from biomass waste included laboratory soil incubation studies using biochar from a Western Australian demonstration plant over an eight-week period. The data from the laboratory study suggested that biochar would provide a source of P for plant growth and could have applications on soils as a slow release form of P. This may be more useful in sandy soils where P leaches from the surface into groundwater. Bridle’s research suggested that applying biochar to agricultural land would minimise the risk of nitrate leaching, as the levels of nitrate and ammonium did not increase in soil for 56 days after application. The soil incubation study revealed that biochar would not initially increase soil mineral N levels, as occurs with other biosolid applications, although soil bicarbonate availability and P levels would increase slowly. It showed the P in the biochar was plant-available but only 55% of the N was retained in the biochar, which was insoluble in water. Therefore, there is potential to use pyrolysis as an effective means to recover and reuse both energy and some minerals present in biosolids. The high temperatures in the biomass to biochar conversion process can also be used to minimise odours, the potential of contamination by organics or pathogens and other negative aspects associated with current biosolids-to-land activities (Bridle 2004).

**Reviewed yield results**

Notwithstanding the various unknowns in biochar application, most of the results of deliberate biochar additions to soil showed increasing crop yields with increasing additions up to very high loadings of 140 tC ha$^{-1}$ (Lehmann and Rondon 2006). Some soils with very high biochar concentrations (close to 40% of total SOC) have been found to increase soil productivity (Lehmann et al. 2006). However, it appears that many crops respond positively to biochar additions up to 50 tC ha$^{-1}$ and may show growth reductions only at very high applications. For most plant species and soil conditions this maximum was not reached even
with 140 tC ha\(^{-1}\) (Lehmann et al. 2006). Refining the resolution of biochar research to assess the viability biochar additions to both sequester C and increase productivity for specific crops and agricultural systems is a growing field of endeavour (Byrne et al. 2007).

Glaser et al (2002) undertook experiments in the tropics to compare mineral fertilisers, manure and biochar applications on soil types in highly weathered soils. The researchers found that biochar additions equivalent to approximately 60 tC ha\(^{-1}\) in a Ferralsol soil increased rice crop biomass by 17% as compared to control crops that received no biochar (Glaser et al. 2002). In experiments with oats, Glaser et al. (2002) found that applications of manure and biochar were inferior to manure alone in the first growing season. In the second growing season oat yields of the manure only plots decreased more dramatically than the manure and biochar plots. This indicates that biochar additions have positive benefits in the long term, while biochar alone was not capable of maintaining high crop yields (Glaser et al. 2002). A sorghum crop showed biochar only additions did not increase biomass yields and performed the same as control plots. However plots that received biochar, NPK fertiliser and lime applications performed significantly better than plots that only received NPK and lime (Glaser et al. 2002). This strengthens the hypothesis that biochar applications assist in the retention of nutrients in the soil. The study concluded with a statement alluding to the possibility of a positive feedback loop with the increased plant productivity from vegetation conversion leading to increased soil fertility and therefore more vegetative growth, assuming no nutrient limitations occurred (Glaser et al. 2002).

Rondon et al. (2007) grew common beans (*Phaseolus vulgaris L.*) with biochar additions of 30, 60 and 90 g kg\(^{-1}\) of biochar at an equivalent rate of 60.75, 121.5, and 182.25 t ha\(^{-1}\) (assuming a plough depth of 15 cm and an average bulk density of 1.35 t m\(^{-3}\)). N-fixing bean yields increased 46% over the control group at 90 g kg\(^{-1}\), with no change in total biomass production. At the 60 g kg\(^{-1}\) rate, the biomass production increased by 39% over the control, while there was little difference between the yield and the control. Interestingly, soil N uptake by the N-fixing beans decreased by 14, 17, and 50% with 30, 60, and 90 g kg\(^{-1}\) of biochar was applied with corresponding C/N ratios increasing from 16 to 23.7, 28, and 35, respectively. This research suggests a strong role for biochar additions reducing N fertiliser requirements and further research requirements to understand the mechanisms at play (Rondon et al. 2007).
Recent Western Australian research on improving wheat production with deep-banded biochar from Mallee (low-growing, multi-stemmed species of Eucalypt) trees found grain yield improvements from grain survival during periods of stress from drought (Blackwell et al. 2007). Three trials sites in sandy clay and sand in low rainfall regions (around 600 mm annually) in rural Western Australian towns (Kalannie and Pindar), were used to assess the efficacy of biochar in combination with soluble and mineral fertilisers. The biochar was applied at rates between 0 and 6 t ha$^{-1}$, with between 30 and 110 kg ha$^{-1}$ of soluble fertiliser or 100 kg ha$^{-1}$ of mineral fertiliser. Blackwell et al. (2007) found that biochar banded at 6 t ha$^{-1}$ with 30 kg ha$^{-1}$ of soluble fertiliser improved crop yield over control plots with no biochar by around 340 kg ha$^{-1}$ (18%). Biochar applications at 1.5, 3 and 6 t ha$^{-1}$ in combination with mineral fertiliser and arbuscular micorrhiza inoculated grain seed resulted in improved grain yield by around 640 kg ha$^{-1}$ (46%). The research found that biochar additions alone had only small increases on grain yield at the two Kalannie sites (between 6 and 9%), when using recommended rates of soluble fertiliser, with 1.5 and 6 t of biochar respectively. When using half the recommended rate of soluble fertiliser in combination with 6 t ha$^{-1}$ of biochar, the wheat trial achieved 18% grain yield improvement above control yields (Blackwell et al. 2007). The researchers concluded that the increased yield, more plant biomass and higher tissue concentrations were associated with additional early uptake of nutrients.

The uses of biochar may not be limited to only increasing crop productivity and C sequestration as it also suppresses the production of other important agricultural greenhouse emissions from soils. Rondon et al. (2005) found a near complete suppression of methane at biochar additions of 30 g kg$^{-1}$ of soil and a significant reduction of nitrous oxide emissions depending on the crop type (Rondon et al. 2005; Lehmann et al. 2006). This was hypothesised to be due to the improved aeration of soils which reduced the occurrence of anaerobic conditions, and possibly a slowing of the N cycle by an increased C to N soil ratio (Lehmann et al. 2006). However, the combination of returning biochars with high C to N ratios and abiotic buffering of mineral N in some situations may lead to low N availability to crops (Lehmann and Rondon 2006). However, a Swedish experiment by Berglund et al. (2004) showed the addition of activated C biochar to a pine forest increased soil nitrification. N issues may be able to be overcome by the addition of N to biochars, or sufficiently low levels of biochar could be added to soils to allow sufficient N accumulation (Lehmann et al. 2006). Legume yields also known to increase after the application of biochar by reducing the soil acidity and levels of exchangeable aluminium (Al), but at the same time increased the calcium and magnesium availability to plants. Al concentrations in soils are also known to be
significantly lower when mineral fertilisers are applied with biochar, relative to applying the fertiliser alone (Steiner et al. 2007).

Conclusion

The addition of biochar to soil seems to perform many functions including: increasing the ability of soils to retain cations in a plant available form; minimising the possibility of contamination by organics or pathogens from biomass application; provides a slow release source of P and N; minimises the risk of nitrate leaching; assists in the retention of trace elements in the soil; reduces soil acidity; decreases levels of exchangeable Al, and; can suppress the production of some important agricultural greenhouse emissions. In terms of mitigation options for climate change, biochar seems to have the potential to greatly reduce mitigation costs if the C species produced has a residence time sufficient to become a viable longer-term C sink.

While noting the lack of exhaustive scientific research supporting many of these assertions, this impressive list of effects gives a strong stimulus for continued research in the specific effects of biochar applications on particular crops in a range of agricultural systems and climates. There is a real need for development and extension to reduce the investment risk associated with industrial-scale biochar use to an acceptable level to ensure industry and governments endorse sustainable production and use for conventional farming and climate change mitigation and adaptation.

References

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Department of Agriculture Western Australia, Department of Conservation and Land Management, Forest Products Commission et al (2002) Greenhouse, land management and carbon sequestration in Western Australia. In: Department of Agriculture Chief Executive Officer (Ed). Western Australian Department of Agriculture, Perth


Graetz RD, Skjemstad JO (2003) The charcoal sink of biomass burning on the Australian continent. CSIRO Atmospheric Research Technical paper No. 64. CSIRO, Aspendale


Ogawa M (2007) Introduction to the pioneer works of charcoal uses in agriculture, forestry and others in Japan. Osaka
Figure 1. Biochar occurs naturally in the Australian SOC pool and can be readily seen in relatively large pieces. This photo shows an approximately 60 year old decomposing Australian native hardwood log with a large piece of biochar remaining on its surface at the tip of the pencil. The biochar was produced from the log incompletely burning in a forest fire many decades ago. Note how the biochar remains relatively in-tact whilst the remaining log degrades around and under it.
Table 1. Selected biochar and agricultural crop yield research results with potential relevance to WA agriculture.

<table>
<thead>
<tr>
<th>Study</th>
<th>Biochar application</th>
<th>Soil type</th>
<th>Crop</th>
<th>Results Vs. Controls</th>
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<tbody>
<tr>
<td>Blackwell et al (2007)</td>
<td>Banding 6 t in 10cm rows 60 cm apart (equiv. to 1 t ha$^{-1}$) with 30 kg ha$^{-1}$ of soluble fertiliser</td>
<td>Haplic Xerosol (sandy loam)</td>
<td>Wheat</td>
<td>Increased yield by 340 kg ha$^{-1}$ (18%).</td>
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<tr>
<td>Blackwell et al (2007)</td>
<td>Banded at 1.5, 3, 6t ha$^{-1}$ with 100 kg ha$^{-1}$ of mineral fertiliser inoculated with arbuscular mycorrhizal fungi</td>
<td>Haplic Xerosol (sandy loam)</td>
<td>Wheat</td>
<td>Increased yield by around 640 kg ha$^{-1}$ (46%).</td>
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<td>Glaser et al (2002)</td>
<td>57-66 tC ha$^{-1}$</td>
<td>Xanthic Ferralsol</td>
<td>Rice</td>
<td>Rice biomass increased up 17%, due to improved P and K nutrition</td>
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<tr>
<td>Glaser et al (2002)</td>
<td>Sand &amp; biochar (5% w/w); Sand &amp; biochar (5% w/w) &amp; NPK; Sand &amp; biochar (2.5% w/w) &amp; compost (2.5% w/w); Sand &amp; NPK; Sand &amp; compost (5% w/w)</td>
<td>Sand</td>
<td>Oats</td>
<td>In both growing seasons the compost and NPK treatment produced a superior crop height and yield than biochar alone, or the biochar combined with compost and NPK soils. The biochar and compost amended oat height and yields decreased less in the second growing season, although was still slightly lower than the compost and NPK amendment. This research explicitly showed the inability of biochar alone in sand to achieve or sustain high crop yields. The results also show a decrease of both height and yield in the second year of the NPK amended sand relative to the control sand.</td>
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<td>Glaser et al (2002)</td>
<td>Biochar (12.5%), lime (12.5%) and NPK in soil</td>
<td>Xanthic Ferralsol</td>
<td>Sorghum</td>
<td>Significant increase in sorghum plants during the second growing season following a soil amendment experiment season with rice, confirming the nutrient retention ability of biochar. This combination amendment performed on a par with the chicken manure only, lime only (25%), lime (25%) with NPK amendments.</td>
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<tr>
<td>Study (cont.)</td>
<td>Biochar application</td>
<td>Soil type</td>
<td>Crop</td>
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<td>Rondon et al (2005)</td>
<td>0, 7.5, 15 &amp; 30 g kg⁻¹ of soil</td>
<td>Acidic and low nutrient Haplustox</td>
<td>Forage grass <em>(Brachiaria humidicola)</em></td>
<td>A near complete suppression of CH₄ and a significant reduction (80%) of N₂O emissions from soils in greenhouse experiments with no statistical tropical forage grass biomass change at the 30 g kg⁻¹ application rate.</td>
</tr>
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<td>Rondon et al (2005)</td>
<td>0, 7.5, 15 &amp; 30 g kg⁻¹ of soil</td>
<td>Acidic and low nutrient Haplustox</td>
<td>Soybean <em>(Glycine max, cult. ICA 6)</em></td>
<td>Increase in soybean biomass of around 50% at the 30 g kg⁻¹ application rate in greenhouse experiments, with a near zero CH₄ emissions, although no significant reduction in N₂O emissions.</td>
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<td>Steiner et al (2007)</td>
<td>11 Mg biochar ha⁻¹</td>
<td>Xanthic Ferralsol</td>
<td>Rice &amp; Sorghum</td>
<td>Increased pH, Ca &amp; Mg availability, decreased exchangeable Al and doubled crop yields.</td>
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<td>Steiner et al (2007)</td>
<td>11 Mg biochar ha⁻¹</td>
<td>Xanthic Ferralsol</td>
<td>Rice &amp; Sorghum</td>
<td>Soils with biochar lost only 11% of their initial soil C and 13% of total N, in comparison to 23% of C and 23% of N on plots without biochar.</td>
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<td>Study Reference</td>
<td>Biochar Application</td>
<td>Soil Type</td>
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<td>Findings</td>
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<td>11 Mg biochar ha⁻¹</td>
<td>Xanthic</td>
<td>Rice &amp; Sorghum</td>
<td>Plots receiving just charcoal or charcoal plus mineral fertiliser (without compost) lost only 4 and 8% of their soil C content, regardless of mineral fertilization.</td>
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<td>Tagoe et al (2008)</td>
<td>50 &amp; 100 kg N ha⁻¹</td>
<td>-</td>
<td>Soybean</td>
<td>Carbonized chicken manure increased soybean seed yield by 23 % and 43 % for the 50 and 100 kg N ha⁻¹ rates respectively. Dried chicken manure application increased soybean seed yield by 7 % and 30 % for the 50 and 100 kg N ha⁻¹ rates, respectively. The difference was attributed to higher P availability.</td>
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<td>Unger and Killorn (2008)</td>
<td>0, 4.5, 18 t ha⁻¹ biochar with 0, 56, 112, 224 kg N ha⁻¹ (urea)</td>
<td>-</td>
<td>Maize</td>
<td>In the first year there was no statistical difference with the biochar additions.</td>
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<td>Yeboah et al (2009)</td>
<td>- 3 t ha⁻¹ biochar with 120 kg N ha⁻¹ (urea)</td>
<td>Chromic Lixisol &amp; Ferric Acrisol</td>
<td>Maize</td>
<td>Addition of biochar with inorganic N however, resulted in positive N use efficiency (NUE) (%) in the sandy loam, but exhibited a negative NUE% at the silt loam site.</td>
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