Chapter 3: Does the science support the claims?

Part 1: Biochar and the carbon cycle

The UK Biochar Research Centre describes the key premise of biochar being promoted for climate change mitigation: "Annually, plants draw down 15-20 times the amount of CO2 emitted from fossil fuels…Since the plant biomass is relatively constant globally, the magnitude of new plant growth must be approximately matched by harvests, litterfall, etc. Intercepting and stabilizing plant biomass production reduces the return of carbon to the atmosphere, with a relative reduction in atmospheric CO2."[i]

Plants contain over 80% as much carbon as the atmosphere, soils 2.1 times as much[ii]. However, ecosystems, including soils, tend to recycle carbon as they recycle nitrogen and other nutrients. This is not the full story: In recent decades, land-based ecosystems have drawn down or sequestered more than a quarter of all the carbon emitted annually from fossil fuel burning and deforestation, while oceans have been absorbing as much carbon again. This is a direct response to climate change, yet as the climate continues to warm rapidly and ecosystems are being degraded and destroyed further, the biosphere might well in the future release more carbon than it draws down, further accelerating warming[iii]. The idea behind biochar is to reduce the amount of carbon that is naturally being recycled by plants and soils and instead to 'stabilize' it by turning wood, grasses, crop residues and other biomass into charcoal. A proportion of the carbon in plants would be turned into 'additional' carbon in soils and new crops, trees and other plants would then further capture more carbon dioxide (CO2) from the atmosphere before once again being removed and charred. Over time, this was reduce the amount of CO2 that would otherwise have been in the atmosphere and thus reduce global warming. An additional benefit would come from using the energy released during charring (pyrolysis) to replace some fossil fuels that would otherwise have been burnt.

As the UK Biochar Research Centre admits, this would need to be done successfully on a very large scale to make any difference to the climate: "On a scale of millions of tonnes needs to occur, preferably hundreds of millions of tonnes"; others have spoken of billions of tonnes.

The rationale behind biochar for climate change mitigation is thus fundamentally about geo-engineering: It is about manipulating the carbon cycle to 'improve' it by 'stabilizing' large amounts of plant carbon in soils rather than allowing them to be naturally recycled.

For this scheme to work, three conditions would need to be fulfilled:

First, one would need to be sure that a large proportion of the carbon contained in biochar will in fact be stable over long periods.

Second, adding biochar to soils would need to lead to an overall increase in soil carbon. This means it must not cause other soil carbon to be emitted as CO2, at least not a significant proportion of it.

Finally, charring hundreds of millions (or billions) or tonnes of biomass would need to be done without, either directly or indirectly, resulting in more carbon emissions than those 'saved' through biochar. Not only would there have to be a way of avoiding deforestation, wetland or grassland destruction for biochar, but even if residues were used, the carbon 'gains' from turning them into biochar would have to be greater than those from leaving them in the soil would have been.

Even if the biochar 'carbon balance' was indeed positive, one would still have to consider other climate impacts, such as biochar's likely effects on the earth's reflectivity or 'albedo', which also plays an important role in climate change (discussed below).

To further investigate these assumptions, we must first return to the question "what is biochar?" According to Kurt Spokas, a soil scientist with the US Department of Agriculture[iv] biochar, though produced mainly for the purpose of carbon sequestration, "covers the range of black carbon forms". Hence, in order to understand how biochar affects soils, including soil carbon and soil fertility, we need to understand what black carbon is - or rather what the 'range of black carbon forms' are.

What is black carbon and how do different forms of black carbon vary?

Black carbon is generally defined as 'the product of incomplete combustion'. When wood or other biomass is exposed to high temperatures, whether in a wildfire or a charcoal kiln, etc., it undergoes various and complex chemical transformations, starting with hydrogen and oxygen and other volatile compounds being released. If the biomass does not burn completely to ash during a fire, or if the process is controlled and oxygen is limited, then char or charcoal will remain at the end. Furthermore, particularly during an open fire, some of the carbon particles, rather than all turning into carbon dioxide, will instead be released as soot. All of the carbon-rich compounds, ranging from slightly charred logs to charcoal to soot are called black carbon. Yet chemically, they are extremely different. For example, partially charred wood will have a chemical structure similar to the original wood and its particles will be fairly large, at least initially. At the other extreme, soot particles do not resemble the original biomass (or fossil fuels) which they came from in any way - they are virtually identical, no matter what source of biochar they are derived from, and very tiny. Many soil scientists speak of a 'black carbon continuum', ranging from partially charred biomass to soot[v]. In between the two extremes, one can find a whole range of different forms of black carbon, with different chemical properties and components, different molecule structures, differences including in how stable they are and in their ability to adsorb (see footnote[1]) for example nutrients, water or microbes.

This background is essential for understanding the debates about biochar because it explains why, as Kurt Spokas has illustrated, "biochar is not a description of a material with one distinct structure of chemical compositions". Even if one was to only look at studies about biochar produced through modern pyrolysis - which would mean ignoring the vast majority of studies on which claims about biochar are based - one would still be looking at very diverse materials. In modern pyrolysis, temperatures can range from 400°C or even less to as high as 1000°C (more commonly up to 800°C), and biomass can be exposed to high temperatures for half a second to 30 minutes[vi]. The type of biomass and the way the biochar is cooled down and stored will also make a significant difference to its properties.

This immediately raises questions about any claims about 'universal' impacts of biochar, for example on soil fertility or soil carbon. If there is a wide range of very different biochars then one would expect their impacts on soils to also vary. The evidence for this will be discussed further below.

How stable is biochar carbon?

According to Johannes Lehmann, soil scientist and Chair of the International Biochar Initiative (IBI), 1-20% of the carbon in biochar will react with oxygen and turn into CO2 relatively early on, while the remainder will be stable for several thousands of years[vii]. Is such a degree of certainty really borne out by the evidence? And does it apply to the full range of different biochars in different soil conditions or, otherwise, can anyone predict to which biochars it will apply in which soils?

Claims by Lehmann and other biochar advocates rely largely on three different sources of evidence:

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[1] Adsorption means that particles, such as minerals, nutrients or water adhere or stick to the surface, in this case the surface of biochar particles.

- Laboratory incubation studies, whereby samples of soil with black carbon, or biochar mixed with solutions of microbes are kept at steady and usually warm temperatures for periods of time and then analysed;
- Studies of older black carbon found in soils, commonly black carbon from former wildfires, but also 'terra preta' (see box);
- Field studies in which losses of black carbon are being measured.

There are problems with each type of evidence.

The UK Biochar Research Centre pointed out in their 2010 biochar review: "*As yet, there is no agreed-upon methodology for calculating the long-term stability of biochar.* " Different studies, including different laboratory incubation studies, rely on different methodologies and their results therefore are often difficult to compare.

Virtually all ***laboratory incubation studies*** have found that some black carbon is turned into CO2 but that most of this 'loss' happens early on and that the rate at which it happens decreases over time. Lehmann and others have argued that this is because a small proportion of the biochar carbon is unstable or 'labile' and will quite quickly be turned into CO2, whereas the remainder of the carbon will be far more stable. Observations of the chemical structures of biochar support the hypothesis that some biochar carbon particles are inherently less stable than others, although a 'two-types-of-biochar-carbon' model is rather simplistic[viii] . If one extrapolates from studies which show early biochar carbon losses, the results can therefore be biased and underestimate the length of time the carbon will remain sequestered in soils. But there is another bias in the opposite direction: Many studies have shown that there are soil microbes and fungi which can turn black carbon (even black carbon which chemically appears very stable) into CO2[ix]. Soil incubation studies will at best contain a small sample of the microbes, and often none of the fungi that are found in the soils which are studied. What is more, the microbes in the laboratory incubation studies tend to diminish over time for many different reasons, hence biochar losses due to microbes would also automatically diminish[x]. Laboratory incubation studies thus cannot replicate what happens in 'real life' field conditions.

Studies of older black carbon in soils have been undertaken to estimate how long some black carbon can remain in soils. The basic idea is to compare the amount of black carbon found in soils with the amount estimated to have been produced by fires in the past, in order to extrapolate how much would have been lost compared to how much remained stable. There are major problems with this approach: Firstly, when the carbon is dated, the date generally relates to when the original tree or other vegetation grew, not the date it burned down and got partly charred. Secondly, the assumptions about how much black carbon would have been produced by fires in the past rely to a large part on how much biomass carbon is converted to black during fires, yet this conversion rate varies greatly, quite apart from the fact that past fire regimes are very difficult to reconstruct. There is no doubt that the rate of black carbon left behind after wildfires will vary according to the intensity and duration of fires, the type and amount of vegetation burned, etc. A scientific commentary article by Rowena Ball cites literature estimates ranging from 3-40% of original biomass carbon being turned into black carbon during wildfires[xi]. A scientific review by Johannes Lehmann et al suggests that on average only 3% of biomass carbon is turned into black carbon during fires[xii]. An experimental burning trial in Germany, on the other hand, found 8.1% of the original carbon being turned into black carbon in a wildfire which mimicked what is known about Neolithic swidden agriculture[xiii]. The maximum 40% biomass carbon to black carbon conversion figure[xiv] is far higher than what more recent studies have found and indeed a later study co-written by one of the co-authors of the former study suggests a much lower figure (4% of overall biomass carbon and 14% of burned biomass carbon turning into black carbon)[xv]. However, the 3% figure suggested by Lehmann et al is at the lowest end of estimates and far below what was measured in the German trial. The differences between estimates are important: If the amount of charcoal historically produced during fires is underestimated then it will appear that a lot more of it has remained stable over long periods. If the original amount of charcoal was 2-3 times higher than estimated by some authors, then only between half and a third as much black carbon will have remained stable in soils compared to the authors' estimates.

Regardless of the methodological problems, studies illustrate a great variety in the average length of time that black carbon remains in different soils in different climate zones. For example, a study by Lehmann et al in Australia suggested that black carbon remained stable in soils on average for 1,300-2,600 years, although that study relied on modeling based on assumptions about past fire patterns which are impossible to verify [xvi]. A study of Russian steppe soil showed black carbon remaining in soil for a period between 212 and 541 years[xvii]. On the other hand, a study by Nguyen et al based in Western Kenya found that, on land understood to have burnt eight times over the past century, 70% of the black carbon was lost over the first 30 years[xviii]. Another study compared two dry tropical forest soils in Costa Rica, only one of which had been exposed to regular fires and thus black carbon formation in the past. Although the soil which had been exposed to regular fires had a higher black carbon content, the "mean values were not significantly different" and, furthermore, the authors highlighted the difficulties in identifying and quantifying black carbon and the lack of an agreed method to do so [xix]. The (common) methods which they used had uncertainties of 40-50% and, given those uncertainties, it could not be shown whether or not centuries of regular fires at one site had actually led to the soil having any more black carbon than the other soil where vegetation had not been burned regularly. The studies in Western Kenya and Costa Rica only looked at carbon found in the top 10 cm, so they would have missed counting any black carbon that had moved deeper down in the soil, as could be expected from other studies. A study in Zimbabwe compared black carbon contents of two soils, one protected from fire which had not been exposed to burning for the past 50 years, the other regularly burned during that time. The authors calculated from the differences in black carbon content that the average period for which black carbon remained in the top 5 cm of soil was less than a century[xx]. Yet another study, looked at black carbon concentrations in soils underneath a Scots pine forest in Siberia which had been regularly exposed to fire[xxi]. The authors found low levels of black carbon which they could only partly explain through the fact that less biomass would have been turned into black carbon during forest fires compared to fires in tropical forests. They suggested that black carbon loss through erosion or downwards movements, deeper into the soil, were both unlikely reasons and that, instead, black carbon in the study had "low stability against degradation". The results of studies that look at black carbon naturally found in soils, including due to wildfires, are thus very mixed, suggesting residence times of a few decades to millennia, probably depending on different types of black carbon, climate zones, vegetation etc. – and also on different methods used by researchers. The reasons for black carbon losses in different cases are not known. They may include erosion and downward movement of black carbon,both of which could mean the carbon was still stable, just elsewhere. However, in the Siberian study the authors felt this was not likely. In sum: it is quite possible that most of the black carbon lost in other studies may have been turned into CO2, and there is no way to estimate how much was lost over time without knowing how much was generated in the first place.

Field study indications about the stability of black carbon: Because laboratory studies using sterile soils and controlled conditions have limited applicability, field studies are essential for understanding the impacts of different biochars in different conditions. Unfortunately, the number of peer-reviewed field studies is small. We have found 13 peer-reviewed studies based on 11 different field trials. One of those looked at soil underneath charcoal kilns, i.e. at soil which had itself been pyrolysed[xxii]. Overall carbon levels were reduced in those soils – but pyrolysing soil is rather different from most people's idea of biochar, where pyrolysed biomass is added to soils which have not been burned themselves. Of the remaining field trials, only five considered the impact of biochar – or rather of crushed traditional charcoal – on soil carbon and in all but one of those studies, the results did not distinguish between black carbon and soil organic carbon previously found in the soil or newly accumulated. The studies, which will be discussed below, thus say far more about the overall impacts of biochar on soil carbon – which is also most relevant to the question whether or not biochar can sequester carbon and theoretically (ignoring land use change), mitigate climate change.

Conclusions about the stability of black carbon

What is certain is that, on average, black carbon does not react with oxygen as easily as other forms of carbon found in soils. After all, some of the tests used to identify black carbon involve exposing carbon to high temperatures of 375°C and/or to acids, on the assumption that all of the carbon that remains after such conditions must be black carbon. It is also clear that some black carbon in certain circumstances will remain in soils for thousands of years – although on the other hand, some soil carbon which is not black carbon and which has is found in deeper soil levels is also several thousand years old[xxiii]. What the evidence does not support is the claim that the great majority of all black carbon will remain stable for long periods -. One scientific literature review[xxiv] suggests that six different factors control the storage and stability of black carbon in soils: Fire frequency (with more frequent fires turning more biomass carbon into black carbon, but also turning more black carbon into CO2), the type of original biomass and the conditions under which it was burned, soil turbation (i.e. disturbance and mixing of different soil layers), the presence of different minerals such as calcium and phosphorous in soils, different communities of microbes, whose ability to degrade black carbon will vary, and land use practices. All those variables, together with the problems linked to measuring black carbon and predicting or deducing its stability, make claims such as the International Biochar Initiative's assertion that "scientists have shown that the mean residence time of this stable fraction is estimated to range from several hundred to a few thousand years"[xxv] appear rather naive.

Does biochar lead to an overall increase in soil carbon?

There are different reasons why biochar might fail to lead to an overall increase in soil carbon, which do not relate to the stability of the black carbon in the biochar:

One possible reason can be ***erosion, either by water or wind***. If biochar erodes then its carbon will not automatically turn into CO2 but might still remain stable, albeit somewhere else. However, given the different factors which influence its stability discussed above, it will be even more difficult to make any prediction if the biochar ends up in an unknown place under unknown conditions. Some black carbon which ends up washed into in ocean sediments may remain there for longer periods than it would have done in soil[xxvi], for example, whereas some may be transported to sites where it will be exposed to conditions making it less likely to remain stable.

One study, which looked at the fate of black carbon from swidden agriculture on steep slopes in Northern Laos, found that it was significantly more prone to water erosion than other soil carbon, due partly to its low density and weight[xxvii]. The same properties also make black carbon, especially smaller particles, prone to wind erosion[xxviii]. Wind erosion of black carbon raises particularly concerns with regards to global warming impact, which are discussed below.

Another reason why biochar might not lead to an overall increase in soil carbon is called ***'priming', i.e. biochar additions causing the loss of other, per-existing soil carbon.*** When carbon-containing matter – whether biochar or any type of organic carbon – is added to soil, it can stimulate microbes to degrade not just newly added carbon but also soil carbon which had previously been relatively stable. [2]. Whether or to what extent such priming happens depends on various and still poorly understood factors. According to the soil research institute SIMBIOS Centre, "to make progress in this area, it would be necessary to first understand why some fractions of the organic matter present in a soil are not degraded under normal conditions (in the absence of priming)"[xxix] Given the general gaps in knowledge of this priming effect it seems highly unlikely that any one study could 'prove' whether or not biochar will always cause priming and thus the loss of existing soil carbon, or how serious this effect will be. After all, priming depends on the responses of different soil microbes, yet scientists have so far only been able to culture and thus closely observe 1% of soil bacteria species and none of the multitude of varieties of soil fungi [xxx]. A widely reported Swedish study involved placing mesh bags containing charcoal or humus or a 50:50 mix of charcoal and humus into boreal forest soil for a period of 10 years. At the end of the trial, the amount of carbon in the mesh bags with the charcoal and humus mix was significantly less than could have been expected from the carbon contained in either the charcoal or the humus bags [xxxi]. A comment by Johannes Lehmann and Saran Sohi argued that the results may reflect the loss of carbon in charcoal and that 'priming' might be less likely because most of the carbon loss occurred during the first year of the trial [xxxii]. In response, the authors pointed to the fact that very little carbon was lost from the charcoal-only bags and that most 'priming', by its nature, occurs early on [xxxiii]. Different biochar studies, most of them laboratory ones, have had very different results: some demonstrated biochar can cause microbes to turn existing soil carbon into CO2, others demonstrated that it may have no effect on losses of existing soil carbon and that, in some circumstances, it can even reduce losses (an effect called 'negative priming'). One laboratory study looked at the impact of 19 different biochars on five different soils, in each case using a very high rate of biochar application, equivalent to 90 tonnes per hectare [xxxiv] Initially, biochar additions increased the rate at which existing non-black soil carbon was lost in most of the biochar- plus-soil combinations. Later on in the trial, a variety of outcomes were evident: in some, the rate of soil carbon loss continued to be higher with than without biochar (though the rate of carbon loss slowed compared to what it had been early on in the experiment), in others, there difference disappeared and in yet others, soil carbon losses were slowed down in the presence of biochar. One problem with that study however is that all soil and biochar samples were inoculated with soil microbes taken from a forest floor, not from the actual soils being tested, which means that the microbes which degraded some of the carbon were not the ones which would have been present had this been a field rather than a laboratory trial. Priming has also been observed in other laboratory studies. For example in one study switchgrass residue was added to soils with biochar, the biochar increased carbon losses from that residue[xxxv]. In sum: biochar can cause a proportion of other carbon in soils to be turned into CO2, but this effect depends on the particular type of biochar, as well as the nature of the soil and on any organic residue added to soil and is thus very difficult to predict, particularly since relatively few studies have been published which look at this possibility.

Field study results

The five peer-reviewed field studies which look at biochar impacts on soil carbon do not clearly identify what exactly happened to which type of carbon in soil. Nonetheless, they provide the best 'real-life test' of the claim that biochar, at least at the field level, can be relied on to sequester carbon. So far, only two biochar field trials have been published which have lasted for more than two years, both of them four-year long trials. A larger number of longer- or even medium-term field studies would show more clearly how different biochars impact carbon in different soils.

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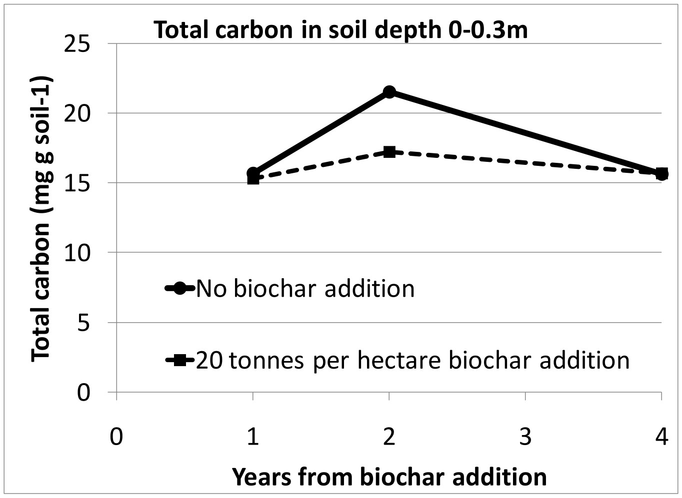
[2] For the purpose of this report, we are using the term 'priming' only to refer to biochar stimulating soil microbes to degrade other carbon in soil and residues. Elsewhere, however, it is also used to refer to the loss of biochar carbon through microbes, stimulated by other soil carbon, an issue discussed separately above.

What those published so far show, however, is that biochar impacts on soil carbon are variable, unpredictable and by no means always positive.

Field trial on savannah soil under a maize and soya rotation, Colombia[xxxvi]

This was a four-year field study, in which biochar at the rate of 0, 8 and 20 tonnes per hectare was applied (together with the same fertilisers) to relatively carbon-poor soil from which savannah vegetation had just been cleared. Maize and soybean were grown in rotation. Total soil carbon was tested after one, two and four years although on the plots with 8 tonnes/hectare of biochar, it was only measured once, after four years.



In the first, third and fourth year, there was no statistically significant difference between amounts of carbon in different plots. Even a high biochar rate of 20 tonnes per hectare had not increased soil carbon. In the second year, the plots which had been amended with biochar held significantly less carbon than those without. It is not known how much of this was due to the loss of biochar or other organic carbon, although biochar had effects on crop yields and soil properties through the trial, so at least some of it must have remained in the soil, making the loss of other soil carbon ("priming") more likely. In the third and fourth year, carbon levels recovered on the plots with biochar, though they did not exceed the control plots and this is understood to be due to higher crop yields. Greater crop growth and yields will, temporarily, lead to crops depositing more carbon in the soil.

Field trial on savannah soil under regrowing native savannah vegetation, Colombia[xxxvii]

This was a two-year trial in the same region as the four-year one discussed above. Native savannah vegetation was removed before biochar application but then allowed to regrow. Biochar was applied at the rates of 0, 11.6, 23.2 and 116.1 tonnes per hectare. ***After two years, there was no statistically significant difference in the amount of carbon found in the top 30cm of soil between the plots with no biochar and those with 11.6 or 23.2 tonnes of biochar per hectare.*** Only a very large amount of biochar addition - 116.1 tonnes per hectare resulted in significantly higher carbon levels, than control plots. It is uncertain what happened to the 'missing carbon'. The authors of the study measured the amount of black carbon and other carbon emitted as CO2 from the soil ('soil respiration') and found that only 2.2% of the biochar carbon was lost that way. Other soil carbon was lost at a higher rate from plots with biochar, than from those without biochar – 40% higher in the first and 6% higher in the second year, but that was not enough to account for the missing carbon. There may have been problems with those measurements in that they were supposed to have been done on small 'rings' kept free from vegetation, but the authors suggest that the readings might have been influenced by plant growth, which indicates that the rings might have got overgrown, which would have distorted the results. According to the lead author water erosion may have played an important role[xxxviii]. However, erosion was not measured and it appears surprising in that the ground was relatively flat and savannah vegetation would have grown back very quickly, which should have minimised or stopped water erosion. In sum: the results indicate that very large amounts of carbon simply disappeared and are unaccounted for.

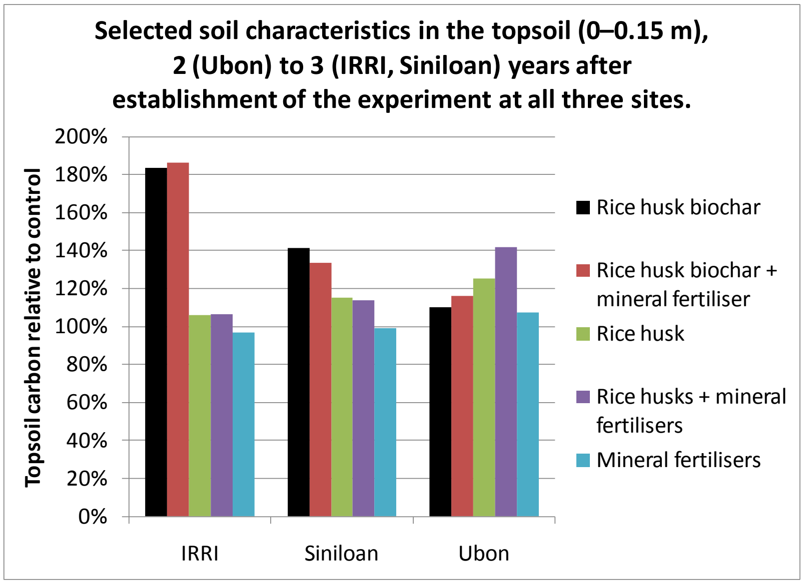
Field trial in Central Amazonia, Brazil, under rice and sorghum cultivation[xxxix]

Results from two years of a field trial in Central Amazonia have been published. This took place on the same type of highly-weathered soil from which Terra Preta is understood to have been created. Secondary forest was cleared for the trial and different plots were amended with different combinations of mineral fertiliser, charcoal, chicken manure, burned and unburned leaf litter and compost. They were then cultivated first with rice and then with sorghum. ***After five months, soil carbon was measured. Total soil carbon was not significantly higher when charcoal or most of the combinations including charcoal were used, compared to controls.*** They were only significantly higher for a combination of charcoal plus mineral fertiliser plus compost. After the second harvest, soil carbon was only measured on control plots, those with mineral fertilisers only and those with combinations of compost and charcoal. Plots with either compost and charcoal plus mineral fertilisers had higher total carbon than those with compost only or mineral fertilisers only (those with charcoal only were not tested for soil carbon at that time). No carbon measurements were done for the two later harvests.

Field trial in the Philippines, under rice cultivation[xl]

This was a four-year field trial on three different soils under rice cultivation in the Philippines. Different plots were amended with 1) biochar made from rice husks (at a rate of 16.4 tonnes/hectare) or 2) uncharred rice husks, with or without mineral fertilisers, or 3) left unamended or 4) with mineral fertilisers only.

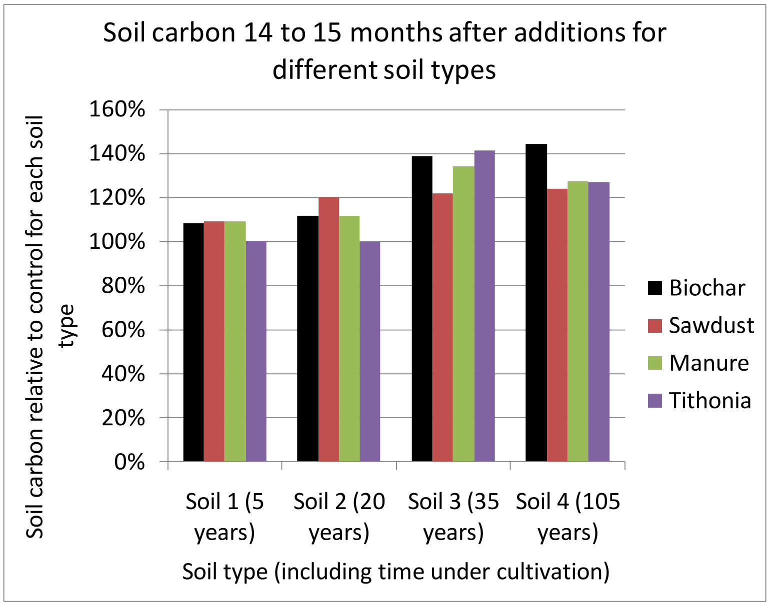
After 2-3 years, soil carbon levels were higher on plots with biochar (with or without fertilisers), compared to both control plots and those with uncharred rice husks on two types of soil. On the third soil, total carbon was higher on the plots with biochar compared to the control plots or those with fertiliser only, but they were highest on plots amended with uncharred rice husks.



Field trial in Western Kenya under maize cultivation [xli]

An 18 month study was conducted on four different soils, which differed according to how long they had previously been under continuous cultivation – 5, 20, 35 and 105 years. The longer the soils had been under cultivation, the less carbon they contained. For each soil, plots were amended with biochar, manure, sawdust, fresh Tithonia leaves (commonly used as green manure) or left as controls. At the end of the trial, biochar-amended plots had the highest carbon concentrations on only one of the four soils – the one which had been cultivated the longest. On another soil, biochar, manure and Tithonia all raised carbon levels compared to controls, with no significant difference between them; on a third, sawdust resulted in the highest carbon levels and on another, there was no significant difference in soil carbon between any of the plots, including controls. Thus, although biochar increased soil carbon compared to plots without any amendments, it did not perform any better in that respect than other organic residues.

Summary results from field studies



The five relevant field studies involved 11 different soils/vegetation. If we look at those as 11 separate 'samples' then there would have been no carbon sequestration compared to unamended control soils on five samples (excluding the unrealistically high rate of 116.1 tonnes/hectare in one of those trials) and a temporary net carbon loss linked to biochar on one of those. In three samples, biochar resulted in higher total carbon compared to largely unamended soils, but not when compared to common alternative soil amendments. And in three samples, biochar did result in more carbon sequestration than the alternatives tested, though a different range of alternatives was used in different studies. The basic proposition of most carbon sequestration offset projects – an increase in soil carbon compared to what would have happened in the absence of the project (i.e. common farming practices in an area) – would thus have been met in only three out of eleven cases, at least over the short duration of the trials.

Part 2: Climate impacts of airborne biochar

When black carbon becomes airborne, it absorbs solar energy rather than reflecting it back into space and thus contributes to global warming. The effect is worsened when black carbon particles, which can travel for thousands of miles, are deposited on snow or ice and accelerate melting[xlii]. The warming effect of black carbon is short-lived but so powerful that NASA scientists suggest that, evened out over a century, airborne black carbon particles have 500-800 times the warming effect of a similar volume of CO2[xliii]. Airborne black carbon has been mainly discussed in the context of soot, since soot particles are particularly small, i.e. in the submicron range. However, some fresh biochar particles are in the same size range as soot which would make them as liable to becoming airborne, as dust particles which can also become airborne. For example, in a non-peer-reviewed field trial study in Quebec "an estimated 30% of the material was wind-blown and lost during handling, transport to the field, soil application and incorporation"[xliv]. The particle size of the biochar produced by the company which supplied that trial was analysed by the Flax Farm Foundation, who found that it "approaches a low of 5 µm in size"[xlv]. This is smaller than the size of many (airborne) soot particles. Furthermore, according to a report published by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), "the size of biochar particles is relatively rapidly decreased, concentrating in size fractions <5µm diameter"[xlvi]. In other words, over time, larger biochar particles are likely to also break down to the size of black soot particles. Given that wind erosion of black carbon is well documented[xlvii], it seems surprising that no scientific literature has been published about the potential warming effects of airborne small biochar particles. The magnitude of the warming effect of black carbon in the atmosphere is such that, if even a small proportion of biochar particles was to become airborne, this is likely to reverse any of the proposed 'climate benefits' of biochar (themselves unproven).

Part 3: Biochar impact on nitrous oxide emissions from soils

Nitrous oxide is the third most important greenhouse gas involved in global warming, after carbon dioxide (CO2) and methane. Its warming effect is about 300 times as strong as that of the same volume of CO2. Nitrous oxide is produced by soil bacteria as a natural part of the nitrogen cycle, but the amount produced that way has been greatly increased by the use of nitrogen fertilisers as well as fertilisation with large quantities of manure.

The International Biochar Initiative's prediction about the amount of greenhouse gas emissions that could be 'offset' by biochar relies partly on the assumption that biochar will reduce the amount of nitrous oxide emitted from soils[xlviii]. However, only one peer-reviewed field trial has looked at the effect of biochar on nitrous oxide emissions. That trial, which took place on pasture in New Zealand, compared the impacts of 15 and 30 tonnes of biochar per hectare compared to none when added to patches of cow urine[xlix]. The higher amount of biochar reduced N2O emissions from the cow urine by 70%, but the lower amount had no statistically significant impact. According to the UK Biochar Research Centre review, only one peer-reviewed (short-term) laboratory study exists which found reduced nitrous oxide emissions with biochar use. A greenhouse gas trial in Colombia reported to have shown a 50% reduction in nitrous oxide emissions from soybean production with biochar, was never published[l]. Three laboratory studies with conflicting results also remain unpublished. There thus appears to be far too little evidence for drawing any conclusions about biochar impacts on nitrous oxide emissions.

TERRA PRETA

Terra preta soils, found in Central Amazonia, are frequently cited as 'evidence' for the beneficial properties of biochar in soils. The soils, which are highly fertile and rich in carbon, including black carbon, are found mostly in patches of, on average, 20 hectares , though in some cases up to 350 hectares, mostly, though not exclusively, along the Amazon and its tributaries. Terra preta soils are associated with past farming practices by indigenous communities around 500 to over 2,500 years ago. According to the Food and Agriculture Organisation, "the knowledge systems and culture linked to the Terra Preta management are unique but have unfortunately been lost"; what is, however, known is that it the farming methods involved "diverse organic nutrient sources...such as fish residues, turtle shells, weeds and sediment from the rivers, manures, and kitchen waste other than fish" . Furthermore, Terra preta is characterised by an abundance of pottery shards and minerals left behind from ceramics Sediments from seasonal river flooding played a role in at least some places and evidence that perennial trees and shrubs as well as long-crop cycles all played a role in those pre-colonial farming methods. Charcoal was thus only on component in a complex biodiverse farming system and soils amended with biochar, unsurprisingly, have different properties from Terra preta.

Part 4: Biochar and crop yields

According to the International Biochar Initiative, biochar can boost food security, discourage deforestation and preserve cropland diversity...Biochar can improve almost any soil. Areas with low rainfall or nutrient-poor soils will most likely see the largest impact from addition of biochar‟[li]. This claim suggests that biochar will usually improve crop yields.

The large variations between different biochars as well as different soils suggest that impacts on crops are likely to differ, too. The UK Biochar Research Centre review identifies the different ways in which biochar can affect crop yields, which are discussed below. The additional comments and explanations about each effect are the authors', i.e. not taken from the UKBRC report.

a) As discussed above, a proportion of ***biochar carbon*** is easily degradable and ***provides food for soil microorganisms***. Those microorganisms will then build up stores of nutrients in soils which are needed by plants. However, this can also be a negative short-term effect: Compared to plant residues, compost or manure, biochar contains a high proportion of carbon relative to nitrogen. If a soil is already nitrogen limited, then microbes, stimulated by the carbon which they digest, can proliferate and out-compete plants – using up the accessible nitrogen. This can suppress plant growth and thus crop yields temporarily, during the first harvest or year.

b) Fresh biochar contains different proportions of ***ash, which is rich in minerals*** and benefits plant growth. This is a temporary positive effect, allowing biochars rich in ash to serve as a fertiliser early on, until the minerals have been depleted. That fertiliser effect may be delayed and extended if minerals adsorb to the pores in the biochar and thus become available to plants only more gradually.

c) Most, though not all, biochars are alkaline. Adding anything alkaline – including ***alkaline biochar - to acidic soils*** can boost plant growth. This is because acidic soils make it less possible for plants to absorb key soil nutrients, such as nitrogen, phosphorous, potassium, calcium and magnesium. Furthermore, acidic soils have increased concentrations of some trace metals, such as aluminium, which are toxic to plants in larger quantities. Biochars can only make soils more alkaline for a limited period of time, possibly a few years.

d) One important measurement of soil fertility is called the ***Cation Exchange Capacity (CEC)***. The CEC measures the ability of soils to hold and to release to plants various different elements and compounds, including soil nutrients such as calcium, magnesium, potassium and sodium. It is important for the ability of soils to retain nutrients and to protect groundwater from some forms of contamination. Highly-weathered tropical soils tend to have a low CEC, whereas the CEC is high in Terra Preta. The high CEC of Terra Preta, appears to be linked to the black carbon content, and so improving CEC has been cited repeatedly as a likely 'benefit' of biochar, including by companies[lii] There are two problems with that claim: First, soil scientists distinguish between the 'potential CEC' and the 'effective CEC' and the latter is thought to be linked most closely with soil fertility, yet that is not particularly high in Terra preta, which means that different properties may be responsible for the high fertility of those soils [liii]. Secondly, it is thought that the charcoal remains in Terra preta would only have gained a high CEC over time, as a result of slow changes to black carbon in soils over a long period of time[liv]. According to a laboratory study in which samples of biochar was incubated for a year at different warm and high temperatures, it was concluded that it would take around 130 years for biochar particles to have undergone the changes found in black carbon particles in Terra preta which are responsible for Terra preta's high CEC[lv]. Although some increase in CEC could be expected sooner, especially in a warm climate, it is still a very slow process, except in the case of certain biochars such as those made from cow manure[lvi] or some biochars produced at relatively low temperature, around 350°C[lvii].

e) Other changes to soil properties: All biochars are porous. Depending on their pore sizes and distribution (which vary greatly), they can hold water and adsorb various chemicals, including nutrients, pesticides, etc. It is also thought that the porous and light nature of biochar can help to improve the structure of compacted soils and improve soil aggregation[3]. Again, the effects which different biochars of different ages have on different soils vary greatly. For example, the impact of biochars on the water holding capacity of soils varies with different biochars and different soil types and the 'positive' impact can be reduced or negated by the fact that fresh biochar particles can be water-repellent. For example, in a laboratory trial, biochar produced through fast pyrolysis increased the water holding capacity of a sandy loam soil by nearly one third, but biochar produced through slow pyrolysis had a very small impact on water retention, apparently too small to be statistically significant[lviii]. And in a laboratory study which looked at the impact of two different biochars on three soil types from Ghana, the water holding capacity was increased, but it was higher when biochar was applied at a relatively low rate of 5 tonnes per hectare compared to a higher rate of 15 tonnes/hectare[lix].

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[3] Well aggregated soils are ones in which soil particles are hold together well, for example by organic matter, moist clay, fungi, etc. and which are more stable and less prone to erosion. Pores within and between 'clumps' of soil particles allow air, water, microbes, nutrients and organic matter to be stored.

f) Providing a habitat for micro-organisms: At least some biochars have pores large enough to provide shelter for various soil microbes as well as the hyphae[4] of beneficial fungi, and helping microbes and fungi to access nutrients. Of particular interest is the link between black carbon and mycorrhizal fungi, small, diverse fungi which enter into a usually symbiotic relationship with plant roots, helping plants to access various mineral nutrients and receiving sugars in return. Terra preta appears to provide a rich habitat for mycorrhizal fungi. There are several different ways in which black carbon could support such fungi, as well as other microorganisms, although biochar's high ratio of carbon to nitrogen could, in the short term, have a negative impact on microorganisms as described previously[lx].

What do field studies show?

The lack of longer-term field studies makes it impossible to predict what the long-term effects of different biochars on soil fertility and soil properties will be. Long-term effects are particularly important because of the relatively large quantities of biomass required to produce biochar. Most trials have involved applying biochar at a rate of at least 10 tonnes per hectare, which would require at least 40 tonnes but more likely 50-60 tonnes of biomass to produce. If biochar could be relied upon to raise crop yields or, more likely, to reduce the use of mineral and/or organic fertilisers over long periods, this would increase the likelihood of it becoming economically viable without subsidies or carbon offsets, at least for large farmers, agribusiness and other plantation companies who can afford upfront payments and investments. For example, interim results of a Cornell University Life Cycle Assessment suggest that several decades of expected higher yields with lower fertiliser use greatly increases the economic potential of biochar[lxi].

So, does biochar application reduce fertilizer demand and increase crop yields? What is the evidence? Eight of the peer-reviewed field trials which we have found look at biochar impacts on soil fertility. Those include the trial involving 'charred soil' rather than biochar, leaving us with seven relevant field trials.

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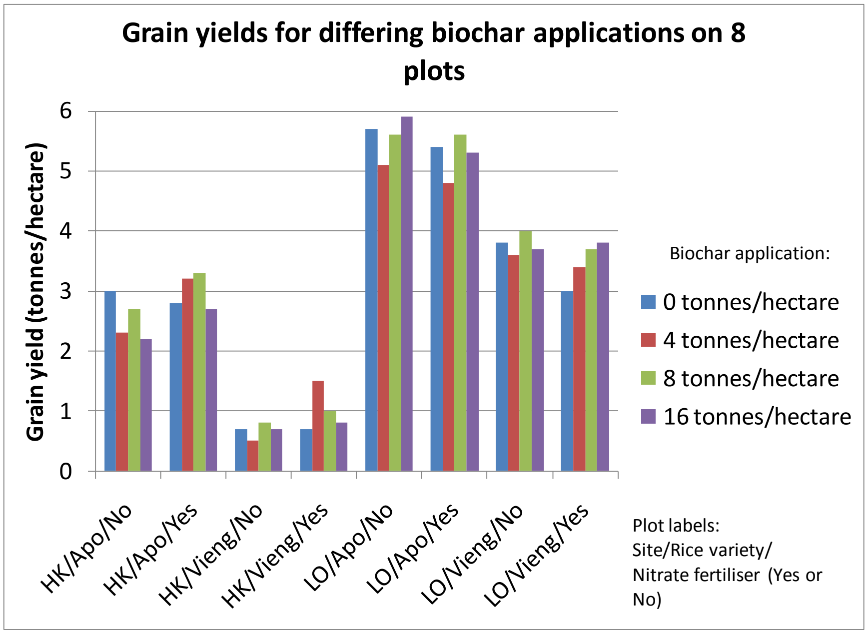
[4] Hyphae are the long, branching structures which most fungi have and on which they rely to access nutrients.

Field trial involving biochar for rice production in Northern Laos[lxii]

This was a six-month trial which involved three different field experiments, involving traditional charcoal applied at rates of 0, 4, 8 and 16 tonnes/hectare, with and without mineral fertilisers, with two different rice varieties grown. Impacts on crop yields varied greatly, from negative to neutral to positive.

Biochar appeared to increase the water holding capacity of soils, but to reduce the availability of nitrogen to plants, particularly if used in larger quantities.

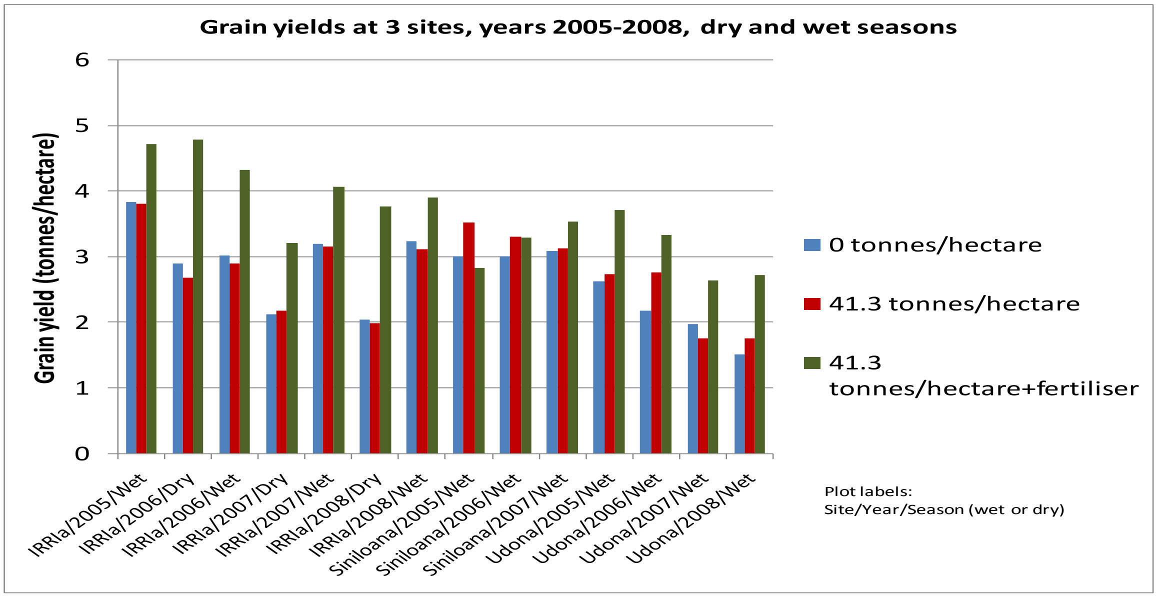


Field trial looking at the impacts of pine chip and peanut hull biochars on soil cultivated with maize in the SE US[lxiii]

This was an 18 month trial using biochars made from either pine chips or peanut hulls at rates of 0, 11 and 22 tonnes per hectare, with and without nitrogen fertilisers. The maize was irrigated, though not enough to prevent drought stress in the second year.

Field trial in the Philippines, under rice cultivation[lxiv]

This trial has been described above in relation to soil carbon impacts. At one site, the effect of biochar on grain yield was generally negative, possibly due to the high proportion of carbon in relation to nitrogen, which may have suppressed nitrogen take-up by plants. At the second site, different treatments with fertilisers and/or biochar made little difference overall. At the third site, combinations involving biochar mixed with mineral fertilisers and/or rice husks achieved the highest yields during three of four harvests, but biochar on its own had no effect.

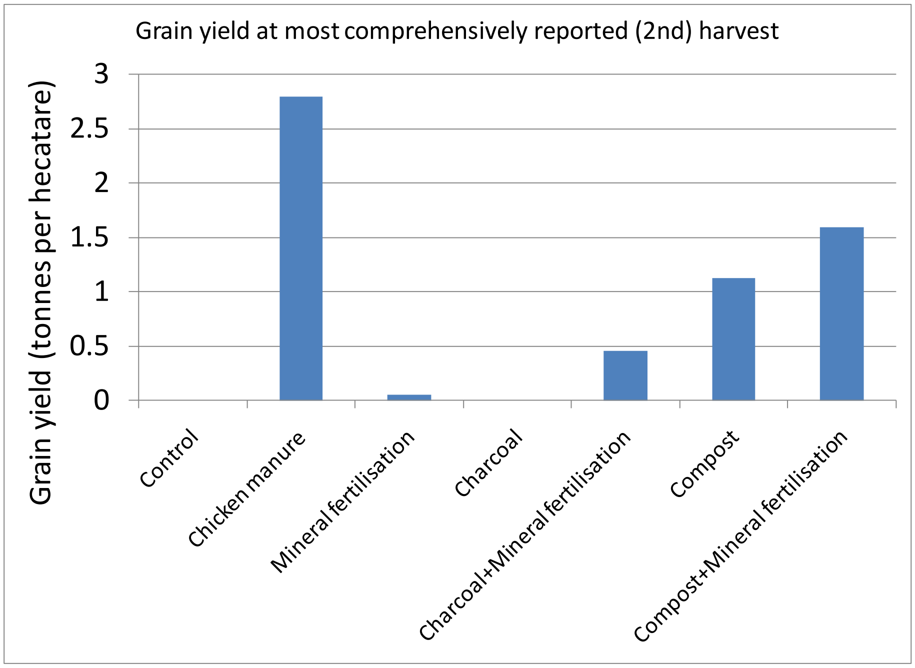


Field trial on savannah soil under a maize and soya rotation, Colombia[lxv]

This trial has been described above in relation to soil carbon impacts. Maize yields were measured annually for four years, soybean yields during the fourth year only. During the first year, biochar had no statistically significant impact on crop yields. During subsequent years, it raised maize yields, applying 20 tonnes per hectare of biochar raised maize yields more than 8 tonnes per hectare. In the fourth year, all maize yields declined sharply, although yields on plots with biochar were significantly higher than those on control plots, on which only mineral fertiliser had been used. Soybean yields were not affected by biochar.

Field trial in Central Amazonia, Brazil, under rice and sorghum cultivation[lxvi]

This trial has been described above in relation to soil carbon impacts. Both overall biomass and grain yields were highest when chicken manure was applied, followed by a combination of compost and mineral fertilisers. Applications of biochar on its own were associated with the lowest yields other than those for control plots and in the second year, soil amended with nothing but charcoal did not support any growth of crops at all.



Field trial in South Sumatra, under maize, cowpea and peanut cultivation[lxvii]

This was a short, three month trial, with three different sites. The experiments at two sites took place a year earlier than those at the third. Traditional charcoal was produced from Acacia wood waste from pulp and paper production and applied to fields on which maize, cowpea and peanut were grown. Three different locations were selected: One was located in the garden of a farmhouse, a second in a garden reclaimed from a chicken farm, and a third on former grassland which had recently been turned into farmland. The two treatments compared at the first site were mineral fertiliser alone and mineral fertiliser combined with charcoal, with control plots being unfertilised and unamended. At the first site, yields of maize and peanut were significantly greater when charcoal and fertilisers were combined than when fertiliser alone was used, whereas charcoal had no significant impact on cowpea yields. Maize yields doubled when charcoal was added to fertilisers. At the second site, there was no statistically significant difference between the two treatments, both of which raised yields compared to the unfertilised control plots. At the third site, overall maize yield increased significantly when charcoal was added to fertilisers and resulted in similar yield increases when it was applied on its own, compared to plots amended with mineral fertilisers only.

This is the only field trial described here which did not use the "randomised block design with replicates" method which has been described as good practice in the International Biochar Initiatives guide to biochar field trials. This makes the results of this study less reliable than others.

Field trial in Western Australia under wheat cultivation[lxviii]

This was a short, 3-4 months field trial on acidic sandy clay loam in Western Australia. Charcoal was made from oil mallee (Eucalyptus oleosa) after extraction of the oil. Different combinations of charcoal, at rates of 0, 1.5, 3 and 6 tonnes per hectare and either water-soluble mineral fertilisers or slow-release mineral fertilisers inoculated with mycorrhizal fungi were tested, with nitrogen and phosphorous fertilisers applied to all plots. When soluble fertilisers were used, only one biochar combination out of six (6 tonnes per hectare of biochar and 30 kg/hectare of fertiliser) significantly improved yields. Biochar raised yields in combination with the inoculated mineral fertilisers.

Summary findings from field studies

Field trials illustrate the variable and as yet unpredictable impact which biochar has on crop yields, which can be positive, negative or neutral, depending on different types of biochar, soils and even crop varieties, and on combinations with different organic and mineral fertilisers. Although biochar researchers are looking at the possibility of producing 'designer biochars' for different conditions, the large variation in impacts compared to the small amount of field data makes it difficult to see how this would be possible or practical, at least in the foreseeable future. Given how inconsistent biochar impacts on yields are and how little is known about their longer-term impacts, farmers who are to use biochar on their fields are taking considerable risks, even more so if they have to invest in producing or purchasing the biochar, rather than taking part in a trial in which biochar was supplied for free.

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[i] An Assessment of the benefits and issues associated with the application of biochar to soil, UK Biochar Research Centre, Simon Shackley and Saran Sohi, 2010

[ii] www.nasa.gov/centers/langley/news/researchernews/rn_carboncycle.html

[iii] Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, Peter M. Cox et al, Nature 408, 184-187 (9 November 2000)

[iv] Review of the stability of biochar in soils: predictability of O:C molar ratios, Kurt Spokas, Carbon Management (2010) 1(2), 289–303

[v] See for example New Directions in Black Carbon Organic Geochemistry, C.A. Masiello, Marine Chemistry 92 (2004) 201– 213

[vi] Co-production of gas and liquid from biomass feedstocks using slow pyrolysis, H. Luik et al, Zero Emission Power Generation Workshop, 16th to 18th April 2007 in TUBITAK MRC Gebze Turkey

[vii] www.biochar-international.org/images/Lehmann_Biochar_ASA2008.pdf

[viii] Dynamic Molecular Structure of Plant Biomass-derived Black Carbon (Biochar), Marco Keiluweit et al, *Environ. Sci. Technol.*, 2010, *44* (4)

[ix] Controls on black carbon storage in soils, Claudia I. Czimczik1 and Caroline A. Masiello, Global Biogeochemical Cycles, VOL. 21, GB3005, doi:10.1029/2006GB002798, 2007 and priming of black carbon and glucose mineralisation, U. Hamer et al,*Org. Geochem.* 35(7), 823–830 (2004).

[x] Spokas et al(2010)

[xi] Combustion of Biomass as a Global Carbon Sink, Rowena Ball, The Open Thermodynamics Journal*,* 2008, *2,* 106-108

[xii] Bio-char sequestration in terrestrial ecosystems - A Review, Johannes Lehmann et al, Mitigation and Adaptation Strategies for Global Change (2006) 11: 403–427

[xiii] Conversion of biomass to charcoal and the carbon mass balance from a slash-and-burn experiment in a temperate deciduous forest, Eileen Eckmeier et al, *The Holocene* 2007 17: 539

xiv Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning, W. Seiler and P. J. Crutzen, *Climatic Change*, vol. 2, no. 3, pp. 207-247, September 1980

xv Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles, Paul Crutzen and Meinard Andreae, Science, 21st December 1990

xvi Australian climate-carbon cycle feedback reduced by soil black carbon, Johannes Lehmann et al, Nature Geoscience, vol 1, pp832-835

xvii Centennial black carbon turnover in a Russian steppe soil, K Hammes et al, 2008b. Biogeosciences 5, 1339–1350.

xviii Long-term black carbon dynamics in cultivated soil, Nguyen et al. Biogeochemistry 89: 295-308, 2003

xix Characterization of soil organic matter and black carbon in dry tropical forests of Costa Rica, Klaus Lorenz et al, Geoderma, 2010, vol.158, no 3-4, pp. 315-321

xx Bird, M. I., C. Moyo, E. M. Veenendaal, J. Lloyd, and P. Frost (1999), Stability of elemental carbon in a savanna soil, *Global Biogeochem. Cycles*, 13(4), 923–932, doi:10.1029/1999GB900067.

xxi How surface fire in Siberian Scots pine forests affects soil organic carbon in the forest floor: Stocks, molecular structure, and conversion to black carbon (charcoal), C.I. Czimzkik et al, Global Biogeochem. Cycles, 17(1), 1020, doi:10.1029/2002GB001956, 2003.

xxii Effects of charcoal production on maize yield, chemical properties and texture of soil, Philip G Oguntunde et al, Biol Fertil Soils (2004) 39:295?99

xxiii Stability of organic carbon in deep soil layers controlled by fresh carbon supply, Sebastien Fontaine et al, Nature, Vol 450, 8th November 2007

xxiv Controls on black carbon storage in soils, Claudia I. Czimczik1 and Caroline A. Masiello, GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 21, GB3005, doi:10.1029/2006GB002798, 2007

xxv http://www.biochar-international.org/biochar/faqs#q9

xxvi Enhanced: Black Carbon and the Carbon Cycle, T.A.J. Kuhlbush, Science, volume 280, 1998, pp 1903-1904

xxvii Preferential erosion of black carbon on steep slopes with slash and burn agriculture, C. Rumpel et al, Catena 65 (2006) 30 – 40

xxviii See for example: Combining charcoal and elemental black carbon analysis in sedimentary archives: Implications for past fire regimes, the pyrogenic carbon cycle, and the human–climate interactions, Florian Thevenon et al, Global and Planetary Change 72 (2010) 381–389 AND New directions in black carbon organic geochemistry C.A. Masiello, Marine Chemistry 92 (2004) 201– 213

xxix http://simbios.abertay.ac.uk/research/background%20on%20core%20theme.php

xxx Methods of studying soil microbial diversity, Jennifer L. Kirk et al, Journal of Microbiological Methods 58 (2004) 169– 188

xxxi Fire-Derived Charcoal Causes Loss of Forest Humus, David A. Wardle et al, 2008, Science 320(5876): 629

xxxii Comment on " Fire-Derived Charcoal Causes Loss of Forest Humus", Johannes Lehmann and Saran Sohi, Science, Vol 321, September 2008

xxxiii Response to Comment on " Fire-Derived Charcoal Causes Loss of Forest Humus", David A. Wardle et al, Science, Vol 321, September 2008

xxxiv Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils, Andrew R. Zimmerman et al, Soil Biology & Biochemistry(2011), 2011 10.1016/j.soilbio.2011.02.005

---

xxxv Short-term CO2 mineralization after additions of biochar and switchgrass to a Typic Kandiudult, J.M. Novak et al, 2010 Geoderma 154, 281e288

xxxvi Maize yield and nutrition during 4 years after biochar application to a Colombian savannah oxisol, Julie Major & Marco Rondon & Diego Molina & Susan J. Riha & Johannes Lehmann, Plant Soil (2010) 333:117–128

xxxvii Fate of soil-applied black carbon: downward migration, leaching and soil respiration, Julie Major at all, Global Change Biology, Volume 16, Issue 4, April 2010

xxxviii Personal correspondence with Julie Major, 11th March 2011

xxxix Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil, Christoph Steiner et al, 2007, Plant Soil DOI 10.1007/s11104-007-9193-9 AND Nitrogen Retention and Plant Uptake on a highly weathered central Amazonian Ferralsol amended with Compost and Charcoal, Christoph Steiner et al, J. Plant Nutr. Soil Sci. 2008, 171, 893–899

xl Effects and fate of biochar from rice residues in rice-based systems, S.M. Haefele et al, Field Crops Research 121 (2011) 430?40

xli Stability and stabilisation of biochar and green manure in soil with different organic carbon contents, Joseph M. Kimetu and Johannes Lehmwww.biochar-international.org/biochar/soilsann, Soil Research 48(7) 577–585, 29th September 2010

xlii Influence of dust and black carbon on the snow albedo in the NASA Goddard Earth Observing System version 5 land surface model, Teppei J. Yasunari et al, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, D02210, 15 PP., 2011

xliii Can Reducing Black Carbon Emissions Counteract Global Warming?, T.C. Bond and H. Sun, 2005, Environmental Science & Technology 39: 5921-5926 AND Climate Change and Trace Gases, James Hansen et al, 2007., Philosophical Transactions of the Royal Society 365(1856):1925-1954

xliv Commercial scale agricultural biochar field trial in Québec, Canada, over two years: Effects of biochar on soil fertility, biology, crop productivity and quality, Barry Husk and Julie Major, 2009, www.blue-leaf.ca/main-en/files/BlueLeaf%20Biochar%20Field%20Trial%2008-09%20Report-1.pdf

xlv www.colorado.gov/cs/Satellite?blobcol=urldata&blobheader=application%2Fpdf&blobkey=id&blobtable=MungoBlobs&blobwhere=1251600562674&ssbinary=true

xlvi Biochar, Climate Change and Soil: A Review to Guide Future Research", Saran Sohi et al, February 2009, CSIRO

xlvii See endnote xxx above and also: Sedimentary records of black carbon in the sea area of the Nansha Islands since the last glaciation, JIA Guodong et al, Chinese Science Bulletin, Vol. 45 No. 17, September 2000 AND

xlviii http://www.biochar-international.org/sites/default/files/final%20carbon%20wpver2.0.pdf

xlix Biochar Incorporation into Pasture Soil Suppresses in situ Nitrous Oxide Emissions from Ruminant Urine Patches, Arezoo Taghizadeh-Toosi et al, J. Environ. Qual. 40:468-76 (2011)

l Marco Rondon et al, Charcoal additions reduce net emissions of greenhouse gases to the atmosphere. Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration, Baltimore, USA, March 21-24 2005

li www.biochar-international.org/biochar/soils

lii See for example http://www.thefertilizerguide.com/biochar.html and http://www.hedon.info/cat357&deep=on

liii See footnote lv

liv See footnote lv

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lv Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence, C.H. Chen et al, 2008, Geochimica et Cosmochimica Acta 72, 1598-1610

lvi Characterisation and evaluation of biochars for their application as a soil amendment, Balwant Singh et al, Australian Journal of Soil Research , 2010, Vol. 8, pp 516-525

lvii 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, Masahide Yamato et al, Soil Science and Plant Nutrition (2006) 52, 4891495

lviii Application of Fast Pyrolysis Biochar to a Loamy soil - Effects on carbon and nitrogen dynamics and potential for carbon sequestration, Esben Bruun, Risø-PhD-78 (EN), May 2011, http://130.226.56.153/rispubl/reports/ris-phd-78.pdf

lix Bio-char from sawdust, maize stover and charcoal: Impact on water holding capacities (WHC) of three soils from Ghana, Emmanuel Dugan et al, Symposium Report, http://www.ldd.go.th/swcst/Report/soil/symposium/pdf/1158.pdf

lx Mycorrhizal responses to biochar in soil – concepts and mechanisms, Daniel D. Warnock & Johannes Lehmann & Thomas W. Kuyper & Matthias C. Rillig, Plant Soil (2007) 300:9–20

lxi Kelli Roberts, Life-Cycle Assessment of Biochar Systems in Developing Country Settings: Greenhouse gas and economic analysis, presentation at UK Biochar Research Centre Conference 2011, Edinburgh, http://www.livestream.com/esktn/video?clipId=flv_9b4386a1-7270-44b0-b3f3-0f975d089d7f

lxii Biochar amendment techniques for upland rice production in Northern Laos, 1. Soil physical properties, leaf SPAD and grain yield, Hidetoshi Asai et al, Field Crops Research 111 (2009) 81:4

lxiii Effect of Peanut Hull and Pine Chip Biochar on Soil Nutrients, Corn Nutrient Status, and Yield, J.W. Gaskin et al, Agronomy Journal 102, 2010

lxiv Effects and fate of biochar from rice residues in rice-based systems, S.M. Haefele et al, Field Crops Research 121 (2011) 430?40

lxv Maize yield and nutrition during 4 years after biochar application to a Colombian savannah oxisol, Julie Major & Marco Rondon & Diego Molina & Susan J. Riha & Johannes Lehmann, Plant Soil (2010) 333:117–128

lxvi Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil, Christoph Steiner et al, 2007, Plant Soil DOI 10.1007/s11104-007-9193-9 AND Nitrogen Retention and Plant Uptake on a highly weathered central Amazonian Ferralsol amended with Compost and Charcoal, Christoph Steiner et al, J. Plant Nutr. Soil Sci. 2008, 171, 893–899

lxvii 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, Masahide Yamato et al, Soil Science and Plant Nutrition (2006) 52, 4891495

lxviii Mycorrhizal root colonisation, growth and nutrition of wheat, M. Solaiman Zakaria, *Soil Research* **48**(7) 546–554, 28th September 2010