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The Basics of Biochar: A Natural Soil Amendment

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Biochar is a fine-grained, highly porous charcoal substance that is distinguished from other charcoals in its intended use as a soil amendment. Biochar is charcoal that has been produced under conditions that optimize certain characteristics deemed useful in agriculture, such as high surface area per unit of volume and low amounts of residual resins. The particular heat treatment of organic biomass used to produce biochar contributes to its large surface area and its characteristic ability to persist in soils with very little biological decay (Lehmann and Rondon 2006). While raw organic materials supply nutrients to plants and soil microorganisms, biochar serves as a catalyst that enhances plant uptake of nutrients and water. Compared to other soil amendments, the high surface area and porosity of biochar enable it to adsorb or retain nutrients and water and also provide a habitat for beneficial microorganisms to flourish (Glaser et al. 2002, Lehmann and Rondon 2006, Warnock et al. 2007).

Background

"Biochar" is a relatively new term, yet it is not a new substance. Soils throughout the world contain biochar deposited through natural events, such as forest and grassland fires (Krull et al. 2008, Skjemstad et al. 2002). In fact, areas high in naturally occurring biochar, such as the North American Prairie (west of the Mississippi River and east of the Rocky Mountains), are some of the most fertile soils in the world. Historical use of biochar dates back at least 2000 years (O'Neill et al. 2009). In the Amazon Basin, evidence of extensive use of biochar can be found in the unusually fertile soils known as Terra Preta and Terra Mulata, which were created by ancient, indigenous cultures (O'Neill et al. 2009). Due to the large amounts of biochar incorporated into its soils, this region still remains highly fertile despite centuries of leaching from heavy tropical rains. In parts of Asia, notably Japan and Korea, the use of biochar in agriculture also has a long history. Recently, heightened interest in more sustainable farming systems, such as Korean Natural Farming, has revived the use of biochar in Western agriculture.

Environmental impact

Biochar can be a simple yet powerful tool to combat climate change. As organic materials decay, greenhouse gases, such as carbon dioxide and methane (which is 21 times more potent as a greenhouse gas than CO_2), are released into the atmosphere. By charring the organic material, much of the carbon becomes "fixed" into a more stable form, and when the resulting biochar is applied to soils, the carbon is effectively sequestered (Liang et al. 2008). It is estimated that use of this method to "tie up" carbon has the potential to reduce current global carbon emissions by as much as 10 percent (Woolf et al. 2010).

Production of biochar

Biochar is created by heating organic material under conditions of limited or no oxygen (Lehmann 2007). There are many ways to achieve this result. The type of organic matter (or feedstock) that is used and the conditions under which a biochar is produced greatly affect its relative quality as a soil amendment (McClellan et al. 2007, McLaughlin et al. 2009). The most important measures of biochar quality appear to be high adsorption and cation exchange capacities and low levels of mobile matter (tars, resins, and other short-lived compounds) (Glaser et al. 2002, Liang et al. 2006, McClellan et al. 2007, McLaughlin et al. 2009). Production of biochar generally releases more energy than it consumes, depending on the moisture content of the feedstock (Lehmann 2007). Heat, oil, and gas that are released can be recovered for other uses, including the production of electricity. A sustainable model of biochar production primarily uses waste biomass, such as greenwaste from municipal landscaping, forestry, or agriculture (for example, bagasse).

Frequently asked questions

Can barbeque charcoals be used as biochar?

Generally, no. Charcoal briquettes are mostly made from de-volatilized coal and contain chemicals that can be toxic to plant growth and should not be used in soils (McLaughlin et al. 2009). Lump charcoals, such as those made from kiawe (mesquite) or oak, are designed for use as cooking fuel. Analysis of several such charcoals revealed variation in quantities of undesirable tars, resins, and polycyclic aromatic hydrocarbons (PAH) and, typically, lower adsorption capacities, thus lessening their ability to improve soil quality (McClellan et al. 2007, Mclaughlin et al. 2009).

Is there scientific research showing increased plant growth with applications of biochar?

Yes. Studies in both tropical and temperate climates have demonstrated biochar's ability to increase plant growth, reduce leaching of nutrients, increase water retention, and increase microbial activity. In a study done on a Colombian Oxisol (a soil type also found extensively in Hawai'i), total above-ground plant biomass increased by 189 percent when biochar was applied at a rate of 23.2 tons per hectare (Major et al. 2005). Research indicates that both biological nitrogen fixation and beneficial mycorrhizal relationships in common beans (*Phaseolus vulgaris*) are enhanced by biochar applications (Rondon et al. 2007, Warnock et al. 2007). In Brazil, occurrence of native plant species increased by 63 percent in areas where biochar was applied (Major et al. 2005). Studies have also shown that the characteristics of biochar most important to plant growth can improve over time after its incorporation into soil (Cheng et al. 2006, 2008; Major et al. 2010).

Production of biochar. Top, *Melochia* species logs (3–4 inches diameter) can serve as organic matter for biochar production. Center, biochar produced by heat treatment. Bottom, close-up of biochar particles; this material's size is called ½$^{-}$ ("half minus") because it consists of ½-inch or smaller particles.

Is there scientific research indicating negative effects of biochar on plant growth?

Yes. Most cases of decreased plant growth due to biochar application can be attributed to temporary levels of pH, volatile or mobile matter (MM), and/or nutrient imbalances associated with fresh biochar (McClellan et al. 2007). Biochar often can have an initially high (alkaline) pH, which is desirable when used with acidic, degraded soils; however, if soil pH becomes too alkaline, plants may suffer nutrient deficiencies. "Mobile matter" refers to tars, resins, and other short-lived substances that remain on the biochar surface immediately after production and can inhibit plant growth (McClellan et al. 2007, McLaughlin et al. 2009). Good production practices can decrease the amount of MM in the biochar. Microbial activity can decompose and transform the carbon-rich MM into nutrients for plants; however, in the process, the microorganisms require nitrogen and other soil elements, rendering them temporarily unavailable for uptake by plants. These transitional imbalances are later corrected as MM decays, pH neutralizes, and unavailable nutrients are released.

What kind of biochar is the best?

The most important measures of biochar quality include adsorption, cation exchange capacity, mobile matter (tars, resins, and other short-lived compounds) and type of organic matter feedstock used. Over time, adsorption capacity of biochar decreases, whereas its cation exchange capacity increases (Cheng et al. 2008, McLaughlin et al. 2009). Mobile matter can block porosity and initial adsorption but is highly susceptible to biological decay, which can mitigate those effects. The physical structure of the feedstock, mainly its pore size, which greatly determines surface area, water retention, and biological utilization of the biochar produced, is essentially locked into form during "thermal modification." While a greater proportion of micro-pores may yield a higher surface area, and thus greater nutrient retention capability, many soil microorganisms are too large to utilize such small spaces and benefit from some amount of larger pore sizes (Warnock et al. 2007). In terms of increasing plant growth, biochar with various pore sizes may be best suited to enhance the physical, chemical, and biological characteristics of soils.

The process by which a biochar is produced is an important factor influencing its quality. While some methods have consistently produced low-quality biochar, other processes, when done properly, can yield high-quality biochar.

How long does biochar last?

Research on the Amazon Basin's Terra Preta soils and naturally occurring biochar from forest and grassland fires implies that biochar can persist for millennia with very little decay. Laboratory studies using the latest technology estimate that biochar has a mean residence time in soils on the order of 1300–4000 years (Cheng et al. 2008, Liang et al. 2008).

How much biochar should be applied?

The optimum application rate for biochar depends on the specific soil type and crop management. Formal scientific studies with Hawai'i's soils to answer this question have not yet been done. Informal observations of crop growth after biochar applications of between 5 and 20 percent by volume of soil have consistently yielded positive and noticeable results (see photos). Some research indicates that much lower application rates yielded positive results (Glaser et al. 2002). Biochar can also be applied incrementally and incorporated with fertilizer regimens or compost applications.

How is biochar applied to soil?

Biochar is most commonly incorporated into the soil. First, evenly spread the desired amount onto the soil, then till it in with machinery or by hand. In some cases, such as fruit orchards and other perennial crops where tilling is not an option, biochar can be (1) applied to the soil surface and, preferably, covered with other organic materials, (2) applied mixed with compost or mulch, or (3) applied as a liquid slurry if finely ground (on a large scale, this could be done with a hydromulcher). When planting trees or other potted plants, biochar can be mixed with the backfill material. Deep banding can also be been used under appropriate conditions.

Biochar as a component of compost can have synergistic benefits. Biochar can increase microbial activity and reduce nutrient losses during composting (Dias et al. 2010). In the process, the biochar becomes "charged" with nutrients, covered with microbes, and pH-balanced, and its mobile matter content is decomposed into plant nutrients.

Regardless of the application method, it is important to be cautious when handling dry biochar, which is very dusty and should not be spread in windy conditions. This

The biochar being applied in these photos weighed approximately 500 pounds per cubic yard. It should be spread evenly over the soil in a layer ¼–¾ inches thick (equivalent to 8.4–25.2 tons per acre). Hand tillage or a tractor-drawn rotavator can be used to incorporate it into the soil.

can be easily remedied by wetting the biochar before application. Respiratory protection (e.g., dust mask) should be worn when handling the dry material.

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The Guardian
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By GEORGE MONBIOT

Article 2

Woodchips with everything. It's the Atkins plan of the low-carbon world

The latest miracle mass fuel cure, biochar, does not stand up; yet many who should know better have been suckered into it

- 
  - George Monbiot
  - The Guardian, Tuesday 24 March 2009

Whenever you hear the word miracle, you know there's trouble just around the corner. But no matter many times they lead to disappointment or disaster, the newspapers never tire of promoting miracle cures, miracle crops, miracle fuels and miracle financial instruments. We have a limitless ability to disregard the laws of economics, biology and thermodynamics when we encounter a simple solution to complex problems. So welcome, ladies and gentlemen, to the new miracle. It's a low-carbon regime for the planet that makes the Atkins diet look healthy: woodchips with everything.

Biomass is suddenly the universal answer to our climate and energy problems. Its advocates claim that it will become the primary source of the world's heating fuel, electricity, road transport fuel (cellulosic ethanol) and aviation fuel (biokerosene). Few people stop to wonder how the planet can accommodate these demands and still produce food and preserve wild places. Now an even crazier use of woodchips is being promoted everywhere (including in the Guardian). The great green miracle works like this: we turn the planet's surface into charcoal.

Sorry, not charcoal. We don't call it that any more. Now we say biochar. The idea is that wood and crop wastes are cooked to release the volatile components (which can be used as fuel), then the residue - the charcoal - is buried in the soil. According to the magical thinkers who promote it, the new miracle stops climate breakdown, replaces gas and petroleum, improves the fertility of the soil, reduces deforestation, cuts labour, creates employment, prevents respiratory disease and ensures that when you drop your toast it always lands butter side up. (I invented the last one, but give them time).

They point out that the indigenous people of the Amazon created terras pretas (black soils) by burying charcoal over hundreds of years. These are more fertile than the surrounding soils, and the carbon has stayed where they put it. All we need to do is to roll this out worldwide and the world's problems - except, for the time being, the toast conundrum - are solved. It takes carbon out of circulation, reducing atmospheric concentrations. It raises crop yields. If some of the carbon is produced in efficient cooking stoves, it reduces the smoke in people's homes and means they have to gather less fuel, curtailing deforestation.

This miracle solution has suckered people who ought to know better, including James Lovelock, Jim Hansen, the author Chris Goodall and the climate campaigner Tim Flannery. At the UN climate talks beginning in Bonn on Sunday, several governments will demand that biochar is made eligible for carbon credits, providing the financial stimulus required to turn this into a global industry. Their proposal boils down to this: we must destroy the biosphere in order to save it.

In his otherwise excellent book, Ten Technologies to Save the Planet, Goodall abandons his usual scepticism and proposes we turn 200m hectares of "forests, savannah and croplands" into biochar plantations. Thus we would increase carbon uptake by grubbing up "wooded areas containing slow-growing trees" (that is, natural forest) and planting "faster growing species". This is environmentalism?

But that's just the start of it. Carbonscape, a company that hopes to be among the first to commercialise the technique, talks of planting 930m hectares. The energy lecturer Peter Read proposes new biomass plantations of trees and sugar covering 1.4bn hectares.

The arable area of the UK is 5.7m hectares, or one 245th of Read's figure. China has 104m hectares of cropland. The US has 174m. The global total is 1.36bn. Were we to follow Read's plan, we would either have to replace all the world's crops with biomass plantations, causing instant global famine, or double the cropped area, trashing most of the remaining natural habitats. Read was one of the promoters of first-generation liquid biofuels, which played a major role in the rise in the price of food last year, throwing millions into malnutrition. Have these people learned nothing?

Of course they claim everything can be reconciled. Peter Read says the new plantations can be created across "land on which the occupants are not engaged in economic activity". This means land used by subsistence farmers, pastoralists, hunters and gatherers and anyone else who isn't producing commodities for the mass market: poorly defended people whose rights and title can be disregarded. Both Read and Carbonscape speak of these places as "degraded lands". We used to call them unimproved, or marginal. Degraded land is the new code for natural habitat someone wants to destroy.

Goodall is even more naive. He believes we can maintain the profusion of animals and plants in the rainforests he hopes to gut by planting a mixture of fast-growing species, rather than a monoculture. As the Amazon ecologist Philip Fearnside has shown, a mixture does "not substantially change the impact of very large-scale plantations from the standpoint of biodiversity".

In their book Pulping the South, Ricardo Carrere and Larry Lohmann show what has happened in the 100m hectares of industrial plantations established around the world so far. Aside from destroying biodiversity, tree plantations have dried up river catchments, caused soil erosion when the land is ploughed for planting (meaning loss of soil carbon), exhausted nutrients and required so many pesticides that the run-off has poisoned marine fisheries.

In Brazil and South Africa, tens of thousands of people have been thrown off their land, often by violent means, to create plantations. In Thailand the military government that came to power in 1991 sought to expel five million people. Forty thousand families were dispossessed before the junta was overthrown. In many cases plantations cause a net loss of employment. Working conditions are brutal, often involving debt peonage and repeated exposure to pesticides.

As Almuth Ernsting and Rachel Smolker of Biofuelwatch point out, many of the claims made for biochar don't stand up. In some cases charcoal in the soil improves plant growth, in others it suppresses it. Just burying carbon bears little relation to the farming techniques that created terras pretas. Nor is there any guarantee that most of the buried carbon will stay in the soil. In some cases charcoal stimulates bacterial growth, causing carbon emissions from soils to rise. As for reducing deforestation, a stove that burns only part of the fuel is likely to increase, not decrease, demand for wood. There are plenty of other ways of eliminating household smoke which don't involve turning the world's forests to cinders.

None of this is to suggest that the idea has no virtues, simply that they are outweighed by hazards, which the promoters have overlooked or obscured. Nor does this mean that charcoal can't be made on a small scale, from material that would otherwise go to waste. But the idea that biochar is a universal solution that can be safely deployed on a vast scale is as misguided as Mao Zedong's Great Leap Backwards. We clutch at straws (and other biomass) in our desperation to believe there is an easy way out.

Portions of the article which begins on the next page are unnecessary for this activity and have been redacted; they are blacked out.

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Introduction

As we face catastrophic impacts of climate change, efforts to "engineer" the climate are proliferating along with a host of technofix "solutions" for addressing the many consequences of climate change. Among these is the proposal to use soils as a medium for addressing climate change, by scaling up the use of biochar.

Indeed soils around the globe have been severely depleted of carbon as well as nutrients – in large part due to destructive industrial agriculture and tree plantations as well as logging practices, raising serious concerns over the future of food production. Soil depletion has led many to conclude that improving soils might contribute significantly to addressing climate change as well as other converging crisis, by sequestering carbon, boosting fertility, reducing fertiliser use, protecting waterways etc.

But is biochar a viable approach?

Biochar is essentially fine grained charcoal, added to soils. Advocates claim it can sequester carbon for hundreds or even thousands of years and that it improves soil fertility and provides various other benefits – they seek support in order to scale up production. A common vision amongst biochar supporters is that it should be scaled up to such a large scale that it can help to reduce or stabilise atmospheric concentrations of carbon dioxide.

Research to date on biochar has had mixed results and clearly indicates that biochar is not one product but a wide range of chemically very different products which will have very different effects on different soils and in different conditions. Many critically important issues remain very poorly understood; there are likely to be serious and unpredictable negative impacts of this technology if it is adopted on a large scale and there is certainly no "one-size-fit-all" biochar solution.

Soils are extremely diverse and dynamic. They play a fundamental role in supporting plant, microbe, insect and other communities, interacting with the atmosphere, regulating water cycles and more. Unfortunately, like other such schemes, to engineer biological systems, the biochar concept is based on a dangerously reductionist view of the natural world which fails to recognize and accommodate this ecological complexity and variation.

Biochar proponents make unsubstantiated claims and lobby for very significant supports to scale up biochar production. But these supports have largely not been forthcoming. Nonetheless, vigilance is required. In particular, there is potential that agriculture and soils may be broadly included in carbon markets, which could open new potential for supports for biochar. Likewise, as climate geo-engineering discussions are becoming more prominent and accepted, there is potential that biochar could move forward under that guise.

It is imperative that we do not repeat past errors by embracing poorly understood, inherently risky technologies such as biochar that will likely encourage expansion of industrial monocultures, result in more "land grabs" and human rights abuses, further contribute to the loss of biodiversity, and undermine an essential transition to better (agro-ecological) practices in agriculture and forestry.

The following is a substantially expanded update of our initial 2009 briefing: "Biochar for Climate Mitigation: Fact or Fiction?" It is an interim version with the final report to be published during the UN Climate Conference in Durban in late 2011. Since our first briefing as published, there has been a considerable amount of new research, and many new industry and policy developments for biochar. In this update, we also address criticism of our previous briefing by the International Biochar Initiative.[1]

We hope this report will generate a deeper understanding of the issues and more critical thinking about biochar.

1 www.biochar-international.org/sites/default/files/Biochar%20Misconceptions%20and%20the%20Science.pdf

Terra preta

According to the UN Food and Agriculture Organization (FAO), some terra preta soils may be up to 2,500 years old. They are found in patches, generally along the Amazon and tributaries, and are otherwise surrounded by the infertile soils typical of this region. Researchers have found evidence of "garden cities" along the Berbice River in Guyana Amazon: areas with rich Terra Preta soils where a large variety of trees, shrubs and perrenial crops were grown in long crop cycles with intercropping and seasonal flooding. The soils contain large amounts of turtle shells, fish and mammal bones, pottery shards, kitchen waste and human excreta – as well as charcoal. These provide insights into the production of Terra Preta, but as the FAO states: " The knowledge systems and culture linked to the Terra Preta management are unique but have unfortunately been lost. Amazon Dark Earths are, however, still an important, yet threatened resource, as well as an agricultural heritage that needs better scientific understanding". Win Sombroek, described as the "founding father of the carbon-negative biochar initiative" had prior to his death, worked to "replicate and emulate the anthropogenic black earths of the pre-Colombian Indian tribal communities."

Many soils around the world do contain charcoal – from wildfires and in some cases likely the result of swidden cultivation in the past. British researchers have begun studying ancient dark, carbon-rich soils in different West African countries, the African Dark Earths Project. Problematically, the project aims combine studying "indigenous knowledge and practices" with looking at "the value now attributed to biochar for soil enhancement, carbon sequestration and clean energy production". As with terra preta, this raises the concern of indigenous knowledge being appropriated and used to help attract subsidies and carbon offsets for biochar entrepreneurs and companies in the North. Various patent applications and trademarks for biochar and 'terra preta' production have already been submitted by companies.

Traditional terra preta methods appear to be a lost art - according to an agronomist with 35 years experience working with small farmers across different states in Brazil, the deliberate use of charcoal as a soil amendment was never encountered (she had only heard about biochar in the context of carbon offsets). Elsewhere there are anecdotal reports that farmers in the Batibo region of Cameroon use charcoal made by burning mounds of grass covered by earth as a soil amendment. The indigenous Munda communities in Northern India reportedly add charcoal from cooking stoves with burnt grass and farmyard manure to their soils.

Biochar advocates claim that burying charcoal in soils is a viable means of sequestering carbon for hundreds or even thousands of years. According to the IBI, biochar could sequester 2.2 billion tonnes of carbon every year by 2050 and that carbon would be stored in soils for hundreds or thousands of years. This and similar claims are repeated over and over in biochar literature. In addition, they state that using syngas and pyrolysis oils to displace burning of fossil fuels, will further reduce carbon in the atmosphere. Advocates claim that using biomass is carbon neutral, but that biochar goes yet further to be "carbon negative" because not only will trees/plants grow back, but also some portion of the carbon from each generation of biomass produced and charred will supposedly be more or less permanently sequestered.

The assumption that biochar carbon will remain stable in soils for hundreds or thousands of years is based on making an analogy between modern biochar and ancient Terra Preta soils. Terra Preta, also called "Amazon Dark Earths" are soils made by indigenous peoples in the Amazon region long ago, using charcoal along with various other materials. Those soils remain highly fertile and carbon rich hundreds and even thousands of years later. The processes involved in creating Terra Preta are no longer known, but likely bear little resemblance to modern biochar. The addition of modern biochar to soils as it is has been practiced in the limited number of field tests to date, involves industrial agriculture practices – monocultures, using some combination of biochar with synthetic fertilizers, manure, or both, as well as pesticides and other agrochemicals. Terra Preta soils contain charcoal, but this is likely the extent of any commonality.

Given that there are so many known, and likely more unknown differences between modern biochar practices and the creation of Terra Preta, it is a stretch to draw the analogy. Yet some companies even refer to their biochar products as "Terra preta", or make claims that use of their biochar will enable users to turn their soils into Terra preta.[7]

What is deeply concerning is that the long term stability of biochar carbon in soils, the basis for claims that biochar is a viable solution for climate change - is *assumed* on the basis of this weak analogy. A review of research on the stability of biochar carbon in soils is therefore quite important, and follows in chapter 3.

Irrespective, many biochar advocates envision very large scale global deployment with the idea that it will contribute significantly to reducing greenhouse gas emissions. James Amonette describes the potential for sequestering 130 billion tones of CO2 over a century. Jim Fournier goes so far as to claim that biochar could resequester all carbon ever emitted from fossil fuel burning over 50 years. While some biochar advocates have been adamant in claiming that only "wastes and residues" should be used for biochar production, clearly many have no hesitations in calling for quite large scale land conversion and dedicated plantations for biochar feedstocks. An article published in Nature Communications and authored by members of the International Biochar Initiative examined the "theoretical potential" for biochar.[8] They claim that very large scale implementation of biochar on a global scale could reduce global emissions of greenhouse gases by 12% annually. This number is based on calculations of biomass availability that would require fantastic infrastructure and capacity to harvest and transport large quantities of biomass from virtually all landscapes, process in pyrolysis facilities, and then redistribute the biochar and till it into soils – over very large areas of the earth's surface. They also base this number on the conversion of over 556 million hectares of land to the production of biomass crops for char production. All based on the assumption that biochar actually "works".

At the pinnacle of large scale biochar promotion is the push to have biochar considered as a viable means for climate geo-engineering, under the category of technologies that are referred to as "Carbon Dioxide Removal" (CDR). Members of IBI submitted a recommendation to the Royal Society consultation on geo-engineering and a number of IBI science advisory committee members advocate directly for biochar as climate geo-engineering, (or indirectly – by advocating very large scale deployment and land conversion). In this context, advocates have taken to describing biochar as a means to "manage" and "enhance" the carbon cycle to withdraw more CO2 from the atmosphere.[9]

In addition to the claims regarding the potential for biochar to sequester carbon, other claims are also made, including 1) that biochar improves soil fertility, therefore can increase crop yields and reduce fertilizer demand. 2) that biochar reduces N2O emissions from soils, 3) that deforestation can be reduced by transitioning from traditional slash and burn to "slash and char" agriculture, and 4) that pyrolytic (biochar producing) cookstoves can benefit the poor by providing more efficient and cleaner cookstoves while at the same time providing a soil amendment that will enhance yields. Each of these claims is also analyzed in more detail in the following chapters.

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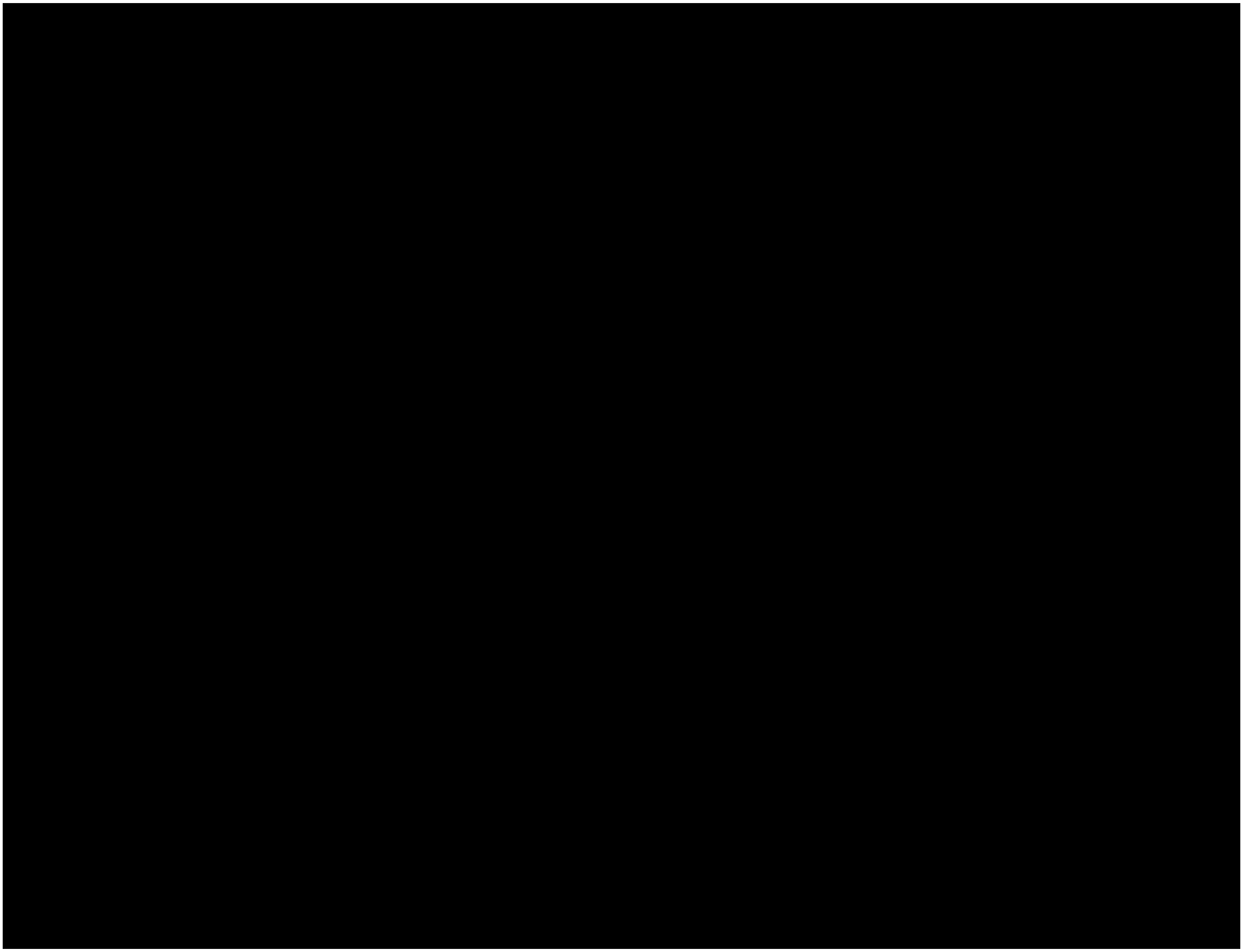
2 http://www.biochar-international.org/biochar/faqs#question1

3 Dimpl, E, Blunck, M. 2010: Small-scale Electricity Generation From Biomass: Experience with Small-scale technologies for basic energy supply: Part 1: Biomass Gasification. Gtz, commissioned by the Federal Ministry for Economic Cooperation and Development

4 Effect of biochar amendment on soil carbon balance and soil microbial activity S. Steinbeiss et al, Soil Biology & Biochemistry 41 (2009)

5 See for example: http://www.carbonbrokersinternational.com/ This website states: "we sell sustainable, renewable replacements for fossil fuel. We offer coal substitutes, bio crude oil, activated carbon and soil biochar… Carbon products resulting from the waste conversion process offer an additional revenue stream in the form of biochar, coal substitute and activated carbon. These products can be used as a substitute for coal based activated carbon, metallurgical coke and for power generation, cooking and heating, a fertilizer enhancer/soil amendment, and many other uses currently using coal."

6 See for example Black carbon contribution to stable humus in German arable soils, Sonja Brodowski et al, Geoderma 139 (2007) 220-228



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[16]. 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:

- 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;

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

- 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[17]. 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[18]. 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[19]. 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[20]. A scientific review by Johannes Lehmann et al suggests that on average only 3% of biomass carbon is turned into black carbon during fires[21]. 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[22]. The maximum 40% biomass carbon to black carbon conversion figure[23] 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)[24]. 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 [25]. A study of Russian steppe soil showed black carbon remaining in soil for a period between 212 and 541 years[26]. 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[27]. 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 [28]. 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[29]. Yet another study, looked at black carbon concentrations in soils underneath a Scots pine forest in Siberia which had been regularly exposed to fire[30]. 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[31]. 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[32]. 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[33] 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"[34] 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[35], for example, whereas some may be transported to sites where it will be exposed to conditions making it less likely to remain stable.

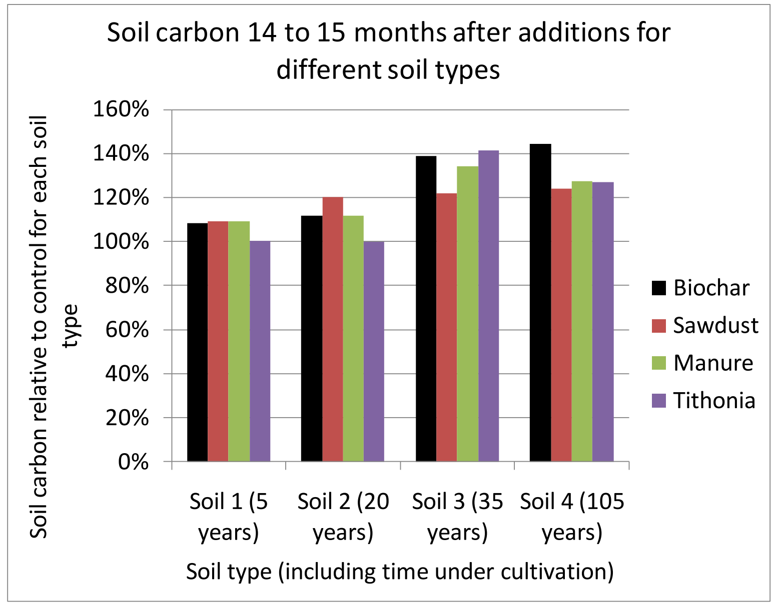
One study, which looked at the fate of black carbon from swidden agriculture on steep slopes in Northern Laos, found that it was significantly more prone to water erosion than other soil carbon, due partly to its low density and weight[36]. The same properties also make black carbon, especially smaller particles, prone to wind erosion[37]. 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. [c]. 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)"[38] 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 [39]. 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 [40]. 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 [41]. 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 [42]. 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 CO_2, 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 [43] 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[44]. In sum: biochar can cause a proportion of other carbon in soils to be turned into CO_2, 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.

[redacted]

c 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.

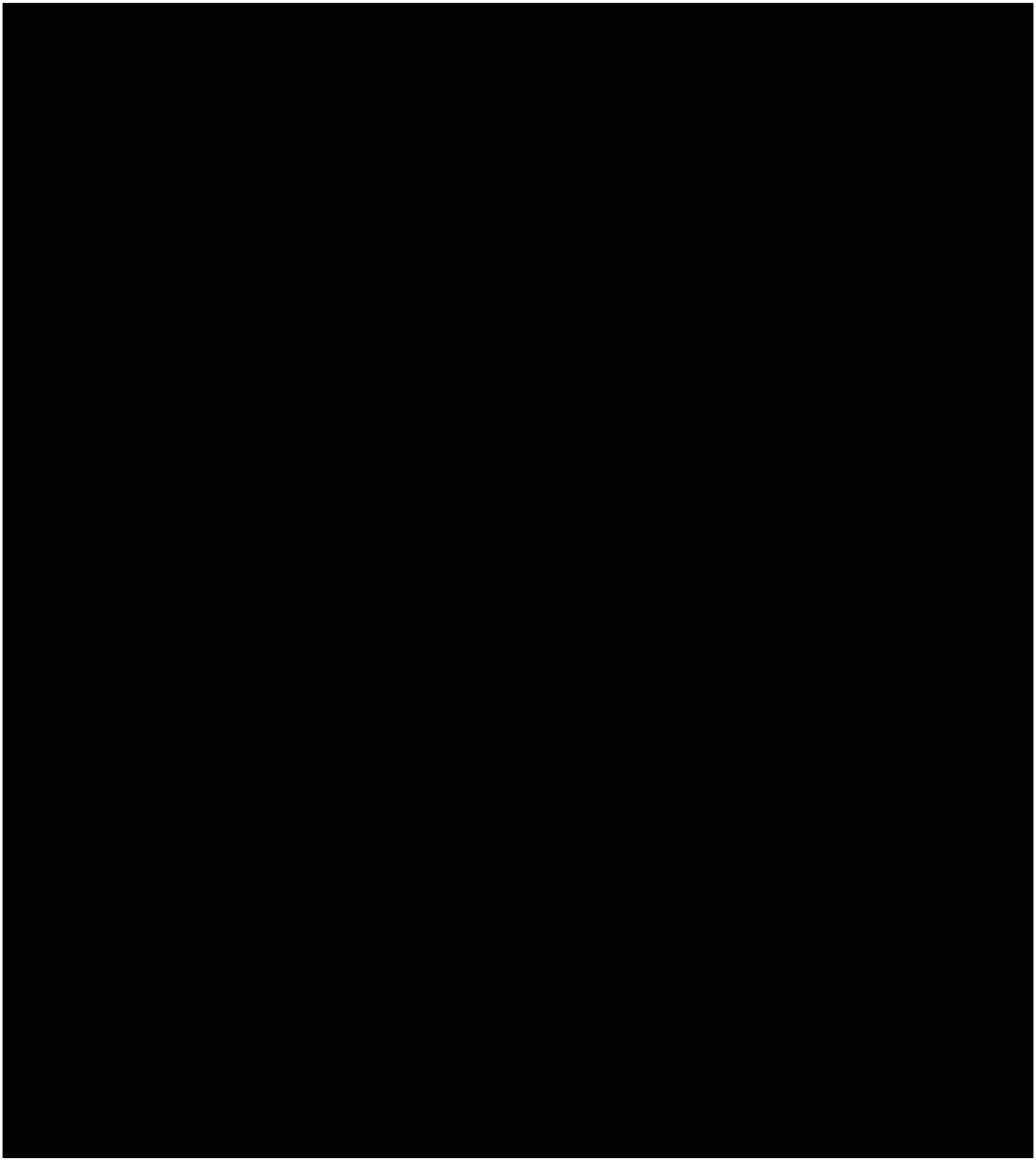
[redacted]



[redacted]

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[51]. 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 CO_2[52]. 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"[53]. 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"[54]. 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"[55]. 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[56], 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).



Biochar cook stoves

Another form of biochar promotion to "benefit the poor" involves biochar cookstoves. According to the World Health Organization, indoors pollution from biomass and other solid fuel cookstoves is responsible for 1.5 million deaths a year, over two-thirds of them in South-east Asia and sub-Saharan Africa[97]. Clean-burning stoves thus need to be a high public health priority. In recent years, clean biomass cook stoves have been increasingly promoted for climate change mitigation as well, because the soot emitted from open cooking fires contributes to global warming. While soot undoubtedly contributes the climate change, the contribution from cook fires in Southern countries remains highly uncertain. Fossil fuel burning as well as destructive fires, such as those set by plantation companies for large-scale forest and land clearance are major contributors to soot globally[98]. However, there is no doubt that clean and fuel-efficient cookstoves are vital for people's health, for reducing the time and impact of collecting wood and other biomass and that reducing all forms of soot emissions is important for reducing the speed and level of climate change.

Biochar cook stoves

Biochar-producing stoves are a type of stove commonly called 'micro-gasifiers' or 'wood gas stoves'. These stoves expose biomass in various forms (depending on design), to very high temperatures such that gases are released and these are then burned in a separate part of the stove for cooking. This reduces (indoor) air pollution, and compared to open cook fires, is a cleaner and more efficient method. Most micro-gasifiers currently gasify all of the biomass except for the ash that is left behind. Those are also called 'char-gasifiers' because the char is used to provide more heat for cooking. Biochar-producing stoves are adapted from this general design and allow the char to be retained and removed instead. No recent independent audit or comparative study of different modern biomass stoves, including micro-gasifiers has been undertaken, which makes it difficult to assess the performance of these different stoves. A recent German report reviewing 'micro-gasifers' summarizes based on the claims made by manufacturers. All are promoted as clean and efficient, but there is no independent data and no assessment of how practical they are for use. For example, some can only burn pelletized biomass, which may not be easily accessible. The German review was produced in collaboration with the IBI, however the data published (largely taken from developers) suggests that char-gasifying stoves provide more heat for cooking from the same volume of biomass compared to stoves that produce biochar. This makes sense given that more of the biomass is converted to useable energy rather than retained as char residue. Biochar producing stove efficiency should best be compared to other efficient biomass stoves, not to open fires. Their relative inefficiency has also been confirmed in a recent study about biochar stoves published by the UK Biochar Research Centre. They state: "More biomass ends up being used where biochar is produced and this additional collection costs time and removes more biomass. In order to counter these very real disadvantages, the benefits of applying biochar to soil would need to be very evident to the stove user and her household". The UKBRC research included pot trials using biochar from stoves the results of which described as 'somewhat mixed'. In some, though not all, cases crop yields improved when such biochar was applied at a rate of 20 tonnes per hectare. Producing this amount of biochar, not for a pot but for a one hectare field, would require a family to save up biochar from a stove over many decades (by which time, of course, it would not longer be fresh biochar and might not have the same impacts on crops). WorldStove for example, reports that a family cooking on one of their stoves three times daily for a year would produce about 438 kg of biochar over the course of the year . Therefore it would take about 46 years to produce enough biochar to treat a hectare of land with 20 tonnes of biochar. However, efficiency is not the only concern. As the UK Biochar Research Centre's stove study confirms, there are also questions whether different micro-gasifiers meet women's practical needs for cooking. For example, once a such a stove has been lit, the cooking temperature cannot generally be turned up or down and it is difficult or impossible to add more biomass or to switch the stove off early, making cooking more difficult and inflexible. Char removal can also be problematic in some designs, which require it to be either removed hot, risking accidental fires or burns, or to be quenched with water, causing the metal of the stove to corrode.