Biochar for soil quality improvement, climate change mitigation and more

A literature review by Julie Major, Ph.D.

Foreword

This review was prepared with the goal of providing science-based information on a wide range of aspects of biochar science and technology and inform the reader about the current state of this science and technology, in Canada and elsewhere. Biochar is still a poorly known technology, although it has roots that extend far into the past. However, knowledge about how and why biochar works is being generated at an accelerating rate. Still little is known about practical aspects of working with biochar on farms and in gardens, but as this technology becomes more widely used, it will become possible to formulate best management practices for different biochar use types.

Introduction: the origins of biochar science

Biochar is a new word for many, but the technology is a traditional one in several regions of the world. Biochar refers to a kind of charcoal made from biomass. Unlike charcoal made for fuel, biochar has properties which make it a valuable soil amendment. Before exploring biochar materials in more detail, it is useful to understand where the recent interest for the study and use of biochar as a soil amendment comes from.

Terra preta de Indio, "black soil of the Indians"

Soils in the Amazon Basin are largely represented by Oxisols and Ultisols (Brady and Weil, 2008), which are acidic and highly weathered. High temperatures and rainfall throughout the year, coupled to the low ability of these soils to retain positively charged plant nutrients result in highly leached, nutrient poor soils (van Wambeke, 1992). When natural vegetation is cleared and its complex biological networks destroyed, the soil is of low value for agriculture. Partly because of this, for a long time it was believed that large settlements of organized societies did not exist in the Amazon in pre-Columbian times (Evans and Meggers, 1957). The "re-discovery" of *Terra preta* soils starting about 40 years ago (Sombroek, 1966) sheds a doubt on such theories: *Terra preta* soils were most likely formed in the kitchen middens of indigenous people, by the accumulation of charcoal and nutrient-rich food and bone wastes among others (Lehmann et al., 2003a). The resulting soils are up to 2 m deep and cover areas ranging from several hundred square meters to several hectares, indicating large amounts of people living at these locations for long periods of time, until contact with Europeans. It is difficult to estimate the total area covered by these anthropogenic soils, since the majority of them are currently covered by vegetation. However, it is the fact that these soils remain fertile to date (Major et al., 2005), centuries to millennia after they were formed (Liang et al., 2008), that motivated researchers to learn from *Terra preta* with the goal of improving soil fertility in other regions of the world. Indeed the charcoal, or biochar, which makes these soils black has been shown to be a beneficial soil amendment.

Other examples of traditional use of charcoal in agriculture

In Japan, biochar has been employed at least since 1697, where the oldest published mention of rice husk biochar use in soil is made (Ogawa and Okimori, 2010). Biochar has been used since then in agriculture and horticulture, including for improving the vigor of ancient pine trees near shrines (Ogawa and Okimori, 2010). R.L. Allen's 1846 *A Brief Compend of American Agriculture* makes several mentions of charcoal use in agriculture, including as a soil amendment and feed additive. In Spain, the construction of structures similar to charcoal kilns was historically used to fertilize soil, and this technique is still used in India and Bhutan today (Olarieta et al., 2010).

What biochar is and what it is not

Biochar can be made from any biomass feedstock including crop, forestry and yard wastes, and animal manures. The feedstock undergoes a process called pyrolysis, which results in a rearrangement of the biomasse's molecules, yielding black biochar and other products. Charcoal, which is a fuel made from biomass, is also produced by pyrolysis. However, charcoal has specific properties which make it a good fuel, and while to date no classification and standardization system exists for biochar, scientists believe that characteristics which will make a good biochar soil amendment will differ from those which make a good fuel. Biochar characteristics are explored further below.

Biochar is very different from mineral coal. Mineral coal originated as biomass, but was formed by geological processes over geological time scales. Biochar always contains some ash, because biomass always contains elements other than carbon (C), hydrogen and oxygen. But biochar contains stable C in various amounts, whereas actual ash does not.

How is biochar made?

The pyrolysis process

Biochar is made by "baking" biomass in the presence of little or no oxygen. This differs from actually burning biomass because in an open fire, plenty of oxygen is available to fully oxidize the C in the biomass to CO_2, thus practically all the C leaves as CO_2 and only ashes and small amounts of C are left behind. Restricting oxygen availability results in a greater retention of C in the biomass, however the efficiency of the process in terms of C is usually 50% or less (Lehmann, 2007), i.e. only half the C in the feedstock or less remains in the biochar. This is because not only biochar results from the pyrolysis process: combustible gases and volatile compounds also escape from the pyrolyzing biomass.

When biomass is heated up from ambient temperatures, it begins to dry. First, moisture in the biomass must be driven off and this requires the supply of energy because the heat capacity of water is high: large amounts of energy are required to vaporize water (Taylor and Mason, 2010). This has consequences for the use of wet feedstocks to make biochar: they should ideally be passively dried (e.g. in the sun) to 10-15% moisture before being subjected to pyrolysis. Once the biomass is dry, the torrefaction process begins. During torrefaction, the biomass is “roasted”, and becomes darker in color as chemical changes occur and some gases and volatile compounds exit the biomass. As the biomass is further heated and reaches ~ 300°C, true pyrolysis begins and the process becomes exothermic. The biomass completely rearranges itself into solid biochar, combustible gases and volatile compounds (Taylor and Mason, 2010). Overall, pyrolysis produces heat as well as fuels which can be burned at once to produce more energy in the form of heat and potentially electricity, or gases and volatiles can be refined and used as fuels in other applications. Thus, the pyrolysis process by which biochar is made produces renewable energy which can be used to displace fossil fuels.

Pyrolysis can further be subdivided into fast and slow pyrolysis, and the gasification process can also generate biochar, under certain conditions. Differences between these general pyrolysis types include the time over which pyrolysis occurs, but many other conditions of the pyrolysis process can be varied and have an impact on the characteristics of the resulting biochar. These include but are not limited to the maximum temperature reached and the pressure in the pyrolysis chamber. Also, the type of feedstock used to make biochar has an impact on the qualities of the resulting biochar, and these are further discussed below.

Making biochar in practice

Pyrolysis units can take a wide range of shapes and sizes, but they all share at least one design characteristic: a closed reaction compartment where pyrolysis occurs in the absence (or the presence of small amounts) of oxygen. The level of engineering complexity of pyrolysis units can also vary widely: from hand-made cook stoves to large plants and all sizes in between. The following are some examples of pyrolysis units which display a wide range of scales and engineering complexities. They are by no means the only examples and their selection here does not imply any guarantee of safety or efficiency or an endorsement of the technologies, units or their makers.

<u>Biochar cook stove</u>

Many biochar-making types of cook stoves have been developed, but none are currently widely used in developing countries. Several factors influence the extent to which improved stoves are used, including the benefits they actually provide to users, their price and availability. Figure 1 shows a clay cook stove, handmade in a village in Kenya from locally available clay. While women in Kenya traditionally use wood to cook, and wood is used here to provide the heat necessary to bring the biomass feedstock to pyrolysis temperatures, this stove can char finely divided feedstocks such as crop residues. This is a batch process pyrolysis unit, meaning that the biomass feedstock is loaded into the stove, and biochar is unloaded only after the completion of the process and the cooling down of the stove. Stoves such as this one greatly reduce the amount of smoke produced during cooking, compared to traditional wood fires, and this could have a major impact on the health of women and children.

Figure 1. Hand-made biochar cookstove in Kenya. Photo by D. Torres.

<u>55 gallon retort kiln</u>

This unit may be appropriate for small farmers and gardeners. Its construction does require metal working skills, but it can be made from widely available materials. A 55 gallon drum is fitted with a chimney which redirects the smoke (i.e. gases and volatile matter exiting the charring biomass) under the drum where a fire was lit to start the process (Fig. 2). This ensures that the process is “clean”, i.e. no smoke is produced since it is burned clean to CO_2 and H_2O. The unit as shown is not designed to make use of the heat generated in the process. This is also an example of a batch pyrolysis unit. Many different pyrolysis unit designs make use of 55 gallon drums.

Figure 2. Biochar kiln made from a 55-gallon drum. Photographer unknown.

<u>Biochar Engineering Corp.’s U5 unit</u>

This is a more complex, continuous flow but mobile unit currently available for purchase (Fig. 3). It is transported and operated on a trailer. Feedstock can be delivered to the unit by an auger continuously, while biochar also exits the unit continuously. Process heat can be used if additional equipment is connected to the unit. Unit operations are controlled by computer, and it does not produce smoke.

Figure 3. U5 Beta, a mobile continuous flow pyrolysis unit. Photo provided by Biochar Engineering Corp.

Pacific pyrolysis

This is a stationary, continuous flow pyrolysis unit. The unit shown in Fig. 4 processes 300 kg of dry biomass per hour, but Pacific Pyrolysis has designs for units which process up to 4 tons of dry biomass per hour (96 tons per day). The unit shown here produces biochar from "green waste" (e.g. yard waste and tree prunings) and powers a 200 kW electricity generator.

Figure 4. Fixed pyrolysis unit. Photo provided by Pacific Pyrolysis.

Before setting out to make biochar, it is necessarily to obtain information on and abide by all locally applicable rules and regulations. One should also seek help from experienced biochar makers to ensure not only that they produce quality biochar, but that they handle it properly after making it. For example, biochar can spontaneously ignite when it is exposed to air soon after it was produced (Blackwell et al., 2009).

Biochar as a material

A notable characteristic of biochar is its high porosity. The bulk density of biochars made from plant biomass is lower than that of the corresponding feedstock (Downie et al., 2009). Biochar generally retains the cell wall structure of the biomass feedstock, as observed in scanning electron micrographs (Fig. 5). At a smaller scale, biochar consists largely of amorphous graphene sheets, which give rise to large amounts of reactive surfaces where a wide variety of organic (both polar and non-polar) molecules and inorganic ions can sorb (Levine, 2009). Indeed the pore space of biochar is many orders of magnitude greater than that of uncharred biomass (Downie et al., 2009).

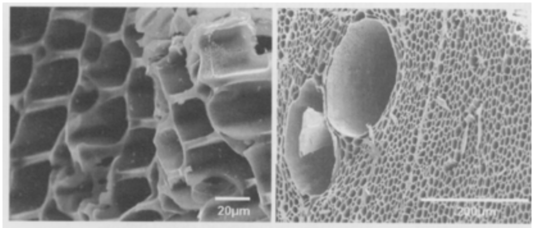

Figure 5. Xylem structures observed in wood-based biochar. Left picture by S. Joseph, right picture by Yamamoto.

To date, no widely accepted quality standards exist for biochar, although several groups including the International Biochar Initiative are working on developing some. Such standards are necessary to protect the nascent biochar industry from "snake oil" dealers, since at this time anyone can sell anything as biochar. Many industry players are interested in developing their own standards before have some imposed upon them, which were developed outside the industry. Biochar characterization, classification and standardization schemes will need to include specific methodologies for analyzing biochar to determine its characteristics. While analytical methods can be adapted from existing soil and charcoal analysis methods in many cases, many will need to be modified for analyzing biochar. In the case of soil analysis methods, modifications may be necessary because biochar does not behave like soil and some soil analytical procedures simply do cannot be carried out with biochar. For example, the pH of soil can be measured in a 1:2.5 soil:water ratio, but for certain biochars the ratio needs to be widened, for example to 1:10 (Major et al., 2010b). The low density of biochar and its propensity to float before it is fully imbibed result in more water begin required. In the case of standard fuel charcoal analysis techniques, some methods will need to be modified to produce results which relate to the effect biochar will have in soil. For example, "volatile matter" in charcoal is measured at 950ºC, and it is difficult to relate this "volatile matter" to functions of biochar in soil.

Generally speaking, biochar can be understood to contain four important fractions: moisture, ash, stable and unstable matter (McLaughlin et al., 2009). The words "stable" and "unstable" have not been widely adopted, but the fractions they represent as explained below are generally considered to be key determinants of the effects of biochar in soil.

<u>Moisture</u>

The moisture content of biochar does not have an impact on its usefulness as a soil amendment, but does have serious implications for the purchasing, handling and application of biochar to soil. When it exits the pyrolysis unit, the reaction of air with biochar can cause it to spontaneously ignite (Blackwell et al., 2009). Trucks transporting biochar have caught fire in transit, and it is considered a dangerous material for shipping. A simple way of avoiding spontaneous combustion is to spray the biochar with water as soon as it exits the pyrolysis unit, however this is undesirable to the extent that it makes the biochar more heavy for transportation. Biochar can hold up to three times its own weight in moisture (McLaughlin et al., 2009; see Fig. 6), and it can contain a large percentage of moisture without looking like it does. Since currently the biochar market is a "buyer beware" one, those who purchase biochar must ask about the moisture content of the material. It is also important to report biochar application rates on a dry basis, to facilitate comparisons between experiments.

Ash

The different feedstocks used to make biochar contain various amounts of ash, and this ash it mostly maintained in the biochar. However, it represents a greater proportion of the overall material since some C, hydrogen and oxygen are lost during pyrolysis. Wood contains less ash (< 1%) than straws and other crop residues (up to 24%), which also contain more silica (Raveendran et al., 1995), thus for example wood biochar contains less ash than straw biochar made under similar conditions. Manures produce what are known as "high-ash biochar", with ash contents up to 45% (Koutcheiko et al., 2007). The ash content of biochar is measured by heating it to high temperatures in the presence of air: all of the non-mineral matter is combusted and the ash left behind. Standard methods developed for determining the ash content of fuel charcoal can be used for biochar, e.g. ASTM D1762.

Biochar ash consists mainly of calcium (Ca), iron (Fe), magnesium (Mg), sodium (Na), potassium (K), phosphorus (P), silica (Si) and aluminum (Al) (Amonette and Joseph, 2009). The ash of biochar made from plant parts generally contains very small amounts of nitrogen (N). With the exception of Al these elements are plant nutrients, thus applying them to soil with biochar may alleviate deficiencies and improve crop growth. This effect is explored further in the section on agronomic benefits of biochar. However, it is possible to cause salt stress in plants, if large amounts of high-ash biochar are applied to soil. Revell et al. (2010) found that lettuce seed germination was inhibited due to salt stress when chicken litter biochar containing 60% ash was added at to soil at 34 t/ha.

Unstable matter

Conceptually, unstable matter refers to the fraction of biochar which is decomposed by soil microorganisms in the days and months following soil application. This fraction is important because its decomposition has the potential to lead to N immobilization, if insufficient N is available in the soil during decomposition. Indeed some authors observed reductions in biomass yield with biochar application, and attributed this effect to potential N immobilization by biochar (Asai et al., 2009; Blackwell et al., 2010; Rondon et al., 2007). Also, since it decomposes on a short time frame, it is important to know the size of this fraction of biochar in order to assess the C sequestration potential of a biochar material. Total C analysis alone does not fully indicate the C sequestration potential of biochar, it is necessary to know the amounts of unstable and stable matter (and C) it contains.

In practice, it is difficult to directly measure the size of this fraction. Long-term soil incubation studies are underway, but large data sets will be required to fully understand how different biochar materials decompose in different soils, and under different abiotic conditions. Long-term field studies are an even better tool to assess the longevity of biochar in soil, but these are costly and logistically difficult to maintain. Finding rapid and cheap laboratory tests that provide data relating to the fractions of biochar which decompose in soil in the short to medium term would be ideal. To date, members of workgroups on biochar characterization around the world have proposed heating the biochar to temperatures around 450ºC, under an oxygen-free atmosphere, and quantifying the amount of “unstable” matter as the difference in mass before and after heating (e.g. McLaughlin et al., 2009). This is economical and quick, but more data is needed in order to relate information provided by this test to biochar decomposition in soil by biotic and abiotic factors.

<u>Stable matter</u>

The recalcitrant fraction of biochar, which persists in soil over the long term, can be termed “stable matter”. This fraction of biochar includes domains which are chemically recalcitrant to biotic and abiotic decomposition in soil. The size of the stable and unstable biochar fractions can vary, as illustrated in Fig. 6.

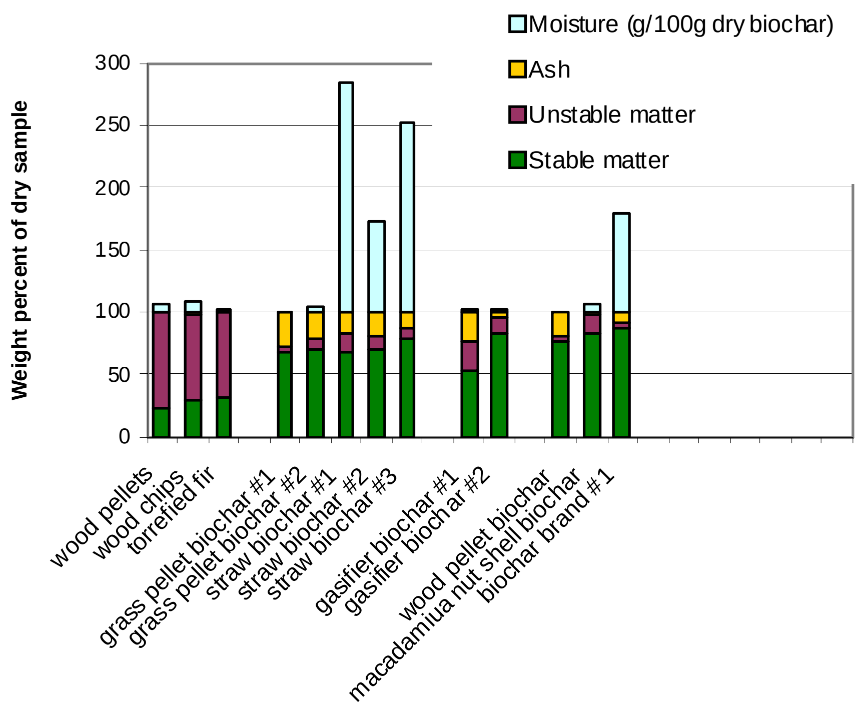

Figure 6. Moisture, ash, stable and unstable fractions of several different biochar materials and 3 biochar feedstocks. “Unstable matter” was determined by heating biochar to 450ºC in the absence of oxygen. From McLaughlin et al. (2009).

Finally, biochar is very friable and always contains small particles. Especially fast pyrolysis biochars, which are made from finely divided feedstocks, can be extremely dusty. This is an important issue when handling and applying biochar to the field. In a biochar field trial in Québec, it was estimated that 30% of the biochar to be applied was lost during handling, transport to the field and application (Fig. 7, Husk and Major, 2010). This is a problem not only because users need biochar to be in their soil and not elsewhere, but also because it is harmful to breathe small biochar particles.

Figure 7. Clockwise from top left: Biochar losses during handling, transportation to the field, application and incorporation in a field trial in Québec. Photos by B. Husk.

A best management practice when working with biochar is to ensure the control of dust, either by moistening it with water or mixing it with another soil amendment, for example compost or manure.

Biochar impact on soil quality

The effect of biochar on soil quality and crop productivity has been observed to vary, but is generally positive. Among the first experiments (ca. 1980-2009) where biochar was applied in the field, and for which results have been published, the majority was carried out in soils of low fertility, including acidic tropical soils. In general, large yield improvements were obtained when biochar was applied on such soils, up to 300% over adequate, unamended controls (reviewed by Blackwell et al., 2009; and Lehmann and Rondon, 2006; also Peng et al., 2011; Van Zwieten et al., 2010c). In flooded rice paddy soils of China, biochar improved yield by up to 14% (Zhang et al., 2010a). Long-term positive effects of biochar applications were observed in a few studies which were monitored over several years (Blackwell et al., 2009; Major et al., 2010b; Steiner et al., 2007). Some authors noticed a greater effect of biochar in poorer than more fertile soil.

More recently, biochar has been tested in soils of temperate climates and of generally higher fertility, with more modest biomass production improvements in the range of 4-20% (Laird et al., 2009; Husk and Major, 2010). As demonstrated for the dataset in Figure 8, no general trend relating amounts of biochar applied to effects on yields can be observed. This stems from the fact that trials involved different soil types, crops, soil amendments other than biochar, etc. To date it is still not possible to make recommendations for biochar application rates to different soil types and cropping systems, nor have “excessive” application rates been determined. For one-time applications, the upper limit may need to be set by practical considerations relating to applying and incorporating biochar in soil. In the literature, 5-50 t/ha of biochar have been shown to improve crop growth in pot and field experiments. On farms, amounts greater than 10 t/ha might not be practical in cases where existing field machinery is used for application and incorporation. As demonstrated by Blackwell et al. (2010), the interaction of biochar with fertilizer rate and type as well as other factors such as inoculation with mycorrhizae is complex and not yet well understood. More field trials like that of Blackwell et al. (2010), which are carried out simultaneously on several sites and assess the effect of biochar in combination with several levels or other production factors, are required.

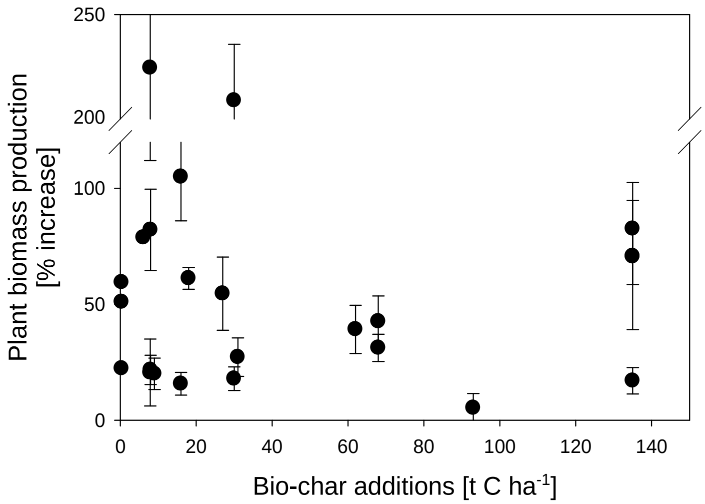

Figure 8. Percent biomass production increase with biochar application to soil. Biochar-amended treatments were compared to plots under best management practices, without biochar amendment. Crops include several bean types, rice, alfalfa, corn and native savanna grasses. From Lehmann and Rondon (2006).

Some studies documented lower yields when biochar was applied compared to unamended controls. In some cases the authors attributed reductions to N immobilization with biochar (Asai et al., 2009; Blackwell et al., 2010; Rondon et al., 2007), and this phenomenon is expected to be of relatively short duration while the “unstable” fraction of biochar is decomposed. Kishimoto and Sugiura (1985, cited in Chan and Xu, 2009) found 37 and 71% lower soybean yields with biochar application of 5 and 15 t/ha, respectively, and attributed the reduction to the rise in pH induced by the biochar, which lead to micronutrient deficiencies. This occurred because the pH of the soil was already at the high end of the optimal range for soybean production. Gaskin et al. (2010) observed lower corn yields with peanut hull biochar applied at 22 t/ha compared to the unamended control under fertilized conditions, in the 2 years following biochar application in the field. When pine chip biochar was applied, yield reductions occurred at both 11 and 22 t/ha of biochar in the first but not the second year of the trial. Both trial years were marked by drought (Gaskin et al., 2010).

It is interesting to note that in the 3rd year of a biochar field trial in the Estrie region of Québec, the forage value of mixed species grown on soil which had received 3.9 t/ha of biochar 3 years earlier was markedly greater than in forage growing on unamended soil (Husk and Major, 2011). While this trial is not a replicated one, the increases in forage quality and expected cow milk produced from the forage (44%

increase) are very encouraging, and occurred with modest (4%) increases in biomass production. There is interest in testing the effect of biochar on the nutritional value of human food, but no data is available on this yet.

Biochar is a durable, or even permanent, soil amendment. This is what distinguishes it from other soil amendments such as composts and green and animal manures, for example. The mechanisms by which biochar improves soil fertility and which have been studied to date are described below, and many also apply to other "un-charred" soil amendments. However, the latter do not persist in soil on the long term. Details on the permanence of biochar in soil are given in the section on soil C sequestration.

Biochar and soil physical properties

Biochar has a low density and high porosity. Much like sphagnum moss, it can be difficult to wet when dry, but can hold large amounts of water. When applied to sandy soil, biochar can improve soil water holding capacity (Briggs et al., 2005; Tryon, 1948; Fig. 9), although different biochar materials differ in their ability to positively impact soil water retention. Novak et al. (2009b) found that biochar made from switch grass improved the water holding capacity of a light textured Norfolk soil more than biochars made from pecan shells, peanut hulls and poultry litter. Biochar applied to clay soils has been found to have no significant effect on water holding capacity (Major, 2009), or to reduce it (Tryon, 1948). Researchers in areas where water availability for farming is low are interested in the potential of biochar to retain moisture, either applied by irrigation or received from rain events, and release this moisture to crops as the soil dries. However, to date no data has been published to demonstrate specifically that water retention by biochar can alleviate water stress in plants and result in improved yields because of this effect.

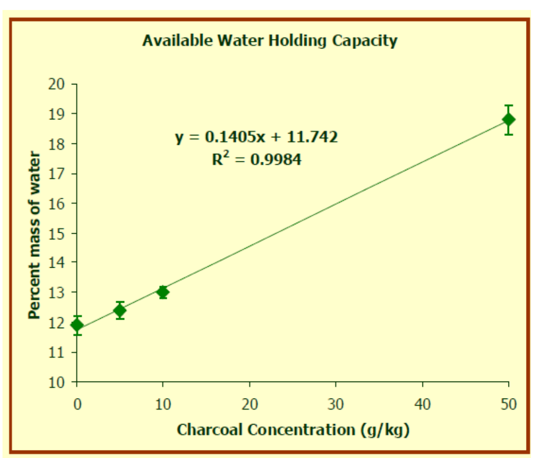

Figure 9. Impact of pine wood biochar on the water holding capacity of a sandy soil. From Briggs et al. (2005).

Biochar interacts with other soil constituents including minerals and "resident' organic matter. In old *Terra preta* soil, an important part of the biochar is found inside soil aggregates (Glaser et al., 2000). The reaction of biochar with other soil constituents may lead to better soil aggregation in some cases. For example, the macroporosity of

Terra preta was found to be 5-11% greater than that of adjacent soils of similar mineralogy (Glaser and Woods, 2004). Such aggregation processes occur over the long term, and can change the aeration of the soil and the flow of water inside and on the surface of the soil profile. Surface water infiltration in biochar-amended soil was found to be unchanged or improved (Asai et al., 2009; Major, 2009; Husk and Major, 2010).

An interesting question relates to the effect of biochar on soil color. Darker soil has a lower albedo (i.e. it reflects less of the radiation it receives, and absorbs more). Such an increase in radiation absorption could potentially aggravate global warming. It is unclear whether this mechanism is of concern for widespread biochar use. If biochar-amended soil improves biomass production, less bare soil would be exposed and biomass has a cooling effect on the climate (unless the soil is purposefully kept bare or plant growth is severely limited, for example by lack of available water). The fact that biochar sorbs moisture must also be taken into consideration. For example, Verheijen et al. (2010) argue that if biochar sorbs more water than surrounding soil, it will warm up more slowly than adjacent soil due to the high heat capacity of water. If soil color with biochar application is shown to be an issue, this will need to be accounted for in recommended maximum application rates and application methods. Banding could reduce the effect of biochar on surface soil color, although there are limits to the amounts of biochar which can be applied by banding equipment.

Biochar and soil pH

Many authors measured rises in soil pH when biochar was applied to soil (e.g. Chan et al., 2008; Laird et al., 2010; Peng et al., 2011; Van Zwieten et al., 2010c). In cases where the soil's pH is below optimal for its intended use, a rise in pH can provide a wide range of benefits in terms of soil quality, notably by chemically improving the availability of plant nutrients, and in some cases by reducing the availability of detrimental elements such as Al (Brady and Weil, 2008). The pH of biochar can vary but it is often above 9, and biochar can have a liming value in the order of several tens of percent (e.g. Van Zwieten et al., 2010c). However, a pine wood biochar material with a pH of 7.5 was observed to have a lowering effect on the pH of soil with an initial pH of 6.4 (Gaskin et al., 2010). Applying a biochar with a liming effect to a soil whose pH is already high can aggravate micronutrient deficiencies and reduce crop yields (Kishimoto and Sugiura 1985, cited in Chan and Xu, 2009).

Biochar and soil nutrients

Biochar has an impact on soil nutrient availability in two general ways: nutrient addition and nutrient retention.

The ash in biochar contains plant nutrients, mostly bases such as Ca, Mg, and K but also P and micronutrients including zinc (Zn) and manganese (Mn). The mineral elements contained in biomass will mostly be found in biochar ash, with the notable exception of N. During the pyrolysis process, significant proportions of biomass N are lost by volatilization (Chan and Xu, 2009). The N remaining in the biochar tends to be poorly available to plants (Gaskin et al., 2010), since a fraction of it is found inside aromatic C structures (Chan and Xu, 2009). One exception may be N in biochars derived from animal manures (Chan et al., 2008; Tagoe et al., 2008). Plant nutrients supplied with the soluble portion of biochar ash are generally readily available for plant uptake (e.g.

Gaskin et al., 2010; Novak et al., 2009a), but similarly to any soluble, mobile nutrient in soil, these are susceptible to leaching. If one were to rely on biochar for providing these nutrients to crops, it would need to be re-applied with each cropping cycle, as is the case with most other fertilizers.

But biochar also has a long-term impact on plant nutrients in soil. After application, the surfaces of biochar weather and become more oxidized (Cheng et al., 2006). Since biochar is highly porous and has a large surface area, its impact on the soil's cation exchange capacity (CEC) over time can be important. Liang et al. (2006) directly observed that biochar particles and organic matter sorbed onto them contributed to the greater surface change of *Terra preta* soils, when compared to adjacent, unmodified soils (Fig. 10).

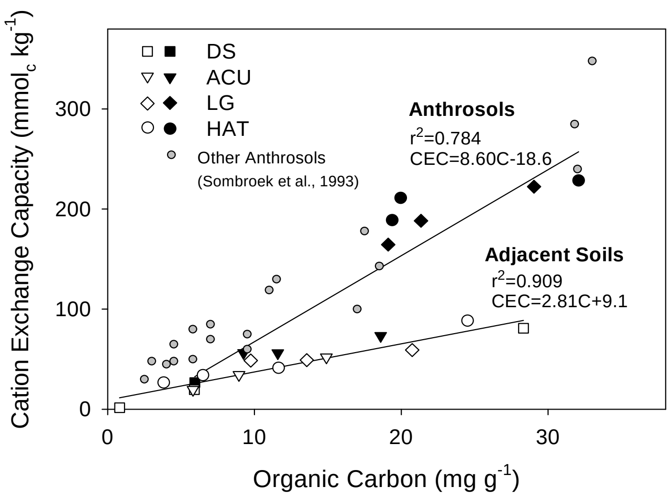

Figure 10. Biochar-rich anthrosol (*Terra preta*) have a higher CEC, for a given organic C content, than adjacent, unmodified soils. From Liang et al. (2006).

In recent experiments, greater soil CEC with biochar additions was also observed (Laird et al., 2010; Major et al., 2010b; Peng et al., 2011; Van Zwieten et al., 2010c; Yamato et al., 2006), but not always (Novak et al., 2009a). It is important to note that nutrients retained by biochar remain available to plants. It is expected that CEC in biochar-amended soil increases with time as weathering occurs, and long-term experiments would be necessary to quantify this effect and see if and when a plateau is reached. Some people are interested in finding ways to accelerate the "reactivity" of biochar and its soil quality-enhancing properties, for example by treating it with hydrogen peroxide, before applying to soil. However, no data is available to date to show whether such techniques are cost-effective.

Implications of greater nutrient retention in biochar-amended soil

<u>Biochar and nutrient leaching</u>

The fact that biochar retains nutrients in the rooting zone also indicates that it reduces nutrient leaching through the soil profile. Indeed, researchers have found reduced nutrient leaching when biochar was added to soil in pot studies (Ding et al., 2010; Laird et al., 2010; Lehmann et al., 2003b; Major et al., 2009; Novak et al., 2009a; Singh et al.,

2010) as well as a field study (Major, 2009). Observed reductions in ammonium and cation (Ca^{2+}, Mg^{2+}) leaching were attributed to greater CEC when biochar had been applied (Ding et al., 2010; Lehmann et al., 2003b; Singh et al., 2010). Some authors observed greater K leaching in biochar-amended soil, and attributed the increase to the relatively large amounts of K added with biochar ash (Lehmann et al., 2003b; Novak et al., 2009a). While most studies involved adding soluble, inorganic forms of nutrients to soil and assessing leaching, Laird et al. (2010) applied dried swine manure and observed reductions in total amounts of N, P, Mg, and Si leached over 45 weekly leaching events. It is interesting to note that reductions in leaching of P, which occurs in soluble form as a negatively charged ion, as well as NO_3^- were also observed. The mechanisms underlying this retention of negatively charged ions could include the anion exchange capacity of the biochar, interactions of biochar with other forms of organic matter in soil, and in the case of nitrate, effects on the biological soil N cycle. These have not been elucidated to date.

Reduced nutrient leaching from agricultural land can imply reduced input of nutrients into surface waters as well as drinking water reserves. Nitrogen and P pollution of surface waters is well known to contribute to the degradation of freshwater and marine ecosystems.

Biochar and fertilizer use efficiency

Another implication of greater nutrient retention in soil is improved fertilizer use efficiency (FUE). Especially in the case of N, greater FUE leads to either reduced input costs for farmers, or greater yields for a given fertilizer application rate. Nitrogen availability often limits crop growth, and N fertilizers represent a large investment for farmers. In the Brazilian Amazon, Steiner et al. (2008) observed greater N use efficiency by crops growing in an acidic soil amended with 11 t/ha wood biochar over 2 years. In 4 field experiments under dryland farming in Australia, Blackwell et al. (2010) found improved P fertilizer use efficiency and attributed it to better plant-mycorrhizal interactions in the biochar-amended soil. With the application of 1 t/ha of biochar in bands, the yield of wheat could be improved more at low rather than high fertilizer application rates. Also, at this low biochar application rate, the wheat yield obtained with a high fertilizer application rate could be reproduced with half the amount of fertilizer (Blackwell et al., 2010). This effect was not observed at higher biochar application rates in this study, and the reasons for this are not well understood. These authors also observed that the effect of biochar on fertilizer efficiency was greater in sand and loam soils than on a clay loam soil. These data suggest that biochar may provide more benefits in situations that are less favourable for crop growth.

In a pot study, Van Zwieten et al. (2010c) observed improved N uptake efficiency in wheat growing on an acidic Ferrasol, but not on an alkaline Calcarosol amended with 10 t/ha papermill waste biochar. Similarly and also in a pot study, Chan et al. (2007) observed improved N use efficiency in radish growing on an Alfisol amended with 50 and 100 t/ha of green waste biochar. They attributed the improved efficiency to the beneficial effects of these high rates of biochar on soil physical properties and thus root growth, since this was a hard-setting soil. However, such high application rates are unlikely to be practical, at least for single applications, in field soil. In flooded paddy rice in China, a field experiment found a statistically significant 130% increase in N fertilizer use efficiency when 40 t/ha of biochar were applied to soil, compared to the unamended control. Although the N use efficiency was also greater with a 10 t/ha biochar application rate, the increase was not statistically significant from the unamended control (Zhang et al., 2010a).

These studies indicate that biochar has the potential to improve fertilizer use efficiency through varied mechanisms, including chemical, biological and physical, and this has important implications for farmers given the rising price of fertilizers.

Biochar and soil biota

Little is known on the effect of biochar on soil biota, but its effect on mycorrhizal fungi has been studied most. The high sorption capacity of biochars can represent a methodological challenge when studying soil biota using molecular techniques: biochar can sorb molecules which are being extracted or evolved from amended soil, and thus confound the quantification of these molecules and related interpretations (Durenkamp et al., 2010; Thies and Rillig, 2009).

In general, it is hypothesized that the large porosity of biochar provides surfaces for soil microbes to colonize and grow, where their predators cannot access them (i.e. the “refuge” hypothesis). Futhermore, the fact that these surfaces sorb inorganic nutrients as well as organic substances and gases might provide ideal environments for microbes. While the pore size range varies in biochar, it is generally adequate for a range of soil microorganisms to colonize (Thies and Rillig, 2009). In the case of pathogenic fungi, these effects of biochar could be undesirable. For example, if biochar retains soil moisture more effectively than bulk soil, pathogens with zoospores (e.g. *Pythium* and *Phytophthora*) could be favoured (Thies and Rillig, 2009).

Matsubara et al. (2002) found that adding biochar to soil reduced the severity of *Fusarium* root rot in asparagus plants also inoculated with arbuscular mycorrhizal fungi (AMF). Biochar made from citrus wood in a simple kiln, applied at 1, 3 and 5% by weight to a sandy soil as well as a coconut fiber-based potting mix was found to induce systemic resistance to gray mold (caused by *Botrytis cinerea*) and powdery mildew (caused by *Leveillula taurica*) on pepper and tomato, and to a mite pest (*Polyphagotarsonemus latus* Banks) on pepper (Elad et al., 2010). However, although powdery mildew was less severe on plants growing in biochar-amended substrate in a long-term (106 day) study, at the end of the period the rate of disease development was similar among both amended and unamended treatments (Elad et al., 2010). The authors hypothesized that biochar may have been beneficial to plants in the presence of pathogens through the effect of phytotoxic compounds found in biochar, through a mechanism known as hormesis. Hormesis is the phenomenon by which a toxin or stressor can produce beneficial effects in living organisms when applied at low doses. In addition, biochar could have modified the dynamics of chemical elicitors, compounds which induce the activation of defence mechanisms in plants (Elad et al., 2010). In a different study, the same research group found better pepper growth and fruit yield in soil-less, coconut-fiber based substrate amended with 1-5% biochar by weight. Tomato height and leaf size were also greater but not fruit yield (Graber et al., 2010). The beneficial effect of biochar was not attributed to better nutrition or water relations in the plants. However, greater amounts of culturable rhizosphere and bulk substrate microbes usually found in soil were present when biochar was applied and pepper was grown (analysis not done in tomato). *Trichoderma* spp. and root-associated yeast were not detected in unamended substrate and increased by 2-3 orders of magnitude in the biochar-amended substrate. Overall, significantly greater numbers of fungi, bacteria and *Pseudomonas* spp. were found in biochar-amended vs. unamended bulk substrate, and the beneficial effect of biochar on microbe abundance was more pronounced in the rhizosphere than the bulk potting substrate. Molecular analyses indicated that 16 of the 20 microbial isolates from biochar-amended treatments corresponded to plant growth promoting and/or biocontrol agents, and these microbes could have played a role in improving yields with biochar. Also, several chemicals identified in an organic solvent extract of the biochar are phytotoxic or biocidal in large concentrations, but may have had a beneficial effect at low concentrations as described above (Graber et al., 2010). These findings support the idea that biochar may improve crop performance in ways which are unrelated to nutrition, water relations or good growth.

Biochar field work in Québec included the analysis of soil biota by Soil FoodWeb Canada Ltd. Data is available for an experiment established in 2008 and where soybean was followed by a mix of perennial forage species. The experiment consisted of two single swaths, one receiving 3.9 t/ha biochar and the other not receiving biochar (thus this was not a standard replicated experiment). The soil was sampled on 5 occasions in 2008 and 6 occasions in 2009. Overall, no clear trends in the dry biomass of microorganisms or hyphal diameter were observed (Husk and Major, 2010). Percent colonization by endomycorrhizal fungi was greater and within the expected range when biochar had been applied. While the number of flagellate and ciliate protozoae per gram of soil did not vary between treatments, generally less amoebic protozoae were found when biochar had been applied. Biochar-amended soil contained more bacterial feeders, fungal feeders, and fungal or root feeders nematodes than the control plot. No clear trends were observed for the number of predatory nematodes and exclusive root feeders. The fact that more bacterial and fungal feeder nematodes were found with no change in the abundance of fungal or bacterial biomass may support the refuge hypothesis (Husk and Major, 2010).

<u>Mycorrhizal fungi</u>

Much work has been carried out by the Japanese relating to biochar's effects on mycorrhizae, and positive impacts of biochar amendments on the infection of crop roots by mycorrhizae (Ogawa et al., 1983; Nishio and Okano, 1991; Saito, 1989). Solaiman et al. (2010) directly observed that biochar applied in bands in a dryland wheat field encouraged mycorrhizal root colonization of the crop in the year after application, and residual effects were also observed 2 years later. In the year after biochar application, improved mycorrizal colonization was linked to improved crop yield not because of improved P nutrition, which was not expected to be limiting, but to greater water foraging (Solaiman et al., 2010). In contrast, Habte and Antal (2010) did not observe improvements in the colonization of roots of the leguminous tree *Leucaena leucocephala* by AMF with biochar made from the same species, in pot studies.

Warnock et al. (2007) reviewed the literature on biochar effects on AMF, ectomycorrhizal fungi (ECF) as well as ericoid mycorrhizal fungi (ERM) abundance and interactions with plants and found usually positive impacts. They proposed 4 mechanisms by which biochar could favour plant-mycorrhizal interactions and mycorrhizae abundance. The first relates to the improvement of soil physico-chemical properties, including improved availability of nutrients. Better availability of nutrients which limit fungal growth could favour mycorrizal fungi, and plant-mycorrhizal interactions could also be favoured by certain changes in available nutrient ratios, for example the available N:P ratio. Secondly, biochar could change the activity of other microbes which have an impact on mycorrhizae. Mycorrhization helper bacteria and phosphate solubilizing bacteria, for example, could find refuge on biochar particles and in turn promote the functions of mycorrhizae. Third, biochar could alter the signalling between host plants and mycorrhizae, or it could detoxify allelochemicals. Changes in the abundance of such compounds can have important impacts on the growth of mycorrhizal fungi and the development of plant-microbe symbioses. Biochar could both sorb and release signalling and allelopahtic compounds, but given that this could be both beneficial (e.g. in the case where allelochemicals are detoxified) or detrimental (e.g. if biochar "sequesters" signalling compounds which would stimulate infections by mycorrhizae), the net effect in any situation is difficult to predict. Lastly, biochar could serve as a refuge for mycorrhizae as discussed above (see Fig. 11) (Warnock et al., 2007).

Figure 11. AMF hyphae growing out of a germinating spore and into biochar pores. Image by Ogawa (1994).

Thies and Rillig (2009) point out that while to date most research has centered on the effect of biochar on interactions between mycorrhizae and single plant species, changes in these interactions could also have impacts on a larger scale, for example in the competitive balance between crops and weeds.

Nitrogen-fixing bacteria

Diazotrophs fix atmospheric N in soil either freely or in symbiotic associations with leguminous plants. No data currently exists on the effect of biochar on free-living N fixers, however it is possible that these organisms would benefit from a reduced partial pressure of oxygen in the small pores of biochar (since oxygen destroys enzymes required for the biological fixation of N). Also, if iron and Mn are sufficiently available free-living N fixers could be favoured on and in biochar particles (Thies and Rillig, 2009). Ogawa (1994) noted that adding biochar to soil seemed to stimulate the activity of free-living N fixers, which might be more competitive relative to other organisms on biochar surfaces as noted above, and also because of the low amounts of available N supplied by biochar.

To date, only one pot study has directly assessed the impact of biochar amendment on symbiotic N fixation by *Rhyzobia*. Rondon et al. (2007) grew common beans on an acidic tropical soil, and through the use of isotopically labelled N fertilizer they assessed amounts of N in bean biomass originating from inorganic soil N or atmospheric N fixation. They found that the proportion of N derived symbiotically increased and the proportion of N derived from the soil decreased as more biochar was applied (Fig. 12). However, biomass yield and total N uptake decreased at the higher biochar application rate (90 g kg^{-1}, or approximately 180 t/ha at 15 cm depth, which is extremely high in field situations).

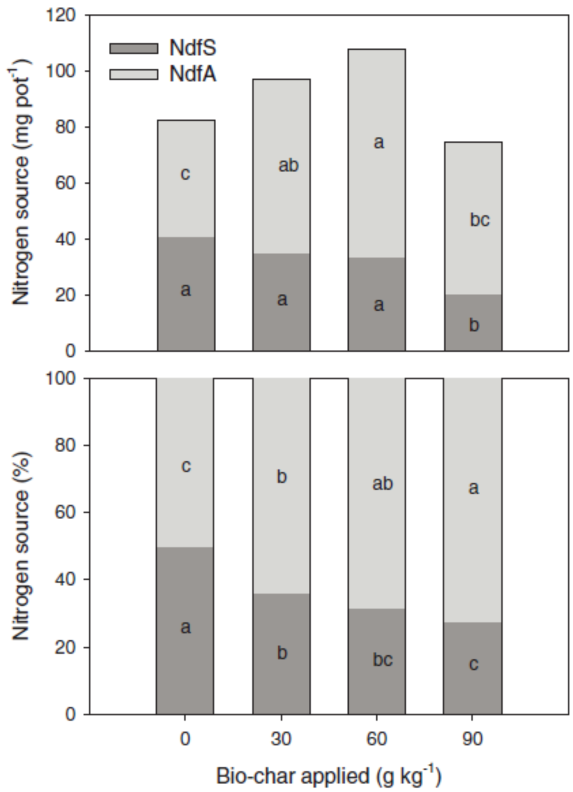

Figure 12. Absolute and relative amounts of N derived from the soil (NdfS) and from the atmosphere (NdfA) in bean plants grown with varying amounts of biochar. From Rondon et al. (2007), different letters indicate statistically significant differences ($p<0.05$).

The authors attributed the greater contribution of N derived from the atmosphere with biochar mostly to greater availability of boron and molybdenum in biochar-amended soil. Indeed, both these elements play key roles in metabolic functions related to symbiotic N fixation. Rondon et al. (2007) also suggest that, to a lesser degree, a reduction in inorganic N availability in the soil could have explained the higher proportion of N derived from the atmosphere in plants grown with biochar. Biochar could reduce the availability of NH_4^+ by sorbing it, or impact the mineralization of N from organic matter. Indeed while an analysis of soil inorganic N in the experiment did not reveal any significant differences, bean tissue N content was reduced with all biochar application rates, when compared to the unamended control (Rondon et al., 2007).

<u>Biochar and earthworms</u>

In order to test the safety of biochar materials before applying them to soil, the IBI has published a methodology for a worm avoidance test (Technical Bulletin 101, available online). The bulletin is based on tests to evaluate the presence of hazardous chemicals in soil (e.g. Yeardley et al., 1996). Standard methodologies for the worm avoidance test are available from the International Standards Office (ISO) and the Organisation for Economic Cooperation and Development (OECD). Van Zwieten et al. (2010c) followed such a methodology and found that the composting worm *Eisenia fetida* preferred biochar-amended over unamended Oxisol (acidic and nutrient-poor), while it did not have a preference whether or not a calcareous soil (neutral pH) was amended with biochar (Van Zwieten et al., 2010c).

Liesch *et al*. (2010) tested the effect of applying 0, 22.5, 45, 67.5, and 90 t/ha of either pine chip or poultry litter biochar to a mixture of sand, kaolin and sphagnum on the survival and growth of *E. fetida*. All worms were killed by the 2 highest application rates of poultry litter biochar, most likely due to ammonia volatilization at high pH, and osmotic shock. Worm survival and growth in the lowest application rate of poultry litter biochar and all application rates of pine chip biochar did not significantly differ from the unamended control (Liesch et al., 2010).

A tropical earthworm (*Pontoscolex corethrurus*) was found to prefer biochar-amended soil to unamended soil (as indicated by increased casting activity), and the authors suggested that earthworms may have played a key role in the formation of *Terra preta* soil (Topoliantz and Ponge, 2005). In a different study, Topoliantz and Ponge (2003) observed that *P. corethrurus* ingested charcoal primarily for reasons other than obtaining nutrients, and that it made burrows in biochar-amended soil mostly by pushing biochar particles aside. The role of the earthworms in the incorporation of biochar into soil was again emphasized.

In field work carried out in Québec, earthworm densities were determined by excavating one cubic foot of soil at 3 locations inside both an unamended swath and an adjacent swath receiving 3.9 t biochar/ha. This analysis was carried out on 9 occasions over two growing seasons. While the effect of the biochar treatment varied over time, in general more earthworms were found in the biochar-amended plot (Husk and Major 2010).

Biochar and climate change mitigation

As discussed above, the energy produced during pyrolysis can represent a renewable source of energy and offset fossil fuels. The sections below cover soil-related aspects of biochar's potential role in climate change mitigation.

Biochar and soil carbon sequestration

During pyrolysis, the biomass feedstock's molecules are rearranged. Gas and volatile compounds are formed and escape the biomass, and the solid fraction, biochar, remains in the pyrolysis chamber. The changes which occur during pyrolysis include a condensation of the carbon in the feedstock, where the aromaticity increases. Aromatic carbon structures, including graphitic structures, are difficult to decompose chemically, and thus biochar is much more resistant to both biotic and abiotic decomposition in soil. Some authors (e.g. van Zwieten et al., 2010b) suggest that the molar H/C ratio of biochar is a good indicator of its aromaticity, and hence of its stability in soil. In general, the higher the pyrolysis temperature and the residence time in the pyrolysis unit, the higher the stability of the biochar in soil (Peng et al., 2011). Studies have found that biochar is part of the oldest C pool in soil (Pessenda et al., 2001) and deep-sea sediments (Masiello and Druffel, 1998), and that black C may represent a significant global sink of C (Schmidt and Noack, 2000).

It is methodologically challenging to determine the turnover rate of biochar in soil, precisely because this rate is so slow. While it can be possible to date old biochar-C in soil samples, it is impossible to know how much of this C was present initially (and thus how much was lost over its residence time), and in many cases losses can occur by means other than decomposition, for example by physical transport. Controlled experiments are necessary to document the amount of biochar-C added initially, but then long-term results are only available on the long-term and such experiments have only begun in recent years.

As discussed above, biochar consists of more than one fraction in terms of its stability, and it is usually divided into two pools: the "unstable matter" which decomposes on the order of days to months after application to soil (Bruun et al., 2010; Peng et al., 2011; Smith et al., 2010), and the "stable matter" which remains over centuries to millennia. Using a 2-pool first order decay model, Major et al. (2010a) calculated the mean residence time of biochar in soil, using data reported in incubation as well as field experiments. Mean residence times adjusted to a mean annual temperature of 10ºC were calculated to be 3,300 yr for biochar added to an unmanaged savanna soil in Colombia (Major et al., 2010a), 1,300 yr for an incubation study using charcoal from old storage sites (Cheng et al., 2008), 4,000 yr for biochar in *Terra preta* soils (Liang et al., 2008), and 2,000 yr for ryegrass biochar added to soil (Kuzyakov et al., 2009). Long-term modeling of the turnover of BC from savanna fires in Australia yielded estimated mean residence times of 1,300 and 2,600 yr for a mean annual temperature of 27ºC (Lehmann et al., 2008). Spokas et al. (2009) found no decomposition of biochar added to soil over 100 days in an incubation study, and Bruun et al. (2009) found straw biochar to decompose up to 18 times less than uncharred straw over 2 years, also in the laboratory. In the humus layer of a boreal forest, Wardle et al. (2008) found no significant mass loss of buried biochar, over 10 years in the field.

Another issue linked to the permanence of biochar in soil relates to physical displacements of biochar away from the location where it was applied. This is an important consideration because large amounts of biochar can potentially be "lost" from its place of application, and thus would not be producing expected benefits on soil quality and would not be measured as providing C offsets in that particular location. On steep slopes in Laos, biochar produced by slash-and-burn and deposited on the soil's surface was found to be preferentially eroded, compared to other forms of organic matter (Rumpel et al., 2006). The authors attributed this preferential erosion to the light nature of biochar, the fact that it had not formed mineral associations soon after deposition and that it did not decompose during transport. Working on very slight slopes (estimated at < 2%) in a savanna region of Colombia, Major et al. (2010a) studied the fate of biochar-C in the soil as it moved with leaching water and respired to the atmosphere. While they did not measure surface erosion losses of biochar-C directly, this flux was hypothesized to represent the greatest movement of BC from the plots where it was applied. The authors attribute this migration to very intense rain events which are typical in the study region; indeed these result in standing water which flows in the direction of the slope. In this study the biochar had been incorporated using a disk harrow in mowed, established savanna vegetation, thus incorporation was not optimal. Indeed, best management practices for biochar will involve avoiding erosion losses, and this can be achieved in several ways including thorough incorporation, banding and mulching. While biochar which has moved away from the location of application would not be measured *in situ* in the context of C trading, the C would still be sequestered. In the cases where biochar travels to water bodies or the deep ocean, the level of preservation is even greater than in aerobic soil.

While there still exists considerable uncertainty as to exactly how long biochar-C remains in soil and out of the atmosphere, the fact that it does remain for 1, or more likely 2 or 3 orders of magnitude longer than uncharred biomass clearly makes it a potential tool to mitigate climate change while simultaneously improving soil fertility. The extent to which biochar technologies could actually make a difference for climate mitigation was investigated by various authors. Most recently, Woolf et al. (2010) predicted that sustainable biochar systems could amount to net avoided emissions of up to 1.8 Gt CO_2-C_e a year (or 12% of current emissions), for total net avoided emissions of 130 Gt CO_2-C_e over 100 years. They compared scenarios where biomass was used exclusively for energy production by burning, to the case where biomass is made into energy and biochar for soil application, and concluded that biochar systems resulted in greater offsets. The only exception to this was in cases where soils were fertile, and coal was used to produce energy in the baseline scenario (Woolf et al., 2010). It is important to note that data on biomass types and availability used in this study were deemed to be sustainable, i.e. with no negative impacts on food security, soil or wildlife habitat conservation. Such sustainability issues are of crucial importance when planning any biomass use system. The Pacific Northwest Biochar Initiative (USA) has published a draft biochar sustainability protocol. There is a sense in the biochar community that biochar systems must be sustainable otherwise they can do more harm than good, for example if living trees are harvested to make biochar or if land is planted to biomass crops for biochar instead of food crops, and this results in a change in food availability.

Effect of biochar on non-biochar soil C

Wardle et al. (2008) placed litter bags in the litter layer of a boreal forest, and after 10 years noticed that the loss of humus in bags containing both litter and biochar was greater than could be expected using data from loss in the two materials, when buried separately. They thus concluded that biochar had promoted the loss of forest humus. Lehmann and Sohi (2008) responded that such a priming effect of biochar could not be concluded from the litterbag experiment, stating for example that the physical transport of litter and biochar outside the litter bags was not accounted for. These discussions are very important because if biochar induces a greater loss of non-biochar organic matter in soil, this would reduce its benefits as a soil amendment and potentially also as a tool to mitigate climate change.

In an incubation study, Van Zwieten et al. (2010a) observed similar or lower soil respiration rates when several contrasting biochar materials were added to an acidic soil, compared to unamended controls. However, greater bulk soil respiration rates have also been observed, in an incubation study using field soil where biochar had been banded 2 years before (Solaiman et al., 2010). Also in the laboratory, Spokas et al. (2009) measured respiration from soil-biochar mixtures over 100 days and found that if respiration attributed to the actual biochar was subtracted, “base” soil respiration was reduced with biochar addition.

In a field experiment where biochar as well as green manure were applied at 6 t C/ha, Kimetu and Lehmann (2010) measured soil respiration. On soil with low organic C contents, biochar resulted in a reduction in C loss by respiration by 27% compared to the unamended control, while the green manure resulted in a 22% increase in C loss by respiration. On C-rich soil, neither amendment resulted in significantly greater soil respiration losses compared to the unamended control. Interestingly, in plots receiving biochar 6.8 times more C was found in the intra-aggregate fraction per unit C respired, when compared to plots where green manure had been applied. This suggests that apart from being more stable chemically, biochar may be more efficiently stabilized in soil (Kimetu and Lehmann, 2010). Also working in the field, Major et al. (2010a) found much greater amounts of non-biochar C loss by respiration over 2 years when biochar was applied. However, contrarily to the study by Kimetu and Lehmann, the data collected by Major et al. include root respiration and the decomposition of root exudates and biomass. Since these authors documented a large increase in above-ground biomass production in the plots where biochar had been applied, they attributed the greater respiration to greater root biomass and associated respiration, and not to the “priming” of the decomposition of non-biochar organic matter, by biochar. After biochar was applied while tilling green manure into the soil in Finland, no statistically significant differences in CO_2 emissions were found between biochar-amended and unamended soil (Karhu et al., 2011). Measurements were made between wheat seeding and canopy closure.

Biochar and non-CO_2 greenhouse gas emissions from soil

Note: this section is adapted from a research summary written by J. Major and in preparation for publication online by the International Biochar Initiative

Methane (CH_4) and nitrous oxide (N_2O) are respectively 25 and 298 times more potent greenhouse gases (GHG) than is carbon dioxide (CO_2)(IPCC, 2007b). It follows that reducing emissions of these gases can have a large impact on climate change mitigation. While there are natural sources of CH_4 and N_2O emissions, the major man-made sources of CH_4 include emissions from paddy (flooded) rice fields, livestock production systems, biomass fires, fuel charcoal burning, firewood burning, and the anaerobic decomposition of organic waste (Heilig, 1994). Major anthropogenic sources of N_2O include agricultural soil management (including the application of N fertilizers), animal manure and human sewage management, the combustion of fossil fuels, and the industrial production of certain chemicals (EPA). Evidence available to date suggests that biochar technology can potentially reduce CH_4 and N_2O emissions from field soil, and may help in avoiding CH_4 production from certain biomass wastes.

Overview of mechanisms through which biochar may reduce CH_4 and N_2O emissions

Note: this section is adapted from a research summary written by J. Major and in preparation for publication online by the International Biochar Initiative

Van Zwieten et al. (2009) proposed several mechanisms through which biochar can affect emissions of N_2O and CH_4. Biochar affects soil physical and chemical properties, which can in turn affect the microbes responsible for producing N_2O and CH_4. For example, biochar can potentially improve soil aggregation, which would improve aeration. Due to their porous nature, biochar particles can also directly improve aeration of the soil around them. This improved aeration means that the microbial processes which produce N_2O and CH_4 will not be favored. Changes in soil structure may also favor different species of microbes with different metabolic requirements. Chemically, biochar can impact the soil's pH, the availability of inorganic N, the overall quality of available organic matter for microbes to degrade, and the redox potential of the soil. Biochar can also potentially cause a direct reduction in N_2O emissions through various mechanisms occurring on the surfaces of biochar particles and pores. The highly complex crystalline structure of biochar has areas of high potential for adsorption and reduction of N_2O to N_2. These mechanisms remain to be studied and demonstrated.

Biochar and avoided CH_4 and N_2O emissions

Note: this section is adapted from a research summary written by J. Major and in preparation for publication online by the International Biochar Initiative

Decomposition of biomass, including waste materials, can lead to the production of CH_4 and N_2O. Waste biomass is also the preferred feedstock for biochar production. The process of pyrolysis itself can also produce CH_4 and N_2O, although properly designed and managed pyrolysis systems can ensure these are captured for beneficial use, or suppressed to acceptably (according to relevant emissions standards) low levels.

Most of the available data on CH_4 production from solid waste has been generated from landfills where post-consumer solid waste is deposited and decomposes at varying rates. The Intergovernmental Panel on Climate Change (IPCC) estimates that by 2050, land filled waste will be the primary source of CH_4 emissions, amounting to 2,900 million tons of CO_2-C_e per year, worldwide (Bogner et al., 2008). This amount is comparable to amounts of CO_2 globally emitted from fossil fuels in 2004 (IPCC, 2007a).

Apart from landfilled waste, CH_4 is also produced in piles of biomass residue remaining after biomass processing operations at a variety of scales, such as sawdust, fruit pits, nut shells and empty oil palm bunches after oil extraction. Using appropriate portions of landfilled waste and other biomass waste to make biochar would reduce the quantity of waste that would otherwise decompose and in turn reduces the associated CH_4 emissions.

Rice cultivation in flooded systems produces significant amounts of CH_4, at least partly due to the anaerobic decomposition of crop residue in oxygen-limited conditions (Singh et al., 2008). Using these crop residues to make biochar could reduce emissions of CH_4 generated from their *in situ* decomposition, apparently without reducing soil organic carbon contents on the long term (Singh et al., 2008).

CH_4 emissions from biomass burning contribute about 10% of total CH_4 emissions on an annual basis (Levine, 1990). While some biomass burning is caused by wildfires, the greatest proportion of it results from deliberately set fires to clear land or to burn crop waste. Another significant source of biomass burning is fuel wood used for cooking and heating activities in developing countries. Making biochar from crop residues instead of burning them could reduce CH_4 emissions. Also, improved cooking stoves including biochar-producing stoves, could reduce such emissions if their use is widely implemented.

Biochar and CH_4 and N_2O emissions from soil

Note: this section is adapted from a research summary written by J. Major and in preparation for publication online by the International Biochar Initiative

Rondon et al. (2005) found that N_2O emissions from field soil were reduced by 50% in soybean and 80% in pasture grass over 3 years, when biochar was applied at 20 t/ha, compared with an unamended control. Spokas et al. (2009) also found a reduction in N_2O production when soil was amended with biochar in a laboratory incubation study over 100 days. This reduction was observed only at biochar application rates of 20, 40 and 60% by weight, and no reduction was found at lower rates of 2 – 10% by weight. Such high application rates (approx. 360 – 1100 t/ha for 20 – 60%, assuming a bulk density of soil of 1.2 g/cm^3) are unlikely to be practical, at least for single applications, and their impact on crop growth is unknown. When adding 10% biochar to soil by weight, also in a laboratory incubation, Yanai et al. (2007) found that the effect of biochar on N_2O emissions was highly dependent on the moisture content of the soil. Shortly after rewetting dry soil to 73 and 78% water-filled pore space, N_2O emissions were reduced by 89% when biochar was added, compared to the unamended control. However, when soil was rewetted at 83% water-filled pore space, biochar-amended soils had approximately 50% greater N_2O emissions. The mechanisms underlying these different results remain unclear.

Van Zwieten et al. (2009) also showed in an incubation study that adding 10% biochar to soil by weight had the potential to greatly reduce N_2O emissions from soil shortly after rewetting at 70% of the soil's water holding capacity. However, different biochar materials (made from green waste and poultry litter) with contrasting characteristics were tested and these materials varied widely in their effect on soil N_2O emission. While most biochars used by Van Zwieten et al. (2009) almost completely suppressed emissions of N_2O from soils, one of them (greenwaste biochar produced at 450°C) caused greater emissions than in the unamended control. In more recent work, Van Zwieten et al. (2010a), applied the equivalent of 10 and 50 t/ha of several contrasting biochar materials to a poor soil in a laboratory experiment. All biochars at both application rates significantly reduced N_2O emissions from flooded soil (by up to 84%), compared to the unamended control, but the different biochar treatments did not significantly differ among themselves.

Singh et al. (2010) added the equivalent of 10 t/ha of several different biochar materials to two soil types (a Vertisol and an Alfisol) in a laboratory experiment, and found that biochar application to soil could, under certain conditions, lead to reductions in N_2O production by soil. Most effective materials were those made from wood and from poultry litter at 550°C with steam activation. Poultry litter biochar made at 400°C and not activated actually yielded greater N_2O emissions than the control over the first 4 months of the experiment. During the 5th and last month of the trial, all biochar materials reduced N_2O emissions from both soils by up to 73% compared to unamended controls, indicating that this beneficial effect of biochar improves with time (Singh et al., 2010). Animal manure biochars can contain significant amounts of available N, such as the low-temperature (400°C) poultry litter biochar studied by Singh et al. (2010). While this N may improve crop nutrition, it can potentially contribute N for denitrification and the production of N_2O.

Clough et al. (Clough et al., 2010) studied the effect of applying 20 t/ha of a wood-derived biochar on N_2O production by a pasture soil after the addition of bovine urine, in the laboratory. Over 53 days, N_2O production was not statistically different whether or not biochar had been applied to soil. These authors also did not observe a reduction in the pool of inorganic N in the soil, which is the precursor to the formation of N_2O, when biochar was applied.

Net CH_4 production in laboratory work by Spokas et al. (2009) was negative for all treatments (with and without biochar), meaning that the soils consumed more CH_4 than they produced. Adding biochar especially at higher rates (ranging from 5% to 60% by weight) caused a significant reduction in the net CH_4 consumption capacity of soil (Spokas et al., 2009), meaning that actual CH_4 soil emissions were greater and/or CH_4 consumption was lesser when biochar was applied compared to the un-amended control. Since these authors used very high rates of biochar application, overall microbial activity in soil may have been inhibited. In contrast, Rondon et al. (2006) found that applying 20 t biochar/ha to field soil increased annual CH_4 sinks by 200 mg CH_4/m^2, when compared to an unamended control.

In Finland, in an organically managed field experiment where 9 t/ha of birch biochar was applied before sowing wheat, gas fluxes were measured on 9 occasions until canopy closing. It was observed that immediately after addition to soil, biochar caused significantly greater CH_4 uptake by soil, and thus 96% less emissions when compared to the control (Karhu et al., 2011). Indeed, while CH_4 production by soil was significantly correlated to soil moisture content in the unamended control, it was not in soil which had received biochar. In the same field study, no statistically significant differences in N_2O emissions were found between biochar-amended or unamended soil (Karhu et al., 2011).

In contrast, work done on flooded rice patty fields in China found that applying wheat straw biochar at 0, 10 or 40 t/ha caused greater CH_4 emissions in the first growing season, while N_2O emissions were reduced (Zhang et al., 2010a). Overall, the CO_2-C_e impact of the biochar amendments was significantly greater, both on a per ha and a per ton of rice produced basis, than in the unamended plots (Zhang et al., 2010a). Further study is required to assess the impact of biochar amendment on flooded systems in the long term and irrigation regimes different from that studied. Also, it would be useful to carry out GHG life cycle analyses on this specific production system, to understand the net effect of combined rice crop residue management and biochar management. As indicated above making biochar from rice straw instead of allowing it to decomposed in situ could cause a reduction in CH_4 emissions.

These studies show that while biochar has potential as a tool to reduce greenhouse gas emissions from soil, more research is required to understand the mechanisms which underlie these processes, and to quantify the effects of biochar application on GHG emissions when different biochar materials are added to different field soils and under different production systems.

Biochar and the carbon market

To receive payments for C offsets, projects must be monitored and evaluated according to approved methodologies. Currently, no methodologies have been officially approved to quantify offsets in biochar projects, thus it is not possible to obtain payments for biochar C sequestration. Developing such methodologies and having them approved by standard organizations is costly. In 2009 a methodology for biochar projects was submitted for review to the Voluntary Carbon Standard, but it was not carried forward passed the initial review stage. In 2010 the Biochar Protocol Development work group was formed (www.biocharprotocol.com), and has sought input from the wide biochar community in initial phases of protocol development.

Indeed the development of biochar protocols represents a challenge in terms of the quantification of CO_2-C_e offsets by biochar projects. As discussed above, the ‘stable’ fraction of biochar is responsible for long-term C sequestration and the amount of ‘unstable’ and ‘stable’ carbon in biochar varies. Furthermore, there are currently no widely accepted techniques for measuring these fractions in ways that provide information which is relevant to what happens to biochar in soil. In this respect, the development of biochar material standards and offset protocols are parallel efforts.

Carbon trading methodologies require monitoring to take place. In the case of C sequestration with biochar, a simple soil sample would be required to assess how much biochar is present. However, accurate and affordable techniques to quantify biochar-C in soil do not exist as of yet. Some methodological issues that must be addressed with biochar quantification in soil include the fact that biochar can vary in its chemical structure, it forms interactions with other soil constituents, and many soils contains “background” amounts of biochar-like compounds, which were present before biochar was applied (Manning and Lopez-Capel, 2009). The various methods used to date to quantify biochar in soil include oxidation methods (both wet and using heat), methods using molecular markers, UV oxidation and NMR spectroscopy, and combinations of these. All have limitations, including non-specificity to biochar with respect to other similar compounds in soil, the destruction of biochar, and may result in under- or overestimation of biochar in soil (Manning and Lopez-Capel, 2009). The most accurate method seems to be one combining UV oxidation followed by elemental and NMR analysis of the residue, but it is costly and only a few laboratories worldwide can carry out the procedure. For routine analysis of biochar content in soil, mid-infrared spectroscopy may be the most promising, if it is properly calibrated using soil samples to which known amounts of biochar were added. Other more costly techniques such as thermal analysis could be used as needed in the case of audits and/or to determine the source of a biochar applied to soil (Manning and Lopez-Capel, 2009).

The question of whether C credits should be given to the entity that produces the biochar or the entity who places it in soil, or both, is a valid one. Submitting biomass to pyrolysis is the step that results in the chemical rearrangement of the biomass into a form that is highly stable in the environment, however biochar also has value as a fuel and C is not effectively sequestered until the biochar is placed in soil, or in old mine shafts, for example.

In any case, the current political climate is not favourable to the development of methodologies for biochar C offsets. If it were, the prospect of earning C credits would make a large difference for farmers who are considering biochar technology. Also, as is the case in general for access to C markets, large questions remain regarding the ability of individual small farmers to access these markets.

Biochar in soil remediation and land reclamation

Biochar as a tool for revegetation

Note: this section is adapted from a research summary written by J. Major and published online by the International Biochar Initiative

Often, the goal of land reclamation efforts is to facilitate the establishment of spontaneous vegetation on degraded soils which are acidic and have low organic matter contents. Soil may become degraded due to human activities such as mining and industrial activities as well as the use of certain pesticides in agriculture. As discussed above, most biochar materials have a high pH and can act as liming agents, to increase soil pH. In cases where organic matter and clay levels in soil are low and soil is coarse textured, moisture retention may help the establishment of vegetation and biochar can help with this. Nutrient leaching can also be reduced by biochar application to soil, as also discussed above. Data presented here does not include the effects of activated carbon (AC) on soil properties, although this has been widely studied. Biochar is the precursor to making activated carbon, which typically requires an additional step for activation, for example exposure to a chemical solution or gases. Depending on how they are made, some biochars may approach the sorption properties of AC.

Biochar and the sorption of heavy metals

Note: this section is adapted from a research summary written by J. Major and published online by the International Biochar Initiative

Biochar has been found to sorb a variety of heavy metals, including lead (Pb), arsenic (As) and cadmium (Cd). A dairy manure biochar made at 350°C sorbed several times more Pb than AC (Cao et al., 2009). In this case, sorption by biochar was attributed mostly (85%) to the Pb reacting with ash present in the biochar, and also to direct surface sorption (15%) on biochar surfaces. The authors of this study conclude that the ash in the manure biochar was predominantly responsible for reducing Pb concentrations in water, as is also evident by the fact that AC (very low ash) sorbed much smaller amounts of Pb than did manure biochar.

Mohan et al. (2007) also worked on the removal of heavy metals in an aqueous solution by biochars made from pine and oak wood and bark, at 400-450°C. Due to its greater surface area and pore volume, oak bark biochar outperformed all others and removed similar amounts of Pb and Cd from solution as did a commercial AC material (~100% for Pb and ~50% for Cd). Oak bark biochar also removed ~70% of the As in solution. Heavy metal removal by other biochars, at pH values in the range of most agricultural soils (5-7) removed ~5-25% Pb, ~0-10% Cd and ~0-10% As from solution. These authors concluded that metal adsorption by biochars occurred by ion exchange mechanisms.

Biochar applied at 1% on a weight basis was found to reduce amounts of leachable metals in contaminated soils also containing phenanthrene, thus resulting in better decomposition of phenanthrene and better plant growth. In this experiment, soil treatment with iron filings also reduced metal mobility and improved phenanthrene degradation, but did not allow the restoration of plant cover (Sneath et al., 2009). Because biochar has been shown to have several different properties that enhance plant growth

(Laird, 2008), this suggests that applying biochar to contaminated soils will provide other benefits, beyond heavy metal sorption and enhanced decomposition of organic contaminants (e.g. phenanthrene). Alternatively, soil amended with 0.1 and 0.5 % (w/w) pine biochar sorbed more phenanthrene than non-amended soil, although the authors found that the amount of this contaminant sorbed by biochar varies with the properties of the biochar, soil characteristics and contact time between biochar and soil (Zhang et al., 2010b).

Uchimiya et al. (2010b) found that adding broiler litter biochar to soil enhanced the immobilization of a mixture of Pb, Cd and nickel, and the authors attributed this effect mostly to the rise in pH brought about by the biochar. In a different study, Uchimiya et al. (2010a) tested the effect of "natural" (non-biochar) organic matter and the biochar's unstable carbon fraction, on heavy metal immobilization by biochar. They found that these materials improve Cd immobilization by biochar, had no clear effect on immobilization of Ni, and actually lead to greater mobility of Cu in biochar-amended soil with high pH (>9). Both high-ash and low-ash biochars had the ability to reduce the mobility of Cd, Cu and Ni in this soil, and treating the biochars with phosphoric acid to increase their negative surface charges improved the biochars' immobilization capacity. Over a 60 day pot study using contaminated field soil and charcoal made for cooking, Beesley et al. (2010) found that biochar was much more efficient than compost (on a volume basis) in reducing the bioavailability of Cd and Zn, mostly due to the fact that biochar raised the soil's pH more than compost did. The availability in soil of metals such as these decreases as pH rises.

Biochar and the sorption of pesticides and other organic molecules

Note: this section is adapted from a research summary written by J. Major and published online by the International Biochar Initiative

Organic contaminants include many agricultural pesticides and industrial contaminants. Biochar and the ash contained in biochar have a high affinity for sorbing different organic compounds. Charred organic matter (i.e. biochar, soot, activated carbon) generally sorbs 10 to 1000 times more organic compounds than does un-charred organic matter (reviewed by Smernik, 2009). Indeed, the sorption of many organic molecules in soils and sediments, including polycyclic aromatic hydrocarbons (PAH), has been attributed to the presence of biochar or similar materials in these soils (e.g. materials resulting from vegetation fires or from fossil fuel combustion). Sorption of organic molecules on biochar may be less reversible than sorption on other forms of organic matter, i.e. the probability that a sorbed molecule will later detach itself is lower. The sorption of organic molecules on biochar likely occurs by adsorption directly onto biochar surfaces, thus the greater the surface area and porosity of a biochar, the greater its potential for sorption of contaminants. While biochar is recalcitrant in soil, many other compounds in soil can also sorb to biochar and saturate or "block" its surfaces. Thus, more research is needed to determine the longevity of the effects of biochar on the sorption of organic molecules (Smernik, 2009).

Although sorption dynamics are affected by pH and other factors in soil, many studies have found that adding biochar to soil improved the sorption of pesticides. Cao et al. (2009) found that biochar made from dairy manure sorbed more atrazine (herbicide) in an aqueous solution than un-charred manure. Similar results were obtained by Zheng et al. (2010) for atrazine and simazine, another herbicide. Jones et al. (2010) studied the effect of biochar on soil-applied simazine in detail and found that at wood biochar application rates of 10-100 t/ha, both fresh biochar and biochar aged in field soil for 2 years sorbed simazine on their surfaces. This was visually observed in soil columns where biochar was placed in different configurations, and isotopically labelled simazine was added (Fig. 13). Sorption by biochar reduced the bioavailability of simazine, its decomposition in soil over 21 days, and its leaching down the soil profile. The authors concluded that adding biochar to soil could reduce pesticide pollution and human exposure to pesticides. Simazine is a foliar applied and foliar active pesticide, and in the case of soil-applied and soil-active pesticides, such sorption by biochar would reduce pesticide efficacy. Using larger-sized biochar particles could mitigate this problem, since in the case of simazine finer particles were found to sorb the pesticide faster (Jones et al., 2010).

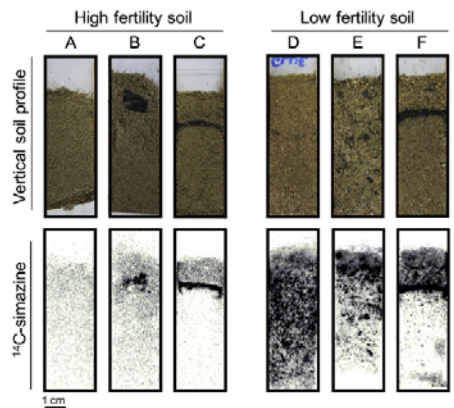

Figure 13. Location of biochar and labelled simazine in soil columns. Unamended soil is in A and D. From Jones et al. (2010).

A study where diuron (herbicide) sorption was compared in biochar amended vs. non-amended soils found that amended soil sorbed more diuron (Yu et al., 2006). Similarly, Spokas et al. (2009) found that soil to which mixed wood chip biochar was added sorbed more atrazine and acetochlor (herbicides) than unamended soil, but organic matter applied to soil at the same rate as biochar would sorb more of these herbicides than the fast-pyrolysis biochar they tested. In contrast, Wang et al. (2010) found that wood biochar sorbed more terbutylazine (herbicide) than biosolids (digested or raw), and the herbicide was also more strongly sorbed by wood-based biochar than by biosolids, in soil.

Yu et al. (2009) studied the microbial degradation of insecticides chlorpyrifos and carbofuran in soil amended with wood-based biochar, and found that their degradation decreased with increasing amounts of biochar applied, while the uptake of the insecticides by onion plants also decreased with greater biochar application rates. This indicates that while the insecticides remained in soil longer, their bioavailability to plants was reduced. Similarly, Yang et al. (2010) worked with soil-applied insecticides chlorpyrifos and fipronil and found that cotton straw biochar applied at 0.1 to 1% (w/w) reduced the losses of insecticides from the soil, while the uptake by Chinese chive plants was also reduced. The authors suggest biochar could be used to sequester these insecticides in a location while reducing their uptake by plants.

Yu et al. (2010) found that eucalyptus wood biochars made at 450 and 850°C were both in the range of 100 times more efficient at sorbing the fungicide pyrimethanil than was an Australian soil. The biochar made at the higher temperature sorbed more fungicide and released less of it after washing.

Several studies assessed the effect of biochar-containing ash on the sorption of pesticides. Yang et al. (2006) found that wheat straw ash containing 13% C added to soil at 1% resulted in 7-80 times more diuron sorption than in un-amended soils, and the amount of diuron remaining after 10 weeks was slightly greater in amended vs. unamended soil. Thus, the bioavailability of diuron was decreased with ash/biochar as demonstrated by a greater survival rate and biomass of barnyard grass. Yang et al. (2003) also showed that wheat straw ash was 600-10000 times more effective at sorbing diuron than unamended soil, up to 12 months after application. This has important implications for weed management, where reduced herbicide activity is undesirable. Similar results were obtained for benzonitrile (solvent) sorption by ash/biochar in soil (Zhang et al., 2006) and for MCPA (herbicide), where ash/biochar amended soil was 90-1490 times more effective at sorbing MCPA than unamended sandy soils (Hiller et al., 2007).

Biochar and hydrocarbon contamination

Note: this section is adapted from a research summary written by J. Major and published online by the International Biochar Initiative

Laboratory work using crude oil contaminated desert soil showed that of 12 materials tested, coconut charcoal was most efficient in promoting oil biodegradation (Cho et al., 1997). Polycyclic aromatic hydrocarbons (PAH) are potent contaminants which are produced by fuel burning. Total PAH contents and PAH bioavailability in a contaminated field soil over 60 days was found to be reduced more by biochar than by compost (compared on a volume basis), although not all treatment comparisons were statistically significant (Beesley et al., 2010).

Other uses for biochar

Biochar as a medium for fungal inoculants

Note: this section is adapted from a research summary written by J. Major and published online by the International Biochar Initiative

Peat is commonly used as a carrier for rhizobial inoculants, which are used to promote proper nodulation and biological nitrogen fixation in legume crops. However, peat is not available in all regions and is arguably not a renewable resource since its formation takes a very long time. Biochar can also be used as a carrier for microbial inoculants. Stephens and Rask (2000) indicate that carriers for microbial inoculants should, among other factors, support the growth of the target organisms, have high moisture holding and retention capacity, and be environmentally safe. Properly produced biochar has these characteristics. When testing the survival rate of rhizobial inoculum, charcoal performed similarly to peat, oil and other carriers (Kremer and Peterson, 1983). Similar results were found by Sparrow and Ham (1983), where rhizobial inoculant survival rates were greater in peat, charcoal and vermiculite than in peanut hulls or corn cobs. While we are unaware of charcoal being used as a carrier for mycorrhizal inoculants, soil-applied biochar has been demonstrated to be beneficial to mycorrhizal fungi (reviewed by Warnock et al., 2007).

Biochar as a "bulking agent" in compost

Note: this section is adapted from a research summary written by J. Major and published online by the International Biochar Initiative

Studies to date show that the composting process can be accelerated by adding biochar to poultry manure (Dias et al., 2009; Steiner et al., 2010). For example, maximum temperatures of the compost were reached faster when biochar was applied (Steiner et al., 2010) and the degree of humification of the resulting compost was greater (Dias et al. 2009) with biochar application. Steiner et al. (2010) assumed that biochar did not decompose during the 42 day trial, and found that the loss of poultry manure biomass was not different in cases where biochar was added as 0, 5 or 20% of the mixture on a dry weight basis. Dias et al. found that total mass loss in their 1:1 by wet weight mixture of biochar and poultry litter was intermediate compared to equivalent mixtures with coffee husks and sawdust, and alluded to the fact that biochar could have undergone decomposition although their data did not allow this to be determined. More research is needed on the effect of biochar on the C and mass balance during composting, however a faster "ripening" of compost as demonstrated by both authors is desirable for compost makers.

Total nitrogen losses over 42 days of composting sewage sludge were reduced by 64% by adding 9% biochar to the sludge as opposed to a control not receiving biochar (Hua et al., 2009), and also over 42 days adding 20% of biochar to poultry litter reduced ammonia emissions by 64% (Steiner et al. 2010) compared to a non-amended control. Dias et al. (2009) found that N losses when using biochar as a bulking agent were lower than when coffee husks were used, but greater than when sawdust was used as a bulking agent. These results are promising, especially considering the resilience of biochar in soil compared to other bulking agents, and the potential for biochar to retain inorganic N against leaching, after soil application. Indeed Steiner et al. (2007) found greater yield of maize and sorghum on an acid soil after four years, when biochar was applied with compost as opposed to being applied with synthetic fertilizer.

Biochar in golf courses

Note: parts of this section are adapted from a research summary written by J. Major and published online by the International Biochar Initiative

A 1943 report from the USA states that biochar was successfully applied to established turfgrass, using a home-made handheld device which delivered biochar into the aeration holes made by other equipment. Using a very fine material (passing a 0.6 mm sieve), application rates equivalent to 3.9-5.4 t/ha were achieved (U. S. Golf Association).

Biochar could be mixed with sand, topsoil, compost, or turfgrass substrate prior to application to the landscape. In the case of high-traffic areas of golf courses and sporting turfgrass, resistance to compaction and rapid drainage are important characteristics of man-made rooting zones. Mixing biochar homogeneously with sand for example, could allow fast drainage and resistance to compaction of sand, while increasing moisture retention and availability to turf. Contrarily to peat moss for example, biochar would provide these benefits on the long term.

Biochar could also potentially be applied in layers below the rooting zone of grass, to serve as a barrier for leached nutrients and pesticides. In many cases such layers would need to offer adequate drainage and not cause waterlogged conditions above them, and this can likely be managed with the particle size of the biochar. Slavens et al. (2009) compared biochar (made from grass clippings) and peat moss amendments to quartzite sand in free-draining lysimeters where creeping bentgrass was seeded. Whether or not fertilizers were applied, the biochar amendment yielded better grass cover and visual quality than the peat moss amendment or the unamended sand, under the same fertilization level. The hydraulic conductivity of the biochar-amended sand did not significantly differ from that of pure sand or of peat moss-amended sand. Unexpectedly, biochar-amended sand leached more P, whether or not fertilizers were applied, than any other treatment. Nitrate leaching was also greater in the biochar-amended sand and unamended sand than in the peat moss-amended sand, however the differences decreased over time. It is interesting to note that P leaching did not differ whether or not fertilizers were applied, in the biochar-amended pots. This indicates that the greater leaching was due to biochar itself, and not fertilization (Slavens et al., 2009). It is possible that the grass clipping biochar used contributed more P than the peat moss amendment. Other others also noticed greater leaching of K in biochar-amended soil (Lehmann et al., 2003b), and attributed this effect to K supplied with biochar. This would presumably be a short-term effect. In sand-based microcosms similar to those used by Slavens *et al*., Brockhoff *et al*. (2010) observed reduced N leaching and also greater moisture retention with switchgrass biochar made by fast pyrolysis, but hydraulic conductivity decreased linearly as biochar application rate increased to 25% by weight. Also, the rooting depth of creeping bentgrass decreased at biochar application rates > 10% (Brockhoff et al., 2010).

Biochar in green roofs

Biochar's ability to sorb water and reduce nutrient leaching would provide key benefits in the building of green roofs. Beck et al. (2011) added 7% by weight of a biochar made from 70% agricultural waste and 30% pyrolyzed car tires to a commercial substrate designed for green roofs, and found that leachate from trays filled with biochar-amended medium contained 79% less nitrate, 43% less phosphate, 42% less total phosphorus and 72% less total organic carbon than leachate from trays not receiving biochar. Water retention with biochar was 4% greater (Beck et al., 2011)

Biochar as an animal feed additive

Note: parts of this section are adapted from a research summary written by J. Major and published online by the International Biochar Initiative

"Ecological delivery" of biochar, could be a way of applying biochar to soil in low amounts, where biochar would be fed to animals and then excreted onto fields or applied with manure collected in confined areas (Blackwell et al., 2009; McHenry, 2010). While there are constraints on the amount of biochar which can be delivered to soil in this way, it can potentially provide other advantages. It has been known for a long time that adding charcoal or various zeolite-like materials to the feed of livestock improves their ability to utilize protein and assimilate protein-derived nitrogen from poor-quality (tannin-rich) fodder, most probably via control of loss of ammonia that is subsequently used for microbial protein synthesis in the rumen. Van et al. (2006) showed that growth rate was 20% greater, and final animal weight was 5% greater when goats fed tannin-rich *Acacia* sp. fodder were also fed less than 1 g bamboo charcoal per kg animal weight per day. This trial lasted 12 weeks. A technical bulletin from the Food and Fertilizer Technology Center (FFTC, year unknown) in Taiwan also proposes feeding bamboo charcoal to cattle, pigs and poultry to reduce smells in barns as well as providing other benefits to animal health. Similarly, Allen (1846) gives the following advice on keeping pigs: "If they are closely confined in pens give them as much charcoal twice a week as they will eat. This corrects any tendency to disorders of the stomach". Studies are needed to understand which characteristics ensure biochar is safe for feeding to animals, the mode of action (adsorption, etc.) and which amounts are beneficial.

Other non-fuel uses for by-products of the pyrolysis process

As noted above, the pyrolysis process also yields condensable liquids, including wood vinegar (also known as pyroligneous acid or smoke water). The chemical composition of these condensates can vary widely, but in 2005 organizations in Japan published reference standards for wood and bamboo vinegars sold on the market (Joseph et al., 2010). Dilute bamboo vinegar has been shown to promote seed germination and radicle growth in several plant species (Mu et al., 2003). Interestingly, dilute vinegar from the pyrolysis of bamboo and wood exhibited a marked inhibitory effect towards sap-staining fungi of the genus *Ophiostoma*, and these vinegars were suggest to be potentially useful as wood preservatives (Velmurugan et al., 2009). Another study suggested that bamboo vinegar can have an inhibitory effect on the mycelial growth of several plant pathogenic fungi species (Wang et al., 2005), and wood vinegar can serve as a pesticide for termites (Yatagai et al., 2002). When various concentrations (up to 0.3%) of wood vinegar were added to the diet of piglets, wood vinegar significantly and linearly improved the weight gain in the piglets, as well as the digestibility of dry matter, crude protein and gross energy in their feed (Choi et al., 2009). In a second experiment wood vinegar was compared to other routinely used growth promoters: organic acids and antibiotics. While antibiotics produced the greatest growth, wood vinegar resulted in better growth than organic acids and all three additives resulted in the same level of digestibility for dry matter, crude protein and gross energy. The gut of piglets fed wood vinegar contained significantly more *Lactobacillus* than when piglets were fed the other diets, and the guts of piglets fed all three additives contained significantly less harmful coliforms than piglets fed the control diet (Choi et al., 2009).

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