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Bio-Char Soil Management on Highly Weathered Soils in the Humid Tropics

Johannes Lehmann[1] and Marco Rondon[2]
[1]*Cornell University, New York, USA*
[2]*International Center for Tropical Agriculture (CIAT), Colombia*

CONTENTS

Maintaining an appropriate level of soil organic matter and biological cycling of nutrients is crucial to the success of any soil management in the humid tropics. Cover crops, mulches, compost, or manure additions have been used successfully, supplying nutrients to crops, supporting rapid nutrient cycling through microbial biomass, and helping to retain applied mineral fertilizers better (Goyal et al., 1999; Trujillo, 2002). The benefits of such amendments are, however, often short-lived, especially in the tropics, since decomposition rates are high (Jenkinson and Ayanaba, 1977) and the added organic matter is usually mineralized to CO_2 within only a few cropping seasons (Bol et al., 2000). Organic amendments therefore have to be applied each year to sustain soil productivity.

Management of black carbon (C) — increasingly referred to as bio-char — may overcome some of those limitations and provide an additional soil management option. This is a highly aromatic form of organic matter that is present in most soils to varying extents (Schmidt and Noack, 2000; Skjemstad et al., 2002). Interest in and application of biomass-derived black carbon — using incompletely combusted organic matter such as charcoal (Glaser et al., 2002) — was prompted by studies of soils found in the Amazon Basin, referred to as *Terra Preta de Indio* (Lehmann et al., 2003c). These Amazonian Dark Earths are anthropic soils that were created by Amerindian populations between 500 and 2500 years ago. They have maintained high amounts of organic carbon, and their high fertility, even several thousand years after they were abandoned by the indigenous population, contrasts distinctly with the low fertility of the adjacent acid upland soils (Lehmann et al., 2003b).

The reasons for these soils' high fertility are multiple, but the source of the large amounts of organic matter and their high nutrient retention has been attributed to the extraordinarily high proportions of black carbon (Glaser et al., 2001). Such large amounts of black carbon can only originate from incompletely combusted biomass carbon, such as wood from kitchen fires or possibly from in-field burning (Smith, 1980; Hecht, 2003). This chapter considers the beneficial effects of this bio-char soil management system and discusses opportunities for applying such management within a sustainable system that can be called "slash-and-char," as well as within other smallholder agricultural systems.

36.1 Bio-Char Management and Soil Nutrient Availability

Black carbon is found along a continuum of forms of aromatic carbon, from charred organic materials to charcoal, soot, and graphite (Schmidt and Noack, 2000). Biomass-derived black carbon, or bio-char, is produced through burning at 300 to 500°C under partial exclusion of oxygen (Antal and Gronli, 2003). The result is a highly aromatic organic material with carbon concentrations of about 70 to 80% (Lehmann et al., 2002).

Increases in soil fertility attributable to charcoal are known from naturally occurring fires (although the increases have often been attributed to adsorption of phenolics, e.g., Wardle et al., 1998) and from remnants of charcoal hearths (Chidumayo, 1994; Mikan and Abrams, 1995; Young et al., 1996; Oguntunde et al., 2004). Additions of bio-char to soil have shown definite increases in the availability of major cations and phosphorus as well as in total nitrogen concentrations (Glaser et al., 2002; Lehmann et al., 2003a). Both CEC and pH are also frequently increased through such applications, by up to 40% of initial CEC and by one pH unit, respectively (Tryon, 1948; Mikan and Abrams, 1995; Topoliantz et al., 2002). Higher nutrient availability for plants is the result of both the direct nutrient additions by the bio-char and greater nutrient retention (Lehmann et al., 2003a), but it can also be an effect of changes in soil microbial dynamics, discussed in the following section.

Yield increases have frequently been reported that are directly attributable to the addition of bio-char over a control without bio-char (Lehmann et al., 2003a). However, growth depressions have been found in some instances (Mikan and Abrams, 1996). The immediate beneficial effects of bio-char additions for nutrient availability are largely due to higher potassium, phosphorus, and zinc availability, and to a lesser extent, calcium and copper (Lehmann et al., 2003a). Longer-term benefits for nutrient availability include a greater stabilization of organic matter, concurrent slower nutrient release from added organic matter, and better retention of all cations due to a greater cation exchange capacity.

The effect of bio-char on plant productivity depends on the amount added. Progressive growth improvement with greater bio-char applications is seen with comparatively low levels of bio-char; already at very low application rates of 0.4 to 8 t C ha^{-1}, significant improvements in productivity can be observed ranging from 20 to 220% (biomass production equal to 120 to 320% of the control in Figure 36.1). In many cases, nitrogen limitation will be the reason for declining yields at high application rates, as nitrogen availability decreases through immobilization by microbial biomass at high C:N ratios (Lehmann et al., 2003b), although other growth-limiting factors may be responsible as well. With increasing rates of application, plant response at a given site is positive until some maximum is reached, above which growth response is negative, as shown for beans with applications of 31 to 93 t C ha^{-1} (data points 16, 17 and 18 in Figure 36.A1).

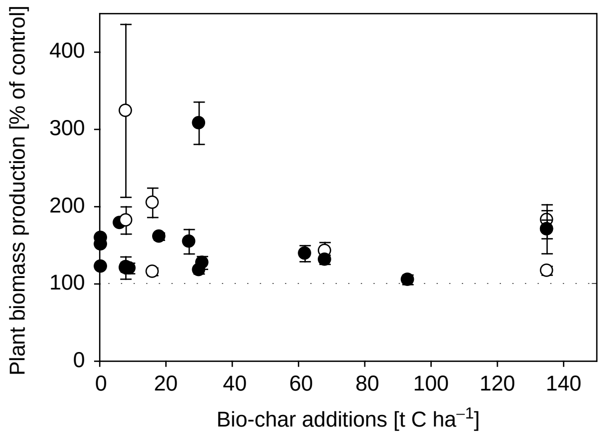

FIGURE 36.1
Plant biomass increase over control as a function of the amount of bio-char applied (means and standard errors). Open symbols = unfertilized; filled symbols = fertilized. Site and crop information are given in Table 36.A1 in annex to this chapter.

The response function is additionally dependent on the properties of the bio-char (Tryon, 1948), soil properties (greater response occurs on nutrient-deficient, sandy soils), concurrent nutrient and organic matter additions, and plant species. Legumes appear to thrive under greater bio-char additions, more than do gramineae species, since they can compensate for limited nitrogen availability by increased biological nitrogen fixation (BNF). Additions of nutrients from using inorganic or organic fertilizers are usually essential for high productivity and increase the positive response of the bio-char amendment. However, the relative effect of the bio-char addition may not be as high as for unfertilized crops (Figure 36.1).

Bio-char soil management, with associated increases in nutrient availability and pH, not only enhances crop yields and decreases risk of crop failure, but also opens new possibilities for cropping, i.e., high-value crops can be produced on sites that would normally not be suitable for production. Nutritious and easily marketable produce can improve cash returns and health among farmers who currently only have access to poor soils. Carrots and beans grown on steep slopes and on soils with a soil reaction of less than pH 5.2 have had yields significantly improved by bio-char additions (Rondon et al., 2004). Improvement of rural livelihoods is possible not only through increased crop yields, but also through increased quality and variety of the crops grown.

36.2 Microbial Cycling of Nutrients in Soils with Bio-Char

Interactions of bio-char with soil microorganisms are complex. On the one hand, soil microbial diversity and population size, as well as population composition and activity, may be affected by the amount and type of bio-char present or added to soil. On the other hand, microorganisms are able to change the amount and properties of bio-char in soil. Both effects will have significant influence on nutrient cycles and nutrient availability to plants.

Some indications exist from soils that are rich in bio-char that microbial community composition, species richness, and diversity change with greater bio-char concentrations (Pietikäinen et al., 2000; Yin et al., 2000; Thies and Suzuki, 2003). Pietikäinen et al. (2000) found a greater bacterial growth rate in layers of charcoal than in the underlying organic horizon in a temperate forest soil. Already small amounts of 7.9 t C ha^{-1} of bio-char in a highly weathered soil in the tropics significantly enhanced microbial growth rates when nutrients were supplied by fertilizer (Steiner et al., 2004). A greater microbial biomass was reported in forest soils in the presence of charcoal by Zackrisson et al. (1996), and higher microbial activity (CO_2 production as well as organic matter decomposition) was found in soils exposed to black carbon aerosols derived from charcoal making (Uvarov, 2000). Apparently, bio-char provides a suitable habitat for a large and diverse group of soil microorganisms.

A higher retention of microorganisms in bio-char soils may be responsible for greater activity and diversity due to a high surface area as well as surface hydrophobicity of both the microorganisms and bio-char. A strong affinity of microbes to bio-char can be expected since the adhesion of microorganisms to solids increases with higher hydrophobicity of the surfaces (Stenström, 1989; Huysman and Verstraete, 1993; Castellanos et al., 1997; Mills, 2003). Activated carbon, which is chemically similar to black carbon or bio-char in soil, has been shown to sorb microorganisms strongly, and this adsorption was seen to increase with higher hydrophobicity (Rivera-Utrilla et al., 2001).

Strong microbial adhesion can be achieved between microorganisms and organic surfaces in the presence of divalent cations and specifically of Ca^{2+} (Rivera-Utrilla et al., 2001; Mills, 2003). Whether the mechanism is electrostatic bondage or increased hydrophobicity is not yet clear. Pore geometry and size distribution has been found definitely to promote the growth and activity of certain microorganisms.

Bio-char is also able to serve as a habitat for extraradical fungal hyphae that sporulate in their micropores due to lower competition from saprophytes, and it can therefore act as an inoculum for arbuscular mycorrhizal fungi (Saito and Marumoto, 2002). Root infection by arbuscular mycorrhizae significantly increased by adding 1 kg m^{-2} of bio-char to alfalfa in a volcanic ash soil that related well with growth of alfalfa ($r = 0.88$; $P < 0.01$; $N = 7$) being 40 to 80% greater after the application (Nishio and Okano, 1991; Nishio, 1996). Similarly, mycorrhizal infection increased when bio-char (7 g kg^{-1} soil) was added to soil that was inoculated with spores of *Glomus etunicatum*, improving the yields of onion (Matsubara et al., 1995).

Methods have already been developed to inoculate soils with ectomycorrhizas using carbonized rice husks (Mori and Marjenah, 1994). A more rapid cycling of nutrients in soil organic matter and microbial biomass as well as better colonization of roots by arbuscular mycorrhizal fungi will improve nutrient availability and crop yields by (1) retention of nutrients against leaching in highly weathered soils of the humid tropics that have little cation exchange capacity, and (2) a better access of the plants to fixed phosphorus due to inoculation by mycorrhizae.

The effect of microorganisms on bio-char is difficult to determine considering its long half-life. Bio-char is quite recalcitrant to microbial attack. However, we know that even bio-char must ultimately be broken down (Schmidt and Noack, 2000). Mineralization rates are not clear, and available data show rates of decomposition that are both rapid (Shneour, 1966; Bird et al., 1999) and slow (Shindo, 1991). It appears that a large part of bio-char is mineralized over a short time-scale, and a small part remains in a very stable, highly aromatic form, displaying greater ^{14}C age than the oldest SOM fractions (Pessenda et al., 2001).

The greater amount of cation exchange capacity per unit C found in soils with high amounts of bio-char such as the Amazonian Dark Earths (Sombroek, 1966) may be the result of a greater surface area of the bio-char and a higher charge density per unit surface area. A concomitant adsorption of low-molecular organic matter has been proposed since cation adsorption could be increased by coating of bio-char with manure extracts (Lehmann et al., 2002). In either case, the consequence is a greater cation exchange capacity per unit C found in soil with large amounts of bio-char compared with those with low amounts. Abiotic oxidation was also found to increase abundance of carboxylic acids on bio-char surfaces (Adams et al., 1988), and this may contribute to higher CEC after long periods of time in tropical ecosystems that experience high soil temperatures.

36.3 Biological Nitrogen Fixation in Soils with Bio-Char

Bio-char additions not only affect microbial populations and activity in soil, but also plant–microbe interactions through their effects on nutrient availability and modification of habitat. Rhizobia spp. living in symbiosis with many legume species are able to reduce atmospheric N_2 to organic nitrogen through a series of enzymatic reactions (Giller, 2001). This BNF is regarded as an important opportunity to mitigate nitrogen deficiency in cropping systems worldwide (Chapter 27). BNF significantly decreases, however, if available nitrate concentrations in soils are high, and if available calcium, phosphorus, and micronutrient concentrations are low (Giller, 2001).

Soils with appreciable concentrations of bio-char show the reversed situation as evident from Amazonian Dark Earths. With large bio-char concentrations, available nitrate concentrations are usually low and available calcium, phosphorus, and micronutrient concentrations are high, which is ideal for maximum BNF (Lehmann et al., 2003b). Indeed, BNF by common beans (CIAT BAT477), as determined by ^{15}N dilution, increased from 50 to 72% of total nitrogen uptake with increasing rates of bio-char additions (0, 31, 62, and 93 t C ha^{-1}) to a low-fertility Oxisol (Rondon et al., in preparation).

In addition to changing nutrient availabilities that are conducive to high BNF, inoculation with Rhizobia may be more effective in the presence of bio-char due to the habitat offered by the bio-char. In fact, several studies indicate that bio-char is an excellent support material for Rhizobium inoculants (Pandher et al., 1993; Lal and Mishra, 1998). Consequently, BNF determined by nitrogen difference was found to be 15% higher when bio-char was added to soil at early stages of alfalfa development, and 227% higher when nodule development was greatest (Nishio, 1996). Bio-char additions are, therefore, able to increase the net input of nitrogen into agricultural landscapes.

This does not necessarily mean that the nitrogen nutrition of the legume is improved, especially if large amounts of bio-char are added. Lehmann et al. (2003a) showed that while biomass production and nitrogen uptake of cowpea increased through large amounts of bio-char additions, plants' nitrogen nutrition decreased. With appropriate application rates of bio-char and supplementary nutrient additions, nitrogen input to agricultural systems can be increased without decreasing plant productivity. Such a soil management system may be interesting in the context of mixed legume–cereal intercropping or of agroforestry with woody legumes. Soil nitrogen stocks and eventually nitrogen availability can be increased and be made available to the nonlegume in a rotational system.

36.4 Slash-and-Char as an Alternative to Slash-and-Burn

Building on the evidence that bio-char additions significantly improve soil fertility as seen above, land-use systems have been developed that incorporate this technology. One such technology is a slash-and-char system, conceived as an alternative to slash-and-burn, and building on the socioeconomic and biophysical environment of such shifting-cultivation systems. This alternative entails — similar to slash-and-burn — that biomass from a given area is used as a soil conditioner for that same unit area while at the same time the field is cleared in a rapid and cost-efficient way. Woody biomass is charred on site in simple pits or under grass covers similar to small-scale charcoal production systems. For this effort to be successful, sufficient biomass has to be available, and the system has to utilize tree biomass efficiently for the production of bio-char. In fact, often in a slash-and-burn system, large proportions of the biomass are not burned completely, e.g., large branches, trunks, and roots. Such large woody debris are only partially charred and are usually seen as an obstacle for field preparation. However, in a slash-and-char system, they can become a source of bio-char.

36.4.1 Efficiency of Conversion

Analyses of conversions of woody biomass to bio-char have shown an average recovery of 54% of the initial carbon in the bio-char (Lehmann et al., 2002). This value largely derived from laboratory experiments and commercial charcoal operations, however. Conversion using earthen pits and mounds will more likely range around 30 to 40%. The production of bio-char in agricultural fields using recently slashed organic matter requires specific skills. However, farmers who practice slash-and-burn are intimately familiar with cutting of biomass and the process of burning, and many farmers regularly produce charcoal for sale in local markets. Therefore, charring organic matter in simple earthen mounds or pits should not be limited by the availability of local knowledge. Improvements in the wood-to-bio-char conversion efficiency are feasible with changes in the geometry of the pits or piles and in management of the air supply during the charring process.

36.4.2 Supply of Material

Amounts of aboveground biomass largely depend on site characteristics, the age of the forest, whether it is a primary or secondary forest, as well as the history of land use (Buschbacher et al., 1988; Silver et al., 2000). A guideline presented in Figure 36.2 shows the amounts of bio-char that can be produced and applied to 1 ha of land as a function of forest age for various regions. Comparing these values with the positive growth and yield responses already at 5 to 10 t C ha^{-1} obtained from several experiments (Figure 36.1), about 4 to 8 years of growth of a secondary forest are needed to produce the bio-char equivalent to improve effectively the productivity of crops grown in a slash-and-char system. These amounts of regrowth necessary for the system can clearly be achieved under humid tropical conditions as seen in Figure 36.2.

These data establish that bio-char management is feasible with the amounts of biomass already available for systems such as slash-and-burn or slash-and-mulch without requiring any biomass transfers. This conclusion confirms the feasibility of creating the amounts of bio-char found in Amazonian Dark Earths with the resources that are available on the same piece of land that will be cropped. Applying a Terra Preta soil management system is therefore feasible under most conditions in the humid tropics. Therefore, slash-and-char does not increase but reduces anthropogenic CO_2 emissions, and bio-char even constitutes a long-term carbon sink in addition to improving soil fertility and production potential.

36.4.3 Duration

Slash-and-char not only increases crop yields after bio-char application, but also increases the number of cropping cycles before crop yields decrease to unacceptably low levels that

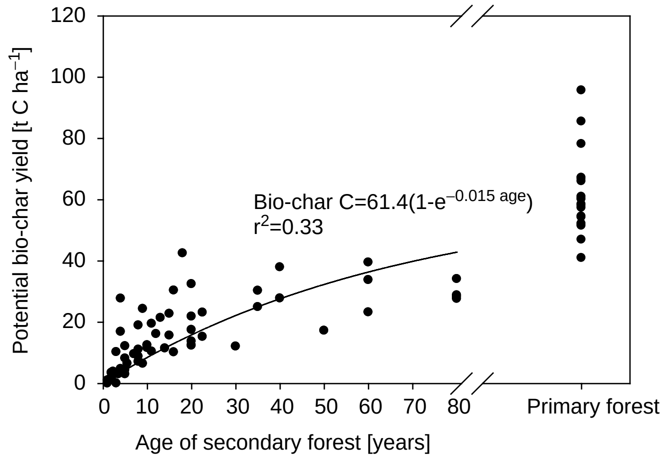

FIGURE 36.2
Potential bio-char yield from the woody biomass of secondary and primary forests in the humid tropics. (A typical biomass loss of 69.4% upon bio-char conversion and a C concentration of 75.7% was calculated from data in Lehmann et al. (2002). The maximum of 61.4 t ha^{-1} for the plotted regression was the mean of all primary forest sites. Data on woody biomass volumes were obtained from Toky and Ramakrishnan (1983), Uhl and Jordan (1984), Buschbacher et al. (1988), Saldarriaga et al. (1988), Lugo (1992), Fearnside et al. (1993), Foster Brown et al. (1995), Kauffman et al. (1995), Alves et al. (1997), Camargo et al. (1999), Fearnside et al. (1999), Gehring et al. (1999), Graca et al. (1999), Gerwing and Farias (2000), Hughes et al. (2000), Mackensen et al. (2000), Sorrensen (2000), Johnson et al. (2001), and Feldpausch (2002). Woody biomass for the Alves, Camargo, Gehring and Sorrensen studies was assumed be equal to the average proportion of woody biomass of total biomass calculated from all other cited publications, i.e., 89.7% for older secondary forests, and 92% for primary forests.

make a fallow period necessary. A recent study has shown crop productivity to be low directly after slash-and-burn on a Typic Hapludox in the central Amazon, and even this could not be sustained for more than 1 year after slashing using mineral fertilizer, whereas application of bio-char resulted in low but sustainable grain yields (Steiner et al., 2004).

Continuous cultivation on Amazonian Dark Earths rich in bio-char has been reported to be more than 40 years in some instances (Petersen et al., 2001). On these soils, historically amended with bio-char, recovery of soil conditions is usually rapid, and only very short fallow periods of 1 to 2 years are required (German, 2001). On the other hand, slash-and-burn cycles are typically 2 to 3 years of cropping followed by 10 years of fallow (Nye and Greenland, 1960). In the absence of long-term studies with slash-and-char, its ratio between crop and fallow cycles can only be estimated, but this should be greater than unity.

36.4.4 Sustainability

In addition to higher proportions of crop vs. fallow periods, slash-and-char opens up the possibility for farmers of changing to permanent cropping. Black carbon is usually several thousand years older than nonblack carbon in soils and sediments (Masiello and Druffel, 1998; Schmidt et al., 2002). The polyaromatic structure of black carbon is extremely resistant to microbial attack, and only specialized fungi with unique extracellular enzymes are able to mineralize black carbon, as shown with coal (Willmann and Fakoussa, 1997; Hofrichter et al., 1999).

We can therefore expect that the beneficial effects of a slash-and-char intervention will persist in soil for a significant period of time. In contrast, amendments of mulches, manures, or composts are typically mineralized to carbon dioxide within a time frame of months to years, due to rapid decomposition rates in tropical soil ecosystems (Jenkinson and Ayanaba, 1977). The fraction of bio-char and nonbio-char, which is stabilized inside aggregates and organo-mineral complexes, can currently only be estimated, but it is certainly much higher for bio-char than for manures or mulches.

36.4.5 Labor Requirements

Labor inputs will most likely be greater during land clearing using a slash-and-char technique as woody biomass has to be charred and applied to soil. In many situations the additional labor may be low, however, as secondary burns and piling up or removal of unburned branches are already part of many slash-and-burn practices (Ketterings et al., 1999). This technology therefore has the potential for farmers in many ecoregions of the humid tropics to escape from the vicious cycle of declining productivity and soil degradation as a result of high population pressure and resulting shortened fallow periods.

36.5 Discussion

Bio-char can be obtained from a variety of other sources in addition to slashed woody biomass, which was described above, and bio-char production can be built into several land-use systems. Crop residue from grain processing (e.g., rice husks) and wood residue from lumber processing (e.g., sawdust) can be used to produce bio-char. The production of bio-char from rice husks is a procedure recommended by the Food and Fertilizer Technology Center for the Asian and Pacific Region (FFTC, 2001). Such conversions of crop residues can be done with locally available techniques, such as using residue mounds and firing (FFTC, 2001), simple firing chambers, or more sophisticated furnaces. Such obtained bio-char can be applied to any cropping system.

A better utilization of residues from charcoal production itself provides opportunities for a combination with a bio-char soil management system. Charcoal is still used in many parts of the world as an important source of energy for food preparation (World Energy Council, 2001). Worldwide an estimated 41 million tons (Mt) of charcoal were produced in 2002, with Brazil being the largest producer with 12 Mt (FAO, 2004). Much more charcoal is produced in developing countries (40 Mt in 2002) than in developed countries (1.4 Mt). Africa is the highest producer (21 Mt), followed by South America (14 Mt) and Asia (4 Mt).

During any production process, a significant proportion accumulates as waste that cannot be sold as fuel. The percentage varies, of course, and depends on the charring method as well as the wood type and environmental conditions, such as moisture content and temperature, as well as on postcharring management and packing of the charcoal. An estimate of waste accumulation from simple small-scale production systems of charcoal for barbeques in Colombia was 30 to 40% waste by weight of the produced charcoal. However, a growing local demand for charcoal of smaller sizes (1 to 2 cm) was observed as support material for growing ornamental plants in nurseries. The fraction of waste material that is not suitable for the market, and thus is discarded, lies between 10 and 15%.

Another source of bio-char is the pyrolysis of biomass (from agricultural and forestry sources) to produce energy, where bio-char is a by-product (Day et al., 2005). An additional improvement of the properties of such bio-char provides the conversion of gas emissions from the power plant (or other CO_2-producing industries) into NH_4HCO_3 by using the H_2 that was produced during the combustion process (Lee and Li, 2003). This ammonium bicarbonate can be adsorbed to the bio-char to increase nitrogen levels similar to commercially available nitrogen fertilizers. The resulting relatively low C:N ratios would make the bio-char a source and not a sink of nitrogen. Once refined, this relatively new technology could be used in small communities to provide energy while producing a soil conditioner rich in stable carbon and nitrogen.

Bio-char amendments have so far shown beneficial effects when applied to rice, sorghum, corn, various beans (soybean, common bean, cow pea, moongbean), banana, and vegetables such as carrots. Since bio-char is a valuable commodity, applications can be successfully applied to smaller units of area than entire fields, such as high fertility trenches in contour rows of steep land for vegetables or grain crops, and planting holes for tree crops. Bio-char has been widely applied in tree nurseries and is a recommended amendment (Jaenicke, 1999). It is used for propagation, in some cases due to its ability to adsorb inhibitory substances (Nhut et al., 2001). The particle size of the bio-char appears to play a minor role in its effect on soil fertility and crop production (Lehmann et al., 2003a), which simplifies the application of the technology.

Many questions still remain to be answered regarding the mechanisms governing surface properties of bio-char and how nutrient dynamics are affected by bio-char. The opportunities for carbon sequestration and the reduction of greenhouse gas emissions have not been explored at all, but they are potentially significant. It is clear already, however, that bio-char can significantly improve soil fertility in acid and highly weathered soils, and it has the potential for widespread application under various agroecological situations by mobilizing and improving the complex of chemical, physical, and biological properties of soil systems.

Annex: Site and crop information for Table 36.1

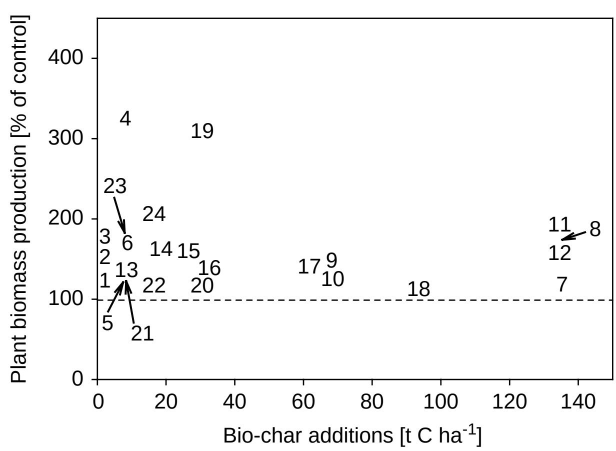

FIGURE 36.A1
Plant biomass increase over control as a function of the amount of bio-char applied, identifying data points in Figure 36.1 of this chapter. Numbers refer to site and crop information given in Table 36.A1.

TABLE 36.A1

Crop Species and Experimental Details of Trials with added Bio-Char that are Shown in Figure 36.A1. Trial Numbers (Left Column) Refer to Numbers in Figure 36.A1

Trial Number[a]	Plant Species	Soil	Amount of Bio-Char Applied[b] (t C ha^{-1})	Origin of the Bio-Char	Type of Experiment (Replicates)	Source
1	Moong bean (*Vigna radiata*)	Nd	0.38[c]	Commercial charcoal	Pots ($N = 3$)	Iswaran et al. (1980)
2	Soybean (*Glycine max*)	Nd	0.38	Commercial charcoal	Pots ($N = 3$)	Iswaran et al. (1980)
3	Pea (*Pisum sativum*)	Nd	0.38	Commercial charcoal	Pots ($N = 3$)	Iswaran et al. (1980)
4, 5	Rice (*Oryza sativa*)	Oxisol	7.9	Commercial charcoal	Field ($N = 5$)	Nehls (2002)
6	Alfalfa (*Medicago sativa*)	Andosol	6.1	Commercial charcoal from bark	Pots ($N = 3$)	Nishio and Okano (1991)
7, 8	Rice (*Oryza sativa*)	Oxisol	68	Commercial charcoal	Lysimeters ($N = 4$)	Lehmann et al. (2003a)
9, 10	Cowpea (*Vigna unguiculata*)	Oxisol	68	Commercial charcoal	Pots ($N = 5$)	Lehmann et al. (2003a)
11, 12	Cowpea (*Vigna unguiculata*)	Oxisol	135	Commercial charcoal	Pots ($N = 5$)	Lehmann et al. (2003a)
13	Soybean (*Glycine max*)	Oxisol	9	Commercial charcoal (*Swinglea glutinosa*)	Pots ($N = 4$)	Rondon et al. (unpublished data)
14	Soybean (*Glycine max*)	Oxisol	18	Commercial charcoal (*Swinglea glutinosa*)	Pots ($N = 4$)	Rondon et al. (unpublished data)
15	Soybean (*Glycine max*)	Oxisol	27	Commercial charcoal (*Swinglea glutinosa*)	Pots ($N = 4$)	Rondon et al. (unpublished data)
16	Bean (*Phaseolus vulgaris*)	Oxisol	31	Commercial charcoal (*Eucalyptus deglupta*)	Pots ($N = 4$)	Rondon et al. (unpublished data)
17	Bean (*Phaseolus vulgaris*)	Oxisol	62	Commercial charcoal (*Eucalyptus deglupta*)	Pots ($N = 4$)	Rondon et al. (unpublished data)
18	Bean (*Phaseolus vulgaris*)	Oxisol	93	Commercial charcoal (*Eucalyptus deglupta*)	Pots ($N = 4$)	Rondon et al. (unpublished data)
19	Carrots (*Phaseolus vulgaris*)	Andosol	30	Commercial charcoal (*Gliricida sepium*)	Field ($N = 4$)	Rondon et al. (2004)
20	Bean (*Phaseolus vulgaris*)	Andosol	30	Commercial charcoal (*Gliricida sepium*)	Field ($N = 4$)	Rondon et al. (2004)
21	Corn (*Zea mays*)	Oxisol	8	Commercial charcoal	Field ($N = 3$)	Rondon et al. (unpublished data)
22	Corn (*Zea mays*)	Oxisol	16	Commercial charcoal	Field ($N = 3$)	Rondon et al. (unpublished data)
23	Native savanna	Oxisol	8	Commercial charcoal	Field ($N = 3$)	Rondon et al. (unpublished data)
24	Native savanna	Oxisol	16	Commercial charcoal	Field ($N = 3$)	Rondon et al. (unpublished data)

[a] First number = unfertilized plants, second number = fertilized plants.

[b] In case of pot experiments, calculated for a depth of 0.1 m.

[c] Assuming 76% C in bio-char (Lehmann et al., 2002).

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EDITED BY

Norman Uphoff

Andrew S. Ball
Erick Fernandes
Hans Herren
Olivier Husson
Mark Laing
Cheryl Palm
Jules Pretty
Pedro Sanchez
Nteranya Sanginga
Janice Thies

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