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REVIEW ARTICLE

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Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review

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Abstract Rapid turnover of organic matter leads to a low efficiency of organic fertilizers applied to increase and sequester C in soils of the humid tropics. Charcoal was reported to be responsible for high soil organic matter contents and soil fertility of anthropogenic soils (Terra Preta) found in central Amazonia. Therefore, we reviewed the available information about the physical and chemical properties of charcoal as affected by different combustion procedures, and the effects of its application in agricultural fields on nutrient retention and crop production. Higher nutrient retention and nutrient availability were found after charcoal additions to soil, related to higher exchange capacity, surface area and direct nutrient additions. Higher charring temperatures generally improved exchange properties and surface area of the charcoal. Additionally, charcoal is relatively recalcitrant and can therefore be used as a long-term sink for atmospheric CO_2. Several aspects of a charcoal management system remain unclear, such as the role of microorganisms in oxidizing charcoal surfaces and releasing nutrients and the possibilities to improve charcoal properties during production under field conditions. Several research needs were identified, such as field testing of charcoal production in tropical agroecosystems, the investigation of surface properties of the carbonized materials in the soil environment, and the evaluation of the agronomic and economic effectiveness of soil management with charcoal.

Keywords Carbon sequestration · Charcoal addition to soil · Nutrient leaching · Soil amelioration · Sustainable landuse

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Introduction

An intensification of agricultural production on a global scale is necessary in order to secure the food supply for an increasing world population. As a result, fallow periods are often reduced in shifting cultivation in the humid tropics leading to irreversible soil degradation and increased destruction of remaining natural forests due to cultivation of new areas after slash-and-burn (Vosti et al. 2001). In most tropical environments, sustainable agriculture faces large constraints due to low nutrient contents and accelerated mineralization of soil organic matter (SOM) (Tiessen et al. 1994; Zech et al. 1997). As a consequence, the cation exchange capacity (CEC) of the soils, which is often low due to their clay mineralogy, decreases further. Under such circumstances, the efficiency of applied mineral fertilizers is very low when the loss of mobile nutrients such as NO_3^- or K from the topsoil is enhanced by high rainfall (Melgar et al. 1992; Cahn et al. 1993). Additionally, many farmers cannot afford the costs of regular applications of mineral fertilizers. Therefore, nutrient deficiency is prevalent in many crop production systems of the tropics.

The most common form of landuse in the tropics is shifting cultivation using slash-and-burn techniques. During burning of the aboveground biomass the nutrients are rapidly released into the soil. These nutrient additions have positive effects on soil fertility only for a short period (Cochrane and Sanchez 1980; Kauffman et al. 1995; Kleinman et al. 1995). Additionally, burning releases large amounts of the greenhouse gases CO_2 and NOx which lead to global warming (Fearnside et al. 1999). Applications of mulches, composts, and manures have frequently been shown to increase soil fertility. However, under tropical conditions organic matter is usually mineralized very rapidly (Tiessen et al. 1994) and only a small portion of the applied organic compounds will be stabilized in the soil in the long term, but successively released to the atmosphere as CO_2 (Fearnside 2000). An alternative is the use of more stable compounds such as carbonized materials or their extracts. Recent investigations (Glaser 1999; Glaser et al. 2000, 2001a) showed that carbonized materials from the incomplete combustion of organic material (i.e. black C, pyrogenic C, charcoal) are responsible for maintaining high levels of SOM and available nutrients in anthropogenic soils of the Brazilian Amazon basin. These so-called Terra Preta do Indio (Terra Preta) characterize the settlements of pre-Columbian Indios. In Terra Preta soils large amounts of black C indicate a high and prolonged input of carbonized organic matter probably due to the production of charcoal in hearths, whereas only low amounts of charcoal are added to soils as a result of forest fires and slash-and-burn techniques (Fearnside et al. 1999; Fearnside 2000).

Coal from geological deposits ("coal") and from various specialized procedures were successfully used for soil amelioration (Berkowitz et al. 1970; Radlein et al. 1996; Rakishev et al. 1996). As carbonized materials comprise a wide range of materials from partly charred material to graphite and soot particles, with no general agreement on clear-cut boundaries according to their different physical and chemical properties (Schmidt and Noack 2000), we will focus in this review on the influence of highly aromatic "charcoal" amendments to soil. The objectives were to discuss: (1) the effects of charcoal on nutrient availability and nutrient retention in soil; (2) the possibility to increase C sequestration with charcoal amendments; and (3) to evaluate the economic feasibility of using charcoal amendments in smallholdings in the humid tropics.

Charcoal amendments to soil and crop production

Improving crop yields with charcoal amendments

Adding charcoal to soil can significantly increase seed germination, plant growth, and crop yields (Table 1). Chidumayo (1994) reported generally better seed germination (30% enhancement), shoot heights (24%) and biomass production (13%) among seven indigenous woody plants on soils under charcoal kilns compared to the undisturbed Zambian Alfisols and Ultisols (Table 1). Kishimoto and Sugiura (1985) found that the heights of sugi trees (*Cryptomeria japonica*) increased by a factor of 1.26–1.35, and the biomass production increased by a factor of 2.31–2.36, five years after application of 0.5 Mg charcoal ha^{-1}. Not only trees but also annual

Table 1 Relation between charcoal amendments to soil and crop response

Treatment	Amendment (Mg ha^{-1})	Biomass production (%)	Plant height (%)	Root biomass (%)	Shoot biomass (%)	Plant type	Soil type	Reference
Control	–	100	100	–	–	Bauhinia wood	Alfisol/Ultisol	Chidumayo (1994)
Charcoal	Unknown	113	124	–	–	Bauhinia wood	Alfisol/Ultisol	
Control	–	100	–	–	–	Soybean	Volcanic ash soil, loam	Kishimoto and Sugiura (1985)
Charcoal	0.5	151	–	–	–	Soybean	Volcanic ash soil, loam	Iswaran et al. (1980)
Charcoal	5.0	63	–	–	–	Soybean	Volcanic ash soil, loam	Kishimoto and Sugiura (1985)
Charcoal	15.0	29	–	–	–	Soybean	Volcanic ash soil, loam	
Control	–	100	–	–	–	Pea	Dehli soil	Iswaran et al. (1980)
Charcoal	0.5	160	–	–	–	Pea	Dehli soil	
Control	–	100	–	–	–	Moong	Dehli soil	
Charcoal	0.5	122	–	–	–	Moong	Dehli soil	
Control	–	100	–	100	–	Cowpea	Xanthic Ferralsol	Glaser et al. (2002a, 2002b)
Charcoal	33.6	127	–	–	–	Oats	Sand	
Charcoal	67.2	120	–	–	–	Rice	Xanthic Ferralsol	
Charcoal	67.2	150	–	140	–	Cowpea	Xanthic Ferralsol	
Charcoal	135.2	200	–	190	–	Cowpea	Xanthic Ferralsol	
Control	–	100	100	100	100	Maize	Alfisol	Mbagwu and Piccolo (1997)
Coal humic acid	0.2	118	114	122	114	Maize	Alfisol	
Coal humic acid	2.0	176	145	186	166	Maize	Alfisol	
Coal humic acid	20.0	132	125	144	120	Maize	Alfisol	
Control	–	100	100	100	100	Maize	Inceptisol	
Coal humic acid	0.2	125	119	122	127	Maize	Inceptisol	
Coal humic acid	2.0	186	148	198	173	Maize	Inceptisol	
Coal humic acid	20.0	139	131	147	130	Maize	Inceptisol	
Control	–	100	100	100	–	Sugi trees	Clay loam	Kishimoto and Sugiura (1985)
Wood charcoal	0.5	249	126	130	–	Sugi trees	Clay loam	
Bark charcoal	0.5	324	132	115	–	Sugi trees	Clay loam	
Activated charcoal	0.5	244	135	136	–	Sugi trees	Clay loam	

crops were found to have higher yields after applications of carbonized organic matter. Crop yields could be increased by up to 200% upon higher charcoal additions (Table 1). Similar observations were made after additions of humic acids from coal deposits, which increased maize growth by up to 1 g kg^{-1} on Nigerian Alfisols and Inceptisols (Mbagwu and Piccolo 1997). In addition to supplying essential plant nutrients, humic acids were reported to have hormone-like properties that enable a stimulation of plant growth (Nardi et al. 2000). On the other hand, large additions of charcoal or coal-derived humic acids may also have detrimental effects on crop growth. Yield declines of soybeans and maize were observed with an addition of 5 Mg charcoal ha^{-1} and 15 Mg charcoal ha^{-1} (Kishimoto and Sugiura 1985; Table 1) and >1 g coal-derived humic acids kg^{-1}, respectively (Mbagwu and Piccolo 1997). The reason for these reductions can be attributed to an increase in pH for pH-sensitive plants, such as observed for pine (Tryon 1948) or due to pH-induced micro-nutrient deficiencies (Kishimoto and Sugiura 1985). However, crop yields did not generally decline after additions of large amounts of charcoal. From the few data available, no general optimum range can be deduced. Instead, for optimum plant growth, the amount of added charcoal may have to be determined for each type of soil and plant. Additionally, recent investigations showed that crop yields can be enhanced even more compared to control soils if charcoal amendments are applied together with inorganic or organic fertilizers (Glaser et al. 2002a; Lehmann et al. 2002).

Charcoal amendments and nutrient availability

The application of charcoal can increase the pH and decrease the Al saturation of acid soils, which often are major constraints for productive cropping in highly weathered soils of the humid tropics (Cochrane and Sanchez 1980; Mbagwu and Piccolo 1997). The accumulation of the ashes from burned biomass and its effect on soil pH is a well-documented mechanism for improving soil fertility (e.g. Sanchez et al. 1983). In the Peruvian Amazon, topsoil pH was 0.4 pH units higher after slash-and-burn (Kauffman et al. 1995). The addition of coal ash (110 Mg ha^{-1}) was shown to increase the pH of an eroded Palouse soil from 6.0 to 6.8 (Cox et al. 2001). Also, the addition of charcoal increased the pH of soils with various textures by up to 1.2 pH units from pH 5.4 to pH 6.6 (Mbagwu and Piccolo 1997). This effect was still detectable 3 years after charcoal application where the pH values were 5.8 and 6.3 in the control and the charcoal plots, respectively (Kishimoto and Sugiura 1985). As expected, the pH increase was larger in sandy and loamy soils than in clayey soils (Tryon 1948). Consequently, also the base saturation increased and was tenfold higher after charcoal amendment (Table 2).

Tryon (1948) also found increasing amounts of exchangeable bases after additions of 45% hardwood and conifer charcoals to sandy and loamy soils (Table 2). With respect to the cations, he used the term “available” rather than “exchangeable” because the sum of the determined cations exceeded the CEC by a factor of about 3. This observation could be explained by the fact that most of the cations in the ash contained in the charcoal were not bound by electrostatic forces but present as dissolvable salts and, therefore, readily available for plant uptake. From these results it might be concluded that charcoal is not only a soil conditioner which increases the CEC (Glaser 1999; Glaser et al. 2000, 2001a) but may act as a fertilizer itself. Applications of charcoal which inevitably contain ash add free bases such as K, Ca, and Mg to the soil solution, increasing the pH value of the soil and providing readily available nutrients for plant growth. However, despite the positive effects of charcoal additions on CEC and available nutrients, high charcoal applications of >100 Mg ha^{-1} are certainly inadequate for practical use. But estimates from this study allow the conclusion to be drawn that also lower amounts of added charcoal will significantly increase the availability of base cations in soil. Equally total N and available P forms were higher after charcoal amendments to soil (Table 2).

Charcoal amendments and nutrient retention

Not only the nutrient contents but also the nutrient retention can be improved with charcoal additions to soil, but not with the addition of coal degradation products such as coal ash or fly ash. This is especially important in highly weathered soils with low ion-retention capacities. Mixing relatively large amounts of hardwood charcoal with soil increased the CEC by 50% compared to the unamended soil (Tryon 1948; Mbagwu and Piccolo 1997; Table 2). But even low amounts of weathered charcoal (Glaser 1999) could increase the CEC of soil (Table 2), whereas the additions of coal ash (Cox et al. 2001) or fly ash were ineffective in increasing the nutrient retention in soil. Fujita et al. (1991) estimated an anion sorption capacity of pure wood charcoal of 88.2 $cmol_c$ kg^{-1}. In comparison, soils of Amazonia have 1.0–6.0 $cmol_c$ kg^{-1} (Sombroek 1966), and a higher retention of ions may be expected from charcoal applications. NH_4^+ leaching from an unfertilized Ferralsol was reduced when charcoal was applied and resembled the low values found in an Anthrosol (Terra Preta) with a high pyrogenic C content (Lehmann et al. 2002), indicating that NH_4^+ was adsorbed by the charcoal, and the elevated N uptake by rice after the combined application of charcoal and fertilizer was partly an effect of NH_4^+ retention. This retention could not be found for other cations or anions, because K, Ca, and Mg were in higher supply with charcoal additions (Lehmann et al. 2002).

Additionally, charcoal has the potential to form organo-mineral complexes (Ma et al. 1979), which was also observed in charcoal-containing soils (Glaser et al. 2000). It is assumed that slow oxidation (biotic and/or abiotic) on the edges of the aromatic backbone of char-

Table 2 Effective cation exchange capacity (*ECEC*), base saturation, and nutrients of soils amended with charcoal. *Oxi* Oxisol, *TP* Terra Preta

Charcoal ($g\ kg^{-1}$)	ECEC ($cmol_c\ kg^{-1}$)	BS (%)	Available K ($cmol_c\ kg^{-1}$)	Available Ca ($cmol_c\ kg^{-1}$)	Available Mg ($cmol_c\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)
Sand, hardwood charcoal (Tryon 1948)							
0	3.4	35	0.03	1.00	0.17	0.7	7.0
150	4.2	155	0.22	6.01	0.29	1.2	23.0
300	5.1	281	0.46	13.46	0.41	2.4	37.4
450	5.9	336	0.57	18.56	0.71	2.6	37.7
Sand, conifer charcoal (Tryon 1948)							
0	3.4	35	0.03	1.00	0.17	0.7	7.0
150	3.0	44	0.12	1.10	0.11	0.8	7.0
300	3.3	85	0.24	2.26	0.30	0.7	16.1
450	3.3	102	0.22	2.80	0.36	0.8	17.2
Loam, hardwood charcoal (Tryon 1948)							
0	4.4	53	0.16	1.78	0.38	0.6	3.6
150	5.4	128	0.37	6.16	0.36	0.6	6.6
300	6.6	212	0.60	12.80	0.56	1.9	19.3
450	6.9	310	0.82	19.81	0.74	2.5	27.0
Loam, conifer charcoal (Tryon 1948)							
0	4.4	53	0.16	1.78	0.38	0.6	3.6
150	4.3	55	0.22	1.82	0.33	0.6	4.4
300	4.3	89	0.29	3.03	0.52	0.7	5.7
450	4.2	140	0.37	4.90	0.62	0.7	9.0
Sandy soil, activated charcoal (Rajput and Sastry 1984)							
0	85.6	–	–	–	–	0.67	–
1	97.6	–	–	–	–	0.68	–
Sandy soil, activated charcoal (Rajput and Sastry 1984)							
0	10.0	–	–	–	–	0.78	–
1	10.3	–	–	–	–	0.78	–
Oxi, TP 30–40 cm (Glaser 1999)							
0.1 (Oxi)	0.79	4	0.004	0.00	0.06	0.27	2
1.4 (TP)	3.20	97	0.239	2.58	0.33	0.45	183
0.1 (Oxi)	1.64	2	0.004	0.02	0.02	0.50	3
5.4 (TP)	2.54	89	0.026	1.62	0.63	0.74	285
0.1 (Oxi)	1.64	2	0.004	0.02	0.02	0.50	3
6.0 (TP)	7.93	99	0.034	6.51	1.30	0.70	199
0.2 (Oxi)	0.25	71	0.048	0.08	0.05	0.41	1
5.3 (TP)	2.00	25	0.014	0.32	0.17	1.03	70
0.1 (Oxi)	7.6	4	0.014	0.19	0.07	0.90	2
11.9 (TP)	28.9	60	0.026	15.43	1.71	2.31	98
Ferralsol, secondary forest charcoal (Lehmann et al. 2002)							
0	5.4	96	2.8	1.5	0.9	3.2	8
135	29.0	98	25.8	1.7	1.0	4.0	11
Alfisol, coal humic acid (Mbagwu and Piccolo 1997)							
0	5.6	97	0.2	2.0	1.0	–	–
0.2	8.0	100	–	–	–	–	–
2.0	16.3	100	–	–	–	–	–
20.0	20.8	100	–	–	–	–	–
Inceptisol, coal humic acid (Mbagwu and Piccolo 1997)							
0	6.6	69	0.2	2.7	3.5	–	–
0.2	10.3	72	–	–	–	–	–
2.0	15.9	100	–	–	–	–	–
20.0	26.7	100	–	–	–	–	–

coal forming carboxylic groups is responsible for both the potential of forming organo-mineral complexes and the sustainably increased CEC (Glaser 1999; Glaser et al. 2000, 2001a).

Not only metal ions but also dissolved organic matter and dissolved organic nutrients will be retained through charcoal additions to soil. There are numerous applications of charcoal and activated C in industrial processes, but discussion of this would divert us from the reviewed topic. However, it should be mentioned at this point that charcoal can effectively sorb both polar compounds, such as polar organic pesticides (Sudhakar and Dikshit 1999), and hydrophobic molecules, such as polycyclic aromatic hydrocarbons (Kleineidam et al. 1999; Schmidt and Noack 2000), lignin and tannin (Mohan and Karthikeyan 1997). On the other hand, charcoal does not contain significant amounts of (available) harmful substances such as polycyclic aromatic hydrocarbons (Glaser 1999).

A higher nutrient retention can also be achieved merely by a retention of soil water in micro- and mesopores (see next section). If water percolation through soil can be reduced, nutrient leaching will also decrease. By this mechanism nutrients can be retained which are normally not sorbed to soil and are very mobile and susceptible to leaching, such as NO_3^- at high pH, or base cations at low pH. These results show that charcoal may contribute to an increase in ion retention of soil and to a decrease in leaching of dissolved organic matter and organic nutrients.

Charcoal amendments and water retention and structural stability of soils

Low SOM contents may be responsible for the low available water capacity and the weak structure of many agricultural soils (Bembridge 1989; Mbagwu 1989; McRae and Mehyus 1985; Piccolo et al. 1996; Rose 1991). Charcoal may not only change soil chemical properties, but also affect soil physical properties such as soil water retention and aggregation (Piccolo and Mbagwu 1990; Piccolo et al. 1996). These effects may enhance the water availability to crops and decrease erosion (Mbagwu and Piccolo 1997; Piccolo et al. 1997). Intensive mechanized cultivation heavily contributes to the decline of SOM contents in soils in the tropics. Attempts have been made to improve the physico-chemical properties of such soils through soil management practices based on the incorporation of organic residues like green manure, organic wastes, and coal-derived humic substances (Mbagwu et al. 1991; Piccolo and Mbagwu 1990). Some studies showed that the water holding capacity of the amended soils increased relative to the controls (Bembridge 1989; Mbagwu 1989; Rose 1991; McRae and Mehyus 1985). The effectiveness of the organic residues depended, however, on the type and stage of decomposition as well as on soil characteristics (Mbagwu 1989). An important disadvantage of using organic residues is that large amounts, between 50 and 200 Mg ha^{-1}, were required to obtain substantial improvements in both soil water retention capacity and structural stability. For practical field applications, these rates are not realistic (Piccolo et al. 1996). In addition, organic wastes may be rich in inorganic and organic pollutants.

Mbagwu and Piccolo (1997) compared the behaviour of undecomposed organic residues and coal-derived humic acids with respect to their potential for improving the aggregate stability of four soil orders from southern Nigeria. The authors found substantial improvements of the macro-aggregate stability, varying from 20% to 130%, following additions of low amounts (1.5 Mg ha^{-1}) of coal-derived humic acids, whereas very large amounts (50–200 Mg ha^{-1}) of undecomposed organic residues were needed to obtain significantly higher aggregate stability. Reduced soil bulk density following humic acid amendments was reflected by the increased total porosity and macroporosity as well as water infiltration rates. Piccolo et al. (1996) studied the potential of coal-derived humic substances to improve the available water holding capacity and aggregate stability of typical Mediterranean soils in the laboratory using agricultural surface soils (0–20 cm) from three regions (Sicily, Tuscany, and Venetia) and five rates of humic acid additions (0, 0.05, 0.10, 0.50, 1.0 g kg^{-1} on a dry matter basis). The field capacity and the available water holding capacity were significantly ($P<0.05$) higher when only 0.05 g kg^{-1} humic acids was applied to soil. At an application rate of 1.0 g kg^{-1}, the relative improvements in available water holding capacity over the control were 30%, 10%, and 26% for soils of the three different regions, respectively. Low rates (0.05–0.10 g kg^{-1}) of humic acids were also needed to obtain a 40–120% increase in aggregate stability relative to the control. The possible mechanisms by which coal-derived humic acids improve soil physical properties are the formation of organo-mineral complexes by functional groups of the humic acids. The hydrophobic polyaromatic backbone reduces the entry of water into the aggregate pores leading to an increased aggregate stability and water availability.

On the other hand, it is well known that charcoal has a high surface area due to its porous structure. Kishimoto and Sugiura (1985) estimated inner surface areas of 200–400 m^2 g^{-1} of charcoal formed between 400°C and 1,000°C. As a result soil water retention increased by 18% upon addition of 45% (by volume) charcoal to a sandy soil (Tryon 1948). Glaser et al. (2002b) reported that charcoal-rich Anthrosols whose surface areas were 3 times higher than those of surrounding soils increased the field capacity by 18%. Tryon (1948) also studied the effect of charcoal on the percentage of available moisture in soils of different textures. Only in sandy soil did the addition of charcoal increase the available moisture (Table 3). In loamy soil, no changes were observed, and in clayey soil the available soil moisture even decreased with increasing coal additions, probably due to hydroph-

Table 3 Effect of charcoal on percentage of available moisture in soils on a volume basis (Tryon 1948)

Soil	0% Charcoal	15% Charcoal	30% Charcoal	45% Charcoal
Sand	6.7	7.1	7.5	7.9
Loam	10.6	10.6	10.6	10.6
Clay	17.8	16.6	15.4	14.2

Table 4 CEC at natural pH value (effective CEC, ECEC; cmol$_c$ kg^{-1}) of charcoals formed under different conditions

Charcoal	Formation conditions	ECEC	Reference
Hardwood	Unknown	5.5[a]	Tryon (1948)
Conifer	Unknown	0[a]	
Activated charcoal	Unknown	1.2[b]	Rajput and Sastry (1984)
Maple	Flash pyrolysis 480°C	490[c]	Radlein et al. (1996)
Wheat straw	Flash pyrolysis 500°C	440[c]	
Poplar aspen	Flash pyrolysis 450°C	490[c]	
Poplar aspen	Flash pyrolysis 500°C	440[c]	
Poplar aspen	Flash pyrolysis 550°C	450[c]	
Peat moss	Flash pyrolysis 520°C	300[c]	
	Flash pyrolysis 480°C	490[c]	
Rape straw	4 h, 300°C	80[c]	B. Glaser, unpublished data
Rape+HNO_3+$CaCO_3$	4 h, 300°C	120[c]	
Reed	4 h, 300°C	100[c]	
Reed+HNO_3	4 h, 300°C	130[c]	
Lignite	4 h, 165°C under O_2 pressure	1,230[d]	Gürüz (1980)
Lignite	4 h, 165°C under O_2 pressure	1,310[e]	
Lignite	4 h, 165°C under O_2 pressure	1,200[f]	
Lignite	4 h, 165°C under O_2 pressure	1,020[g]	

[a] Calculated from the difference between soil–charcoal mixtures and soil alone (Table 5)
[b] CEC was determined with sodium acetate
[c] Calculated as the sum of carboxylic and phenolic groups (Table 2)
[d] Base exchange capacity by shaking with 1 N HCl for 16 h
[e] Base exchange capacity by shaking with 1 N HNO_3 for 16 h
[f] Base exchange capacity by shaking with 1 N H_2SO_4 for 16 h
[g] Base exchange capacity by shaking with 1 N H_3PO_4 for 16 h

obicity of the charcoal. Therefore, improvements of soil water retention by charcoal additions may only be expected in coarse-textured soils or soils with large amounts of macropores.

Controlling the chemical properties of charcoal

Information on the physico-chemical properties of charcoal in soils is limited (Golchin et al. 1997a, 1997b). Scientists assume that charcoal consists of a range of combustion-produced materials with high amounts of aromatic, elemental, or graphitic C (Goldberg 1985; Schmidt and Noack 2000). The polynuclear aromatic and heteroaromatic ring systems as structural units have been unambiguously shown for coals (Hayatsu et al. 1981) and charcoals (Haumaier and Zech 1995; Glaser et al. 1998). Due to this structure, a chemical and microbiological inertia is attributed to charcoal.

Three main factors influence the properties of charcoal: (1) the type of organic matter used for charring, (2) the charring environment (e.g. temperature, air), and (3) additions during the charring process. The source of charcoal material strongly influences the direct effects of charcoal amendments on nutrient contents and availability. The pH of various soils was higher after applications of hardwood (pH 6.15) than of conifer charcoals (pH 5.15) probably due to their different ash contents of 6.38% and 1.48%, respectively (Table 2). Thus, hardwood charcoals are more effective in reducing soil acidity than conifer charcoals. Consequently, also the Ca, Mg, and K contents were higher with hardwood than with conifer charcoals. Even more pronounced was the different effect of both types of charcoal on CEC. While hardwood charcoal increased the CEC compared to the original soils it decreased when conifer charcoal was used (Table 2).

The charring conditions were shown to influence the degree of aromaticity and, therefore, the adsorption characteristics of charcoal. The degree of aromaticity increased with increasing charring temperature (Shafizadeh and Sekiguchi 1983) and charring time (Glaser et al. 1998). Charcoals obtained by heating at 200–700°C with exclusion of air had fewer ion-exchanging functional groups than when oxidized with air (Table 4).

The properties of charcoal can additionally be influenced by additions of N compounds. For coal, Aleksandrov et al. (1988) reported that the oxidation of coal to humic acids was significantly enhanced by a 1-month incubation in the presence of 5% diammonium phosphate. Consequently, the sorption capacity increased by 55–147%. Added N compounds chemically reacted with coal forming carboxyl and phenol groups. Radlein et al. (1996) produced an organic slow-release N fertilizer by pyrolysing NH_3 or urea with organic wastes. Knicker et al. (1996) showed that during coalification, amide-N is progressively converted to stable pyrrolic N. Charring at high temperature and pressure in the presence of a weak oxidizing reagent seems to be the best way to produce carbonized materials with a high CEC but requires specialized equipment. On the other hand, charring of rape straw and reed under low pressure and temperature without oxidants yielded CEC values of 80–130 cmol$_c$ kg^{-1} which are up to 3 times lower than the CEC values of SOM which ranged between 200 and 400 cmol$_c$ kg^{-1} (AG Boden 1994; Russell 1973).

In addition to these three factors, microbes may also have an important impact on the properties of charcoal (e.g. surface oxidation). Some information exists about the effect of coal flay ash on microbial activity in soil and in turn on the degradation of coal by microorganisms. This information may only be applied with caution to charcoal, since different coals and lignites span a large range of chemical structures which are only rudimentarily known (Fakoussa and Hofrichter 1999; Schmidt and Noack 2000). Microbial respiration, populations and enzyme activity decreased with increasing applications of fly ash to a loamy soil (Pichtel and Hayes 1990), which may also be decreased by charcoal applications. On the other hand bacteria and fungi are able to liquefy low-ranking coal (Fakoussa and Hofrichter 1999) and possibly change its surface properties. Tschech (1989) observed that hydroxylation of aromatic rings is one of the primary steps in the microbial degradation of aromatic compounds under aerobic conditions. Van Krevelen (1961) stated that oxidation is the most important process of coal weathering leading to an increase in functional groups such as carbonyl and carboxyl in the coal structure (Kister et al. 1988; Martinez and Escobar 1995). These observations support the hypothesis that in soil oxidation of charcoal produces carboxylic groups providing cation exchange sites (Glaser 1999; Glaser et al. 2000, 2001a, 2002b). Possibly, manganese peroxidase, laccase or hydrolase may also oxidize charcoal surfaces as described for coal (Fakoussa and Hofrichter 1999). This is an important research topic which should be focused on in the future.

Effective C sequestration by soil amendments of charcoal

Transformation of biomass C to stable soil organic C

The role of soils as a sink for atmospheric CO_2 is ambiguous. Some processes have been reviewed which may lead to higher C sequestration in soils such as in improved grasslands or agroforests as well as tropical pastures through redistribution in deeper soil horizons or the omission of burning (Batjes 1998). Much of the C is released as CO_2 upon the application of rapidly decomposing organic fertilizers such as slurry (Glaser et al. 2001b) or manure (Amelung et al. 1999; Bol et al. 2000) within a short period, even in temperate climate ecosystems. Therefore, such manures have to be frequently applied to maintain high SOM and nutrient levels.

Also in common slash-and-burn systems, most of the biomass C is rapidly released into the atmosphere upon burning, and only small amounts of C are transformed into charcoal (Table 5). In their pioneering work on biomass burning, Seiler and Crutzen (1980) estimated charcoal formation of about 25% in shifting cultivation fields based on published photographs. The published data average at about 3% charcoal formation of the original biomass C (Table 5). Biomass C which is not converted to charcoal or elemental C in the smoke is gradually released through combustion and decay. Reburning may affect the transformation of charcoal into slow-cycling pools in either direction: by oxidizing charcoal formed in the initial burning of primary forest or by creating new charcoal (Fearnside et al. 1993; Graca 1997). On a global basis, an estimated 4–8 Gt of biomass C is annually exposed to burning, of which 1.3–7.5 Gt is emitted to the atmosphere through combustion and 0.5–1.7 Gt is converted to charcoal (Seiler and Crutzen 1980). Therefore, C entering the soil as charcoal is a significant sink for atmospheric CO_2 and may be important for global C sequestration.

In comparison to burning, controlled carbonization, converts even larger quantities of biomass organic matter into stable C pools which are assumed to persist in the environment over centuries (Glaser et al. 1998; Haumaier and Zech 1995; Schmidt and Noack 2000; Seiler and Crutzen 1980; Glaser et al. 2001a). The amount of charcoal which can be produced from different forest vegetation primarily depends on the woody biomass available, and additionally on the production procedure, such as the charring environment (e.g. O_2), temperature and time (Table 5). The average recovery of charcoal mass from woody biomass is 29% according to the published data compiled in Table 5. The effect of different charcoal production methods on its recovery in laboratory experiments varies tremendously, depending on the charring conditions, and even under field conditions charcoal and C yields varied by a factor of up to 3, although it is known that charcoal production is an exothermic process taking place at between 350°C and 400°C (Falbe and Regnitz 1992). The weighted average C recovery from charred woody biomass is relatively high at 50% compared to only 3% after conventional slash and burn techniques (Table 5). Therefore, applications of charcoal to soil could serve as a long-term CO_2 sink.

Recalcitrance of charcoal in soil

Theoretically, charcoal can disappear from soil in three different ways: (1) by erosion from the surface, (2) by abiotic, and (3) biotic degradation. Under soil erosion, superficial charcoal accumulations in depressions have been observed in the Amazon (Bassini and Becker 1990). Thermodynamically, the abiotic oxidation of elemental C to CO_2 is a strong exothermic reaction ($\Delta H=-94{,}052$ kJ). However, under environmental conditions, this process is extremely slow (Shneour 1966).

Several studies showed a relationship between a deep black soil colour and the presence of charred organic matter (Schmidt and Noack 2000). These observations support the concept that charcoal is an important source of the chemically stable aromatic components of SOM. The question arises whether the oxidation of charcoal is significantly increased by the soil microorganisms. It is well known that fungi and bacteria are capable of degrading low-rank coals such as brown coal (Fakoussa and Hofrichter 1999). It was clearly shown by Hofrichter et al. (1999) that extracellular manganese peroxidase is the crucial enzyme of wood-rotting and leaflitter-decaying basidiomycetes capable of degrading macromolecular fractions of brown coal (lignite). As a result of such decay, reactive products such as phenoxy, peroxyl and C-centred radicals are formed which subsequently undergo non-enzymatic reactions leading to the cleavage of covalent bonds, including the fission of aromatic rings. If such reactions significantly contribute to the degrada-

Table 5 Biomass conversion into charcoal. *n.d.* Not determined

Tree species	Charring temperature (°C)	Production method	Charcoal recovery by weight (%)	*n*	Charcoal C content (%)	C yield (%)	Source
Charring							
Cellulose	300	Laboratory furnace	89.4	2	44.0	92	Shafizadeh and Sekuguchi (1983)
	325		63.3	2	47.9	71	
	350		31.8	2	59.9	45	
	400		16.6	2	76.5	30	
	450		10.5	2	78.8	19	
	500		8.7	2	80.4	16	
Pinus sylvestris (saw dust)[a]	300		43.3	2	68.5	59.2	Glaser et al. (1998)
Robinia pseudoacacia	350		37.9	60	76.4	64.4	Lehmann et al. (2002)
Acacia mangium	450		33.2	65	71.3	52.6	Lelles et al. (1996)
Eucalyptus camaldulensis	450		32.4	25	46.3	54.9	Vital et al. (1994)
Eucalyptus grandis	470		33.8	60	80.7	60.6	Vital et al. (1986)
Deciduous trees	500		30.2	8	84.7	56.8	Zhurinsh (1997)
Leucaena leucocephala	350–400[b]	Metal kiln	27.4	–	83.1	50.6	San Luis et al. (1984)
Coconut trunk	350–400[b]		25.0	–	77.8	43.2	
Mixed tropical wood, Manaus, Brazil	350–400[b]	Brick kiln	41	–	74.8	68.2	Correa (1988)
Miombo woodland	350–400[b]	Earth kiln	23.3	–	n.d.	–	Chidumayo (1991)
Mixed tropical hardwood	350–400[b]	Earth pit	–	–	69.0	–	FAO (1983)
Secondary forest, fruit orchard	350–400[b]	Earth mound	14.3	98	90.0	32.0	Coomes and Burt (2001)
Weighted average[c]			28.5		79.6	49.9	
Charring							
Secondary forest	–	Slash and burn	–		15–23		Seiler and Crutzen (1980)
Secondary forest	–		–		5–10		Crutzen and Andreae (1990)
Primary forest, Manaus, Brazil	–				3.5		Fearnside et al. (1993)
Primary forest, Manaus, Brazil	–				4.7		Graca (1997)
Secondary forest, Altamira, Brazil	–				1.6		Fearnside et al. (1999)
Secondary forest, Manaus, Brazil	–				1.8		
Average					3.0		

[a] Weight and C yields decreased with increasing charring time, values after 1 h and 2 h of charring

[b] It is known that charcoal production is an exothermic smouldering process where temperature increases to 350–-400°C after initial burning of the woody material (Falbe and Regnitz 1992)

[c] Due to the tremendous differences among different charring conditions the average was weighted with the number of replicates from each study

tion of highly aromatic charcoal in natural environments such as soil remains to be shown, because the presence of charcoal from forest burning in soils and sediments even after thousands of years indicates the high persistence of this C species under natural conditions (Glaser et al. 2000, 2001a; Saldarriaga and West 1986). This point of view was corroborated by Shindo (1991) who amended a natural soil with charred and uncharred plant materials. The author found no evidence that the charred material had been significantly utilized by the microbial population after 40 weeks of incubation. On the other hand, Shneour (1966) was successful in oxidizing artificial graphitic ^{14}C to $^{14}CO_2$ in the presence of soils with high microbial activity. In comparison to a sterile soil, $^{14}CO_2$ evolution which was 3–5 times higher was measured in the nonsterile soils. Therefore, charcoal is also mineralized in soil and there is no doubt that charcoal is not a permanent sink of atmospheric CO_2. Otherwise the earth's surface would be converted into charcoal within a period of time of <100,000 years (Kuhlbusch and Crutzen 1995). However, it can be assumed that the turnover time of charcoal is much lower than that of plant litter applied to soil (Glaser et al. 2001a; Haumaier and Zech 1995; Schmidt and Noack 2000; Seiler and Crutzen 1980; Shindo 1991). Therefore, the application of charcoal will lead to higher C sequestration in comparison to the application of equal amounts of non-charred organic matter. Compared to slash-and-burn techniques, "slash-and-char" significantly increases the C sequestration to soil by a mean factor of 17 (Table 5).

The Terra Preta phenomenon – a model for sustainable agriculture in the humid tropics

As mentioned above, Terra Preta, a black earth-like anthropogenic soil shows an enhanced fertility due to high levels of SOM and nutrients such as N, P, and Ca (Glaser 1999; Glaser et al. 2000, 2001a; Smith 1999; Sombroek 1966; Zech et al. 1990; Table 2). Terra Preta soils are typically embedded in a landscape of infertile soils occurring in small patches averaging 20 ha, but 350-ha sites have also been reported (Smith 1980, 1999). These anthropogenic soils which are slightly older than

2000 years can be found throughout the Brazilian Amazon basin (Glaser 1999; Glaser et al. 2000, 2001a; Sombroek 1966; Sombroek et al. 1993; Woods et al. 1999; Zech et al. 1990) and other regions of South America such as Ecuador and Peru (W. Zech, unpublished data) but also in West Africa such as in Benin and Liberia (Zech et al. 1990) and in the savannas of South Africa (Blackmore et al. 1990).

Terra Preta soils are very popular among local farmers and are preferably used to produce cash crops such as fruits and vegetables, which have higher yields and more rapid plant development than on surrounding infertile soils (German and Cravo 1999; Lehmann et al. 2002). Fallow periods on Oxisols usually last 8–10 years, whereas fallow periods on Terra Preta soils which lead to the effective restoration of their fertility can be as short as 6 months (German and Cravo 1999). The cropping period on Terra Preta, however, is generally shorter than on adjacent Oxisols, i.e. 0.3–2 years in comparison to 2–3 years, respectively, due to weed invasion on the fertile soils (German and Cravo 1999). Weed management has to be considered in continuous cropping on Terra Preta and deserves more attention.

Terra Preta soils not only contain higher levels of available nutrients but also higher amounts of stable SOM (Glaser 1999). The total organic C stocks can be as high as 250 Mg ha^{-1} in the agronomically important soil depth of 0–0.3 m and as high as ca. 500 Mg ha^{-1} up to 1 m soil depth (Glaser 1999). In comparison, adjacent Oxisols/Ferralsols may contain only 100 Mg C ha^{-1} and 149 Mg C ha^{-1} in the 0–0.3 m and up to 1 m soil depth, respectively. Therefore, C sequestration was 3.4 times higher in the Terra Preta than in adjacent soils. The total C sequestration on a landscape level is unclear and should be the subject of future research.

Additionally, the stable C is very resistant to microbial decay. Recent investigations showed that Terra Preta soils contained up to 70 times more pyrogenic C (charcoal) than the surrounding soils (Glaser 1999; Glaser et al. 2001a). It is assumed that pyrogenic C persists in this environment over centuries due to its chemical stability caused by the aromatic structure. The complex chemical structure makes the compound also resistant to microbial degradation (Goldberg 1985; Schmidt et al. 1999; Seiler and Crutzen 1980). This assumption was emphasized by ^{14}C dating results of 1,000–2,000 years for this C type (Glaser et al. 2000). Oxidation during this time produced carboxylic groups on the edges of the aromatic backbone, which increased the nutrient retention capacity. It was concluded that pyrogenic C found in these anthropogenic soils could act as a significant C sink and is a key factor for maintaining fertile soils, especially in the tropics. On the other hand, according to Ladd et al. (1993) every compound is degraded in soil and only physical protection can make C compounds resistant to microbial degradation.

Economic and ethnologic viability

With regular fertilizer and lime applications, crop production can be considerably extended beyond typical cropping cycles for shifting cultivation (Smyth and Cassel 1995). However, the high amounts of required mineral fertilizers cannot be afforded by subsistence farmers, especially in remote areas. Charcoal and other carbonized organic matter can be easily produced by local farmers in most regions of the world. The procedures of charcoal production are well known and the required tools and resources (organic materials) are readily available (Graca 1997). However, charcoal is a valuable cash product in most developing countries (e.g. Coomes and Burt 2001). Therefore, it should be emphasized that charcoal production for fertilization purposes will only be economically feasible if organic waste products are charred and applied as fertilizer, whereas slashed timber is certainly more valuable when used as construction materials or as charcoal sold on the local market.

Although charcoal-enriched Terra Preta soils typically contain between 15 and 60 Mg ha^{-1} of charcoal in the agronomically important depth of 0–0.3 m, charcoal additions in the range of 1–3 Mg ha^{-1} might be sufficient for significantly increasing crop production as shown before. To produce 1 Mg charcoal, a kiln containing 9.45 m^3 wood-equivalent and a labour investment of about 26 days for one person would be necessary (Coomes and Burt 2001). Sold on the local market, this amount of high quality charcoal would yield about 80 US dollars. Low-quality charcoal (waste charcoal from high-quality charcoal production or using organic wastes as kiln loads) could be used for soil fertilization purposes without additional labour investments. Thus money could be saved which would otherwise be spent on buying commercial fertilizers. Additionally, charcoal additions to soil sustainably increase soil fertility which saves labour and investment costs as mineral fertilizers have to be applied more frequently. Both from an ecological and economic point of view, it seems most promising to replace slash-and-burn systems by slash-and-char techniques. To what extent charcoal amendments may substitute mineral and organic fertilizers and if they are economically feasible for cash crop production have not been clarified, and warrant further research.

Conclusions

The use of charcoal as a soil conditioner for sustainable agriculture in the humid tropics presents the following advantages:

1. High nutrient contents and nutrient retention capacity lead to improved nutrient supply for plants and reduced nutrient losses by leaching. We assume that two processes are responsible for this: (1) nutrients are physically trapped in the fine pores of amorphous carbonized materials, and (2) slow biological oxida-

tion produces carboxylic units on the edges of the condensed aromatic backbone of the charcoal which increases the CEC.
2. Transformation of labile plant organic matter into stable C pools can reduce the release of the greenhouse gas CO_2 into the atmosphere during land clearing and can increase C sequestration in the soil. There are strong indications that charcoal is very slowly mineralized in the soil environment.
3. Charcoal from fallow vegetation and/or organic wastes can be easily produced by local farmers and also by those with a low income. Charcoal production is a well-known technique and the required tools and resources are readily available.

Using charcoal as a tool for improving soil fertility while at the same time increasing C sequestration in soil is far from being a well-recognized technology. However, the demonstrated positive effects of charcoal additions on soil properties and productivity should stimulate further investigations to test the possibilities for developing a slash-and-char technique as an alternative to traditional slash-and-burn or slash-and-mulch systems. Within such a framework the charcoal would be generated from the same field to which it is applied, and a slash-and-char technique does not therefore bear the danger of additional forest destruction. Future research needs to focus on testing charcoal amendments in experimental plots and under field conditions and achieving a better understanding of chemical and physical properties of charcoal surfaces. Finally, an evaluation of the agronomic effectiveness and the economic viability of charcoal as a soil amendment under field conditions is needed.

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