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SHORT COMMUNICATION

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The ‘Terra Preta’ phenomenon: a model for sustainable agriculture in the humid tropics

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Abstract Many soils of the lowland humid tropics are thought to be too infertile to support sustainable agriculture. However, there is strong evidence that permanent or semi-permanent agriculture can itself create sustainably fertile soils known as ‘Terra Preta’ soils. These soils not only contain higher concentrations of nutrients such as nitrogen, phosphorus, potassium and calcium, but also greater amounts of stable soil organic matter. Frequent findings of charcoal and highly aromatic humic substances suggest that residues of incomplete combustion of organic material (black carbon) are a key factor in the persistence of soil organic matter in these soils. Our investigations showed that ‘Terra Preta’ soils contained up to 70 times more black carbon than the surrounding soils. Due to its polycyclic aromatic structure, black carbon is chemically and microbially stable and persists in the environment over centuries. Oxidation during this time produces carboxylic groups on the edges of the aromatic backbone, which increases its nutrient-holding capacity. We conclude that black carbon can act as a significant carbon sink and is a key factor for sustainable and fertile soils, especially in the humid tropics.

In the lowland humid tropics, highly weathered soils of low fertility and sustainability predominate (Tiessen et al. 1994). Numerous studies have been conducted to investigate the relationship between soil fertility and land-use practices (e.g. Guggenberger et al. 1994; Tiessen et al. 1994; Kleinman et al. 1996; Westerhof 1998; Thomas and Ayarza 1999). One of the major problems of sustainable agriculture in the humid tropics is the rapid decomposition of organic matter (Zech et al. 1990) due to the high temperatures, large amounts of precipitation, and the lack of stabilizing minerals. Mean residence times of less than 4 years have been calculated for particulate organic matter in undisturbed soils of the Venezuelan rain forest (Tiessen et al. 1994). Inorganic fertilizers are often too expensive for the indigenous population to use and their effect is only short-lived due to the low nutrient-holding capacity of the poor soils.

On the other hand, black-earth-like anthropogenic soils with enhanced fertility, known as ‘Terra Preta’ (*do Indio*), have been described. These usually occur in areas averaging 20 ha (Smith 1980; Zech et al. 1990; McCann et al. 2001), but very large ‘Terra Preta’ sites up 350 ha have also been reported (Smith 1999). It is estimated that the total area covered by ‘Terra Preta’ sites exceeds 50,000 ha in Central Amazonia between the rivers Tapajós and Curuá-Una alone (Smith 1980; Woods and McCann 1999). The ‘Terra Preta’ phenomenon is not only restricted to areas near rivers, but also occurs on the ‘Terra Firme’ at higher elevations (Smith 1999). The similarity of the texture and mineralogy with that of the surrounding soils (Zech et al. 1990) and the occurrence of pre-Columbian ceramics in the upper horizons of ‘Terra Preta’ soils (Sombroek 1966; Smith 1980) suggest man-made soils derived from surrounding poor soils. The enhanced fertility of ‘Terra Preta’ soils is expressed by higher levels of soil organic matter (SOM), nutrient-holding capacity, and nutrients such as nitrogen, phosphorus, calcium and potassium, higher pH values and higher moisture-holding capacity than in the surrounding soils (Sombroek 1966; Smith 1980; Zech et al. 1990). According to local farmers, productivity on the ‘Terra Preta’ sites is much higher than on the surrounding poor soils. ‘Terra Preta’ soils are equipped with thick carbon-rich topsoils that persist centuries after their abandonment by the native Amerindian population.

The regular occurrence of charcoal in ‘Terra Preta’ soils (Sombroek 1966; Sombroek et al. 1993) and their highly aromatic humic substances (Zech et al. 1990) indicate that residues of incomplete combustion (black carbon), derived mainly from cooking fires, may contribute to the SOM of ‘Terra Preta’ soils. It has been proposed that polyphenols and condensates (e.g. of lignin-degradation products) contribute the major part of the aromatic compounds in SOM (Stevenson 1994). Recent investigations, however, revealed that at least a part of the aro-

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Fig. 1 Typical profiles of 'Terra Preta' (**a**) and Oxisol (**b**) sites

matic carbon in soil is black carbon (Haumaier and Zech 1995; Skjemstad et al. 1996; Golchin et al. 1997; Schmidt et al. 1999; Schmidt and Noack 2000), which is a major component in the residues of charred plant material (Glaser et al. 1998).

Fires produce considerable amounts of highly refractory aromatic organic matter consisting of charcoal or partially charred plant material on the surface and incorporated into soils (Seiler and Crutzen 1980; Golchin et al. 1997). The presence of black carbon can have a major impact on SOM composition and turnover, especially in tropical forest or savannah areas (Fearnside 1985; Sanford et al. 1985), but the contribution of black carbon to SOM is largely unknown and its contribution to the global carbon cycle remains to be determined (Golchin et al. 1997), although Kuhlbusch and Crutzen (1995) and Kuhlbusch et al. (1996) suggested that black carbon represents an important sink for atmospheric CO_2.

The objective of this study was to verify whether black carbon could be responsible for the SOM stability and sustainable fertility of 'Terra Preta' soils. The study was carried out in Central Amazonia (Brazil) on the plateau 150–200 m above the Amazon, which is covered by Tertiary sediments of various composition (Sombroek 1966). Mean annual temperature in Manaus for instance is 26°C and mean annual rainfall is 2,050 mm with a dry season between August and November (Otzen 1992). Heavily weathered soils with a predominance of kaolinite in the clay fraction and an accumulation of iron and aluminium oxides developed. 'Terra Preta' sites were always identified by their deep (40–80 cm) black A horizons together with the presence of ceramics and charcoal particles (Fig. 1a). Adjacent soils (Fig. 1b) sometimes had visible charcoal too, but only in the topsoil. For this study, we investigated three sandy 'Terra Preta' sites near Manaus and two clayey 'Terra Preta' sites about 200 km north of Manaus and near Santarém, with nearby soils (within 1 km) for comparison. Their position suggests that the sites have never been under colluvial or alluvial influence. None of the investigated soils showed hydromorphic features. Localities, site descriptions and basic characteristics of the investigated soil profiles are described in detail elsewhere (Glaser et al. 2000).

Four sites were used as home gardens (papaya, passiflora, mango, cassava). On one clay-rich site, secondary rain forest (*capoeira*) had developed on an abandoned rubber (*Hevea brasiliensis*) plantation.

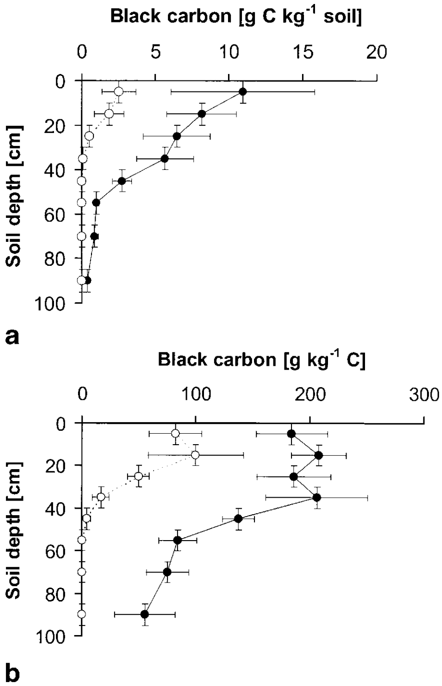

Fig. 2 Mean concentrations and standard deviations of black carbon in the fine earth of ‘Terra Preta’ (●) soils and nearby Oxisols (○) with increasing profile depth (**a**); Concentrations and standard deviations of black carbon in the soil organic matter of ‘Terra Preta’ (●) soils and nearby Oxisols (○) with increasing profile depth (**b**). Note that for statistical comparison no mean values were taken, but a pairwise comparison (n=5) was necessary due to the texture gradient from sandy to clayey sites

In the soil samples, we determined organic carbon (OC) by dry combustion and thermal conductivity detection on a Elementar Vario EL C/N analyser, and black carbon using benzenecarboxylic acids (BCA) as molecular markers (Glaser et al. 1998). The principle is based on the observation that charred materials are converted to BCA upon nitric acid oxidation, whereas humic substances and uncharred plant material produce no BCA. In comparison with other methods for the determination of black carbon, the gas–liquid chromatographic determination of BCA allows the specific quantification of the polyaromatic backbone of charred organic materials (Glaser et al. 1998). The radiocarbon age of black carbon was deduced from the ^{14}C measurement (accelerated mass spectrometry) of BCA obtained according to the method outlined above. Statistical comparisons were done pair-wise (Hartung et al. 1993) due to the texture gradient of the soils.

Black carbon concentrations in the control soils decreased more rapidly with soil depth than in ‘Terra Preta’ soils. Up to 60 cm soil depth, the concentrations of black carbon were up to 70 times higher (mean: four times higher; $P<0.001$) in ‘Terra Preta’ soils than in adjacent soils (Fig. 2a). The relative contribution of black carbon to total OC was about twice as high in ‘Terra Preta’ sites than in surrounding soils ($P<0.05$; Fig. 2b). Below 20 cm soil depth, almost no black carbon was detectable in the control soils. At a soil depth of 1 m, the differences diminished and black carbon concentrations were similar in both soils. At a soil depth of 0–10 cm in the control soils, black carbon contributed to 10% to OC, which rapidly decreased with increasing soil depth. In ‘Terra Preta’ soils, however, black carbon contributed to a mean value of about 20% to SOM down to about 40 cm soil depth and 10% in the deeper soil horizons (Fig. 2b).

At a soil depth of 0–30 cm, which is the most important soil layer for the nutrient supply of agricultural plants, ‘Terra Preta’ soils contained around 2.7±0.5 ($P<0.05$) times as much OC as corresponding soils (approximately 250 Mg ha^{-1} m^{-1}), while mean OC stocks of about 100 Mg ha^{-1} m^{-1} have been reported elsewhere for Oxisols of the Brazilian Amazon region (Kimble et al. 1990; Moraes et al. 1995). The mean total amounts of black carbon in ‘Terra Preta’ soils were 25±10 Mg ha^{-1} and 25±9 Mg ha^{-1} at 0–30 cm and 30–100 cm soil depths, respectively. This corresponds to enrichment factors of 8±4 ($P<0.05$) and 73±28 ($P<0.01$) compared with surrounding soils at the same depths. In ‘Terra Firme’ soils of the upper Rio Negro area of the Colombian and Venezuelan Amazon region, 31–248 Mg charcoal ha^{-1} m^{-1} has been found in the upper 50 cm of soil using gravimetry of charcoal pieces (Saldarriaga and West 1986). These values are in the same order of magnitude as the data presented here. As the authors found potsherds on some sites, we assume that some of their investigated soils were ‘Terra Preta’ soils as well, especially those with high amounts of charcoal.

To estimate the quantity of biomass and/or the burning frequency necessary to produce the amounts of black carbon found in ‘Terra Preta’ soils, the following calculations were undertaken. According to Fearnside (1992), the burning of 1.38×10^{6} ha of primary forest during the years 1989 and 1990 released 196 Mg ha^{-1} CO$_2$-C into the atmosphere and incorporated 2.6 Mg ha^{-1} of black carbon into the soil. Assuming these natural fires are the only black carbon sources in ‘Terra Preta’ soils, a total of 25 burnings would be necessary to establish mean black carbon stocks of 50 Mg ha^{-1}.

Another calculation is based on the assumptions that slash-and-burn in the Brazilian Amazon region destroys about 99% of the litter and the superficial root mat, but only 50% of the larger wood pieces >20.5 cm diameter (Kauffman et al. 1995). According to this assumption, burning a superficial primary forest biomass of about 300–400 Mg ha^{-1} would produce 65–150 Mg ha^{-1} black carbon; which means that a single burning would be enough to produce the estimated amount of black carbon found in ‘Terra Preta’ soils. However, ‘Terra Preta’ does not appear to form mainly under conditions of natural burning frequencies, or under the long fallow shifting cultivation and forest fallow agroforestry currently practiced in Amazonia (Woods and McCann 1999).

More likely than natural fires as a source of black carbon in ‘Terra Preta’ soils are the low-heat smouldering domestic fires commonly used by the native population for cooking and heating (Smith 1980, 1999). In addition, the influence of heat on the soils is restricted to small areas and also to the top few centimetres of the soil surface, not influencing soil mineralogy and thus explaining why the mineralogy of ‘Terra Preta’ sites is similar to that of the surrounding soils. To simulate such smouldering, pine wood was isothermally charred in a muffle furnace at 300°C, yielding about 20% of charcoal (Glaser et al. 1998). Supplying black carbon from this source to the soil, about 600 Mg ha^{-1} pine wood has to be charred, producing more than the measured black carbon stocks of ‘Terra Preta’ soils. It is difficult, however, to calculate the ‘true’ charring frequency necessary to produce a specific quantity of black carbon due to the continuum of black carbon, which is produced under different charring conditions (Glaser et al. 1998). Nevertheless, our results show that black carbon is an important constituent of SOM in ‘Terra Preta’ soils. Radiocarbon ages of 1,775±325 years BP of charcoal pieces and wet chemically isolated black carbon in about 60 cm soil depth of a clayey ‘Terra Preta’ near Santarém and radiocarbon ages of 740–2,460 years BP of charcoal found in 30–40 cm soil depth by Saldarriaga and West (1986) not only support the pre-Columbian origin of ‘Terra Preta’ soils, but also the stability of black carbon in soils of the humid tropics. An enrichment of black carbon has also been reported for chernozems (Schmidt et al. 1999) and other black-earth-like soils (Skjemstad et al. 1996).

A high content of aromatic and carboxyl carbon in ‘Terra Preta’ SOM shown by ^{13}C-nuclear magnetic resonance spectroscopy (Zech et al. 1990; Glaser 1999) and the occurrence of substantial amounts of black carbon in a fraction containing organo-mineral complexed organic matter (Glaser et al. 2000) indicates that the polyaromatic core of black carbon was partly oxidized, which is most probably responsible for the high nutrient-holding capacity of ‘Terra Preta’ soils. ^{13}C-nuclear magnetic resonance spectroscopy (Zech et al. 1990; Glaser 1999) and wet chemical analysis (Glaser 1999) showed that no other significant differences exist between the SOM of ‘Terra Preta’ and adjacent soils. However, it was shown by Glaser (1999) that the SOM of ‘Terra Preta’ not only consists of stable black carbon but also of a substantial amount of labile SOM which can be rapidly mineralized. For soil fertility, this is another crucial component with respect to nutrient supply.

In the Brazilian Amazon region, dense populations once successfully farmed poor oxisols for at least 2,500 years (Denevan 1996), leaving behind the rich ‘Terra Preta’ soils, before being displaced by Europeans with their technological superiority. The existence of ‘Terra Preta’ sites proves that we can learn about long-term agricultural strategies from pre-Columbian native populations. According to our results, ‘Terra Preta’ soils may be derived from oxisols by enrichment with black carbon from residues of incomplete burning produced by the early Amerindian population. Due to the highly aromatic structure of black carbon, it is assumed be chemically and microbially stable and persists in the environment over centuries or millennia (Seiler and Crutzen 1980; Goldberg 1985). Thus, a part of the labile carbon pool in the biomass has been converted into a stable SOM pool. Oxidation during this time produced carboxylic groups on the edges of the aromatic core, which increased the cation exchange capacity and the reactivity of black carbon in the soil. It may be speculated that human excrement and biomass accumulated from the surrounding land, together with residues from hunting and fishing, are responsible for the nutrient richness and the high base saturation of ‘Terra Preta’ soils. Proof of this is still lacking but it is evident that ‘Terra Preta’ soils maintained their higher trophic level even after their abandonment centuries ago. Enhanced biomass production at these sites may still result in larger carbon inputs in the topsoil.

Although it has been shown that slash-and-burn offers hope for more sustainable agriculture in the humid tropics (Luna-Orea and Wagger 1996), the tremendous amounts of the greenhouse gas CO_2 released into the atmosphere are ecologically problematic with respect to global warming. Therefore, the idea that, in contrast with burning, charring not only prevents large amounts of CO_2 from being released into the atmosphere but also provides the soil with a persistent SOM pool rich in nutrient-holding capacity, is intriguing.

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