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SHORT COMMUNICATION

Bruno Glaser · Ludwig Haumaier
Georg Guggenberger · Wolfgang Zech

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-

B. Glaser (✉) · L. Haumaier · G. Guggenberger · W. Zech
Institute of Soil Science and Soil Geography,
University of Bayreuth, 95440 Bayreuth, Germany
e-mail: bruno.glaser@uni-bayreuth.de
Tel.: +49-921-552254, Fax: +49-921-552246

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.