

State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (*terra preta de Índio*)

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Abstract

Tropical rainforests are highly important for the global climate regulation and for global biodiversity. However, these ecosystems are characterized by nutrient-poor and highly weathered soils and by high turnover rates of organic matter. Thus, they are fragile ecosystems prone to loss of ecosystem services when anthropogenically disturbed. Currently, the major threat to these ecosystems is deforestation leading to irreversible destruction of rainforests. Surprising and not expected is that within these ecosystems small patches of highly fertile soils occur which are known as Anthropogenic Dark Earths or *terra preta de Índio* (*terra preta*). These soils exhibit high nutrient and soil organic matter stocks and allow sustainable agriculture. Frequent occurrence of pot-sherds of pre-Columbian origin and further evidence for settlement activities clearly demonstrate that *terra preta* is of anthropogenic origin. In recent years, the *terra preta* phenomenon has gained increasing interest because it is assumed that *terra preta* could act as a model for promoting sustainable agricultural practices in the humid tropics and because *terra preta* is an example for long-term CO₂ sequestration into terrestrial ecosystems with additional positive benefits for ecosystem services. These potentials of *terra preta* initiated a great number of studies but also stimulated fantasy about their genesis. Therefore, the aim of this review is to summarize the scientific knowledge about *terra preta* properties and to discuss their genesis. From our own and literature data it is evident that *terra preta* is the product of inorganic [e.g. ash, bones (esp. fish)] and organic (e.g. biomass wastes, manure, excrements, urine, and biochar) amendments to infertile Ferralsols. These ingredients were microbially metabolized and stabilized by humification in soil, fungi playing a bigger role in this process compared to bacteria in surrounding ecosystems. Biochar is a key component for this process due to its stability and its enrichment in *terra preta*. It is still unclear if *terra preta* was produced intentionally or un-intentionally. In addition, it is unclear how much time was needed after the disposal of the materials mentioned above to develop a *terra preta*. Further research is highly desired to investigate these latter two issues.

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1. INTRODUCTION

Protection of rainforests and development of sustainable land-use in the humid tropics is of global significance because rainforests in the humid tropics exhibit a high biodi-

versity and are of high importance for the regulation of Earth's climate (Lewis, 2006; Bonan, 2008; Trumper et al., 2009).

For many years, it has been assumed that environmental limitations inhibit intensive agriculture in Amazonia (Meggers, 1954). Amazonian ecosystems are characterized by low fertility of the predominant, highly weathered soils. Extensive shifting-cultivation was the most adopted agriculture in these ecosystems during recent centuries (Kleinman et al., 1995). In modern times, increasing population pressure caused expansion of the area under cultivation, as well

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as reduced regeneration times followed by soil degradation (IPCC, 2000; Fearnside, 2005). Deforestation was boosted by further overexploitation, especially large-scale cattle raising (Fearnside, 2005). Currently, these ecosystems are rapidly destroyed as a consequence of anthropogenic over-exploitation (Fearnside, 2005; Lewis, 2006; Trumper et al., 2009). Intensive human land-use in Amazonia – now and in the recent past – would always lead to soil degradation (McKey et al., 2010).

Patches of dark-coloured soils have been found in Amazonia (Fig. 1). They are known as Anthropogenic Dark Earths (ADE) or *terra preta* (*de Índio*) and they exhibit completely different properties than most soils in this region (Fig. 1). These soils are characterized by large stocks of stable soil organic matter (SOM) and high nutrient levels (Glaser, 2007; Glaser et al., 2001). After pedological and archaeological investigations, predominantly over the last few decades, the anthropogenic origin of ADE is no longer questioned (Neves et al., 2003; Glaser et al., 2004a; Glaser, 2007; Woods and Denevan, 2009).

Archaeological evidence and radiocarbon dating showed that they were formed by pre-Columbian inhabitants, although *terra preta* formation was a more variable and sometimes faster process than previously thought (Heckenberger et al., 2003; Neves et al., 2003). Radiocarbon dates for *terra preta* sites at the Upper Xingu region and in Central Amazonia ranged between 60 and 1640 AD (Heckenberger et al., 2003) and 2500 and 500 a BP (Neves et al., 2003), respectively.

Amazonian Dark Earths could act as a model for sustainable agriculture in the humid tropics (Glaser et al., 2001; Sombroek et al., 2002; Glaser, 2007) and for other soils which exhibit a low nutrient holding capacity. Agricultural techniques leading to *terra preta* formation have the potential to stop increasing land degradation from recently employed intensive agriculture in these regions and to reclaim degraded areas (Glaser, 2007). Additionally, the high stability of SOM in ADE (Glaser, 2007) and experimental data (e.g. Kuzyakov et al., 2009) show that in principle, carbon can be sequestered for millennia in soils. So regeneration of *terra preta* has the potential to combine sustainable agriculture with long-term CO₂ sequestration.

The existence of ADE has been known for more than 100 years, but only in the last decade has it attracted broad scientific interest (Woods and Denevan, 2009). The potential of ADE not only motivated research, but also stimulated a huge number of hypotheses and ideas concerning their genesis, partly hurrying ahead of the scientific knowledge. Therefore, the aim of this review is to summarize the scientific knowledge about *terra preta*, focussing on properties and genesis.

2. CLASSIFICATION AND OCCURRENCE OF ADE

2.1. Classification

According to the World Reference Base of Soil Classification, *terra preta* has been classified as horticultural, terric or



Fig. 1. Left: Typical Ferralsol profile. The shallow surface horizon is light brown coloured and roots are concentrated at the soil surface. Below this horizon follows a thin transition horizon to a subsoil horizon which can be several meters thick. The texture of these soils is loamy or sandy and the structure is dominated by stable micro aggregates (pseudo-sand). Right: typical *terra preta* profile. The topsoil horizons are dark grey or black coloured and can reach a depth of more than 1 m. Potsherds, small bone and charcoal particles are characteristic for this horizon. Roots reach deeper down in higher density than in Ferralsols and signs of bioturbation and aggregates of biogenic origin can be found frequently. Below follow transition horizons which are lighter coloured and typically show patches of different brown, grey and black colours with clear signs of mixing of topsoil and subsoil material. The subsoil horizons are identical to the subsoil horizons of adjacent soils. *Terras pretas* typically have the same texture like surrounding soils (from Glaser et al., 2001).

plagic Anthrosols (Sombroek et al., 2002; Kämpf et al., 2003; Teixeira and Martins, 2003). However, a unique classification is still missing (Sombroek et al., 2002; Kämpf et al., 2003). To define *terra preta* is complicated by great variability of different sites as well as within single sites. Such differences are caused by differences in occupation time and land use structure. Some authors differentiate among types of dark coloured Anthrosols in Amazonia (e.g. *terra mulata* vs. *terra preta*) to describe soils showing intermediate properties between *terra preta* and surrounding soils (Sombroek, 1966; Woods and McCann, 1999; McCann et al., 2001). Only limited data from these intermediate soils exist. Therefore, this review focuses on typical *terra preta*, which is roughly defined as a soil characterized by a several decimeter-thick topsoil horizon with high levels of SOM, biochar, and nutrients (especially phosphorus) and which contains archaeological artefacts of pre-Columbian origin.

2.2. Occurrence

Terra preta sites occur throughout Amazonia (Sombroek, 1966; Smith, 1980; Denevan, 1996; Woods and McCann, 1999; McCann et al., 2001; Sombroek et al., 2002; Kern et al., 2003; Glaser, 2007; Fig. 2). Accumulation of *terra preta* sites were found in Central Amazonia and in the Upper Xingu region in Brazil, but they occur also in Amazon parts of Peru, Columbia and southern Venezuela and in the Guianas, but with lower density (Denevan, 1996; Sombroek et al., 2002; Heckenberger et al., 2003; Kern et al., 2003).

Only vague estimations exist about their total extension, ranging up to 10% of Amazonia (Mann, 2002). However, survey in southeastern Amazonia and northeastern Rondonia revealed an overall spatial coverage of one Amazonian Dark Earth per 2 km² (Sombroek et al., 2002). Therefore,

the real extent of *terra preta* in Central Amazonia might well be underestimated.

Terra preta can be found in all eco-regions and landscapes of Amazonia (Kern et al., 2003). Most *terra preta* sites have been found near whitewater rivers (Kern et al., 2003). But they also occur also along clearwater and blackwater rivers and in upper catchment areas (Smith, 1980; Sombroek et al., 2002; Kern et al., 2003). They are generally located on non-floodable land (*terra firme*) in strategically advantageous topographic positions (Kern et al., 2003; Fig. 3). However, Teixeira et al. (2008) mentioned that *terra preta* also occurred in floodplains, covered by sediments or destroyed by lateral movements of rivers. Typically, *terra preta* is developed from Ferralsols (Fig. 1) and Acrisols, but it is also described on a variety of other type of soils including Arensols, Podzols, Luvisols, Nitisols, and Cambisols (Kern et al., 2003).

Patches of *terra preta* are described ranging in size from less than a hectare up to several square kilometers (Woods and McCann, 1999; McCann et al., 2001; Sombroek et al., 2002; Kern et al., 2003). Large *terra preta* sites occur near major rivers, while in upper catchment areas only smaller *terra preta* sites were found (Smith, 1980; Sombroek et al., 2002; Kern et al., 2003). It seems logical that large pre-Columbian settlements were located near rivers but it is not clear if they have only been discovered at these easily accessible locations and if they also exist in areas farther away from rivers.

3. ECOLOGICAL PROPERTIES OF *TERRA PRETA*

3.1. pH

Naturally occurring Ferralsols, Acrisols, and Arensols have a high acidity (\approx pH 4; Fig. 4) causing high levels of exchangeable Al (Fig. 4) and thus Al toxicity in plants.

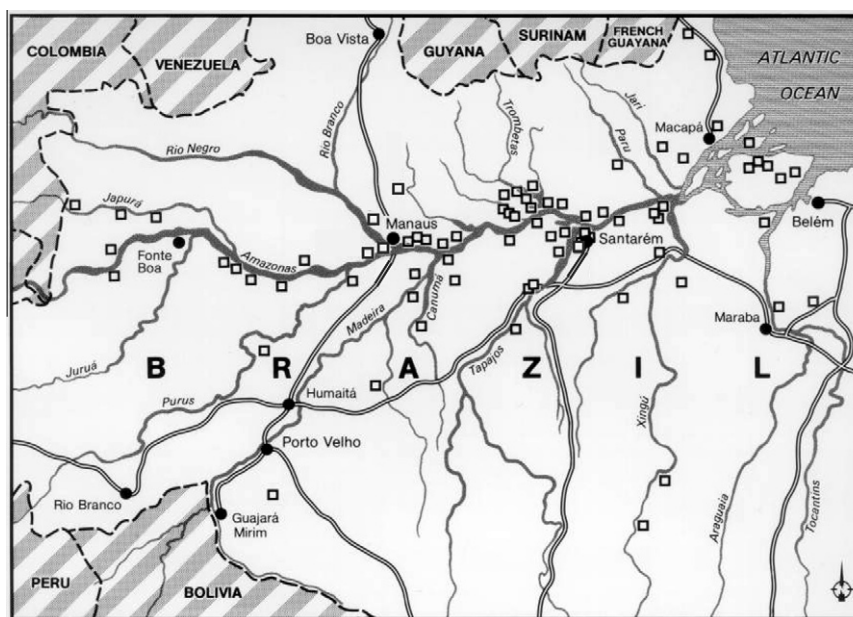


Fig. 2. Known *terra preta* sites in Central Amazonia (Glaser, 2007; modified).

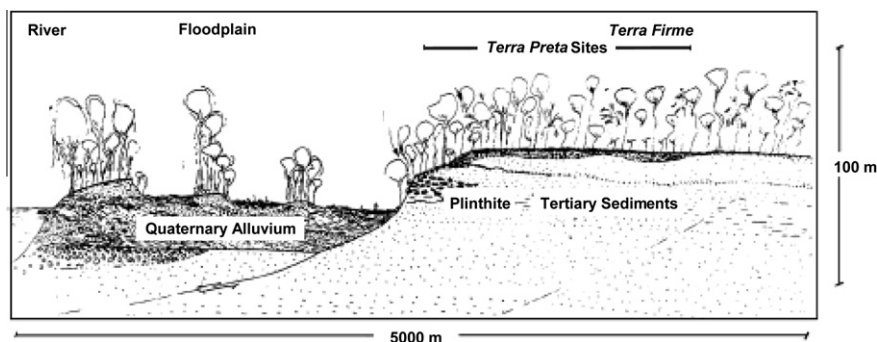


Fig. 3. Typical location of *terra preta* sites at the non-flooded *terra firme* close to the floodplain of large rivers (Lima et al., 2002; modified).

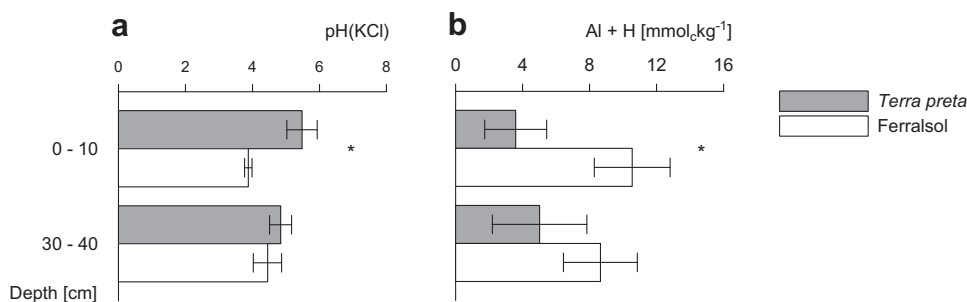


Fig. 4. (a) pH and (b) exchangeable acidity among five *terra preta* sites near Manaus and Santarém and adjacent Ferralsols [data from Glaser et al. (2004a); mean and standard errors; * indicate significant differences ($P < 0.05$) between *terras pretas* and Ferralsols in pair-wise comparisons].

Terra preta is less acidic, pH values ranging from 5.2 to 6.4 (Falcão et al., 2009; Fig. 4). Therefore, plants grown on *terra preta* do not have Al toxicity problems, and this must be one reason for their high productivity (Falcão et al., 2009).

3.2. Nutrients in *terra preta*

Naturally occurring Ferralsols, Acrisols, and Arenosols contain very low amounts of most nutrients. In contrast, *terra preta* is characterized by high levels of P, N, and basic nutrients. Nutrient stocks in *terra preta* are several times greater than those of surrounding soils (Costa and Kern, 1999; Lehmann et al., 2003; Fig. 5).

Total, P, Ca, and Mg are enriched multiple times in *terra preta* relative to surrounding soils and amounts of K, Zn, and Mg were also found at higher levels in *terra preta* (Sombroek, 1966; Zech et al., 1990; Costa and Kern, 1999; Woods and McCann, 1999; Glaser et al., 2001; Lehmann et al., 2003; Glaser, 2007; Falcão et al., 2009; Fig. 5).

However, *terra preta* does not necessarily have high availability of all nutrients important for plant growth (Lehmann et al., 2003). Generally, *terra preta* contains $>200 \text{ mg kg}^{-1}$ of plant-available P, in contrast to surrounding soils which contain about 5 mg kg^{-1} (Falcão et al., 2009). Also plant-available Ca is strongly enriched in relation to surrounding soils, but plant-available K, Mg, Fe, and N are not necessarily higher (Lehmann et al., 2003; Fig. 5).

Therefore, often reported higher crop yields on *terra preta* depend on crop species; e.g. crops with high K

requirements may not grow as well (Lehmann et al., 2003; Falcão et al., 2009) as crops with high P requirements (Lehmann et al., 2003). The low concentrations of plant-available K combined with high concentrations of Ca constitute an imbalanced nutritional status for many crops (Falcão et al., 2009).

3.3. Nutrient holding capacity

In naturally occurring soils of Central Amazonia, low activity clays such as kaolinite predominate in highly weathered Ferralsols and Acrisols, while quartz being the dominating mineral in Arenosols. Both kaolinite and quartz have an extremely low capacity to hold nutrients (normally measured as cation exchange capacity, CEC) being lower than $12 \text{ cmol}_c \text{ kg}^{-1}$. Therefore, SOM plays a major role in the nutrient cycle providing sites for cation exchange. However, due to unfavourable climatic conditions (heavy rainfall and high temperatures) SOM levels of Amazonian soils are normally low because of high mineralization rates. For these reasons, naturally occurring upland Amazonian soils have low nutrient holding capacity. This is the reason why slash-and-burn or fertilization with commercial (NPK) fertilizer is inefficient and not sustainable.

Being rich in SOM, *terra preta* provides a high CEC of $13\text{--}25 \text{ cmol}_c \text{ kg}^{-1}$ (Sombroek, 1966; Zech et al., 1990; Glaser et al., 2001; Glaser et al., 2003; Lehmann et al., 2003; Glaser, 2007; Falcão et al., 2009; Fig. 6), preventing nutrients from leaching. Clay mineral analyses showed a similar

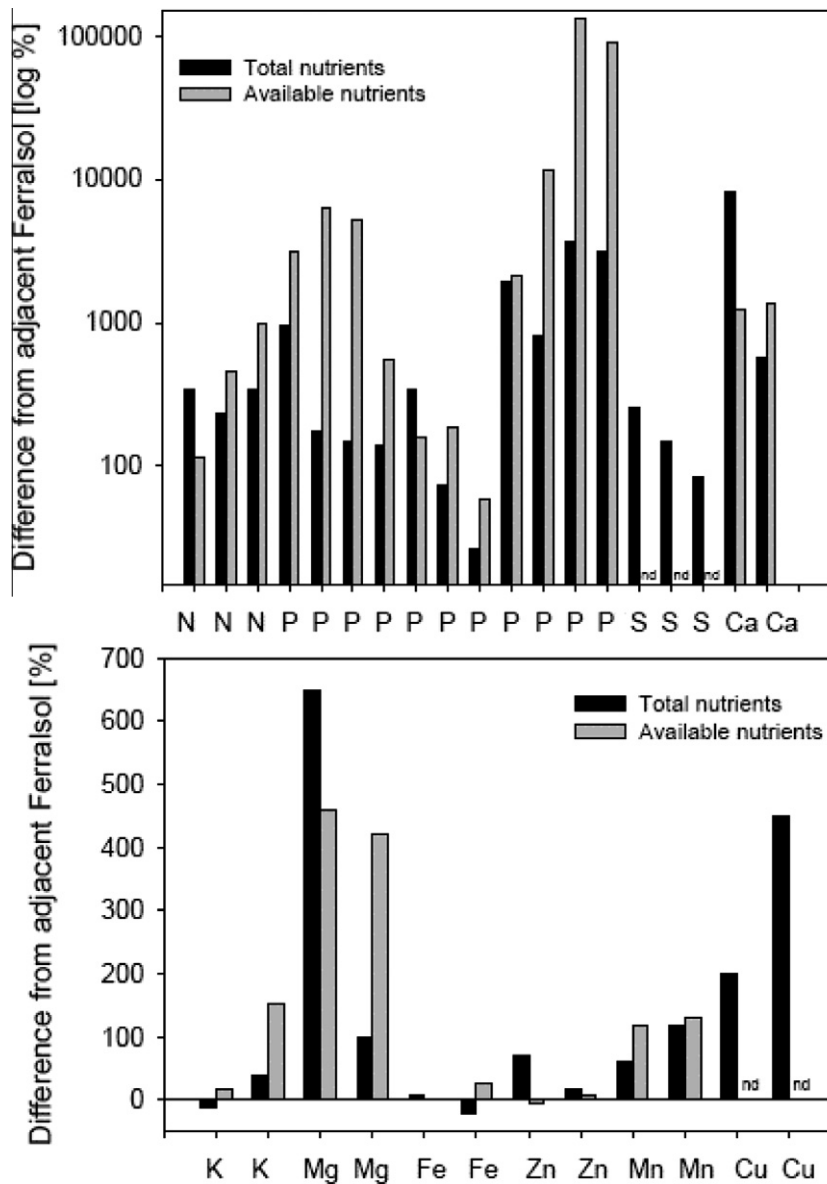


Fig. 5. Available and total nutrient contents of several *terra preta* sites in comparison to adjacent Ferralsols: $\text{Difference}[\%] = \frac{\text{Nutrient content}_{\text{terra preta}} - \text{Nutrient content}_{\text{Ferralsol}}}{\text{Nutrient content}_{\text{Ferralsol}}} \times 100[\%]$. Note differences in scale between the two graphs (Lehmann et al., 2003; modified).

mineral composition of *terra preta* and reference soils, dominated by kaolinite and accessory minerals such as goethite, hematite, anatase (Bechthold, 1982). Correlation of CEC with SOM concentrations shows that SOM is primarily responsible for CEC of *terra preta* as it is naturally occurring in Amazonian soils (Sombroek, 1966). However, *terra preta* has on average three times greater SOM content than surrounding soils (Glaser, 2007; Fig. 6). Not only is the quantity of SOM responsible for the high CEC, but so is SOM quality. ^{13}C NMR (Zech et al., 1990) and DRIFT spectra (Cunha et al., 2009) revealed that SOM in *terra preta* contains higher amounts of carboxylic groups and phenolic groups compared to surrounding soils. For these reasons, SOM in *terra preta* has higher CEC than SOM in naturally occurring soils (Sombroek, 1966; Liang et al., 2006; Fig. 7).

3.4. SOM stability

In the humid tropics, a combination of high temperatures and a favourable soil moisture regime induces high rates of OM decomposition and weathering of primary minerals (Sombroek et al., 1993; Tiessen et al., 1994). For these reasons, naturally occurring Amazonian soils have a low nutrient-holding capacity.

During a laboratory incubation experiment, Glaser (1999) found that *terra preta* under cultivation contained greater amounts of rapidly mineralizable and very stable SOM (passive/recalcitrant) both in absolute terms and as fraction of the total SOM compared to surrounding soils.

Analysis of carbohydrates and lignin suggests that an enhanced input of unaltered plant material is responsible for the higher amounts of labile SOM in *terra preta* under

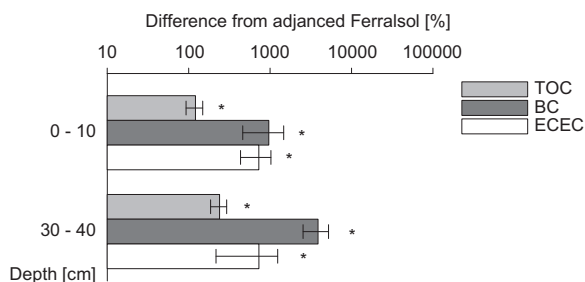


Fig. 6. Cation exchange capacity at soil pH (ECEC), total organic C (TOC) and biochar (BC) concentration of five *terra preta* sites near Manaus and Santarém in comparison to adjacent Ferralsols: $\text{Difference}[\%] = \frac{\text{Value}_{\text{terra preta}} - \text{Value}_{\text{Ferralsol}}}{\text{Value}_{\text{Ferralsol}}} \times 100[\%]$ [data from Glaser et al. (2004a); mean and standard errors; * indicate significant differences ($P < 0.05$) between terras pretas and Ferralsols in pair wise comparisons].

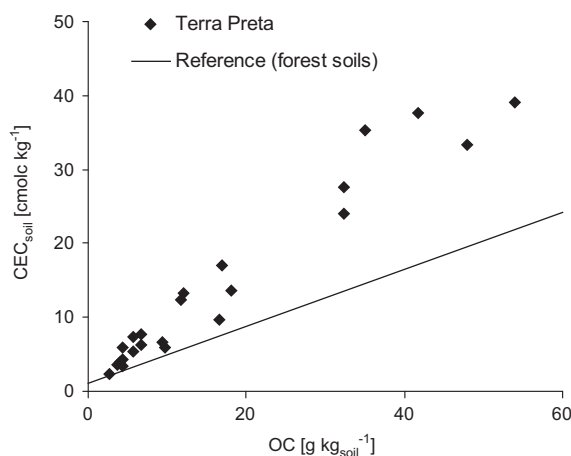


Fig. 7. Correlation between humus content (measured as organic carbon, OC) and nutrient holding capacity (measured as potential cation exchange capacity with ammonium acetate buffered at pH 7) of *terra preta* and surrounding soils. Note that the slope of *terra preta* is higher by a factor of 3 compared to surrounding soils which means that the SOM quality of *terra preta* is much better with respect to the ability to prevent nutrients from leaching (redrawn after Sombroek et al., 1993).

cultivation. Mineralization of labile SOM contributes to the high amounts of plant-available nutrients in *terra preta* (Glaser, 1999), indicating that nutrient cycling in these soils is intimately related to the SOM because of the low supply of weatherable minerals.

Besides this labile SOM pool, *terra preta* contains a higher stable SOM pool than surrounding soils which can be explained by physical and organo-mineral stabilisation and also by higher recalcitrance against microbial degradation (Glaser et al., 2003). A higher physical stabilization via inclusion into the interior of aggregates was found in ADE (20%) compared to adjacent soils (10%) (Glaser, 1999). Thus, there is proportionally more SOM stabilized in aggregates in *terra preta* compared to adjacent sites. Besides a physical stabilization of SOM, density and particle size fractionations revealed that a major part of SOM in *terra*

preta is stabilized by interaction with soil minerals (Glaser et al., 2003). As kaolinite is the dominating clay mineral having a low interaction potential, it is most likely that interaction occurs at the surface of iron and aluminium oxides. Analytical data further showed that the main reason for the high stability is the chemical recalcitrance of SOM in *terra preta*. ¹³C NMR spectra revealed that SOM in *terra preta* is rich in condensed aromatic structures (Zech et al., 1990; Glaser et al., 2003; Novotny et al., 2009). Diffuse-reflectance infrared Fourier transformation (DRIFT) spectrometry, electron paramagnetic resonance (EPR) spectroscopic analyses showed that humic acids in *terra preta* contain more aromatic structures being more condensed than humic acids in reference soils (Cunha et al., 2009).

Benzenepolycarboxylic acids (BPCA) is a molecular marker, but it is not a “natural” marker. It is formed when biochar is treated with nitric acid. It is used as an index of the amount of char in a sample. Using BPCA as molecular markers, it has been shown that the condensed aromatic structures originated from incomplete combustion (Glaser et al., 1998, 2003). These structures were called black carbon containing biochar but also other components such as soot (Glaser, 2007). Five *terra preta* sites in Central Amazonia contained a mean of about 50,000 kg biochar per hectare and one meter soil depth, being enriched by a factor of 70 compared to adjacent soils (Glaser et al., 2001).

It is believed that biochar persists in the environment over millennia due to its biological and chemical recalcitrance caused by the polyaromatic backbone (Goldberg, 1985; Schmidt et al., 1999). The existence of *terra preta* even today proves that biochar is stable over millennia in extreme environments such as the humid tropics. Using ¹⁴C-labelled biochar, Kuzyakov et al. (2009) calculated a mean residence time of biochar to be about 2000 years, although there is clearly a continuum of degradability that is related to the temperature and duration of heating during biochar formation. Nevertheless, biochar is a key factor for the stability of the SOM in *terra preta* (Glaser, 1999; Glaser et al., 2000, 2001) and thus, for the *terra preta* genesis itself.

¹³C NMR spectroscopy further revealed a signal corresponding to aromatic acids such as mellitic acid (Möller et al., 2000), which is considered being an end product of biochar oxidation (Glaser et al., 1998, 2001). Thus, slow biochar oxidation over time produced carboxylic groups on the edges of the aromatic backbone, which increased the nutrient retention capacity (Glaser et al., 2000). From these results it can be concluded that biochar found in *terra preta* is not only responsible for the long-term SOM stability evident today, but is also a direct key factor for the high CEC in *terra preta* (Glaser et al., 2003; Glaser 2007).

4. THEORIES OF TERRA PRETA GENESIS

4.1. Sedimentation of allochthonous soil material vs. *in situ* genesis

Terra preta research began in the 1870s and throughout the publications of the 19th and early 20th centuries, all authors (Hartt, Orton, Smith, Derby, Katzer) recognized that these soils were anthropogenic and clearly stated so.

It was not until the 1940s that we start to get references to geogenic origins in the literature (Woods and Denevan, 2009). For instance, volcanic (Hilbert, 1968) and fluvial (Zimmermann, 1958; Franco, 1962) sedimentation were suggested. With the current pedological knowledge that *terra preta* and the surrounding soils have a similar mineralogical composition and texture, all geogenic hypotheses of *terra preta* formation can be rejected. For instance, upon volcanic sedimentation one would expect the deposition of tephra layers coupled with a different particle-size distribution, the occurrence of volcanic glasses and their weathering products (allophanes), and different heavy minerals (Gillespie et al., 1992; Zech et al., 1996) in *terra preta*. A fluvial sedimentation would also result in a different texture. However, such observations have never been reported (Zech et al., 1979; Sombroek et al., 1993; Glaser et al., 2002).

It is often noted that *terra preta* developed on extensive soils in Amazonia: Ferralsols, Acrisols, and Arenosols. They have also developed from Plinthosols, Cambisols and other types of soils (Kämpf et al., 2003). Due to similar mineral composition of *terra preta* and adjacent sites and an even integration of *terra preta* into the surrounding landscape, a genesis from anthropogenically applied allochthonous soil material is also excluded. Therefore, it is more likely that *terra preta* formed *in situ* by addition of biochar and nutrient-rich waste materials.

4.2. Sources of biochar

The question of how the large amounts of biochar accumulated in *terra preta* has been only partly answered, because it is difficult to distinguish between naturally occurring and anthropogenic biochar formation (Glaser et al., 2004b). Commonly it is assumed that biochar is a pyrogenic material which is the residue of incomplete burning of biomass (charcoal, black carbon). Glaser et al. (2001) calculated that a total of approximately 25 forest burnings would be necessary to accumulate the mean biochar content found in *terra preta* (50,000 kg per hectare). Therefore, exclusively naturally formed biochar as residue after forest fires could be responsible for the *terra preta* formation. However, as naturally occurring forest fires are widespread in Amazonia, one can assume that over periods reported for the *terra preta* formation of up to 3000 years, the whole of Amazonia should be influenced to more or less the same extent. If true, Amazonia should be covered entirely by *terra preta*, which is certainly not the case.

Terra preta does not form in soils under shifting cultivation or slash and burn (Woods and McCann, 1999), strongly suggesting that biochar accumulation into *terra preta* was not due to natural forest fires. Repeated slash-and-burn of abandoned settlement sites, however, could have produced *terra preta* as outlined above (Glaser, 1999). A number of other anthropogenic activities could also be responsible for biochar accumulation and subsequent formation of *terra preta*, such as the use of low heat, smouldering fires for food and pottery preparation, spiritual reasons, or biochar amendments to home gardens (Glaser et al., 2001).

Recently, indigenous groups as well as *caboclos* (people of mixed origin) are using various forms of *terra quemada* or very similar soil conditioner in home gardens which could have contributed to the high biochar levels in *terra preta* if also done during pre-Columbian times. *Caboclos* are sweeping their home gardens and burning or charring the debris before applying to home gardens e.g. around tree seedlings and young trees (WinklerPrins, 2009). Another source of biochar could be heating (charring) of soil by hot fire in home gardens as practiced by an indigenous group near Manaus (Steiner et al., 2009). At the border between Brazil and French Guiana, *caboclos* collect wall material from charcoal kilns consisting of mixed charcoal and heated soil and mix it with manure for seed germination in pots even today. Some people in Brazil cultivate plants in elevated gardens containing high biochar concentration.

4.3. Nutrient sources and further amendments

With respect to potential sources for the high nutrient stocks, *in situ* weathering as a source of P, Mg, K, Zn, and Mn can be excluded, at least for heavily weathered Ferralsols and Acrisols and poorly developed infertile Arenosols, since these soils do not contain high concentrations of these elements (Sombroek, 1966; Zech et al., 1990; Costa and Kern, 1999; Glaser et al., 2001; Lehmann et al., 2003; Glaser, 2007; Cunha et al., 2009). Only N can be induced biologically *in situ* via N fixation (Glaser, 2007). Other elements must be incorporated from the surroundings for nutrient accumulation (Glaser, 2007). Mapping of element concentrations of *terra preta* sites showed different distribution patterns of elements indicating different nutrient sources (Costa and Kern, 1999). As pre-Columbian populations had no access to mineral fertilizers such as NPK, only local resources can be responsible for nutrient accumulation in *terra preta*. The following sources could be identified unambiguously. As biochar contains only traces of nutrients, it does not significantly contribute to the nutrient status (Glaser, 2007). Arroyo-Kalin et al. (2009) and Woods (2003) indicated that ash may have been a significant input into *terra preta*. It is likely that ash was applied on *terra preta* by human activities. However, it is unlikely that the application of ash was a key process leading to *terra preta* formation as slash-and-burn agriculture does not generate *terra preta* despite the fact that a lot of ash is applied to such sites. In addition, ash contains significant amounts of Ca, K, Mg, and P, while *terra preta* is highly enriched in P, but other elements are less enriched or even depleted, especially K (Fig. 5). Therefore, the quantities and ratios of nutrients in *terra preta* indicate that plant materials were not the only nutrient sources.

It has been hypothesised that plant biomass from rivers and organic matter from floodplains were transported to the sites (Denevan, 1996; Lima et al., 2002; Glaser, 2007). Here again, elemental ratios atypical for plants contradict the idea that decomposition of large amounts of plant biomass (not charred or burned) was a key process leading to *terra preta* formation. In addition, application of high amounts of plant biomass from rivers and organic matter

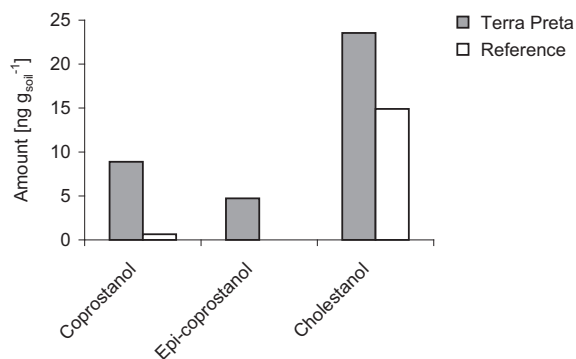


Fig. 8. Concentrations of faecal stanols (coprostanol and epicoprostanol) and concentration of a stanol which was built in the soil (cholestanol) in a *terra preta* sampled near Santarém compared to surrounding soil (30–40 cm; Birk et al., 2010).

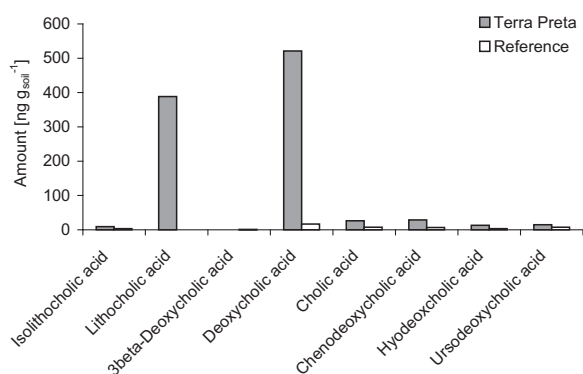


Fig. 9. Bile acid concentrations in a *terra preta* sampled near Santarém compared to surrounding soil (0–50 cm; Birk et al., 2010).

from floodplains could be possible in regions of white water rivers where fertile floodplains (várzea) are found, but does not help explaining the nutrient stocks in numerous *terra preta* sites near blackwater rivers, which are nutrient poor and support only a floodplain characterized frequently by white sands (Prance, 1979).

Plant material originating from mulching or residues of house construction could contribute to the nutrient stocks. This is difficult to test analytically, but like ash and plant biomass from rivers and organic matter from floodplains, it is unlikely to be a key process for *terra preta* genesis. Again here, nutrient patterns in *terra preta* are not typical for plant biomass and soils under natural rain forest show a high litter production, not leading to *terra preta* formation.

Another potential nutrient source is waste, including plant residues from food production, animal remains such as mammal and fish bones which likely contribute to the nutrient stocks. Fish bones can be even observed in *terra preta* profiles today. By scanning electron microscopy in combination with energy-dispersive X-ray spectroscopy (SEM/EDS) Lima et al. (2002) and Schaefer et al. (2004) found evidence for high Ca and P derived from bones in some *terra preta*.

Last, animal manures including human waste may have contributed nutrients to *terra preta* (Smith, 1980; Sombroek et al., 2002; Woods, 2003; Glaser et al., 2004a; Glaser, 2007). Recently, determinations of manure-specific steroids have shown that coprostanol (5β-cholestan-3β-ol) and epicoprostanol (5β-cholestan-3α-ol) are the two most enriched stanols in *terra preta* compared to surrounding reference soils, indicating enhanced input of faecal material in *terra preta* (Fig. 8).

The identification of the type of faeces is hindered by limited data of steroid composition of Amazonian animals. In contrast to coprostanol being a biomarker for faeces of omnivores (Bethel et al., 1994; Evershed et al., 1997; Bull

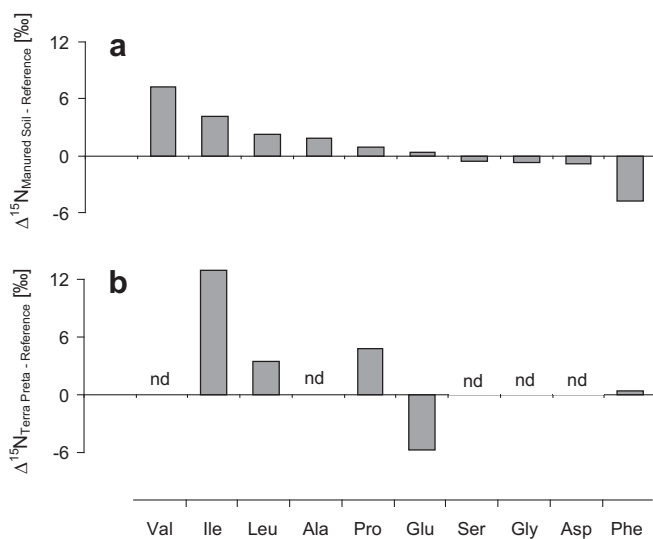


Fig. 10. (a) Differences of $\delta^{15}\text{N}$ values of individual amino acids between a manured soil and a control soil in Europe ($\Delta^{15}\text{N}$; Simpson et al., 1997) and (b) between a *terra preta* (30–40 cm) sampled near Manaus and the surrounding soil (lower part; Birk et al., 2010).

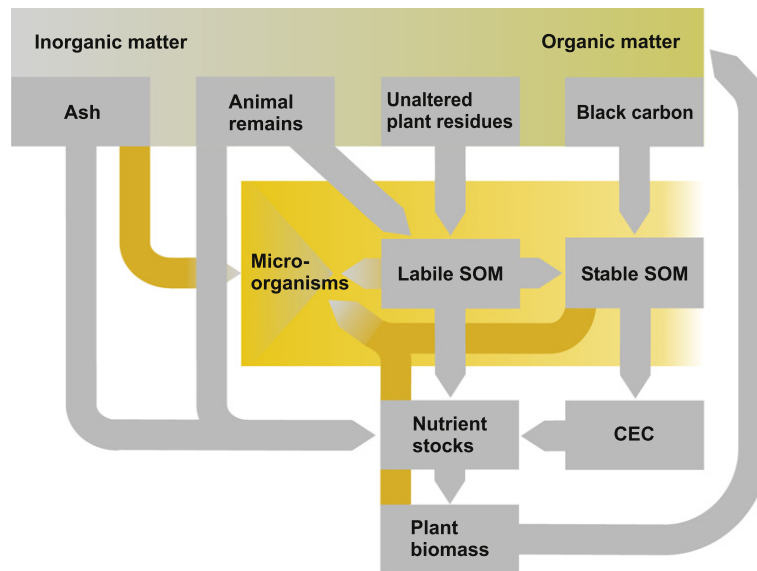


Fig. 11. Model of *terra preta* genesis.

et al., 1999, 2002), the stanols which are characteristic for the faeces of herbivore mammals are not enriched in *terra preta* to same extent. Thus, faeces-derived nutrient input into *terra preta* was most probably introduced by omnivores (Birk et al., 2010). For further identification of faeces-derived nutrient input into *terra preta*, analysis of bile acid pattern might help. Bile acids in a *terra preta* were dominated by deoxycholic acid accompanied by minor concentrations of lithocholic acid (Fig. 9), typical for faeces of humans (Bull et al., 1999, 2002). Therefore, all available steroid data so far unambiguously indicate deposition of human faeces, which could explain the abnormal nutrient pattern dominated by large amounts of P.

The stanols observations are corroborated by compound-specific $\delta^{15}\text{N}$ analysis of individual amino acids. These analyses showed that *terra preta* exhibit more positive $\delta^{15}\text{N}$ values of hydrophobic amino acids than the control soil (Fig. 10), which is characteristic for soils fertilized with excrements (Simpson et al., 1997). This effect could only be detected in deeper horizons of *terra preta*. The lack of higher $\Delta^{15}\text{N}$ values in the topsoil could be caused by recent land use, which effects a dilution of the ancient land use signal.

In conclusion, the following sources of nutrients in *terra preta* seem most likely: plant biomass, mammal and fish bones, ash, biochar, and human excrement (Fig. 11).

4.4. Role of microorganisms in *terra preta* genesis

Much discussion has been associated with the biology and specifically the microbiology in *terra preta* (Lehmann, 2009). It is assumed that microorganisms are responsible for the oxidation of biochar, providing functional groups for nutrient retention (Glaser et al., 2002), that microorganisms contribute significantly to the formation of stable SOM in *terra preta* (Glaser, 2007), or that specific microorganisms were responsible for the genesis of *terra preta* (Woods and McCann, 1999).

Recently, some studies have been focused on the microbiology of *terra preta*. These studies revealed a distinct microbial community in *terra preta*. Methods with direct microbial cultivation as well as direct DNA extractions from soils showed a higher microbial diversity and species richness in *terra preta* compared to reference soils (Kim et al., 2007; O'Neill et al., 2009; Ruivo et al., 2009; Tsai et al., 2009). It turned out that *terra preta* is rich in K-selected bacteria typical for more stable environments, with slower rates of C turnover in contrast to an abundance of r-selected bacteria in reference soils characteristic of rapid C mineralization (O'Neill et al., 2009). Cultivation experiments in different *terra preta* gave evidence for a predominance of fungal populations vs. bacterial populations (Ruivo et al., 2009).

In general, the recent literature suggests that the microbial communities in *terra preta* are a result of the unique *terra preta* habitat as opposed to contributing significantly to *terra preta* genesis. In addition, it is now clear that it will not be possible to extract a special microbial population that can be used to recreate *terra preta* (Lehmann, 2009). However, the microbial community may perform functions that change soil nutrient and carbon dynamics in ways that promote the self-perpetuation of *terra preta* (Lehmann, 2009). The latter is supported by biomarker analyses.

Cultivation experiments and direct extraction of DNA from soils deliver information about the recent microbial community composition which is not necessarily comparable to the composition during the times of *terra preta* generation. Therefore, analyses of more stable microbial biomarkers such as amino sugars and muramic acid being indicators for fungal and bacterial residues, respectively (Amelung, 2001), seems more promising with respect to reconstruction of microbial impact on *terra preta* formation. *Terra preta* showed elevated amino sugar to muramic acid ratios compared to reference soils (Fig. 12), indicating enhanced impact of fungi compared to bacteria (Glaser et al., 2004c). These results clearly indicate the higher

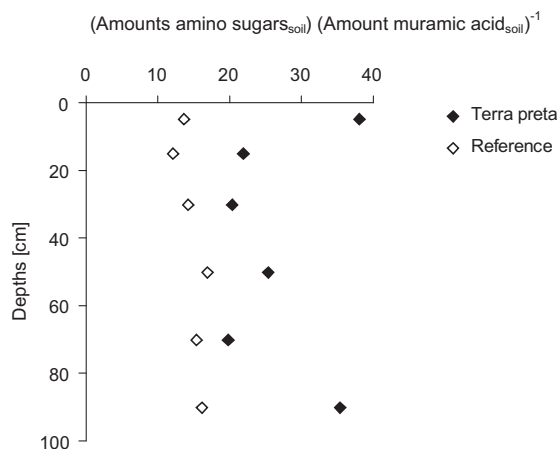


Fig. 12. Amino sugar and muramic acid concentrations in a *terra preta* sampled near Santarém compared to an adjacent soil (Birk et al., 2010).

importance of fungi over bacteria with respect to *terra preta* formation, although amino sugars are certainly not so stable than biochar or black carbon, they are more stable in soil than other microbial biomarkers (Glaser et al., 2004c). In addition, low microbial oxidation in deeper soil has certainly an additional conservation effect. Furthermore, due to similar chemical structure and thus stability, the ratio between glucosamine (=fungal marker) to muramic acid (=bacterial marker) is valid independent from their absolute stability.

The enhanced proportion of fungi in *terra preta* could have favourable consequences on the soil properties of *terra preta*. Recent studies have investigated whether abiotic processes or microorganisms are of greater importance in the oxidation of biochar. Hamer et al. (2004) found a close correlation between glucose mineralization and biochar mineralisation during biotic incubation for model chars, which could suggest a co-metabolic degradation of biochar by microbial oxidation. On the other hand, Cheng et al. (2006) found no differences in surface oxidation of biochar during a 30-day incubation experiment of sterilized biochar and biochar soil mixtures in comparison to these materials inoculated by a commercially available microbial inoculum. They postulated that abiotic processes were more important for oxidation of biochar than biotic processes but qualified that microbial oxidation could play an important role over long periods and that specialized microorganisms could have great influence on biochar oxidation. Such microorganisms could be fungi. The enhanced proportion of fungi in the microbial community in *terra preta* can be interpreted as a hint for a microbial oxidation of biochar.

In addition, there is scientific evidence for biological production of black carbon in *terra preta* by fungi (Glaser and Knorr, 2008). Aspergillin, the black pigment of *Aspergillus niger* (which is ubiquitous in soils) was reported to possibly contain condensed aromatic structures (Lund et al., 1953) similar to those of black carbon or biochar (Schmidt and Noack, 2000). The contribution of aspergillin to soil black carbon contents was estimated to be negligible

in a study by Brodowski et al. (2005). However, Glaser and Knorr (2008) showed by compound-specific stable-isotope analyses in condensed aromatic moieties similar to the ones of black carbon that significant amounts of black carbon in soils are formed by biological – or at least non-pyrogenic – processes in different soil types under different climatic conditions. The highest biological black carbon production of up to 9% annually relative to the total black carbon inventory was observed in a charcoal and manure-amended soil in Central Amazonia (Glaser and Knorr, 2008).

Concluding, there are indications for microbial processes in *terra preta* which promote sustainability. But these microbial processes in *terra preta* are similar to those also observed in “normal” soils and consist mainly of aerobic processes similar to those that occur during composting (Fig. 11). There is no evidence for anaerobic processes such as fermentation, which has been postulated recently (Faccatura et al., 2010). Furthermore, is it even more unlikely that fermentation was done in ceramic pots although potsherds are plentifully found in *terra preta* because it is most unlikely that thousands of cubic metres of *terra preta* is produced without mechanisation under these conditions.

In addition, it is clear that *terra preta* cannot regenerate itself when exploited as often done in Central Amazonia for economic reasons (soil mining). Although enhanced input of plant-derived nutrients such as C and N still can continue and maintain SOM levels, nutrient levels of other elements such as Ca, K, Mg, and P cannot regenerate without further addition of materials discussed in Section 4.3. In addition, from a scientific point of view, a soil’s characteristics might persist for a long time in a state of equilibrium with the local environment. But it is not “regenerating” itself.

4.5. Intentional vs. unintentional *terra preta* creation

Terra preta is preferentially used for agriculture today by *Indios* (Schmidt and Heckenberger, 2009), *caboclos*, and modern farmers. Phytolith data has shown that this was the case already in pre-Columbian times (Bozarth et al., 2009). Our data presented and discussed above support the hypothesis that *terra preta* developed from midden areas with various inputs of organics (including mammal and fish bones, excrement and biochar) and inorganic material (including ash) and further debris (Fig. 11). It is possible that agricultural practices in home gardens contributed to the genesis of *terra preta* as well. Today, midden areas are used as home gardens or home gardens are used as trash areas by indigenous groups (Hecht, 2003; Schmidt and Heckenberger, 2009). Amendments of biochar to home gardens (see Section 4.2. Sources of biochar) are responsible for the high amounts of black carbon. Therefore, *terra preta* genesis can be explained by formation from midden areas and probably home garden agriculture as also practised today. Thus *terra preta* formation is likely a combination of both unintentional soil modification as well as intentional amendments to improve small-scale home gardens.

Pre-Columbian villages were more or less permanently settled or re-settled frequently due to easier clearance of secondary forest with stone axes and due to the enhanced soil

fertility. These two facts could have boosted the genesis of well developed and large *terra preta* sites like a self-perpetuating or self-organization process (Denevan, 1998). In addition, there is no scientific evidence indicating that forgotten agricultural techniques for large scale soil fertility improvement are responsible for *terra preta* genesis.

5. CONCLUSIONS

The existence of *terra preta* even several thousand years after their creation unambiguously shows that improvement of highly weathered tropical soils by human actions is possible. More important, *terra preta* is a model for sustainable soil fertility and long-term C sequestration even today created by an intelligent material flow management. From scientific data discussed in this review it is very likely that *terra preta* was not intentionally created to improve soil fertility at large scales, at least not at the beginning. All available scientific data fit a genesis from midden eventually combined with home garden agriculture. It is most likely that (unintentional) creation of a fertile soil (*terra preta*) attracted more and more people and/or favoured population growth managing more and more resources (biochar, wastes, excrement) which set in motion self-enhancing and self-organizing processes.

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