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Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century

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Terra Preta soils of central Amazonia exhibit approximately three times more soil organic matter, nitrogen and phosphorus and 70 times more charcoal compared to adjacent infertile soils. The Terra Preta soils were generated by pre-Columbian native populations by chance or intentionally adding large amounts of charred residues (charcoal), organic wastes, excrements and bones. In this paper, it is argued that generating new Terra Preta sites ('Terra Preta nova') could be the basis for sustainable agriculture in the twenty-first century to produce food for billions of people, and could lead to attaining three Millennium Development Goals: (i) to combat desertification, (ii) to sequester atmospheric CO_2 in the long term, and (iii) to maintain biodiversity hotspots such as tropical rainforests. Therefore, large-scale generation and utilization of Terra Preta soils would decrease the pressure on primary forests that are being extensively cleared for agricultural use with only limited fertility and sustainability and, hence, only providing a limited time for cropping. This would maintain biodiversity while mitigating both land degradation and climate change. However, it should not be overlooked that the infertility of most tropical soils (and associated low population density) is what could have prevented tropical forests undergoing large-scale clearance for agriculture. Increased fertility may increase the populations supported by shifting cultivation, thereby maintaining and increasing pressure on forests.

Keywords: Terra Preta; Amazonian Dark Earths; C sequestration; humid tropics; charcoal; slash and char

1. INTRODUCTION

Within the landscape of infertile soils (Ferralsols, Acrisols, Lixisols and Arenosols) in central Amazonia, small islands of highly sustainable fertile soils known as Terra Preta (*do Indio*) occur in patches averaging approximately 20 ha (figure 1). Terra Preta soils have on average three times higher soil organic matter (SOM) content, higher nutrient levels and a better nutrient retention capacity than surrounding infertile soils (Sombroek 1966; Zech *et al.* 1990; Glaser *et al.* 2001). Radiocarbon dating indicates that these soils were formed between 7000 and 500 cal yr BP and are of pre-Columbian origin (Neves *et al.* 2001). It still remains a matter of speculation whether these soils were made intentionally or resulted as a by-product of human occupation; what is known, however, is that Terra Preta soils have been under continuous agricultural use for centuries (Woods & McCann 1999; German 2001) and presently Terra Preta is being excavated and sold as fertile soil.

Despite their importance as fertile soil on an otherwise infertile landscape, the traditional knowledge of how Terra Preta soils were produced has been lost. This paper examines the evidence for the processes responsible for Terra Preta genesis and also the reasons why they are so superior in terms of SOM content and nutrient retention capacity in comparison to the surrounding central Amazonian soils. Using this knowledge, the paper addresses the potential of Terra Preta soils in providing future sustainable agriculture in the humid tropics. It concludes that the generation of Terra Preta soils nowadays could enable communities to build up highly productive and sustainable land use systems. They would be, in particular, useful for smallholder farmers for the growth of high-value crops and other horticultural activities.

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One contribution of 14 to a Theme Issue 'Biodiversity hotspots through time: using the past to manage the future'.

2. PROCESSES RESPONSIBLE FOR THE FORMATION OF TERRA PRETA SOILS

(a) *Charcoal formation*

When comparing the SOM composition of Terra Preta soils with adjacent Ferralsols, e.g. by ^{13}C NMR spectroscopy, higher amounts of condensed aromatic (figure 2*b*) and carboxylic moieties are obvious (Zech *et al.* 1990; Glaser *et al.* 2003*b*). Using molecular markers such as benzenepolycarboxylic acids, it has been shown that charring processes are responsible for the formation of condensed aromatic structures (Glaser *et al.* 1998, 2003*a*; Brodowski *et al.* 2005) and that Terra Preta soils contain on average 70 times more charcoal compared to the surrounding Ferralsols (Glaser *et al.* 2001).

Biomass charring leaves behind a continuum of carbon combustion products known as black or pyrogenic carbon ranging from slightly charred organic matter (figure 2*a*) retaining the shape of the original material to highly graphitized soot spheroids derived

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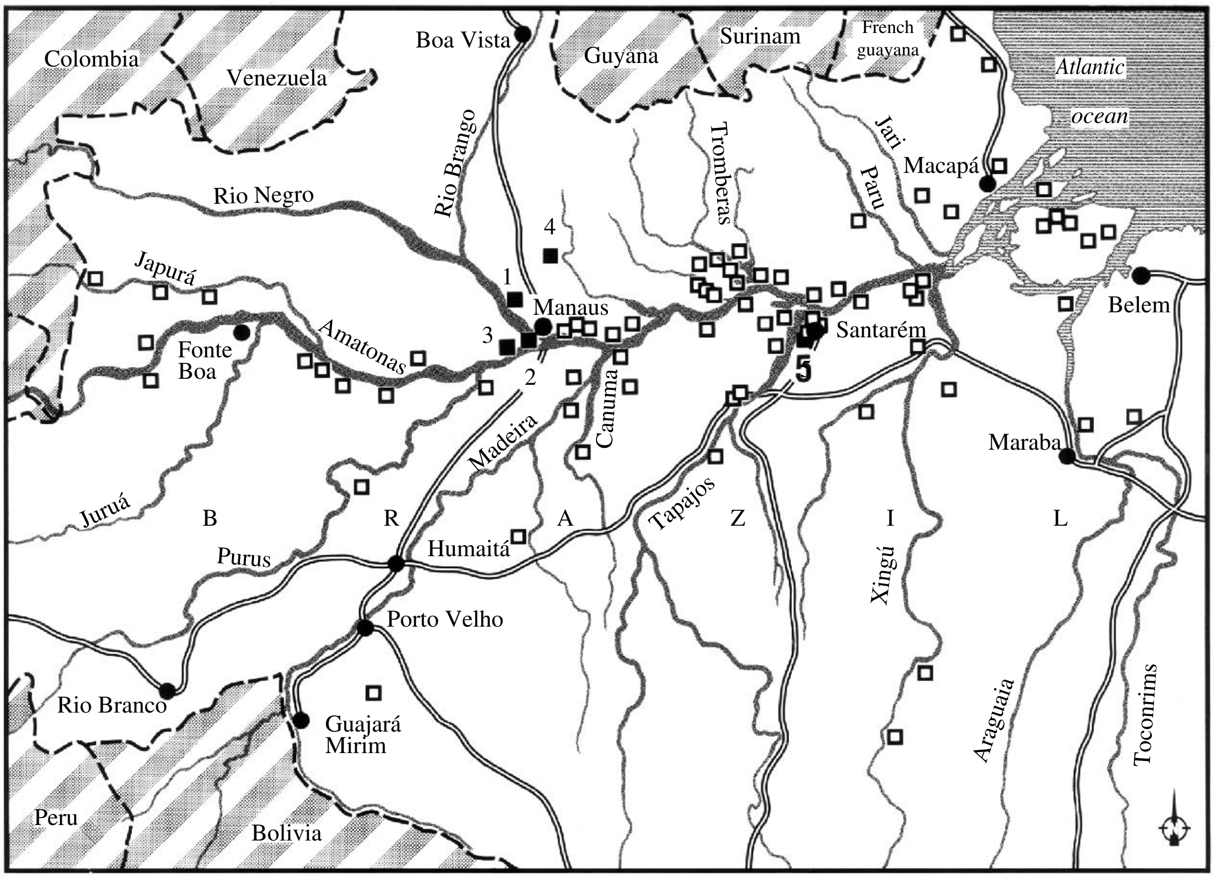

Figure 1. Known occurrence of Terra Preta (do Indio) in central Amazonia.

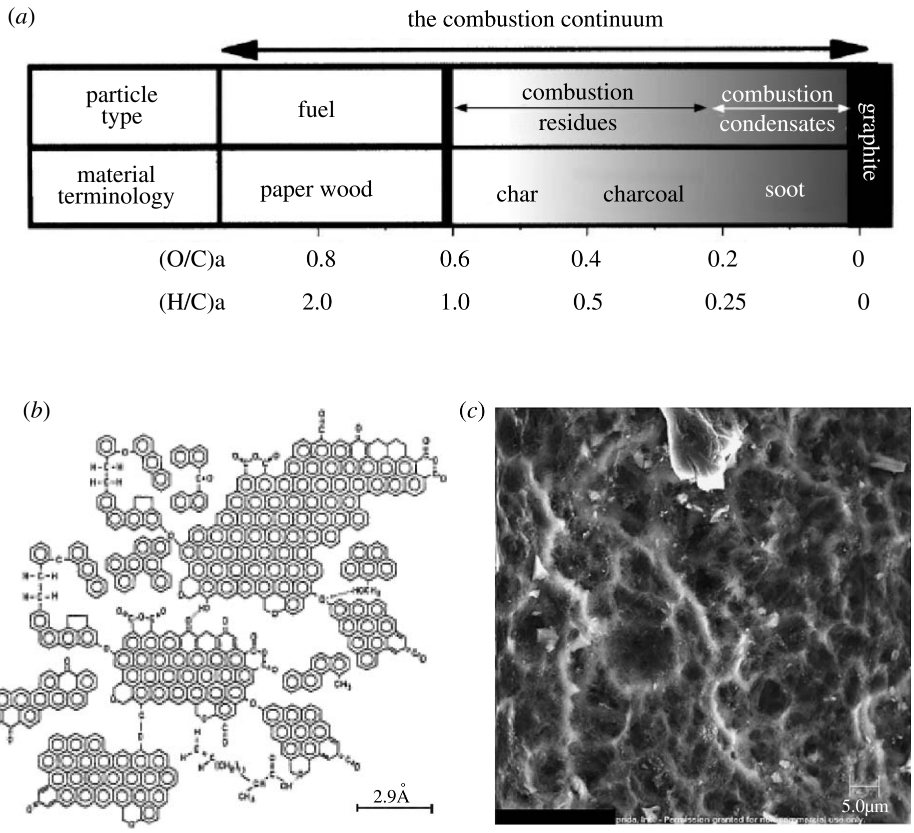

Figure 2. Charred organic matter represents a continuum of (*a*) combustion products with respect to physical, chemical and ecological properties, which can be characterized by the molecular ratios of oxygen to carbon (O/C) and hydrogen to carbon (H/C). (*b*) Poly-condensed aromatic moieties are the backbone of charcoal (black carbon) and assumed to be responsible for its chemical and biological recalcitrance in the environment. (*c*) The porous structure is responsible for the high sorption potential of organic molecules.

from recombination of free radicals (Hedges *et al.* 2000). For ease of description, all types of the charred material will be referred to as charcoal in the following. By convention, thermally altered natural organic matter is assumed as charcoal with an O/C ratio of less than 0.6 (Hedges *et al.* 2000). However, also smaller values have been suggested (Stoffyn-Egli *et al.* 1997). It is almost impossible to unambiguously identify charcoal by a simple O/C ratio determination due to possible interactions with soil minerals and SOM. Therefore, H/C ratio (Kim *et al.* 2004) as a second dimension or molecular markers such as benzenepolycarboxylic acids (Glaser *et al.* 1998) should be used (figure 2*a*).

The chemical structure of charcoal in the Terra Preta soils is characterized by poly-condensed aromatic moieties (figure 2*b*) and these are responsible for both the prolonged stability against microbial degradation and, after partial oxidation, also for the higher nutrient retention (Glaser *et al.* 2001). Besides this remarkable chemical structure, the Terra Preta charcoal has a porous physical structure (figure 2*c*), also being responsible for higher retention of water and dissolved organic nutrients (Pietikäinen *et al.* 2000) and even pollutants such as pesticides and poly-cyclic aromatic hydrocarbons (Kopytko *et al.* 2002), etc.

Radiocarbon dating of the charcoal in the Terra Preta soils has revealed charcoal ages of up to 7000 years (Neves *et al.* 2001) and that, even though this was generated in pre-Columbian times, it has persisted to present day. Studies indicate that the Terra Preta soils contain on average 70 times more charcoal than the surrounding soils (Glaser *et al.* 2001).

The question of how these tremendous amounts of charcoal (on average approx. 50 Mg ha^{-1} m^{-1}; Glaser *et al.* 2001) were accumulated in the Terra Preta soils has been only partly answered until now, because it is difficult to distinguish between naturally occurring and anthropogenically induced charcoal formation by means of the physical, chemical and biological properties of charcoal. Glaser *et al.* (2001) calculated that a total of approximately 25 forest burnings would be necessary to accumulate the mean charcoal content found in the Terra Preta soils. Therefore, exclusively naturally formed charcoal as residues after forest fires could be responsible for the Terra Preta formation. However, as it is known that naturally occurring forest fires are widespread in Amazonia, one can assume that over periods reported for the Terra Preta formation of up to 7000 years, the whole of Amazonia would have been influenced to more or less the same extent. If true, the Terra Preta soils should be covering the whole of Amazonia, which is apparently not the case. Additionally, the Terra Preta does not form in soils under shifting cultivation or slash and burn (Woods & McCann 1999), which strongly suggests that charcoal accumulation into Terra Preta was not due to forest burning. Therefore, it is more likely that anthropogenic activities were responsible for charcoal accumulation and subsequent Terra Preta formation, such as low heat smouldering fires used by the native population for cooking and spiritual procedures (Glaser *et al.* 2001). The only question remaining is whether charcoal was produced and added intentionally or whether it was formed by chance as a by-product of activities in human settlements. This question is currently being investigated using 'land-use' biomarkers for the small-scale (area and soil depth) reconstruction of Terra Preta use, which will be explained in the next section.

(b) *Incorporation of nutrients*

Despite the high amounts of charcoal found in the Terra Preta soils, this does not primarily contribute to higher nutrient content (Woods & Mann 2000). With respect to potential nutrient sources, only C and N can be produced *in situ* via photosynthesis and biological N fixation, respectively. All other elements, such as P, K, Ca and Mg must be incorporated from the surroundings for nutrient accumulation. *In situ* weathering as a nutrient source can be excluded in Amazonia, at least on the heavily weathered Ferralsols, Acrisols, Lixisols and poorly developed infertile Arenosols, since these do not contain high concentrations of these elements. Therefore, for Terra Preta genesis, only the primary and secondary nutrient sources are possible and are as follows:

(i) human and animal excrements (rich in P and N),
(ii) waste including mammal and fish bones (rich in P and Ca),
(iii) ash residues of incomplete combustions (rich in Ca, Mg, K, P and charcoal),
(iv) terrestrial plant biomass (e.g. green manure, compost), and
(v) aquatic plant biomass (e.g. algae).

Research including small-scale field sampling of archaeological remains, the investigation of artefacts and land-use biomarkers is underway in order to reconstruct the genesis of Terra Preta soils with special emphasis on the origin of soil nutrients and possible links to charcoal incorporation. In particular, the occurrence of the archaeological remains such as human and mammal bones, fish bones and turtle backs helps to identify major nutrient input paths especially of P. Lipid biomarkers, which are also assumed to be stable in the environment similar to charcoal, are being used to differentiate between input of human and animal excrements as well as between terrestrial and aquatic biomass (Glaser 2002; Glaser *et al.* 2003*a*,*c*).

If we look first at the potential of lipid biomarkers to differentiate between human and animal excrements as the nutrient sources for Terra Preta formation, sterols and bile acids have been proven to be especially useful. First results of sterol analysis of the Terra Preta show that human excrements do contribute to the nutrient richness of Terra Preta (Glaser *et al.* 2003*c*). Such biomarkers are very stable in the environment, even under extreme environmental conditions (Evershed & Bethell 1996; Simpson *et al.* 1998). However, it still needs to be shown whether excrements contribute a large part of nutrients and whether they were applied at a larger scale, e.g. for fertilization purposes, which is the purpose of current research (Glaser 2002). On the other hand, human excrements strongly support the hypothesis that the Terra Preta sites were pre-Columbian settlements and that cooking fires accumulated charcoal.

A potential contribution of lipid biomarkers to assess the aquatic biomass was detected using *n*-alkanes pattern. While cuticular waxes of terrestrial plants contain predominantly long chain *n*-alkanes (greater than C_{20}), short chain *n*-alkanes (less than C_{20}) are typical for algae (e.g. Collister *et al.* 1994; Bourbonniere *et al.* 1997; Brincat *et al.* 2000; Filley *et al.* 2001; Hoefs *et al.* 2002). The *n*-alkanes distribution of the Terra Preta showed a predominance of the aquatic biomass (Glaser 2002; Glaser *et al.* 2003*a*,*c*). It was also demonstrated, however, that analysis of the long chain *n*-alkanes was biased in the presence of charcoal, probably due to sorption. It is possible, therefore, that the aquatic biomass was either used in pre-Columbian agriculture as a fertilizer on Terra Preta or in the formation of the charcoal in the soil. Lack of aquatic material at the black water rivers such as Rio Negro where also Terra Preta can be found (figure 1), however, suggests that such uses of the aquatic biomass were not ubiquitous and its use varied between regions.

In addition to the human excrements providing a source of P and N (Glaser *et al.* 2003*c*), work by Lima *et al.* (2002) using scanning electron microscopy and energy-dispersive X-ray spectroscopy have found evidence of high Ca and P linked to bones in the Terra Preta. Archaeozoological analysis revealed that bones extracted from the Terra Preta soils are mainly derived from small mammals, fish and turtles (E. G. Neves & H.-V. Karl 2005, personal communication). Attempts to identify these animals using ancient DNA has failed to date (Glaser *et al.* 2003*c*), which might be due to the fact that even these bones are partly charred.

(c) *Role of micro-organisms*

Soil micro-organisms are important for nutrients cycling and supply for plant growth. Soil micro-organisms mineralize partly decomposed litter or SOM and also immobilize inorganic nitrogen preventing nutrient losses by leaching. It was observed that charcoal additions to a Ferralsol increased soil microbial biomass (Glaser *et al.* submitted). Also microbial growth rates increased after charcoal addition to the Ferralsol (Steiner *et al.* 2004). Probably the porous structure of charcoal (figure 2*c*) serves as a habitat for soil micro-organisms in Terra Preta soils. It was also observed that the soil microbial community changed after charcoal addition to the soil whereby the relative abundance of fungi and Gram-negative bacteria were reduced (J. Birk & B. Glaser, unpublished). In contrast, an increase of Gram-positive anaerobic bacteria was observed after application of charcoal and inorganic fertilizer (Birk & Glaser, unpublished). Other studies report on a promotion of ectomycorrhizal and arbuscular mycorrhizal fungi in the presence of charcoal (Lehmann *et al.* 2006).

Evidence obtained so far, however, suggests that Terra Preta soils do not contain a 'super micro-organism' which was proposed as being responsible for the Terra Preta formation or even regeneration after soil mining (Woods & McCann 1999; Sombroek *et al.* 2003). However, recent research does indicate that poly-condensed aromatic structures (figure 2*b*), which had been assumed to be derived exclusively from pyrolytic processes (Schmidt & Noack 2000; Brodowski *et al.* 2005) are produced significantly by micro-organisms in the soils (B. Glaser & K.-H. Knorr, unpublished).

In summary, the processes responsible for the formation of the Terra Preta soils identified so far include intensive human occupation, in the course of which tremendous amounts of charcoal, human excrements and food waste (mammal bones, fish bones and turtle backs) were added to an initially infertile soil. Up to now, there is no scientific evidence for a special micro-organism responsible for the Terra Preta formation, but recently a significant biological black carbon production was identified, especially under humid tropical conditions and it is assumed that *Aspergillus niger* is mostly responsible for this (B. Glaser & K.-H. Knorr, unpublished). However, much more research is needed to verify these results both on a smaller (within site variation) and bigger (from site to site) scale.

3. IMPORTANCE OF TERRA PRETA SOILS IN NUTRIENT CONTENT AND AVAILABILITY AND CROP GROWTH AND YIELD

High amounts of charcoal and nutrient contents of Terra Preta soils as discussed above are responsible for the high crop production potential and higher sustainable soil fertility of Terra Preta soils compared to the surrounding Ferralsols. With respect to the nutrient contents and availability, immediate beneficial effects of charcoal additions are largely due to higher potassium, phosphorus and zinc availability and, to a lesser extent, calcium and copper (Lehmann *et al.* 2003*a*). On the other hand, lower N and Mg uptakes have also been detected in the Terra Preta soils (Lehmann *et al.* 2003*a*). The former might be due to unfavourable high C/N ratio of charcoal being in the range between 200 and 600. The latter might be due to a dilution and/or antagonism effect with Ca.

Longer-term benefits for nutrient availability include a greater stabilization of organic matter, concurrent slower nutrient release from the added organic matter and better retention of all cations due to a greater cation exchange capacity (Glaser *et al.* 2002*a*,*b*). Higher nutrient availability is thus the result of both direct nutrient additions and greater nutrient retention of charcoal (Lehmann *et al.* 2003*a*), but it can also be an effect of changes in the soil microbial dynamics.

The higher fertility of Terra Preta soils described above results generally in higher crop growth and crop production potential, being about double when compared to adjacent infertile soils. Rice and bean yields of 0.5–3.8 and 0.1–1.9 $Mg\,ha^{-1}$, respectively, were reported for Terra Preta sites while yields on adjacent non-Terra Preta sites varied from 1.5–1.8 and 0.3–0.8 $Mg\,ha^{-1}$, respectively (Lehmann *et al.* 2003*b*). Therefore, the crop production potential of Terra Preta sites is up to two times higher compared to adjacent infertile soils, although a high variability and crop dependence is obvious.

4. POTENTIAL OF TERRA PRETA SOILS IN PROVIDING FUTURE SUSTAINABLE AGRICULTURE IN THE HUMID TROPICS

In the tropics, approximately three quarters of the world population are living, with an average annual increase of approximately 1.4%. Among these 4.5 billion people, 790 million do not have enough to eat, according to the

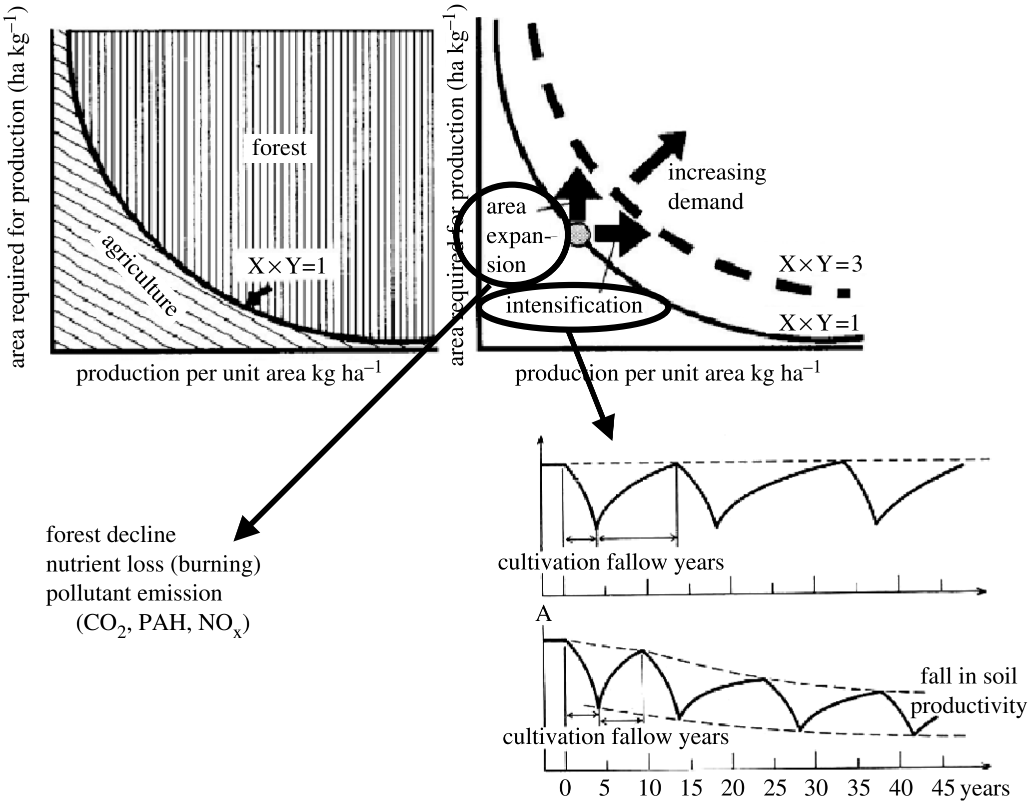

Figure 3. Consequences of increasing population (and therefore food production) pressure on slash and burn agriculture in the humid tropics. Area expansion (agricultural extensification) leads to loss of primary forest, enhanced nutrient volatilization by burning (especially C, N, S and partly P) and subsequent leaching losses due to lack of nutrient holding capacity of the poor soils. Additionally, extensified burning leads to enhance air pollution (especially CO_2, poly-cyclic aromatic hydrocarbons (PAH) and nitrous oxides (NO_x)). Agricultural intensification means more continuous cultivation with reduction of fallow periods resulting in reduced productivity with time. In both cases, area expansion and agriculture intensification, loss of sustainability results.

most recent estimates from 1995 to 1997, representing a decline of 40 million compared to 1990/92 (Galloway & Cowling 2002). To improve this situation, it is imperative that food production is increased, particularly in low-income, food-deficit countries. Research in agriculture is essential for achieving a sustainable food productivity increase, upon which the short- and long-term food security of a growing world population will depend. Multiple benefits would accrue if technology were available that avoids the use of synthetic fertilizers and the reduction of primary forest decline via slash and burn. Only one third of synthetic fertilizers are available in the humid tropics, where three quarters of the world population are living. The reasons for this are: (i) that synthetic fertilizers are too expensive for smallholder farmers, and (ii) nutrients are rapidly leached by the lack of nutrient holding capacity of highly weathered soils, such as Ferralsols, Acrisols and Lixisols as explained above.

Slash and burn is a traditional land use system primarily used in tropical ecosystems (Greenland *et al.* 1992). Smallholder farmers slash the natural vegetation at varying stages of regeneration, or even primary forest, and burn it to allow a crop to be grown. Under this system, soil fertility declines rapidly and weed pressure increases. Once this leads to deterioration in crop yield, the land is left fallow to regenerate. Typical fallow periods in such a system range from 5 to 25 years, while cropping periods are 1–3 years long (Greenland *et al.* 1992). Under these conditions, slash and burn is assumed to be sustainable. Increasing population pressure results in greater proportions of forested land, especially primary forest, needed to be cropped under shifting cultivation and, therefore, results in a loss of biodiversity and greater amounts of CO_2 being released to the atmosphere from biomass and soil, enhancing the anthropogenic greenhouse effect. In most slash and burn systems, the natural vegetation is burned after slashing and between 38 and 84% of the biomass C in vegetation is released during the burn (Hughes *et al.* 2000).

Enhanced food production for the growing world population can be achieved either by expansion of the slash and burn areas or by an intensification of agriculture (van Noordwijk *et al.* 1998). The former would mean a further exploit of natural resources such as primary forests that are rich in biodiversity, with an additional reduction in biodiversity and nutrient losses by leaching and biomass burning-derived pollutants (e.g. carbon dioxide, nitrous oxides and poly-cyclic aromatic hydrocarbons) (van Noordwijk *et al.* 1998). The latter would mean a reduction of fallow periods and, therefore, a reduction of soil productivity in the medium to long term (figure 3). In both cases, area expansion and agricultural intensification, slash and burn will lose its sustainability (figure 3).

Maintaining an appropriate level of SOM and biological cycling of nutrients is crucial to the success of any soil management in the humid tropics (Fernandes *et al.* 1997). If a soil is continuously cultivated, a loss of SOM is the consequence, being approximately 50%

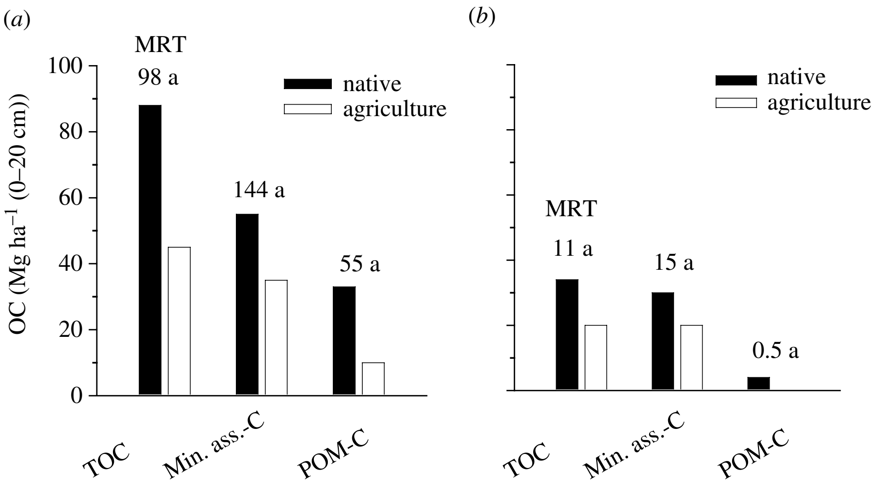

Figure 4. Comparison of soil organic matter turnover in (*a*) temperate and (*b*) tropical continuous agriculture (Data are taken from Tiessen *et al.* 1994). MRT, mean residence time; TOC, total organic carbon; Min.ass.-C, mineral-associated C; POM, particulate organic mater.

of total organic carbon (TOC) after 65 years on a Chernozem under a temperate climate (figure 4*a*). In the case of a highly weathered Ferralsol under a humid tropical climate, a continuous cultivation of only six years leads to a TOC reduction by half (figure 4*b*).

Cover crops (Schroth *et al.* 1995; Lu *et al.* 2000; Lose *et al.* 2003), mulches (Mando 1997; Goyal *et al.* 1999; Büttner & Hauser 2003), compost or manure additions (Mando *et al.* 2005; Topoliantz *et al.* 2005) have been used successfully to supply the nutrients to crops, to support rapid nutrient cycling through microbial biomass, and help to retain applied mineral fertilizers. The benefits of such amendments are, however, short-lived since decomposition rates are high in the tropics compared to temperate regions (figure 4) and the added organic matter is usually mineralized to CO_2 within only a few cropping seasons (Tiessen *et al.* 1994). Large amounts of organic amendments therefore have to be applied each year to sustain the soil productivity.

Additionally, carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (NO_x) are important drivers of the anthropogenic greenhouse effect, and are released both through burning of fossil and biomass fuels as well as decomposition of above- and below-ground organic matter. International efforts aim at reducing avoidable greenhouse gas emissions or offsetting unavoidable emissions through sequestration of C into the environment. Many different strategies have been discussed in the literature, ranging from wide-spread afforestation and reforestation in terrestrial ecosystems (IPCC 2000) to pumping of CO_2 into deep ocean and geological layers. For terrestrial ecosystems, it has been proposed that C sequestration can be increased by increasing soil C stocks (Batjes & Sombroek 1997; Batjes 1998). Such a proposal is sensible, given the fact that more than 80% of the terrestrial organic C stores are contained in soils (IPCC 2000). However, recent analyses urge caution, highlighting that efforts aimed to achieve C sequestration in soil are often offset by other greenhouse gas emissions (Schlesinger & Lichter 2001) and that soils generally show low potential to accumulate natural C; for example, in conjunction with forest growth (Schlesinger 1990; Schlesinger & Lichter 2001; Tilman *et al.* 2001). The consensus appears to be that soil represents a finite natural C sink at best and will only provide a window of opportunity for reducing C emissions or exploring other opportunities for C sequestration (Lal 2003; Freibauer *et al.* 2004; Lal 2004), and that these C sinks may have a low permanency and can be easily depleted upon land use change.

Given the knowledge of the processes responsible for Terra Preta formation, one way forward might be to replace the addition of labile organic matter as discussed above by a more stable one similar to the formation or addition of charcoal in the Terra Preta soils. The easiest way to do this nowadays is to replace burning in a slash and burn system by charring the slashed biomass residues, which means to substitute the complete burning by an incomplete one as discussed above ('slash and char'; figure 5*a*; although it is unlikely that Terra Preta was formed by slash and char). Further alternatives would be charring of all kinds of biomass or biomass wastes ('bio-char'), e.g. the charring of rice husks as recommended by the Food and Fertilizer Technology Centre for the Asian and Pacific region, which can be done easily by smallholder farmers and which is already practised, e.g. in Indonesia (figure 5*b*).

Furthermore, wastes of charcoal production can be used as a soil amendment. Charcoal is a cash product and 41 Tg (equal to million tons) are produced annually worldwide, the major part of it (40 Tg) in the humid tropics (21 Tg in Africa, 14 Tg in South America); 10–15% (approx. 4–6 Tg per year) of the produced charcoal is smaller than 2 cm and cannot be sold. This non-sellable residue can be used as soil amendment. The worldwide C sequestration potential of charcoal residues together with other agricultural wastes which could be charred is approximately 0.16 Pg (equal to 10^{15} g) per year (Lehmann *et al.* 2006). Replacing slash and burn by slash and char would provide another 0.2 Pg stable C per year and modern renewable energy production yielding H_2 as a clean energy source and charcoal as a 'waste' product would currently yield also 0.2 Pg stable C per year (Lehmann *et al.* 2006). In total, it is suggested that under the current conditions, approximately 10% of the global fossil fuel C emissions of 5.4 Pg per year could be sequestered as charcoal into

Figure 5. (*a*) Slashed vegetation is charred instead of burned (slash and char). (*b*) Charring of rice husks (bio-char) which can be done easily by smallholder farmers.

the soil when using all the techniques mentioned above (Lehmann *et al.* 2006).

Field trials in Amazonia with charcoal additions in the range between 5 and 10 $Mg\,ha^{-1}$ increased crop yields up to 220% (Glaser *et al.* 2002*b*; Lehmann *et al.* 2003*a*). Steiner *et al.* (2004) even reported a growth enhancement of rice of 800% after charcoal application to a Ferralsol in Manaus, Brazil. However, growth depressions have been found in some instances, especially at high charcoal additions (Lehmann *et al.* 2006). Additionally, in the longer term, absolute crop yields always declined drastically similar to slash and burn systems (C. Steiner, unpublished data), which shows that Terra Preta formation cannot be simply achieved by charcoal addition to soil. It is likely, however, that combined additions of charcoal and organic manure such as chicken manure could produce sustainably fertile soils providing both stable (charcoal) and labile SOM, and nutrient pools, respectively. However, much more research is needed to make slash and char sustainable like Terra Preta.

When using charcoal intensively for soil amelioration, large amounts of biomass are needed. The question is which biomass resource is the best suited for this high biomass demand. Although primary forests have the highest C stocks averaging approximately 450 $Mg\,ha^{-1}$, they have the lowest productivity with respect to biomass regeneration, ranging from approximately 0.2 Mg C (van Noordwijk *et al.* 1998) to 3.1 $Mg\,C\,ha^{-1}\,a^{-1}$ (Malhi *et al.* 2004). Therefore, cutting primary forests for slash and char would be the worst alternative also from an ecological point of view, e.g. with respect to biodiversity conservation. Much better alternatives would be forest plantations or crop production residues storing approximately 260 and 40 $Mg\,C\,ha^{-1}$, respectively, with annual C production rates of 7 and 10 $Mg\,ha^{-1}$, respectively, being much higher than those of primary forests (van Noordwijk *et al.* 1998). Therefore, the primary forests could be protected for biodiversity conservation.

5. CONCLUSIONS

In this paper, it is argued that Terra Preta soils are a model for sustainable agriculture in the humid tropics. Keys for its sustainable soil fertility are the application of charcoal together with organic wastes such as excrements and bones. The formation of new Terra Preta sites (Terra Preta nova) by, for example, replacing slash and burn by slash and char could help to secure food production of a fast growing population especially in the humid tropics, where infertile soils predominate. Additionally, the formation of sustainably fertile soils such as the Terra Preta nova in the humid tropics would attain three Millennium Development Goals: (i) reduction of desertification by maintaining or generating a sustainably fertile soil, (ii) long-term sequestration of atmospheric CO_2 by generation of charcoal, a chemically and biologically stable C pool with turnover times of hundreds to thousands of years, and (iii) maintenance of biodiversity hotspots such as tropical rainforests because permanent cropping is possible on Terra Preta soils. In conclusion, Terra Preta nova generation certainly has the potential of being a revolution for agriculture at least in the humid tropics, where heavily weathered, infertile soils predominate. However, many questions still remain to be answered regarding the mechanisms governing surface properties of charcoal and how nutrients dynamics are affected. The opportunities for long-term C sequestration and the reduction of greenhouse gas emissions have not been explored at all, but they are potentially significant. Nevertheless, it is already clear that charcoal can significantly improve soil fertility in acid and highly weathered soils, as shown by Terra Preta, and it has the potential for widespread application under various environmental situations by mobilizing and improving the complex of chemical, physical and biological properties of soil systems. Perspectives of the ecological and economic use of charcoal by smallholder farmers in the humid tropics are given in figure 6*a*. Also a 'high-tech' solution of a combined clean energy production from biomass and using the waste product charcoal for C sequestration or enriched with nitrogen as a sustainable fertilizer is readily available (figure 6*b*).

In order to achieve a breakthrough in using charcoal application for sustainable agriculture, the following tasks need to be undertaken:

- Intensification of research using charcoal as a soil amendment. Study of the dynamics of charcoal in soil, especially finding out the conditions under which C sequestration and nutrient retention can be optimized.
- Identifying possible ways to produce charcoal in an environmental friendly (or least detrimental) way, e.g. slash and char instead of slash and burn of defined areas, which could be secondary forests, forest plantations or crop production waste management.

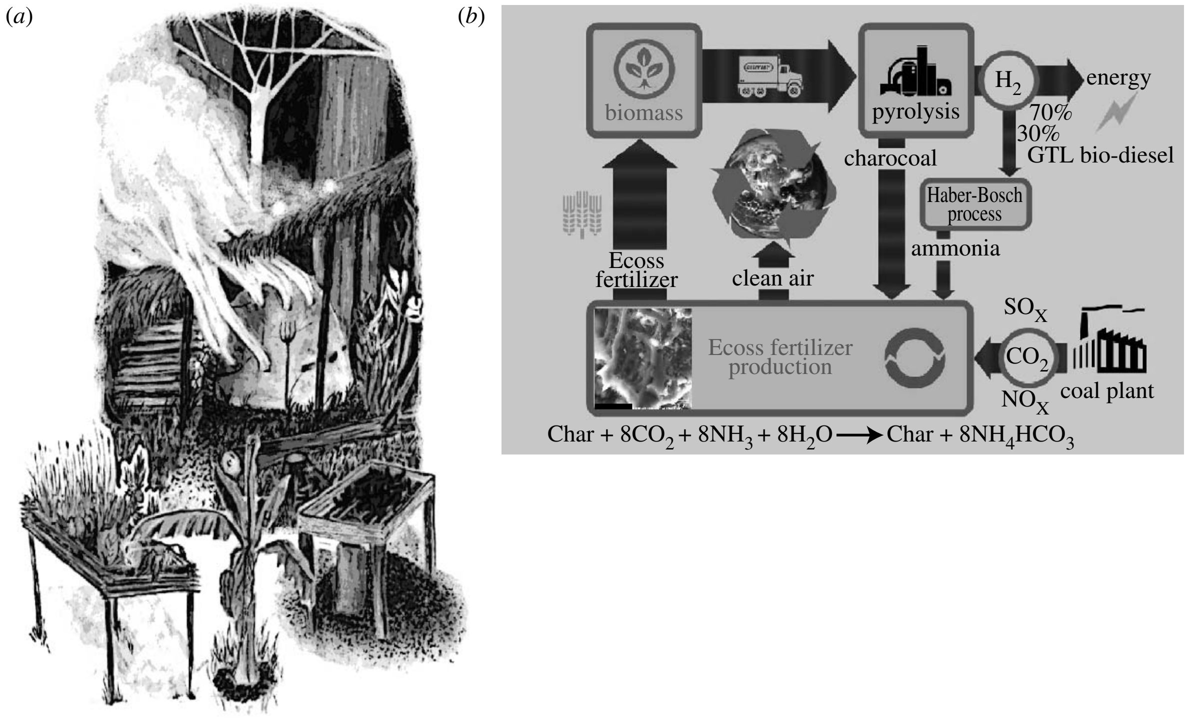

Figure 6. (*a*) Principle of slash and char for smallholder farmers in the humid tropics (Steiner *et al*. 2004): charcoal is produced from biomass (crop residues or fast growing forest plantations), pieces greater than 2 cm can be sold at the local market (cash product), residues less than 2 cm cannot be sold and can be used as soil amendment together with compost or chicken manure; (*b*) high-tech solution, adapted from Day *et al*. (2005).

— Backing of these scientific and technological tasks with economic studies showing the cost–benefit feasibilities of Terra Preta nova formation, and with social studies preparing the background for acceptance by the stakeholders.

Finally, another scenario needs to be discussed. It is equally possible that the infertility of most tropical soils (and associated low population density) is what has prevented tropical forests from undergoing large-scale clearance for agriculture. Increased fertility may increase the populations supported by shifting cultivation, thereby maintaining and increasing pressure on forests. Similarly, the major causes of deforestation in many regions of the tropics are not agricultural extensification by impoverished smallholders, but large-scale conversion of forest to agroindustry (e.g. cattle, soybeans and palm oil). But this issue is far beyond the scope of this paper and needs other mitigation strategies, which certainly warrant further attention.

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