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ANTHROPOGENIC DARK EARTHS AS CARBON STORES AND SINKS

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1. CARBON STOCKS IN THE BIOMASS AND THE SOILS OF THE AMAZON REGION

The Kyoto Protocol (KP) agreement on reducing the net emission of greenhouse gases in general, and of CO_2 in particular, recognises the importance of carbon in the soil as a store, source and potential sink of CO_2, in addition to supporting functions of the aboveground biomass.

The aboveground biomass of the Amazon primary forest vegetation contains between 80 and 160 Mg C ha^{-1}, averaging perhaps 110 Mg C ha^{-1} (Fearnside, 1992,1994,1997; Brown and Lugo, 1992; Phillips et al., 1998). Notably, IPCC (2000) reports a higher average of 270 Mg C ha^{-1} while early estimates by Woodwell (1978) of 360 Mg C ha^{-1} in aboveground biomass have led to excessive statements about the influence of tropical deforestation on the anthropogenic increase of the atmospheric CO_2 concentration and thereby global climatic change. However, the increase in CO_2 concentration is a fact which, in turn, appears to have been influencing the old-growth Amazon forest dynamics since the early 1980s. Until that time, primary forests were supposedly in balance with regards to CO_2 fluxes (i.e., daytime CO_2 uptake through photosynthesis was in balance with CO_2 release via autotrophic and heterotrophic respiration. Monitoring of these fluxes from towers in the old-growth forest by eddy covariance methods, and associated tree-girth measurements, has produced conflicting results. Early measurements (Grace et al., 1995) indicated a net CO_2 sink of 2-7 (av. 4) Mg C $ha^{-1}yr^{-1}$ – on flat interfluve land, with deep and well-drained soils, a short dry season and in non El-Niño years (Phillips et al., 1998; LBA open-science meeting in Belém, 2000; Nobre et al., 2001). However, recent results suggest substantially smaller uptakes, at most 1.0 Mg C ha^{-1} in several cases (LBA open-science meeting, Manaus, 2002). The average uptake for the whole region is likely to be even less, being partially off-set by the substantial out-gassing of CO_2 that has been observed in sediment-rich rivers in the region (Richey et al., 2002).

A part of the CO_2 sink on the non-floodable lands (*terra firme*) in the order of 1.7 Mg C ha^{-1} yr^{-1} (IPCC, 2000) could be ascribed to the extra growth of the aboveground biomass of most tree species with C3 photosynthetic pathway. Most of this C uptake ends up in the soil, through extra litter fall, stronger root growth and ultimately more soil humus. Increases of 3.6 Mg C $ha^{-1}yr^{1}$ in soil humus have been estimated by IPCC for the Manaus area. This figure may be lower for the region as a whole, but is nevertheless substantially larger than in temperate old-growth forests. Belowground living biomass – roots and soil fauna – could contain about a third of the carbon stock of the aboveground biomass (86 Mg C ha^{-1} according to IPCC, 2000), but actual field measurements are scarce.

The soil organic carbon (SOC) under Amazon forest, in the form of soil organic matter or humus (SOM), varies between 80 Mg C ha^{-1} for the sandy soils and

130 Mg C ha^{-1} for the clayey soils (Moraes et al., 1995). This applies to the upper 100-cm depth, with about one-third of SOC concentrated in the upper 10 or 20 cm. Substantially higher values for the upper 100 cm have been recorded for Nitisols/Terra Roxa soils, containing active iron oxides, and for clayey floodplain soils with buried A-horizons (Sombroek, 1992). The above values include neither stocks of SOC in any deeper rootable layers – which may be up to one-third of the amount contained in the upper 100 cm (Nepstad et al., 1994) nor any carbon in the form of charcoal—wether as coarse pieces (>2 mm) or within the fine earth. Routine analysis of soil carbon in the laboratory conducted on the fine earth apply the wet method (i.e. potassium bichromate-sulfuric-acid treatment (Walkley-Black or Tiurin methods), which does not attack charcoal. This can be measured only through dry-combustion total C analysis (Oades, 1988). Charcoal in the soil is not only frequent after deforestation by burning but it is also common in soils under present-day old-growth forest as well (Sanford et al., 1985) as from occasional lightning in trees or accidental large-scale burning during past strong-El Niño dry periods. Carvalho et al. (2001) studied the macro- and microscopic content of both SOM and charcoal in two soils, near Manaus (ZF2-reserve) and Santarém (Tapajós National Forest) respectively, and established that charcoal fragments may account for 30 to 50 % of the total carbon in these soils, with 0.25 to 3.5 Mg C ha^{-1} of charred material. Extremely high amounts (> 1% by volume) are also found in the Amazon Anthropogenic Dark Earths (ADE; *Terra Preta* and *Terra Mulata* soils), apparently as a result of ingenious land management by some groups of pre-Columbian Indians (see below, and other chapters). In view of the above considerations, estimates of soil C stocks of 100 Mg C ha^{-1} (Moraes et al., 1995) and 98 Mg C ha^{-1} (Batjes and Dijkshoorn, 1999) for predominant soils, are likely to be too low for many parts of this region.

2 .AMAZON DARK EARTHS AS CARBON STORES

2.1 *Carbon stocks and concentrations.*

In Figure 1 a map of known SOC concentrations in Amazonian Dark Earths is shown, compiled from 61 profiles available up to now. However, a proper calculation of SOC stocks is not possible at the moment due to the lack of reliable bulk density data. Glaser et al. (2003) reported SOC stocks of 147-506 Mg C ha^{-1} m^{-1} in Amazonian Dark Earths around Manaus and in the Belterra area compared to 72-149 Mg C ha^{-1} m^{-1} in adjacent Oxisols/Ferralsols. This reveals a highly significant ($p < 0.01$) C accumulation in the Amazonian Dark Earths by factors ranging from 1.5 to 4.6, especially in the agronomically important topsoil (0-30 cm depth). Sombroek et al. (1993) calculated SOC stocks of 56 Mg C ha^{-1} m^{-1} for clayey soils and 34 Mg C ha^{-1} m^{-1} for sandy soils as mean of about 30 profiles of Ferralsols and Ferric Acrisols in the Amazon area which compares well with the carbon stocks of the Ferralsols of Glaser et al. (2003). The assessment of the precise amounts of total carbon in Amazonian soils is hampered by (a) uncertainties about the correct conversion factor for the incomplete carbon yields of wet analysis methods (used especially in older literature), (b) uncertainties about the correct bulk density data of the individual soil layers in the field, and (c) short-distance variations and minority presence of soil types not accounted for in traditional reconnaissance soil surveys (Greenland et al., 1992; Sombroek et al., 1999). A constraint in extrapolating these data to a regional scale is the uncertainty of the exact vertical and lateral extent of individual patches of Amazonian Dark Earths, issues that will be discussed in the following section.

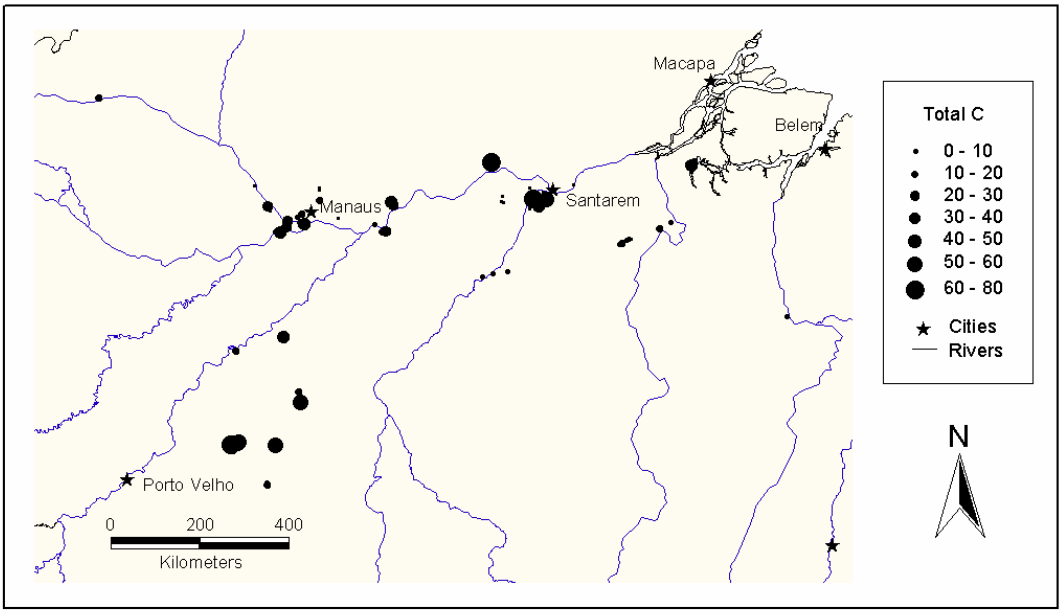


Figure 1. Map of the Amazon Basin with available data on C concentrations in Amazônian Dark Earths significant (P<0.05) up to 60 cm soil depth.

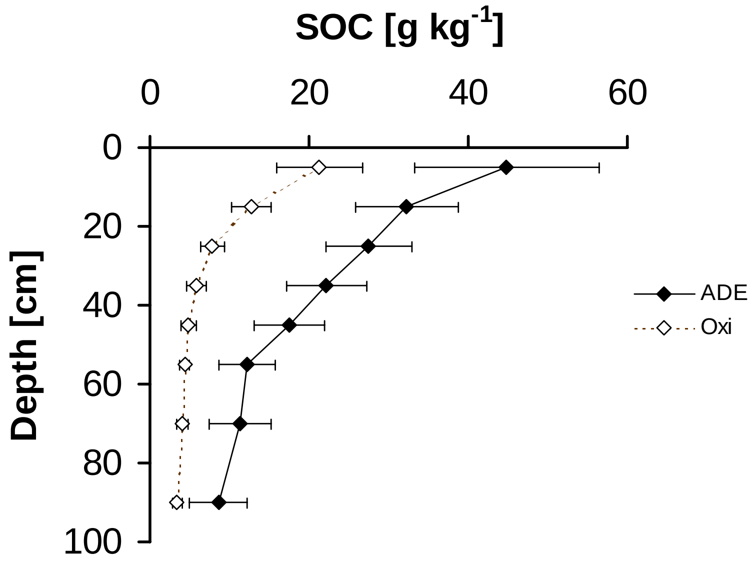
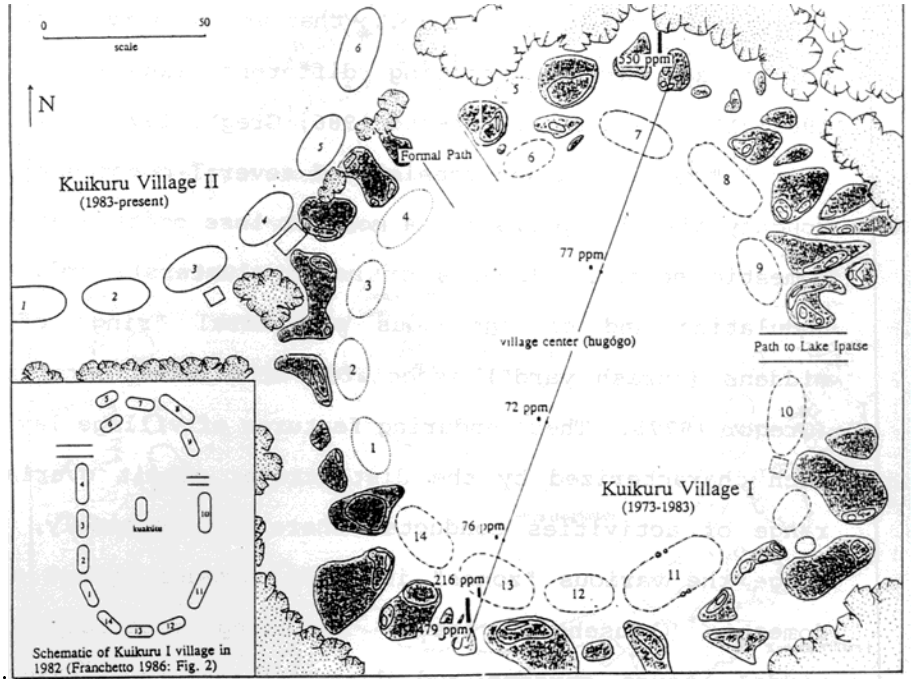


Figure 2. Vertical extent of SOC in Amazonian Dark Earths and adjacent Oxisols near Manaus and from the Belterra area (mean and standard error, n=5). Data taken from Glaser (1999).

Figure 3. SOC distribution in an Amazonian Dark Earth of the Belterra area. Lines indicate the vertical and lateral distribution of identical SOC concentrations. X indicates the occurrence of ceramic artefacts. Figure taken from Bechtold



(1982)..

Figure 4. Organization of the Kuikuru village in the upper Xingú area. It is remarkable that the centre of the village does not show any Amazônian Dark Earth features, neither high SOC nor high P levels Instead, according to this figure, Amazônian Dark Earths seemed to built up behind the houses. Figure taken from Heckenberger (1996)

While Bechtold (1982), Glaser (1999) and others reported the highest SOC concentrations and the highest vertical extent in the center of areas of Amazonian Dark Earths as illustrated in Figure 3, Heckenberger (1996) regularly found concentric patches of Amazonian Dark Earths around a center of yellow or red Oxisols/Ferralsols which was used by indigenous Indians as central plaza (Figure 4). Kern and Kampf (1989) found complete spheres of diminishing soil carbon content around small plazas. Thus, there seems no unique pattern of Amazonian Dark Earth formation with respect to vertical and lateral accumulation of SOC (and probably nutrients as well). While the "center type" Amazonian Dark Earths were reported for the Manaus and Santarém area, the "concentric type" Amazonian Dark Earths seem to be the regular form in the Xingú area.

This difference is likely to be due to absence or presence of horticultural use of the land inside and around the villages, associated with tribal traditions (agricultural traditions of the Tupí-Guaraní groups of tribes, versus foraging and hunting /fishing traditions of other tribal groups).

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3. PERSPECTIVES FOR AMAZONIAN DARK EARTH REPLICATION FOR CARBON SEQUESTRATION

Amazonian soils, having approximately the same as or higher amounts of carbon stocks than the aboveground biomass of old-growth forests, become very important in any regional study of carbon sequestration of the Amazon biome. Amazonian Dark Earths (Terra Preta and Terra Mulata), with their high amounts of stable SOC, are already a not-negligible part of this stock, notwithstanding their small coverage (0.1-0.3 % of the total area of 6 million km^2). If these areas can be augmented to 5-10%, as envisaged for the "Terra Preta Nova" project (Sombroek et al., 2002), then they can become really significant as future sinks and stocks for atmospheric carbon.

Key questions to be addressed before implementation of such a project idea – the recuperation of deforested and degraded Amazon lands through emulation of pre-Columbian Indian land use practises that doubled the amount of stable soil carbon – are the following:

a) What were the ingredients and practises applied by the pre-Columbian Indian agricultural communities in relation to the local natural resources condition (types of climate, soil, river water, aboveground biomass, functional plant species, etc.) - the *pre-historical* aspect;

b) How much of the Net Primary Production (NPP) of the primary or re-growing forest and of a Terra Preta-oriented land-use system ends up in stable SOM and black carbon - the *efficiency* aspect;

c) How long does it take to double the stable soil organic matter content in a Terra Preta-oriented land use system, in comparison to the content under forest: the *time lapse* aspect;

d) What should be the rural conditions under which the small-holder subsistence farmer will be prepared to apply extra and continuous land management labour to create new Terra Preta soils: the *social and profitability* aspect;

e) Which of the Kyoto Protocol mechanisms is the most advantageous for realisation of the Terra Preta Nova approach, from the point of view of the individual small-holder, the rural communities, the state- or national-level economy, or the global environmental protection agencies: the *natural resources policy* aspect.

3.1. The pre-historic aspect

The establishment of the mode of formation of the ancient Terra Preta and Terra Mulata soils requires patient observations and interviews. An example is provided by the practises of a Kayapó Indian community in the upper Xingu area, as described by Anderson and Posey (1989):

“Islands of woody vegetation (apêtê) in savanna are formed through the active transfer of litter, termite nests and ant nests to selected sites. This substrate then serves as a planting medium for desired species, and also facilitates the natural selection, which is further enhanced through active protection of apêtê when the savannas are burned. Compost mounds are prepared from existing islands where decomposing material is beaten with sticks. Macerated mulch is carried to a selected site (often a small depression) and piled on the ground. Organic matter is added from

crushed Nasutitermes spp. (termite) and Azteca spp. (ant) nests. Live termites and ants are included in this mixture. According to the informant, when introduced simultaneously the termites and ants fight among themselves and consequently do not attack newly established plantings. Ants of the genus Azteca are also recognised for their capacity to repel leaf cutter ants (Atta spp.). Seeds, seedlings and cuttings are planted. Mounds are formed at the end of the dry season."

Heckenberger et al. (1999) state that native Indians practised and still practise a pattern of long-term crop rotation of diverse tended plants within a relatively fixed area, which is rather different from the extensive slash-burn-and-abandon pattern of today. From examination of pollen and primary-mineral assemblages it is clear that biomass material of palms (old palm leaves from housing roofs as a form of litter, Kern and Kampf, 1989) were important. Also fresh organic matter from floating river grasses; phosphate-calcium compounds of the off-fall of fishing and hunting (Lima et al., 2002); calcium from shells of mussels and molluscs in clear-water areas, as well as household refuse were important resources leading to primary or secondary carbon sequestration in the soils concerned.

3.2 The efficiency aspect

For the modern replication of Amazonian Dark Earths (Terra Preta /Terra Mulata soils), experiments, monitoring, and modelling of the dynamics of the soil organic matter under humic tropical conditions are required. Long-term-experiments are scarce for the tropics, but some local experimental set-ups in the Manaus and Belém area are about to provide useful information. For modelling purposes, the subpools or fractions of soil organic matter need to be identified. They have been characterised in different ways, and a detailed overview is given by Glaser et al. (year), elsewhere in this volume. The existing carbon conversion models CENTURY (Parton et al., 1987) and RothC (Coleman & Jenkinson, 1996) are still being tested for tropical conditions (Paustian et al., 1997). The Century model of SOM splits incoming residues between "structural" and "resistant" plant material input which are decomposing into three soil pools termed "active", "slow" and "passive" soil organic matter, along with evolved CO_2. The RothC decomposition model for SOM splits incoming plant residues into decomposable plant material, resistant plant material, both ultimately forming microbial biomass), humified organic matter and evolved CO_2 by heterotrophic respiration. The actual rates of composition in relation to an intrinsic maximum is determined by soil moisture, temperature, plant cover and clay content; timing and by mode of plant-carbon input to the soil. Century was not really developed to describe C dynamics in agricultural or forest soils, but in grassland soils. We would expect that it does not work very well under agricultural settings with ploughing or any other human intervention. Neither of the two models contains a factor for the input of animal manure, compost, household refuse ("nightsoil"), sludge or charcoal; for soil faunal activity (worms, termites, ants, larvae of cicadae, etc), or for the influence of any special microbial functional composition/redundancy – all assumed to have been essential in the pre-historical formation of Amazonian Dark Earths.

Some land use practises have been reviewed which may lead to higher carbon sequestration in soils, such as improved grasslands, or agro-forests and planted tropical pastures, through redistribution of the carbon in deeper soil horizons, or the omission of burning (Batjes, 1998). Much of the C is released as CO_2 upon application of rapidly decomposing organic fertilizers such as slurry (Glaser et al., 2001a) or manure (Amelung et al., 1999) within a short time even in temperate climate ecosystems. Therefore, such manures have to be frequently applied for maintaining high SOM and nutrient levels.

Also in common slash-and-burn systems, most of the biomass C is rapidly released into the atmosphere upon burning, and only small amounts of carbon are transformed into charcoal (Glaser et al., 2002). In their pioneering work on biomass burning, Seiler & Crutzen (1980) estimated a charcoal formation of about 25% in shifting cultivation fields based on published photographs. The published data average at about 3% charcoal formation of the original biomass C (Glaser et al., 2002). Biomass C which is not converted to charcoal or elemental C in the smoke is gradually released through combustion and decay. Re-burning may affect the transformation of charcoal into slow-cycling pools in either direction: by oxidizing charcoal formed in the initial burning of primary forest or by creating new charcoal (Fearnside et al., 1993; Graca, 1997). On a global basis, an estimated 4 - 8 Gt of biomass C is annually exposed to burning, of which 1.3 - 7.5 Gt is emitted to the atmosphere through combustion and 0.5 - 1.7 Gt is converted to charcoal (Seiler & Crutzen, 1980). Therefore, carbon entering the soil as charcoal is a significant sink for atmospheric CO_2 and may be important for global carbon sequestration.

In comparison to burning, controlled carbonization, on the other hand, converts even larger quantities of biomass organic matter into stable C pools which is assumed to persist in the environment over centuries (Glaser et al., 1998; Glaser et al., 2001b; Haumaier & Zech, 1995; Schmidt & Noack, 2000; Seiler & Crutzen, 1980). The amount of charcoal which can be produced from different forest vegetation primarily depends on the woody biomass available, and additionally on the production procedure such as charring environment (e.g., oxygen), temperature and time (Glaser et al., 2002). The average recovery of charcoal mass from woody biomass is 29% according to the published data compiled in Table 5 of Glaser et al. (2002). The effect of different charcoal production methods on its recovery in laboratory experiments is tremendous depending on the charring conditions. Even under field conditions charcoal and carbon yields varied by a factor of up to three, although it is known that charcoal production is an exothermic process taking place between 350 and 400°C (Falbe & Regnitz, 1992). The weighted average carbon recovery from charred woody biomass is relatively high with 50% compared to only 3% after conventional slash and burn techniques (Glaser et al., 2002).

3.3. The time-lapse aspect.

For Terra Preta replication one would aim at an initial uptake rate of at least 10 Mg C ha^{-1} yr^{-1} and a stock of at least 200 Mg C ha^{-1}, to be reached within 25-50 years.

Uncertainty exists about the time required for such a sustained doubling of the soil organic carbon content, in addition to physical charcoal input as advocated above. There are ^{14}C indications from archaeological sites that 10 cm of Terra Preta soil may have been produced per decade in pre-Columbian times (Neves et al., 2001), but this may be restricted to the mound-like central parts of TP sites. In the more outlying areas of Terra Mulata (TM), the enrichment may have been slower, due to the natural scarcity of calcium and phosphorus in the areas with strongly weathered soils. However, at TP replication efforts, the supply and application of lime and rock phosphate from outside sources – such as those already identified in the paleozoic and crystalline shield areas through the work of geologists of RADAMBRASIL and CPRM – is assumed to speed up to formation of stable SOM very substantially, provided there is the right mix of biomass input.

The stimulation action of any specific microbial functional composition in the stable SOM forming process (Woods and McCann, 1999) is another factor of uncertainty. Intriguing is also the influence of the soil meso- and mega-fauna and their nest products, as demonstrated in the description of the Kayapó practises by Anderson and Posey, above.

For the margins of tropical forests Sanchez et al. (2000) give, as a summary of 116 long-term sites in the framework of the Alternative-to-Slash-and-Burn (ASB) project, carbon uptake rates and time-averaged system carbon stocks (i.e., above- and below-ground) as follows: Cropping after slash-and-burn results in a carbon uptake rate of –92 Mg C $ha^{-1}yr^{-1}$ with time-averaged 46 Mg C ha^{-1} in the system carbon stock; Crops followed by bush fallow an uptake rate of +3 Mg, resp. 34 Mg; Tall secondary forest fallow +7 Mg, resp. 112 Mg; Complex agroforests +3 Mg, resp. 85 Mg; Simple agroforests +7 Mg, resp. 74 Mg, and *Imperata* grasslands –0.4 Mg C $ha^{-1}yr^{-1}$, resp. 29 Mg ha^{-1}. [Suggest presenting these data in a table acknowledging Table 3 of Sanchez et al. (2000).

According to IPCC (2000, Table 4.4), optimal tropical agro-forestry management has a potential rate of soil carbon gain of 0.5-1.8 (avg. 1.0) Mg C $ha^{-1}yr^{-1}$ over a 25-y period (not counting charcoal inputs) as an estimate with a medium level of confidence. This is nearly as high as the amounts possible in humid temperate grassland management systems: 0.4 – 2.0 (avg. 1.0) Mg C ha^{-1} yr^{-1} accumulation over a 50-y period. Conversion to agroforestry from cropland or grassland at tropical forest margins would yield 1-5 (avg. 3) Mg C $ha^{-1}yr^{-1}$ over the same period, but with low degree of confidence. The latter figures fit with the findings of CIAT (Fisher et al., 1994) who found a substantial SOM increase in the subsurface layer (40-100 cm) of the forest-adjacent *llanos orientales* grasslands of Colombia. After 10 years of the introduction of deep-rooting exotic grasses and leguminous plants, the SOM increase varied from 20 to 44% (80-115, 90-754or 75-108 Mg C ha^{-1}, depending on the mix of grass species introduced. Also, recent trials of the SHIFT/EMBRAPA “Capoeira” project in Belém on the chopping and mulching of enriched secondary forest biomass point to substantial SOM increase, though its sustainability is still to be established.

It has been known for some time that elevated CO_2 concentrations lead to higher NPP, especially in C3 plants (most common crops and woody species) through the so-called “CO_2 fertilisation effect” (Goudriaan, 1995, Scholes and VanBreemen, 1997). This increase in NPP goes accompanied by higher C/N ratios in the over-all biomass, by increased fine-root mass, increased root length and higher root/shoot ratios in general, as well as by higher rhizobial activity of leguminous plants (Bazzaz and Sombroek, 1996). . The increase of root systems and the larger transfer of carbon from the roots through the rhizophere to the stable SOM are presumably quite important, but need to be confirmed by experiments and long-term monitoring sites of root dynamics, laborious as such monitoring may be (cf. Nepstad et al., 1994)

3.4.The social and profitability aspect

Upon replication efforts of Amazonian Dark Earths, two aims may emerge in conflict. The first aim of sequestering substantial amounts of atmospheric CO_2 in a permanent way could be achieved from organic inputs with high lignin/N ratios that lead to high amounts of stable humus in say 20-30 years. The second aim seeks to provide intensive and sustained cropping right from the first year of the TPN land management type, hence requiring high percentages of labile SOM and a risk of substantial leaching.

This trade-off issue of immediate profitability vs. sequestration permanence is already mentioned by Izak (1997) and reflected in IPCC (2000, Figure 3.9). Soil carbon management practises optimal from the perspective of regional or global effectiveness may be different from the perspective of resource-poor small farmers who need short-term food maximisation and security from their efforts. The globally wanted C-sequestration practises are in fact *investments* in natural resources capital which may bring about net and sustained benefit for the farmer only after 4-6 years. There will therefore not be purely voluntary management for stable SOM increase in the region. This is confirmed by Lile-Carpentier et al. (2000) for the south-western Brazilian Amazon. They conclude, using a farm-level bio-economic model (FaleBEM) that under the current socio-economic and political setting, existing intensification systems on already cleared land will not save the forest.

Especially because the envisaged package(s) of recommended TPN practises, likely to be laborious (green manure supply to the site, local charcoal making) and often unsavoury (sludge, manipulation of soil fauna), would require of external stimuli to succeed. Beneficiary compensatory principles should apply, and the compensation for the small-holder should be in the form of improved services of input (implements; cheap and assured supply of inorganic soil amendments such as lime and rock phosphate) and of output (improved marketing infrastructure and guaranteed marketing of farm products in excess of the immediate food needs); better community services, adapted agricultural extension services, loans at zero interest for small-farmers groups which adopt TPN-oriented soil carbon management, and last-but-not-least: securing of land titles (see also Izak, 1997 and FAO, 2001).

3.5. The natural resources policy aspect

There are several alternatives, within the framework of the Kyoto Protocol, for countries that share parts of the Amazon region to stimulate a programme for replication of Amazonian Dark Earths (Fearnside, 2001a, 2001b):

a) Countries that put into practise the Clean Development Mechanism (CDM) of the Kyoto Protocol. For the Protocol's first commitment period (2008-2012) the CDM will only reward land use, land-use change and forestry projects for afforestation and reforestation. Other types of projects, such as carbon sequestration in agricultural soils, may be permitted beginning in 2013. The CDM financially recompenses carbon sequestration efforts that are not only additional to processes that would have occurred in the absence a specific project but also associated with a sustainable development aspect;

b) The country to push for recognition of the value of "avoided deforestation" in the second commitment period (2013-2017), but already to be pre-financed by one or more countries in Annex I of the Framework Convention (i.e., by countries that have agreed to a cap on their national emissions);

c) Brazil and other Amazon countries to join Annex I of the Framework Convention and annex b of the Protocol, thereby taking advantage of the Emissions Trading possibilities (Article 17 of the Protocol) - which requires surmounting less restrictive and costly hurdles than does the CDM, such as showing a causal link to a specific project, "additionality" (demonstration that the carbon benefits claimed would not have occurred in a baseline no-project scenario), geo-referenced accounting for carbon stocks, and determination of the "carbon costs" of the associated measures (such as the mining and haulage of lime and rock phosphate). Instead, emissions trading under Article 17 are based on the much simpler national statistics produced in the national inventories that are required under the Framework Convention. In addition, project-based activities for soil carbon sequestration would be possible under Article 6 ("joint implementation") of the Protocol for international projects, in a manner analogous to the CDM, as well as through domestic projects for agricultural soils under Article 3.4. of the Protocol.

4. TOWARDS A PERTINENT RESEARCH AND DEVELOPMENT PROGRAMME ON AMAZONIAN DARK EARTH REPLICATION

The recent IPCC Special Report on Land Use, Land Use Change and Forestry (IPCC, 2000) gives a complete scheme of the components of the terrestrial carbon pool . This IPCC scheme could form the starting point for a model that is specifically oriented towards Amazonian Dark Earth replication, especially the Terra Mulata variant. The carbon input quantification per land use system, especially agro-forestry (*agro-sylvo-pastoril)* systems, has received much attention, as exemplified by Woomer and Palm (1999) and incorporated in the IPCC 2000 report. As these systems may be somewhat comparable with the early Amerindian land use practises, their figures may be used as proxy.

Both high Cation Exchange Capacities (CEC) and plant nutrient levels are required, the latter not blocked in their availability by acidity of the soil environment. As demonstrated in section 3.2, the early input of finely divided charcoal in the soil as initial CEC provider may be very beneficial. In the framework and spirit of the Kyoto Protocol, the source of this charcoal will have to be the biomass of secondary forests, leaving the primary forests with their high biodiversity, intact; off-fall of FSC-approved selective logging can be considered as well.

The use of charcoal as a physical soil conditioner will anyhow have to be complemented with high organic inputs to assure high amounts of stable SOM as an additional retention and release mechanism for plant nutrients. The gathering of these nutrients, and the control of the acidic, nutrient blocking character of the main natural Amazon soils, was a laborious and slow proces, taking centuries to result in the original Amazon Dark Earths of the pre-Columbian Amer-Indian civilisations. This can nowadays be accelerated by the addition of lime, (rock) phosphates and potassium fertilisers.

Internationally, applied research programmes have been developed in the last 25 years that deal specifically with the dynamics and manipulation of soil organic matter in tropical and subtropical conditions. Examples are the Tropical Soil Biology and Fertility Programme (TSBF), and the International Centre for Research in Agroforestry (ICRAF, Nairobi), the latter notably through its GEF-supported programme on Alternatives-to-Slash-and-Burn (ASB) programme in several regions, including the Amazon. Also the Brazilian-German scientific co-operation programme SHIFT contains sub-programmes on recuperation of deforested and degraded lands, through manipulation of organic matter input: *Capoeira* project in Belém, *Slash and Char* project in Manaus, both with EMBRAPA.

Originally such programmes concentrated on the manipulation of organic matter input to improve crop productivity both in the short and long term, but since the acceptance of the Kyoto Protocol, Article 3.4, these programmes have begun to examine the question of long-term carbon sequestration in tropical soils as well. Carbon sequestration in soils is also the main subject of the IGBP-GCTE Soil Organic Matter Network (GCTE-SOMNET, Smith et al., 1996). Soil carbon sequestration for improved land management in the tropics is also receiving active attention of FAO, through the consultancy work of Jose Benites, Anthony Young, Rattan Lal, Ponce-Hernandes, Myles Fisher, and Michel Petit (FAO World Soil Resources Reports 86, 88, 92, 96, the latter issued in 2001, in both English and Spanish). Rattan Lal and co-editors a also responsible for a series of books on soil carbon and its management on the basis of a series of workshops on carbon sequestration in different ecological regions, including the humid tropic (*Advances in Soil Science* series of CRC-Lewis).

Much of this research is reflected in the IPCC special report on Land Use, Land Use Change and Forestry (IPCC, 2000), which deals specifically with these activities as potential CO_2 sinks. The *Terra Preta Nova* project idea (Sombroek et al., 2002) can be considered as building upon the above programmes, and the ASB in particular. In summary, the project aims at the recuperation of degraded Amazon lands through the application of ingenious traditional knowledge systems of pre-Columbian indigenous groups together with a combination of modern research and development techniques and a steady supply of soil quality conditioners. The results obtained could be strengthened by the CO_2 fertilisation effect and gains in soil carbon content leading all together toward improvements in the livelihood of small-holders rural agricultural communities that enter or are already present in the region. Achievement like this would help protect the areas with primary forests with all their biodiversity and carbon sequestration functions preserved as well as safeguard the rich indigenous cultural-archaeological heritage. It fits in the Framework Convention on Climate Change and its elaboration in the Kyoto Protocol, the Brazil-proposed Clean Development Mechanism, and the Global Environmental Facility as regards international financial support.

5. REFERENCES

Amelung, W., Bol, R., & Friedrich, C. (1999). Natural ^{13}C abundance: A tool to trace the incorporation of dung-derived carbon into soil particle-size fractions. *Rapid Communications in Mass Spectrometry, 1,*: 1291-1294.
Anderson, A.B. & Posey, D.A. (1989). Management of a tropical scrub Savana by the Gorotire Kayapó of Brazil. Advances in Economic Botany 7:159-173
Batjes, N.H. (1998). Mitigation of atmospheric CO2 concentrations by increased carbon sequestration in the soil. *Biology and Fertility of Soils, 27*, 230-235.
Batjes, N.H., & Dijkshoorn, J.A. (1999). Carbon and nitrogen stocks in the soils of the Amazon Region. *Geoderma*, *89*, 273-286.
Bazzaz, F.A., & Sombroek, W.G. (1996). *Global Climatic Change and Agricultural Production: Direct and Indirect Effects of Changing Hydrological, Pedological and Plant Physiological Processes* (345 pp.) Rome and Chichester/New York: FAO and JohnWiley & Sons.
Bechtold, G. (1982). *Terra Preta do Indio: Anorganisch-chemische Kennzeichnung eines brasilianischen Anthrohumoxes*. Master thesis (421 pp.) Bayreuth, Germany: University of Bayreuth.
Brown, S., & Lugo, A. (1992). Aboveground biomass estimates for tropical moist forests of the Brazilian Amazon. *Interciencia, 17*, 8:18.
Carvalho, E. de, Camargo, P.B. de, Trumbore, S.E., Martinelli, L.A. Krushe, A.V., Costa, E.S.de, Victoria, R., Rocha, H.R., Higuchi, N., Santos, J.dos, Oliveira Jr, R. de, Viera, S.A., & Salimon, C.I. (2001). Roots, soil organic matter and fire residues in Eastern Amazonia: modeling of the stocks and turn-over times of the carbon in the soil. [poster at GCTE meeting, Amsterdam]
Colemann, D.C. Oades, J.M., & Uehara, G. (1989). *Dynamics of soil organic matter in tropical ecosystems*. Honolulu: Univ. of Hawaii Press.
Falbe, J., & Regnitz, M. (1992). *Römpp Chemie Lexikon.* Stuttgart: Thieme.
FAO (Robert) , (2001). Soil carbon sequestration for improved land management. World Soil Resources Report 96. Rome: FAO pp58
FAO (Fisher. M.J.), (2000). Sistemas de uso de la tierra en los trópicos húmedos y la emisión e secuestro de CO_2. World Soil Resources Report 88. Rome: FAO, pp98.
Fearnside, P.M. (1992). Forest biomass in Brazilian Amazonia: comments on the estimate by Brown and Lugo. *Interciencia, 17,*: 19-27.
Fearnside, P.M. (1994). Biomassa das florestas Amazônicas brasileiras. In: Anais do Seminário Emissão X Seqüestro de CO_2. Companhia Vale do Rio Doce (CVRD), Rio de Janeiro. pp. 95-124.
Fearnside, P.M. (1997). Greenhouse gases from deforestation in Brazilian Amazonia: Net committed emissions. *Climatic Change, 35*, 321-360.
Fearnside, P.M. (2001a). The potential of Brazil's forest sector for mitigating global warming under the Kyoto Protocol. *Mitigation and Adaptation Strategies for Global Change,* 6, 355-372.
Fearnside, P.M. (2001b). Saving tropical forests as a global warming countermeasure: An issue that divides the environmental movement. *Ecological Economics, 39*, 167-184.
Fisher, M.J., Rau, I.M., Ayarza, M.A., Lascano, C.E. Sanz, .J.I., Thomas, R.J., & Vera, R.R. (1994). Carbon storage by introduced deep grasses in the South American savannas. *Nature, 371*, 236-238.
Glaser, B. (1999). Eigenschaften und Stabilität des Humuskörpers der Indianerschwarzerden Amazoniens. *Bayreuther Bodenkundliche Berichte, 68,* 196 pp.

Glaser, B., Bol, R., Preedy, N., McTiernan, K.B., Clark, M., & Amelung, W. (2001a). Short-term sequestration of slurry-derived carbon and nitrogen in temperate grassland soil as assessed by ^{13}C and ^{15}N natural abundance measurements. *Journal of Plant Nutrition and Soil Science, 164,* 467-474.
Glaser, B., Guggenberger, G., & Zech, W. (2003). Past anthropogenic influence on the present soil properties of anthropogenic dark earths (Terra Preta) in Amazonia (Brazil). In: B. Glaser, B& W. Woods (Eds), *Amazônian Dark Earths* (in press). Berlin and Heidelberg: Springer.
Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (1998). Black carbon in soils: the use of benzenecarboxylic acids as specific markers. *Organic Geochemistry, 29,* 811-819.
Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001b). The Terra Preta phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften, 88,* 37-41.
Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. *Biology and Fertility of Soils, 35,* 219-230.
Goudriaan, J. (1995). Global carbon cycle and carbon sequestration. In: M.A. Beran (Ed.), *Carbon Sequestration in the Biosphere - Processes and Prospects, NATO ASI Series, Global Environmental Change* (pp. 3-18). Berlin, Heidelberg; Springer.
Grace, J., J. Lloyd, J. McIntyre, A.C. Miranda, P. Meir, H.S. Miranda, C. Nobre, J. Moncrieff, J. Massheder, Y. Malhi, I. Wright & J. Gash. (1995). Carbon dioxide uptake by an undisturbed tropical rain forest in southwest Amazonia, 1992 to 1993. *Science, 270,* 778-780.
Greenland, D.J., Wild, D., & Adams, D. (1992). *Organic Matter Dynamics in Soils of the Tropics - From Myth to Complex Reality.* In: R. Lal, & P.A. Sanchez (Eds), *SSSA Special Publication* (pp. 17-34). Madison, Wisconsin, USA: Soil Science Society of America; American Society of Agronomy..
Haumaier, L., & Zech, W. (1995). Black carbon - possible source of highly aromatic components of soil humic acids. *Organic Geochemistry, 23,* 191-196.
Heckenberger, M.J. (1996). *War and Peace in the Shadow of Empire: Sociopolitical Change in the Upper Xingu of Southeastern Amazonia, A. D. 1400 - 2000,* University of Pittsburgh, 481 pp.
Heckenberger, M.J., Petersen, J.B., & Neves, E.G. (1999). Village size and permanence in Amazonia: Two archaeological examples from Brazil. *Latin American Antiquity, 10,* 353-376.
IPCC (2000). *Land use, land use change, and forestry, a special report.* Cambridge and New York: Cambridge University Press.
Izak, A.M.N. (1997). Developing policies for carbon management in tropical regions. *Geoderma, 79,* 261-276.
Kern, D.C., & Kämpf, N. (1989). Antigos assentamentos indigenas na formacao de solos com Terra Preta arqueologica na regiao de oriximina, Para. *Revista Brasiliera di Solo, 13,* 219-225.
Lile-Carpentier, C., Vosti, S.A., & Witcover, J. (2000). Intensified production systems on Western Amazon settlement farms: could they save the forest? *Agriculture, Ecosystems and Environment, 82,* 73-88.
Lima, H.N., Schaefer, C.E.R., Mello, J.W.V., Gilkes, R.J., & Ker, J.C. (2002). Pedogenesis and pre-Columbian land use of "Terra Preta Anthrosols" ("Indian black earth") of Western Amazonia. *Geoderma, 110,* 1-17.

Moraes, J.L., Cerri, C.C., Melillo, J.M., Kicklighter, D., Neill, C., Skole, D.L., Steudler, P.A. (1995). Soil carbon stocks of the Brazilian Amazon basin. *Soil Science Society of America Journal, 59,* 244-247.
Nepstad, D.C., Decarvalho, C.R., Davidson, E.A., Jipp, P.H., Lefebvre, P.A., Negreiros, G.H., Dasilva, E.D., Stone, T.A., Trumbore, S.E., Vieira, S. (1994). The role of deep roots in the hydrological and carbon cycles of Amazonian forsests and pastures. *Nature, 372,* 666-669.
Neves, E.G., Bartone, R.N., Petersen, J.B., & Heckenberger, M.J. (2001). *The timing of Terra Preta formation in the central Amazon: New data from three sites in the central A*mazon, Paper, presented at the Terra Preta Symposium, Rio de Janeiro, pp. 10.
Nobre.C., Artaxo, P., Dias, M.A..S., Victoria, R., Nobre, A.and Krug, T. 2001. The Amazon Basin and Land Cover Change:A Future in Balance?. In: Madari, B. (ed):. Proceedings Third International Conference on Land Degradation, Rio de Janeiro , Sept. 2001. CNPS- Embrapa , Rio de Janeiro. (CD-Rom)
Oades, J.M. (1988). The retention of organic matter in soils. *Biogeochemistry*, 5, 35-70
Parton, W.J., Schimel, D.S., Cole, C.V., & Ojima, D.S. (1987). Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal, 51,* 1173-1179.
Paustian, P., Levine, E., Post, W.M., & Ryzhova, I.M. (1997). The use of models to integrate informationand understanding of soil C at the regional scale. *Geoderma, 79*, 227-260.
Phillips, O.L., Malhi, Y., Higuchi, N., Laurance, W.F., Nunes, R.M., Vaxques, R., Laurance, L.V., Fereira, M., Stern, M., Brown, S., Grace, J. (1998). Changes in the carbon balance of tropical forest:evidence from long-term plots. *Science, 282*, 439-442.
Richey, J.E., Melack, J.M., Aufdenkampe, A.K., Ballester, V.M., Hess, L.L. (2002). Outgassing from Amazon rivers and wetlands as a large tropical source of atmospheric CO_2. *Nature, 416,* 617-620.
Sanchez, P.A. (2000). Linking climate change research with food security and poverty reduction in the tropics. *Agriculture, Ecosystems and Environment, 82*, 371-383.
Sanford, R.L., Saldariaga, J.G., Clark, K.E., Uhl, C. and Herrera, R. 1985. Amazon rainforest fires. Science 227: 53-55.
Schmidt, M.W.I., & Noack, A.G. (2000). Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. *Global Biogeochemical Cycles, 14,* 777-793.
Scholes, R.J. and VanBreemen, N. 1997. The effects of global change on tropical ecosystems. Geoderma 79: 9-24.
Seiler, W., & Crutzen, P.J. (1980). Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climatic Change, 2*, 207-247.
Smith, P., Powlson, D.S., & Glendining, M.J. (1996). The GCTE SOMNET; a global network and data base of soil organic matter models and long-term data set. *Soil use and Management, 12*, 104.
Sombroek, W.G., Fearnside, P.M., & Cravo, M.d.S. (1999). Geographic assessment of carbon stored in Amazonian terrestrial ecosystems and their soils in particular. In: R. Lal, J.M. Kimble, & B.A. Stewart (Eds). *Global Climate Change and Tropical Ecosystems* (pp. 375-389). Boca Raton, FL: CRC-Lewis Publishers.

Sombroek, W.G., Kern, D.C., Rodrigues, T., Cravo, M da S., Cunha , T.J., Woods, W., & Glaser, B. (2002). Terra Preta and Terra Mulata, pre-Colombian kitchen middens and agricultural fields, their sustainability and replication. In: R. Dudal. (Ed.), *Symposium 18, Anthropogenic factors of soil formation*, 17th World Congress of Soil Science. August 2002. Bangkok: Transactions (CD-ROM).
Sombroek, W.G., Fearnside, P.M., & Cravo, M da S. (2000). Geographic assessment of carbon stored in Amazonian terrestrial ecosystems and their soils in particular. In: Lal, R., Kimble, J.M., & Stewart, B.A. (eds). Global climate change and tropical ecosystems. CRC-Lewis Publ., Boca Raton, USA: CRC Lewis Publishers. 375-389 (corrected version).
Sombroek, W.G., Nachtergaele, F.O., & Hebel, A. (1993). Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. *Ambio*, *22*, 417-426.
Sombroek, W.G. 1992. Biomass and carbon storage in the Amazon ecosystems. Interciencia 17(2): 269-272.
Woods, W.I., & McCann, J.M. (1999). *The anthropogenic origin and persistence of Amazonian dark earths.* The Yearbook of the Conference of Latin American Geographers, pp. 7-14.
Woomer, P.L., Palm, C.A, Alegre**, J**. Castilla, C., Cordeiro, D.G., Hairiah, K., Kotto-Same, J., Moukan, A., Rodrigues, V., & VanNoordwijk, M. (1999). *Carbon dynamics in slash-and-burn systems and land use alternatives; findings of the ASB programme*. In: Lal, R, Stewart, B.A., & Kimble. J.M. (Eds), Carbon pools and dynamics in tropical ecosystems (pp ??). Boca Raton, USA: CRC Lewis Publishers.