

Chapter 7

AMAZONIAN 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 CO₂ in particular, recognizes the importance of carbon (C) in the soil as a store, source and potential sink of CO₂, in addition to supporting functions of the aboveground biomass.

The aboveground 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 CO₂ concentration and thereby global climatic change. However, the increase in CO₂ 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 CO₂ fluxes, i.e. daytime CO₂ uptake through photosynthesis was in balance with CO₂ release via autotrophic and heterotrophic respiration. Monitoring of these fluxes from towers in the old-growth forest by Eddy covariance methods, and associated tree-growth measurements, has produced conflicting results. Early measurements (Grace et al., 1995) indicated a net CO₂ sink of 2-7 (av. 4) Mg C ha⁻¹ yr⁻¹ on flat interfluvial 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

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likely to be even less, being partially off-set by the substantial out-gassing of CO₂ that has been observed in sediment-rich rivers in the region (Richey et al., 2002).

A part of the CO₂ 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⁻¹yr⁻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 C 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 C in the form of charcoal – whether as coarse pieces (>2 mm) or within the fine earth. Routine analysis of soil C 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 digest charcoal. This can be measured only through dry-combustion (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 (Sanford et al., 1985) through occasional lightning or accidental large-scale burning during 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), and established that charcoal fragments may account for 30 to 50% of the total C 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 Amazonian Dark Earths (ADE; also referred to as *terra preta* and *terra mulata* soils), apparently as a result of indigenous land management by some groups of pre-Columbian Indians (see below, and other chapters of this book). 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 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 $147\text{-}506 \text{ Mg C ha}^{-1} \text{ m}^{-1}$ in Amazonian Dark Earths around Manaus and in the Belterra area compared to $72\text{-}149 \text{ Mg C ha}^{-1} \text{ m}^{-1}$ in adjacent 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 $56 \text{ Mg C ha}^{-1} \text{ m}^{-1}$ for clayey soils and $34 \text{ Mg C ha}^{-1} \text{ m}^{-1}$ for sandy soils as mean of about 30 profiles of Ferralsols and Ferric Acrisols in the Amazon area which compares well with the C stocks of the Ferralsols of Glaser et al. (2003a). The assessment of the precise amounts of total C in Amazonian soils is hampered by (a) uncertainties about the correct conversion factor for the incomplete C yields of wet-digestion 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.

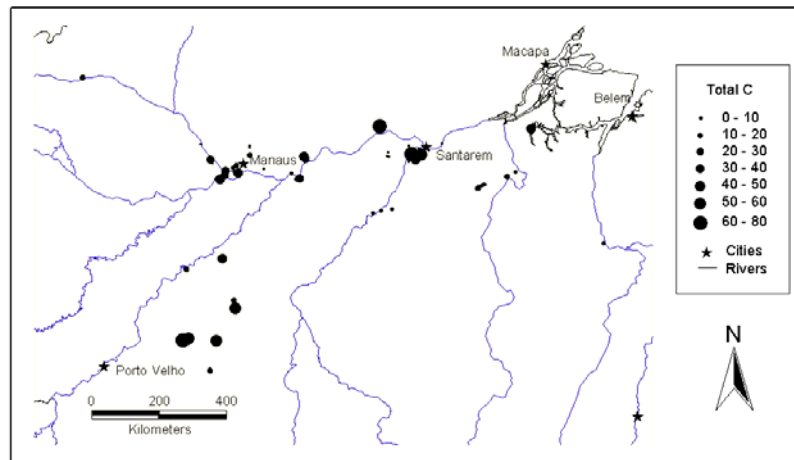


Figure 1: Map of the Amazon Basin with available data on C concentrations (g kg^{-1}) in Amazonian Dark Earths significantly ($P < 0.05$) greater than adjacent soils up to 60 cm soil depth.

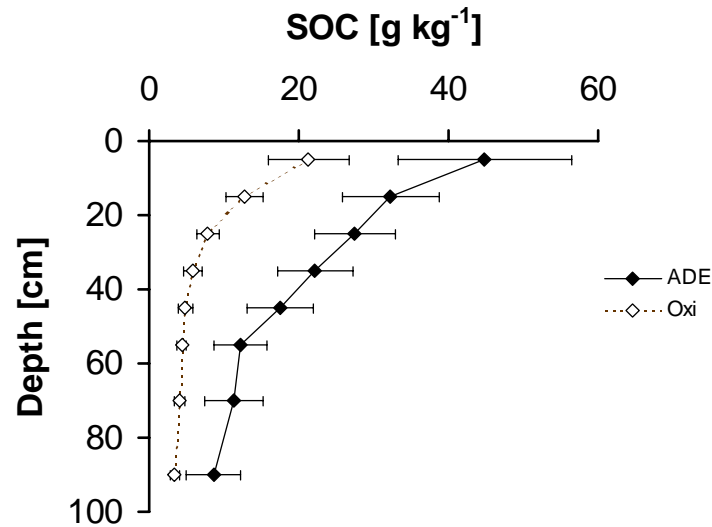


Figure 2: Vertical extent of SOC in Amazonian Dark Earths (ADE) and adjacent Ferralsols (Oxi) near Manaus and from the Belterra area (mean and standard error, $N=5$). Data taken from Glaser (1999).

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 Fig. 3, Heckenberger (1996) regularly found concentric patches of Amazonian Dark Earths around a center of yellow or red Ferralsols which was used by indigenous populations as a central plaza (Fig. 4). Kern and Kämpf (1989) found complete spheres of decreasing soil C contents around small plazas. Thus, there seems no uniform pattern of Amazonian Dark Earth 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 the 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).

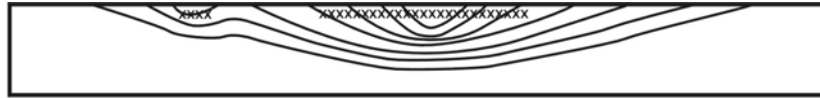


Figure 3: SOC distribution in an Amazonian Dark Earth of the Belterra area. Lines indicate the vertical and lateral distribution of identical SOC concentrations. X indicates the occurrence of ceramic artifacts. Scale, dimension, and SOC concentrations not known. Figure taken with permission from Bechtold (1982).

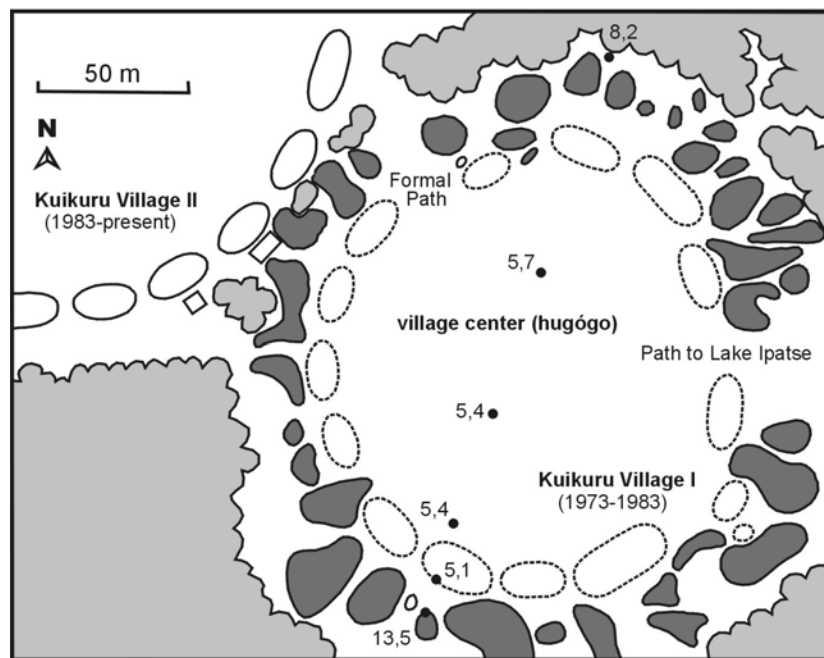


Figure 4: Organization of the Kuikuru village in the upper Xingú area. It is remarkable that the centre of the village does not show any Amazonian Dark Earth features, although SOC is rather high (which are given as percent values along the transect line in the Figure). Instead, according to this figure, Amazonian Dark Earths seem to build up behind the house (Figure taken with permission from Heckenberger, 1996).

3. PERSPECTIVES FOR AMAZONIAN DARK EARTH REPLICATION FOR CARBON SEQUESTRATION

Amazonian soils, having approximately the same or higher amounts of C stocks than the aboveground biomass of old-growth forests, become very important in any regional study of C sequestration of the Amazon biome. Amazonian Dark Earths, with their high amounts of stable SOC, are already a non-negligible part of this

stock, notwithstanding their small coverage (0.1-0.3 % of the total area of 6 million km²). 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 significant as future sinks and stocks for atmospheric C.

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 landuse practices that doubled the amount of stable soil C – are the following:

- a) What were the ingredients and practices applied by the pre-Columbian Indian agricultural communities in relation to the local natural resources (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 landuse 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 landuse 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 labor to create new *terra preta* soils – the *social and profitability* aspect;
- e) Which of the Kyoto Protocol mechanisms are the most advantageous for realization 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 practices of a Kayapó Indian community in the upper Xingú area, as described by Anderson and Posey (1989):

“Islands of woody vegetation (*apêê*) 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 *apêê* 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 recognized 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) stated that native Indians practiced and still practice a pattern of long-term crop rotation of diversely 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 Kämpf, 1989) were important. Also fresh organic matter from floating river grasses; phosphate-calcium compounds from 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 C sequestration in ADE.

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 soil organic matter under humic tropical conditions are required. Long-term experiments are scarce for the tropics, but some local experimental setups 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 characterized in different ways, and a detailed overview is given by Glaser et al. (2003b). The existing C conversion models CENTURY (Parton et al., 1987) and RothC (Coleman and 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 CO₂. 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 CO₂ by heterotrophic respiration. The actual rates of decomposition 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 developed to describe C dynamics in agricultural or forest soils, but in grassland soils. We would expect that it does not describe C dynamics very well under agricultural settings with ploughing or 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 landuse practices have been reviewed which may lead to higher C sequestration in soils, such as improved grasslands, or agroforests and planted tropical pastures, through redistribution of the C in deeper soil horizons, or the omission of burning (Batjes, 1998). Much of the C is released as CO₂ 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 climates. 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 C are transformed into charcoal (Glaser et al., 2002). In their pioneering work on biomass burning, Seiler and Crutzen (1980) estimated a charcoal formation of about 2.5% in shifting cultivation fields based on aerial 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 and Crutzen, 1980). Therefore, C entering the soil as charcoal is a significant sink for atmospheric CO₂ and may be important for global C sequestration.

In comparison to burning, controlled carbonization, on the other hand, converts even larger quantities of aboveground biomass into stable C pools which is assumed to persist in the environment over centuries (Seiler and Crutzen, 1980; Haumaier and Zech, 1995; Glaser et al., 1998; Schmidt and Noack, 2000; Glaser et al., 2001b). 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 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 C 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 and Regnitz, 1992). The weighted average C recovery from charred woody biomass is relatively high with about 50% compared to only 3% after conventional slash-and-burn techniques (Glaser et al., 2002; Lehmann et al., 2002). With such conversion proportions, 13 Mg charcoal-C ha⁻¹ can be produced from typical 4-20 years-old secondary forests in the Amazon Basin (Lehmann et al., 2003).

3.3. The Time-Lapse Aspect

For ADE replication one would aim at an initial accumulation 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 C content, in addition to physical charcoal input as suggested above. There are ¹⁴C indications from archaeological sites that 10 cm of ADE soil may have been produced per decade in pre-Columbian times (Neves et al., 2003), but this may be restricted to the mound-like central parts of ADE sites. In the more outlying areas of *terra mulata* (Kämpf et al., 2003), the enrichment may have been slower, due to the natural scarcity of calcium (Ca) and phosphorus (P) in the areas with strongly weathered soils. However, at ADE 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 substantially speed up the formation of stable SOM, provided there is the right mix of biomass input.

Whether there is a stimulating action of a 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 practices by Anderson and Posey (1989) mentioned 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, C uptake rates and time-averaged system C stocks (i.e., above- and belowground; Table 1).

Table 1. Carbon uptake rates and time-averaged system carbon stocks and differences in C stocks due to land transformation at the margins of the humid tropics. Summary of 116 sites within different land uses before and after slash and burn located in Brazil, Cameroon, Indonesia and Peru (Sanchez et al., 2000, Table 3).

<i>Land use practice</i>	<i>Duration [years]</i>	<i>C uptake [Mg C ha⁻¹ a⁻¹]</i>	<i>C stocks [Mg C ha⁻¹]</i>
Primary forest	unknown	0	234 ±59
Secondary forest	23	7 ±2	119 ±33
Cropping after slash and burn	2	-94 ±18	46 ±9
Crops / bush fallow	4	3 ±1	34 ±3
Complex agroforests	25-40	3 ±1	92 ±37
Simple agroforests	15	7 ±2	79 ±19
Pasture	4-12	-0.4 ±0.2	29 ±2

According to IPCC (2000, Table 4.4), optimal tropical agroforestry management has a potential rate of soil C 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⁻¹yr⁻¹ over the same period, but with low degree of confidence. The latter values 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, 90-754 or 75-108 Mg C ha⁻¹), depending on the mix of grass species introduced. Also, recent trials of the Studies of Human Impact on Forests of the Tropics / Empresa Brasileira of Parana (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 CO₂ concentrations lead to higher NPP, especially in C3 plants (most common crops and woody species) through the so-called "CO₂ fertilisation effect" (Goudriaan, 1995, Scholes and VanBreemen, 1997). This increase in NPP is 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 C from the roots through the rhizosphere 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 (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 CO₂ in a permanent way could be achieved from organic inputs with high lignin/N ratios that lead to high amounts of stable humus in about 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.

The trade-off issue of immediate profitability vs. sequestration permanence is already mentioned by Izak (1997) and reflected in IPCC (2000, Figure 3.9). Soil C management practices advantageous from the perspective of regional or global effectiveness may be disadvantageous from the perspective of resource-poor small farmers who need short-term food maximization and security. The globally wanted C-sequestration practices are in fact *investments* in natural resources capital which may bring about net and sustained benefit for the farmer only after 4-6 years. Therefore, purely voluntary management to increase stable SOM in the region is unlikely. 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 packages of recommended TPN practices, likely to be laborious (green manure supply to the site, local charcoal making) and often unsavory (sludge, manipulation of soil fauna), would require 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 C 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) The practice of the **Clean Development Mechanism (CDM)** of the Kyoto Protocol. For the Protocol's first commitment period (2008-2012) the CDM will only reward landuse, landuse change and forestry projects for afforestation and reforestation. Other types of projects, such as C sequestration in agricultural soils, may be permitted beginning in 2013. The CDM financially recompenses C sequestration efforts that are not only additional to processes that would have occurred in the absence of a specific project but also associated with a sustainable development aspect;

b) **Avoiding 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) **Emissions Trading** possibilities (Article 17 of the Protocol) – which requires surmounting less restrictive and costly hurdles than does the CDM, such as demonstration that the C benefits claimed would not have occurred in a baseline no-project scenario), geo-referenced accounting for C 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 C 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 PROGRAM 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 C pool. This IPCC scheme could form the starting point for a model that is specifically oriented towards Amazonian Dark Earth replication, especially the so-called *terra mulata* variant. The C input quantification per landuse system, especially agroforestry (agro-silvo-pastoral) 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 landuse practices, 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. The early input of finely divided charcoal in the soil as initial CEC

provider may be very beneficial to reduce nutrient leaching (Lehmann et al., 2003). 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 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 process, taking centuries to result in the original Amazonian Dark Earths of the pre-Columbian Amer-Indian civilizations. This can nowadays be accelerated by the addition of lime, (rock) phosphates and potassium fertilizers.

Internationally, applied research programs 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 program on Alternatives-to-Slash-and-Burn (ASB) in several regions, including the Amazon. Also the Brazilian-German scientific co-operation program SHIFT contains sub-programs 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 programs 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 programs have begun to examine the question of long-term C 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 C 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 are also responsible for a series of books on soil C and its management on the basis of a series of workshops on C sequestration in different ecological regions, including the humid tropics (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 CO₂ sinks. The *Terra Preta Nova* project idea (Sombroek et al., 2002) can be considered as building upon the above programs, and the ASB in particular. In summary, the project aims at the recuperation of degraded Amazon lands through the application of 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 CO₂ fertilization effect and gains in soil C content leading all together toward improvements in the livelihood of small-holders rural

agricultural communities that enter or are already present in the region. Achievements such as these would help to protect the areas still covered by primary forests with all their biodiversity and C sequestration functions preserved as well as safeguard the rich indigenous cultural-archaeological heritage. It fits into the Framework Convention on Climate Change and its elaboration in the Kyoto Protocol, the Brazil-proposed Clean Development Mechanism, as well as the Global Environmental Facility.

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