

Chapter

Opening the Black Box: Deciphering Carbon and Nutrient Flows in Terra Preta

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Abstract: The technique of nutrient and carbon balancing is used as a framework to gain understanding on the creation of TP. Using our model we estimated the organic carbon stabilizing capacity, the nitrogen stabilizing capacity and decomposition rate of charcoal. The calculated stabilizing capacity is high and therefore C and N accumulation is likely to continue during (temporary) TP abandonment. A stoichiometric check of our assumptions suggests that besides fish and charcoal there must be another calcium source like shells. Our preliminary data do not provide the final answer on TP formation, but the modelling forms a framework for further studies on TP formation.

Keywords: Modelling, nutrient and carbon balance, formation of TP, stoichiometry

1 INTRODUCTION

The soils of the Amazon region are usually unfertile, due to the high decomposition rate of organic carbon (C), rapid losses of nitrogen (N) and

potassium (K) through leaching, and rapid phosphorus (P) fixation to (hydr-)oxides of iron (Fe) and aluminium (Al). Consequently these soils (oxisols, ultisols) are known for their low suitability for agricultural production purposes. However, relatively fertile, pH-neutral soils also occur in the Amazonian lowlands. Such soils of high fertility are remnants of ancient pre-Columbian inhabitants. They are known as Terra Preta do Indio or Amazonian Dark Earths. Terra Preta contain up to eight times more carbon than adjacent soils. Furthermore, available and total nitrogen is two to eight times higher and there is up to one thousand times more available phosphorus and up to ten times more total phosphorus than in adjacent soils (Glaser et al., 1999; Lehmann et al., 2003).

Four years after Wim Sombroek, who can be considered the founder of research on Terra Preta, passed away, his legacy is still alive in Wageningen (The Netherlands), the city where he spent most of his career. Anthrosols are common in many areas in the Netherlands and consequently much research has been done on these soils in Wageningen. Sombroek's parents used to farm on so called 'eerdgronden' ('Plaggen soils'). The soil formation history of Terra Preta shows similarities to these 'eerdgronden', and both types are classified into the FAO-category of man-made, anthrosols. To compare: P levels of eerdgronden (currently under forest) vary from 375 to 3000 mg/kg (Dercon et al., 2005; Th.W. Kuyper, unpublished) and TP from 73 to 8800 (derived from: Costa and Kern, 1999; Glaser, 1999; Madari et al., 2003; Ruivo et al., 2003; Lehman et al., 2003; Schaefer et al., 2004) whereas adjacent soils (non man-made) contain on average 150-300 mg/kg

(Guttmann et al. 2006). C levels in Northern European sandy anthrosols vary from 1.3 to 2.8 % (Blume et al., 2004) which is lower than C levels in TP which are between 2.8 and 9.0 % (Costa and Kern, 1999; Glaser, 1999; Lehman, 2003; Madari et al., 2003).

In this contribution we will present preliminary results of research on dynamic processes of Terra Preta formation in space and time. Up to now, research on TP has emphasized (static) properties of these soils rather than process rates. The question which practices contributed to these changed properties of TP, and the relative importance of these processes, has not yet been resolved. Glaser et al. (2003) hypothesised that the incorporation of significant amounts of charcoal both stabilised and elevated soil organic matter content. It is likely, however, that additions of riverine clays and food materials (fishes) from nearby rivers also contribute to TP properties. Little is known about the fluxes of nutrients and carbon, induced by the activities of the Amerindian population of the Amazon that led to the formation of the fertile and productive TP. As a consequence there is as yet no mechanistic underpinning of carbon and nutrient cycles in Terra Preta. In order to gain understanding on the formation of these soils, the following questions seem pertinent:

- What were the major inputs and outputs of the Terra Preta land use system?
- Which processes caused the remarkable accumulation of C, N and P in these soils?

- What is the relative importance of the various processes for the accumulation of C, N and P?
- Is an estimate possible about the rate at which Terra Preta soils form based on an understanding of the various processes?

Our research aims at identifying and quantifying the carbon and nutrient fluxes as well as gaining insight in the processes that make the fertility of these soils so persistent. It is likely that formation of Terra Preta almost ended after the European conquest of the Amazon region, so TP have generally remained productive for almost 5 centuries. We will apply the technique of nutrient and carbon balancing as a framework to gain understanding of the creation of TP. Next to estimates of the balances of C, N and P, we need to link these three elements in a joint stoichiometric framework (Sturner and Elser, 2002). Furthermore, data on K, Mg and Ca in these soils will provide further constraints to a linked model of carbon and nutrient fluxes. First, we will explain the concept of nutrient and carbon balances for researching prehistorical soils. Then some of the preliminary model results will be presented which will be discussed and used to identify the knowledge gaps paving the road for future research on TP. Our data will show that deciphering the pathways along which TP soils originated and were maintained will need input from soil science, agronomy, archaeology, anthropology and paleo-economy.

2 METHODOLOGY: MODELLING OF NUTRIENT BALANCES

2.1 Conceptual framework

Nutrient balances describe the inputs and outputs of a certain unit over time. Nutrient balances, together with information about pools and fluxes are a useful tool to assess the sustainability of an agro-ecosystem (e.g. Smaling et al., 1987). Classical nutrient balances are the sum of the output and the input and do consider internal processes as a black box (figure 1). Our goal is not primarily to estimate the quantities that went in or out, because we know that input must have exceeded output in order to make a Terra Preta out of an oxisol. While we are interested in the relative importance of the various input sources, our main interest lies in the functioning of the black box (figure 2), i.e. the soil processes occurring at field to village scale.

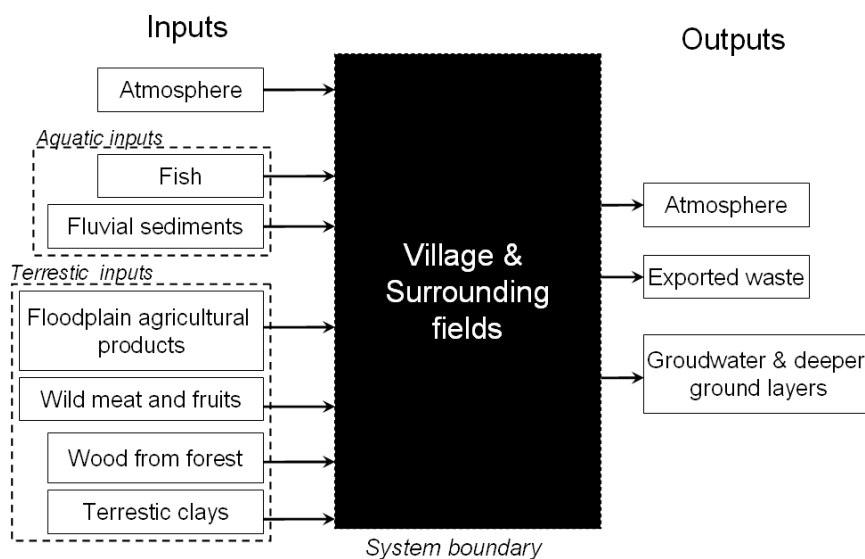


Figure 1: Classical conceptual nutrient balance model in which the internal processes are not considered. All arrows represent flows of C, N and P except the flows to and from the atmosphere, and probably the flow to the groundwater which mainly consist of C and N. Especially the flows of fluvial sediments for ceramics and wood imports, which are later transformed to charcoal, are unique to the Terra Preta system.

Based on several studies on Terra Preta and work of Smaling c.s. (Smaling et al., 1987; Stoorvogel et al., 1993) a Terra Preta nutrient balance was constructed (Figure 2).

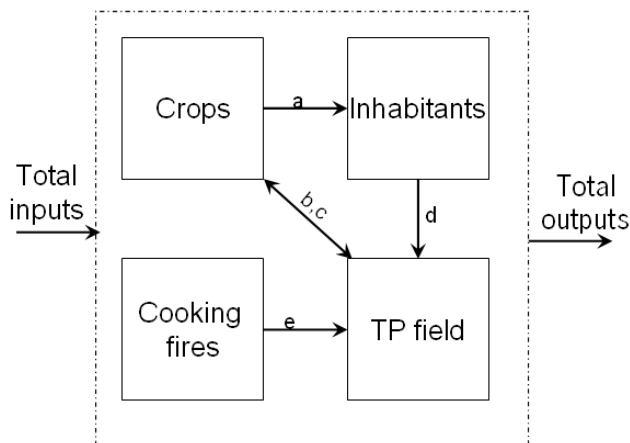


Figure 2 Conceptual model of internal flows that play a role within the village during TP cultivation. All arrows represent flows of C, N and P and consist of a) harvested products b) uptake of nutrients by crops c) nutrients from crop residues d) household waste (including fish bones) and excreta that are applied to the fields e) charcoal from cooking fires

The delineation of the system boundary is an arbitrary task, especially in the case of the complex agro-ecosystems of the historic Amerindian societies. To make

things as comprehensive as possible, we decided to delineate the system at the village level with its directly surrounding fields and gardens (Terra Preta). So floodplains were excluded. In the model the village is not a spatial unit, separate from the agricultural field, but only a component of the TP system. People lived, cropped and excreted their waste on the very same piece of land.

The data were assembled from a Terra Preta site (54°26'W;3°36'S, near Tapajos river; Santarem, Brazil) that was extensively described by Glaser (1999). We choose this site because of the data availability on several nutrients (N, P, Ca, Mg, K) and carbon. Unfortunately, the size and age of the site are unknown, because research on the location was not done in combination with archaeologists. Therefore, a model Terra Preta was constructed based on Glaser's (1999) data. According to Neves et al. (2003) average Terra Preta sites are around two hectares in size with a population of around 100 adult equivalents. As a result, we scaled up the measurements of Glaser (1999) to a Terra Preta site of 2 ha cropland. We assume homogeneity in TP sites, which should be subject to further research.

2.2 Input, outputs and flows

This study is based on estimates of C, N, P, Ca and Mg inputs and outputs. The validity of the estimates is then checked by the ratios of these elements in Terra Preta and the estimated inputs. We assume a closed economy, where population size determines both the amount of food needed and the amount of (charred) wood needed for cooking the food. Additionally, there may be a demand of wood

materials for housing (including roofing). This latter factor will be treated in the discussion.

2.2.1 Food

We assume that the diet of the pre-Columbian society more or less equalled the diet of the contemporary Caboclos, rural Amazonians as researched by Murietta and Dufour (2004). For modelling purposes we simplified the diet of the inhabitants to three sources: (i) fish and other animals caught in the river (0.5 kg day^{-1} fresh weight); (ii) home-grown cassava (0.9 kg day^{-1} fresh weight); (iii) and plant products from the forests such as fruits for which we take papaya (*carica papaya*) as an example (0.2 kg day^{-1} fresh weight). We assume that the density of edible terrestrial animals in these forests on poor soils is too low to make a substantial contribution to the dietary needs. Nutrient flows were calculated using nutrient concentration data (Table 1). For the cultivation of the needed cassava (33 Mg y^{-1}) two hectares of land are needed under low to medium growing conditions (Kawono, 1990). Atmospheric N deposition was estimated at 8 kg ha^{-1} (Feldpausch et al., 2004). Free-living nitrogen-fixing bacteria like *Azospirillum* and Cyanobacteria whose presence is reported in TP (Lehmann et al., 2003) are expected to fix a few kg (3 kg) per hectare per year (Giller and Merckx, 2003). This adds up to a total of 11 kg N from the atmosphere. We assume that the residues of cassava were left on the field to decompose, and not charred.

Understanding waste flows of the Amerindian societies is of key importance to gain insight in the formation of Terra Preta. Most of the human waste (including

excreta) would probably have been accumulated in the vicinity or better in the village on the TP (in formation) (Erickson, 2003; Woods, 2007, pers. comm.). Based on excreta composition (Schouw et al., 2002) we estimate that 72 percent of the carbon in food that is imported to the village is respired and brought outside of the system and that the other 28 percent is incorporated in soil, contributing to the formation of TP. We assume 40% of N directly volatilizes or leaches to deeper soil layers (which is a common figure for the application of fresh wastes and fresh manures in case these are not directly ploughed into the soil), resulting in 60% of N being held by the TP. We assume no P losses due to the high P-fixing capacity of the Fe-rich Amazonian soils.

2.2.2 Char from forest clearing and cooking

Char is one of the main inputs of TP. We consider two sources of char, an initial source when the original biomass was charred at low temperature, and a subsequent source during periods that the sites were settled and wood was used for cooking. The carbonization coefficient (the fraction of C that remains in char) of the initial wood is estimated at 35%, that of wood for cooking fires at 3%.

The first volume of the input of fuel wood was estimated using wood consumption from a comparable tropical area outside the Amazon (Congo) ($700 \text{ kg capita}^{-1} \text{ year}^{-1}$). (Amous, 1999). The char input from charring of the original biomass is estimated using figures from Brown and Lugo (1992), $281 \text{ Mg biomass ha}^{-1}$ is assumed to be carbonized during mouldering fires of the wet season. We

consider the charring of the original vegetation as an input of C and N only, because Ca, P and Mg were already in the system.

2.3 Miscellaneous nutrient and carbon flows

Inputs that we did not include in the nutrient balance are 1) Jungle meat. Mammal densities in tropical forests on poor soils are usually very low and therefore of negligible importance for the diet of native populations. 2) Erosion and sedimentation are negligible, because most of the Amazon is flat. 3) Building materials. The indigenous population used palm leaves for the construction of their houses. We decided not to add a separate flow for this, but to assume that these trees were included in fuel wood. 4) In the quantitative model, we did not include brought up soil in our balance because of lack of evidence of imported sediments in the example used, although Mora et al. (2003) found indications that major soil moving operations took place in an archaeological site in Araracuara, Colombia.

We did not include ceramics in the quantitative balance because the clay for ceramics is of terrestrial origin and mainly contains kaolinite. The P concentrations in the ceramic that is abundantly found in TP is from the fish that was cooked in it (Costa et al., 2004). So, the ceramics are not a P source but a carrier. Some tempers (make pottery harden) made from organic material were added to the clays in small amounts, but we assume the effect on soil fertility to be small.

Table 1 Chemical composition of products

	C	N	P	Ca	Mg
Cassava tuber*	18%	0.14%	0.02%	0.36%	0.02%
Cassava residue (leaves and trunks)**	12%	0.45%	0.07%	0.05%	0.06%
Papaya*	3.9%	0.10%	0.01%	0.02%	0.01%
Fish***	11%	2.4%	0.72%	1.1%	0.01%
Wood****	50%	0.37%	0.01%	0.2%	0.1%
Charcoal*****	84%	0.18%			
Harvest index cassava**	0.6				
Carbonization coefficient of cooking fires *****	3%				
loss fractions in village	0.72	0.4	0		
* USDA, 2006, ** Kawano, 1990, *** Sterner and George, 2000 Hendrixon et al., 2007, **** median value of data from Feldpausch et al., 2004, Vitousek et al., 1984, ***** Adapted from Pastor-Villegas et al., 2006 P,Ca & Mg content depend carbon coefficient changes, ***** Own estimate					

2.4 Modelling of the change of nutrient pools over time

A simple model was built to describe the change in soil C, N and P during periods that the Terra Preta site was occupied and abandonment. In this model, three phases are distinguished. The following occupation history is hypothesized for the model Terra Preta. First, the site was cleared, the biomass partly charred and cultivated for several years (two years in our model). When yields began to decline and/or weed pressure became too high, the site was abandoned – as in other forms of slash-and-burn agriculture. However, the C-stabilising capacity of the latter soils allowed a more prolonged period of use when the sites were cleared a second time. Clearing a second time was probably easier (even with the technological limitations that these Amerindians faced) because the sites were still under an early secondary vegetation. Relocating these sites was made easy both because of their topographical position (on riverine bluffs) and because of a higher abundance of

fruit trees such as papaya which were likely deliberately planted by the inhabitants. The second period of inhabitation could have lasted longer, resulting both in a larger input of external nutrient sources (fishbones, etc.) and a further increase of useful (fruit) trees. It is this interaction between humans and their habitats that changed the Amazon from a pristine rainforest into a park landscape (Heckenberger et al. 2003).

Finally, a third cycle of slash-and-char could have enabled permanent land use and a further spatial expansion of the soils if permanent settlements allowed for some population growth. Permanent land use came to an end when the Europeans colonized the area and the Amerindians went extinct or left their sites. However, cessation of permanent land use did not lead to the end of TP formation (see below).

We assume that the oxisol did not contain any (active) char before the start of the TP formation. During the first year of the TP formation phase a large amount of char is added to the soil by the carbonization of the standing biomass. We consider the charring of the vegetation as an input of C and N, because Ca, P and Mg were already in the system. Char is expected to oxidize slowly at its edges (Trompowsky et al., 2005; Cheng et al., 2006), which increases its reactive capacity. Soil char although highly resistant, is subject to slow decay. When char is decomposed C is emitted to the atmosphere and N is added to the available soil N stock from which it can be immobilized again.

Char is expected to play an important role in nutrient pool dynamics. Besides that, char is expected to act as a stabilizer of non-pyrogenic organic material by

physical entrapment (Lehmann et al., 2005) and increased CEC (Glaser et al., 2003; Liang et al., 2007). Therefore, we assume char stabilizes (non black) soil organic matter and nitrogen, but the stabilizing capacity of the latter is greater because of elevated CEC (Liang et al., 2006) (for the values used see Table 6). Stabilization of C and N is treated as a linear process, proportional to the amount of char in the soil. C stabilization is limited either by the stabilizing capacity of the char in the soil or by the amount of C added to the soil. We assume that char also stabilizes (immobilizes) nitrogen. Therefore N stabilization cannot be simply determined by dividing C stabilization by the carbon nitrogen ratio of the non-char inputs.

Because N deficiency is uncommon on TP (Lehmann et al., 2003), we assume that plant N uptake does not suffer from N binding by char particles; therefore N uptake also limits N stabilization, because N that is taken up by plants cannot be stabilized by char at the same time. We assume that all C and N that is not stabilized or taken up by plants is lost from the system by respiration or leaching, respectively, like in an oxisol where no C and N accumulation take place.

When a TP site is abandoned, at the start of phase II, no char is added anymore, but the stabilization does not stop, if the stabilizing capacity is not the limiting factor. Now, litter fall is the only material to be stabilized. During phase 2 the growth of the emerging vegetation is calculated using a growth function derived from Gehring et al. (2005).

The time of occupation of the TP is calculated using P concentrations in the TP soil, in an adjacent oxisol and the annual estimated P input. Furthermore we assumed that TP formation started 1000 years ago. Using these estimates together

with difference in black carbon, total carbon and nitrogen content between the TP and the adjacent oxisol (Table 2), we derived the coefficients that determine the decomposition of char and the stabilization of non char soil C and N.

Table 2 Amounts C, N and P (Mg ha^{-1}) in an oxisol and Terra Preta as measured by Glaser et al. (0-150 cm) (1999). Ca and Mg contents are estimated based on available Ca and Mg data.

	C-total	C-char	N	P	Ca	Mg
Terra Preta	766	158	47	26	52	5.6
"original" oxisol	221	24	21	12	1	0.3
Nett accumulation	545	134	26	13	51	5.3

3 RESULTS AND DISCUSSION

Table 3 provides insight in the size of the annual carbon and nutrient flows and their main components during the build up of Terra Preta. The greatest C input to the entire system is wood while fish consumption causes greatest N and P inputs to the system.

Table 3 Annual flows through the components of the modelled Terra Preta system in phase 1 after initial clearing and charring of the vegetation (crops, village, cooking fires see Figure 2). Only the Terra Preta is considered as a sink, in the other components total outflow equals inflow. *The only output of Terra Preta is crop nutrient uptake, gaseous losses of C and N, and N leaching are related to soil char content and therefore not shown here. ** Soil surplus is the amount of elements that is available for leaching or accumulation.

Annual flows through (turnover) compartments (see Figure 2) $\text{kg ha}^{-1} \text{yr}^{-1}$

	C	N	P	Ca	Mg
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Crops	4982	98	16	69	12
Village	4184	259	74	166	4
Cooking	17868	128	5	60	20
Inputs to TP	C	N	P	Ca	Mg
Charcoal from cooking	536	1	5	60	20
Plant Residues	1993	75	12	9	9
Waste	1153	155	74	166	4
Deposition		8			
Total	3682	239	90	235	33
Outputs from TP*	C	N	P	Ca	Mg
Crop uptake		98	16	69	12
Total output		98	16	69	12
Soil surplus**	3682	141	75	166	21

Using the data from Table 3 and Table 2 the occupation period was calculated to be 180 years. We checked this figure by exploring the stoichiometry of the inputs with Terra Preta. We observed that P:Ca in the net input is slightly higher in the estimated inputs than in the net input according to the soil data, whereas the Ca to Mg ratio is a bit lower. This can be caused by an extra input of calcareous material like shells which was not taken into account, but which might be of great importance in at least some TP sites (Teixeira, 2006).

Table 4 Element ratios. Net accumulation according to the soil data is the difference in nutrient content between the TP and the adjacent oxisol as measured by Glaser (1999). Calculated accumulation is the accumulation calculated in the model. * the parameters in Table 6 were adjusted in such a way that C:N, N:P and C:P ratios are the same in the model as in the measurements of Glaser (1999).

Nutrient ratios	C:N	N:P	C:P	P:Ca	P:Mg	Ca:Mg
Net accumulation (according to soil data)	21	2	41	0.3	3	9
Calculated accumulation	21*	1*	41*	0.4	3	8

Using the model described above (see appendix I for equations) we determined the conditions needed to generate a TP within 180 years of occupation that after hundreds of years of abandonment shows the characteristics as shown in Table 2. We calculated (using excel solver) that given the inputs above the fraction of charcoal in the soil that decomposes each year should be around 0.05% and one gram char C can stabilize 3.1 gram of non char C, the C-N ratio of the stabilized material is 15.9 (Table 5).

Table 5 Coefficients that determine the soil dynamics of C and N in Terra Preta and allow for Terra Preta formation in 180 years given the annual soil surplus calculated (see Table 3)

Coefficients that determine C and N dynamics in TP	
Decomposition coefficient char ¹	0.0005
The amount of C that can be stabilized by one gram of partly oxidized char (g g ⁻¹) ¹	3.1
Carbon nitrogen ratio of stabilized material (g g ⁻¹) ¹	15.9

The strong stabilization of organic carbon and nitrogen by char causes carbon and nitrogen accumulation to continue even during (temporal) abandonment (Figure 4). However, it is possible that the post abandonment N accumulation can partly be attributed to other processes. Nitrogen inputs could be higher because of an increased nitrogen fixation during TP formation because of higher pH and greater availability of P (Giller, 2001; Rondon et al., 2006). Furthermore, currently re-growing forests on oxisols are probably P and Ca limited (Feldpausch 2005), however on TP soils being rich in P and Ca, the forests might become N-limited and hence no N might be left for stabilization.

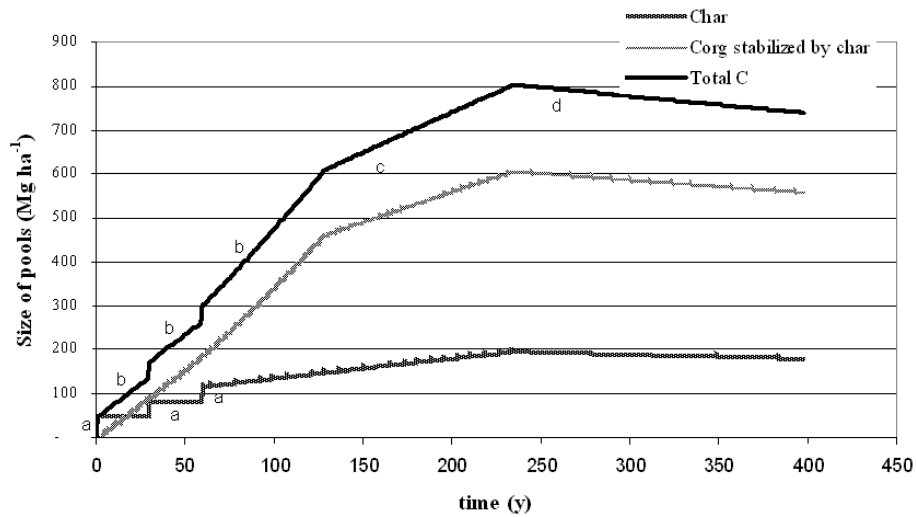


Figure 3 Graph showing the amount of C in soil char (lower), and C stabilized by the char over time (middle) and total soil C accumulation (upper). The graph starts at zero because char and stabilized carbon before the start of TP formation is not taken into account. In this graph the TP site was occupied three times. Two times short (2 years) and one time long (176 years). The fast increase in char after vegetation clearing and charring is indicated with an a. This increased char content caused accumulation of soil organic matter even when the site was not cultivated (b). Initial accumulation (b) occurred fast and was limited by supply of organic matter. At a given moment the stabilizing capacity of char is saturated and the stabilization of organic matter is limited by the amount of char added from cooking fires (c). After abandonment of the TP site, no char is added anymore and soil C stocks slowly decrease.

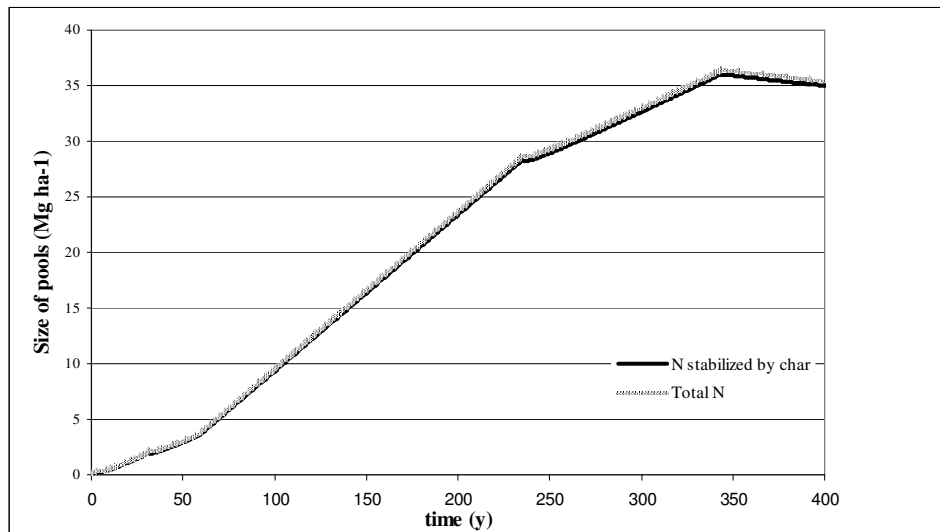


Figure 4 Graph showing the amount of total soil N and N stabilized by the char over time. The graph starts at zero because char and stabilized N before the start of TP formation is not taken in account. A slow accumulation occurs after the first clearing and charring of the vegetation. In this stage nitrogen accumulation is fed by litter fall and hence limited by N fixation of the emerging vegetation, which is different than N fixation during cultivation ($80 \text{ kg N ha}^{-1} \text{ yr}^{-1}$). During the long period of occupation (between $t=60$ till $t=237$), N is added in greater amounts. After abandonment N keeps accumulating during forest regrowth because the N binding capacity was not yet saturated at that point.

The model results are especially sensitive to parameters related to the char input. A 10% increase or decrease in the carbonization efficiency of cooking fires changes the decomposition coefficient with 10% whereas a change in carbonization efficiency of the standing biomass during clearing causes a 5 % change in the decomposition coefficient. The eventual amount of black carbon in the soil is fixed. Therefore, changes in black carbon inputs cause proportional changes in char decomposition but to a much lesser extent to C and N stabilization coefficients which are rather insensitive to parameter changes. Changes in C and N soil surplus

during TP occupation or in N fixation during (temporary) abandonment do not change the coefficients displayed in Table 5, but it changes the shape of the graphs above. Generally speaking, if less C and N is stabilized during TP occupation more is stabilized during abandonment, between certain limits that are determined by the stabilization ratio of the char.

There is discussion whether Terra Preta was formed intentionally. Some claim that Terra Preta was formed as an unintentional side result of large-scale occupation and subsequent waste dumping strategies (Kern et al., 2003); while others argue that they must have been formed intentionally, because of the disproportional amounts of charcoal (Erickson, 2003). Both hypotheses have their problems because the fertility of the site has to exceed a certain threshold before permanent cultivation becomes more profitable than shifting cultivation.

This threshold is partly caused by the minimum amount of change needed before beneficial soil fauna will appear to improve soil characteristics further and faster (positive feedback).

Our hypothesis (see description of scenario above) allows for a more evolutionary perspective. It may well be that a group living in the Amazon once cleared and charred the vegetation instead of cleared and burned it (e.g. because the burning was done in the rainy period). When returning to the place, a few decades later, the inhabitants might have found it more fertile than before and consequently decided to stay. Assuming they remembered that they did something special when charring the vegetation, the technique might have diffused quickly afterwards. The surrounding areas that the initial inhabitants hardly occupied were used as

extensive gardens with fruit trees and useful palm species, which might very well have become Terra Mulata, or the brownish soil often observed around Terra Preta. Terra Mulata (Denevan 1996 et al) is rich in char but has no ceramics and shows often lower P levels.

4 IMPLICATIONS

Besides gaining relevant information on C, N and P flows, we identified some major knowledge gaps. To fill these gaps in our carbon and nutrient model more studies are needed that integrate anthropological and archaeological, agronomic and soil scientific research efforts.

4.1 Anthropological and Archaeological studies

Besides quantitative evidence from Colombia (Mora, 2003) much remains unknown about the extent and importance of fluvial sediment and the incorporation of shells (Teixeira, 2006). However Seabrook's own measurements (unpublished data from ISRIC) shows increased levels of available Ca & Mg, however no char till a depth of 4 meter. This might be caused by fluvial clay particles. The same holds true for inputs from agriculture in the flood plain. New archaeological excavations in combination with analogies of contemporary riverine native peoples could bring us further in understanding the complex agriculture of the Amazonian civilizations. As food and agriculture, and hence soil, are coupled we need to improve our knowledge of the diets of contemporary and ancient inhabitants of South America's vast rainforests. The role of construction materials in the

formation can be larger than expected. An interdisciplinary team of soil scientists, archaeologists, and anthropologists could make better estimates of the size of the flows of nutrients and carbon. Consequently, studies of the use of fuel wood by native residents of the Amazon basin can lead to a better insight to what extent cooking really contributed to charcoal accumulation. Or more generally, how various practices led to fires with different temperatures, charring fractions, and hence char ‘quality’. Our model of two char sources with carbonization coefficients of 35% and 3% may well need fine-tuning.

The carbonization efficiency of cooking fires and infield burning of fallow vegetation (during wet vegetation) remains unknown. Furthermore, the characteristics of these char types are unknown. Field experiments and research on current charcoal and its stabilizing capacity used in agriculture in these areas will contribute to our understanding of TP formation.

Understanding ancient land use practices and having knowledge of the technological scope in which the indigenous population operated is of great importance. For instance what were the yields of ancient cassava and other Amazonian crops like maize, and how did they respond to TP formation. Phytolith research together with field research of traditional crops could bring us closer. Normally, under tropical conditions household waste and excreta are decomposed very fast. It is important to research the relation between chars and the decomposition and leaching from household waste and excreta disposals. Continued modelling work could decipher the actual size of the population responsible for the formation of the Terra Preta and the migration strategy. How

many people would be needed to create a Terra Preta? How much soil needs to be moved? How fast could the Amerindians have returned (if at all) to the same spot?

4.2 Soil scientific studies

Is forest regrowth faster on soils that are amended with charcoal? And is it limited by other nutrients than a normal regrowth? These are interesting studies both for gaining insight on TP formation as well as for understanding the relevance of TP like techniques for restoring degraded areas.

Besides that we need to know whether there were other major P inputs besides fish at village level. And what is the percentage of nutrients disposed of through urine and faeces that can be captured in soils amended with charcoal?

Another exciting aspect of the formation of Terra Preta is the interaction between the inputs. For example, the preliminary results of ongoing research of our group (Gollenbeek et al, in preparation) indicates that char can only stabilise soil organic matter when enough calcium is available. This might explain the shell amendments as observed by Teixeira et al.(2006).

5 REFERENCES

Amous S, 1999, The role of wood energy in Africa, Forestry Department, Food and Agriculture Organization of the United Nations, Rome, Italy

Antal MJ, Gronli M, 2003, The art, science, and technology of charcoal production, *Industrial and Engineering Chemistry Research* 42 (8): 1619-1640

Blume HP, Leinweber P, 2004, Plaggen soils: landscape history, properties, and classification, *Journal of Plant Nutrition and Soil Science*: 319-327 .

Brown S, Lugo AE, 1992, Above ground biomass estimates for tropical moist forests of the Brazilian Amazon, *Interciencia* 17 (1): 8-18

Cheng CH, Lehmann J, Thies JE, Janice E, Burton SD, Engelhard MH, 2006, Oxidation of black carbon by biotic and abiotic processes, *Organic Geochemistry*, 37 (11): 1477-1488

Costa ML da, Kern DC, 1999, Geochemical signatures of tropical soils with archaeological black earth in the Amazon, Brazil, *Journal of Geochemical Exploration* 66 (1-2): 369-385

Costa ML da, Kern DC, Pinto AHE, Trindade Souza JR da, 2004, The ceramic artefacts in archaeological black earth (Terra Preta) from lower Amazon region, Brazil: Mineralogy, *Acta Amazonia* 34 (2): 165-178

Dabrowska H, Meyerburghdorff KH, Gunther KD, 1991, Magnesium status in fresh water fish, common carp and the dietary protein-magnesium interaction, *Fish Physiology and Biochemistry* 9 (2): 165-172

Erickson C, 2003, Historical Ecology and future Explorations. In: J Lehmann, DC Kern, B Glaser, WI Woods (Eds.), *Amazonian Dark Earths: Origin, properties, management*. Kluwer Academic Publishers, The Netherlands: 455-500

Feldpausch TR, Rondon MA, Fernandes ECM, Riha SJ, Wandelii E, 2004, Carbon and nutrient accumulation in secondary forests regenerating on pastures in central Amazonia, *Ecological Applications* 14(4) Supplement: 164-176

Gehring C, Denich M, Vlek PLG, 2005, Resilience of secondary forest regrowth after slash-and-burn agriculture in central Amazonia, *Journal of Tropical Ecology* 21: 519-527

Gehring C, Vlek PLG, de Souza LAG, Denich M, 2005b, Biological nitrogen fixation in secondary regrowth and mature rainforest of central Amazonia, *Agriculture Ecosystems and Environment* 111 (1-4): 237-252

Giller KE, Merckx R, 2003, Exploring the boundaries of N₂-fixation in cereals and grasses: A hypothetical and experimental framework, *Symbiosis* 35: 3-17

Glaser B, Guggenberger G, Zech W, Ruivo M de L , 2003. Soil organic matter stability. In: Lehmann J, Kern DC, Glaser B and Woods WI (Eds.), *Amazonian Dark Earths: Origin, properties, management*. Kluwer Academic Publishers, The Netherlands: 227-241

Glaser, B, 1999, Eigenschaften und Stabilität des Humuskörpers der „Indianenerschwarzerden“ Amazoniens, *Bayreuther Bodenkundliche Berichte*, Band 68, Bayreuth

Guttmann EB, Simpson IA, Davidson DA, Dockrill SJ, 2006, The management of arable land from prehistory to the present: Case studies from the northern isles of Scotland, *Geoarchaeology- an International Journal* 21 (1): 61-92

Heckenberger MJ, Kuikuro A, Kuikuro UT, Russell JC, Schmidt M, Fausto C, Franchetto B, 2003, Amazonia 1492: Pristine forest or cultural parkland?, *Science* 301 (5640): 1710-1714

Hendrixson HA, Sterner RW, Kay AD, 2007, Elemental stoichiometry of freshwater fishes in relation to phylogeny, allometry and ecology, *Journal of Fish Biology* 70 (1): 121-140

Howeler, RH 1991, Long-term effect of cassava cultivation on soil productivity, *Field Crops Research* 26 (1): 1-18

Kawano K, 1990, Harvest index and evolution of major food crop cultivars in the tropics, *Euphytica* 46: 195-202

Lehmann J, Liang BQ, Solomon D, Lerotic M, Luizao F, Kinyangi J, Schafer T, Wirick S, Jacobsen C, 2005, Near-edge X-ray absorption fine structure (NEXAFS) spectroscopy for mapping nano-scale distribution of organic carbon forms in soil: Application to black carbon particles, *Global Biogeochemical Cycles* 19 (1): GB1013

Lehmann J, Silva da JP, Steiner C, Nehls T, Zech W, Glaser B, 2003, Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments, *Plant and Soil* 249 (2): 343-357

Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, Skjemstad JO, Thies J, Luizao FJ, Petersen J, Neves EG, 2006, Black Carbon increases cation exchange capacity in soils, *Soil Science Society of America Journal* 70 (5): 1719-1730

Madari B, Benites VM de, Cunha TJF, 2003, The effect of management of the fertility of Amazonian dark earth soil. In: Lehmann J, Kern DC, Glaser B, Woods WI (Eds.), *Amazonian Dark Earths: Origin, properties, management*. Kluwer Academic Publishers, The Netherlands: 407-432

Mora S, Archaeobotanical Methods for the Study of Amazonian Dark Earths, in .
In: Lehmann J, Kern DC, Glaser B, Woods WI (Eds.), Amazonian Dark Earths:
Origin, properties, management. Kluwer Academic Publishers, The Netherlands:
205-226

Murrieta RSS, Dufour DL, 2004, Fish and Farinha: protein and energy
consumption in Amazonian Rural Communities on Ituqui island, Brazil, *Ecology
of Food and Nutrition* 43 (3): 231-255

Nascimento HEM, Laurance WF, 2004, Biomass dynamics in Amazonian forest
fragments, *Ecological Applications* 14 (4): S127-S138

Neves EG, Petersen JB, Bartone RN, Silva CA da, 2003, Historical and socio-
cultural origins of Amazonian Dark Earths. In: Lehmann J, Kern DC, Glaser B,
Woods WI (Eds.), Amazonian Dark Earths: Origin, properties, management.
Kluwer Academic Publishers, The Netherlands: 29-50

Pastor-Villegas J, Pastor-Valle JF, Rodriguez JMM, 2006, Study of commercial
wood charcoals for the preparation of carbon adsorbents, *Journal of Analytical and
Applied Pyrolysis* 76 (1-2): 103-108

Pettersen RC, 1984, The chemical composition of wood. In: Rowell RM (ed.),
The chemistry of solid wood. Advances in chemistry series 207. Washington, DC,
American Chemical Society

Rondon MA, Lehmann J, Ramírez J, Hurtado M, 2006, Biological nitrogen
fixation by common beans (*Phaseolus vulgaris* L.) increases with biochar additions,
Biological Fertility of Soils (in press)

Ruivo MLP, Arroyo-Kalin MA, Schaefer CER, Costi HT, Arcanjo SHS, Lima HN, Pulleman, MM, Creutzberg D, 2003, The use of micromorphology for the study of the formation and soil properties of Amazonian Dark Earths. In: Lehmann J, Kern DC, Glaser B, Woods WI (Eds.), Amazonian Dark Earths: Origin, properties, management. Kluwer Academic Publishers, The Netherlands: 243-254

Schaefer CEGR, Lima HN, Gilkes RJ, Mello JWV, 2004, Micromorphology and electron microprobe analysis of phosphorus and potassium forms of an Indian Black Earth (IBE) Anthrosol from Western Amazonia, Australian Journal of Soil Research 42 (4): 401-409

Schouw NL, Danteravanich AS, Mosbaek H, Tjell JC, 2002, Composition of human excreta — a case study from Southern Thailand, Science of the Total Environment 286 (1-3): 155-166

Smaling EMA, Oenema O, Fresco LO, 1987, Nutrient Disequilibria in Agroecosystems Concept and Case-studies, Cabi Publishing

Sterner RW, Elser JJ, 2002, Ecological Stoichiometry: The biology of elements from molecules to biosphere, Princeton University Press, Princeton

Sterner RW, George NB, 2000, Carbon, nitrogen, and phosphorus stoichiometry of cyprinid fishes, Ecology 81 (1): 127-140

Stoorvogel J, Smaling EMA, Janssen BH, 1993, Calculating soil nutrient balances in Africa at different scales, Fertilizer Research 35 (3): 227-235

Szott L, Palm C, Buresh R, 1999. Ecosystem fertility and fallow function in the humid and subhumid tropics, Agroforestry Systems 47: 163–196

Teixeira WG, Martins GC, Arrudal MR, Steiner C, 2006, The Rescue of an Old Indigenous Practice in the Tropics—Using Charcoal to Improve Soil Quality, Presentation at 18th world congress of soil science, Symposium: 6B Amazonian Dark Earth Soils (Terra Preta and Terra Preta Nova): A Tribute to Wim Sombroek, Philadelphia

Trompowsky PM, Benites VD, Madari BE, Pimenta AS, Hockaday WC, Hatcher PG, 2005, Characterization of humic like substances obtained by chemical oxidation of eucalyptus charcoal, *Organic Geochemistry* 36 (11): 1480-1489

USDA, 2006, www.nal.usda.gov/fnic/foodcomp

Vitousek PM, 1986, Sanford RL, Nutrient cycling in moist tropical forest, *Annual Review of Ecology and Systematics* 17: 137-167

6 APPENDIX I: EQUATIONS IN NUTRIENT POOL MODEL

6.1 Char in soil over time (CHAR_t (kg ha^{-1}))

$$\text{CHAR}_t = \text{CI} + \text{CHAR}_{t-1} \cdot (1 - a \cdot (t - (t-1)))$$

CI annual char input (kg ha^{-1})

a stands for the decomposition coefficient of char ($\text{g g}^{-1}\text{yr}^{-1}$)

t time (years)

In words: the amount of charcoal in the soil equals the previous amount of charcoal in the soil minus the amount of char that is decomposed.

6.2 C Stabilization capacity of all chars in the soil (SCC_t (kg ha^{-1}))

$$SCC_t = c \cdot CHAR_t$$

c the amount of C that can be stabilized by one gram of fresh char (g g^{-1})

So, all types of char in the soil are expected to be as effective in terms of stabilizing carbon. Char is likely to become more effective over the years as it edges oxidize. Therefore c has to be considered as an average value.

6.3 N Stabilization capacity of all chars in the soil (SCN_t (kg ha^{-1}))

$$SCN_t = e^{-1} \cdot SCC_t$$

e carbon nitrogen ratio of stabilized material (g g^{-1})

6.3.1 Carbon input to soil (CIN_t kg C ha^{-1})

6.3.2 During TP formation

$$CIN_t = (\text{Waste} + \text{Residues}) \cdot$$

Waste and residues in (kg ha^{-1})

In words input to TP consist of waste and excrements from village and the residues of crops.

6.3.3 During regrowth after abandonment

$$CIN_t = LIT(1 + h)^{-1} \cdot (f \cdot h + g) \cdot BMF_t \cdot 250^{-1}$$

f C content woody litter (g g⁻¹)

g C content leafy litter (g g⁻¹)

LIT Annual amount of litter dry biomass (kg ha⁻¹) of a forest with a standing biomass of 250 Mg há⁻¹

h Wood leaf ratio litter (g g⁻¹)

BMF_t Biomass (kg ha⁻¹) of standing forest $131.9 \cdot \log t$, t is time in years (Gehring, 2005)

In words, amount of C input is the sum of the amount of woody and leavy litter times there respective C content. Because the amount of litter is determined in a forest with a standing biomass of 250 Mg há⁻¹ the litter fall is corrected for the amount of standing biomass. A linear relation between standing biomass and litter fall is expected.

Carbon stabilized CS_t

$$CS_t = \min (SCC_t, CS_{t-1} + CIN_t)$$

IN_t carbon in inputs to soil (kg C ha⁻¹)

6.4 Nitrogen stabilized NS_t

$$NS_t = \min (SCN_t, NS_{t-1} + NSS_t)$$

NSS_t soil surplus of nitrogen (kg ha⁻¹) this is calculated by

$NSS_t = NIN - NR_t + i^{-1} \cdot (CF_t + CPO_t)$. In which

NIN is the input of N by biological fixation and domestic wastes (kg ha^{-1}) during TP formation and biological fixation only during forest regrowth.

NR_t is nitrogen removal (kg ha^{-1}) which is harvest during TP occupation phase 1 and nitrogen accumulation by trees during temporal abandonment (phase 2).

i stands for nitrogen carbon ratio char (g g^{-1})

Nitrogen accumulation is calculated by the biomass accumulation ($131.9 \cdot \log t$) times the nitrogen content of wood.

In words, the amount of nitrogen stabilized (NS_t) is the minimum value of the nitrogen stabilizing capacity of the soil and the sum of the previous amount of nitrogen stabilized and the soil nitrogen surplus.

Table 6 The coefficients used in the model described. 1) Calculated using Excel solver. 2) Pastor-Villegas et al., 2006, Antal and Gronli, 2003. 3) Feldpausch et al, 2003. 4) See table 3. 5) Gehring et al, 2005. 6) Szott et al, 1999.

Coefficients		
Decomposition coefficient char ¹ (g g^{-1})	0.0005	a
The amount of C that can be stabilized by one gram of char (g g^{-1}) ¹	3.1	d
Carbon nitrogen ratio of stabilized material (g g^{-1}) ¹	15.9	e
C content woody biomass(g g^{-1}) ³²	0.50	f
Nitrogen carbon ratio char (g g^{-1}) ³²	469	i
Wood leaves ratio litter (g g^{-1}) ³³	0.19	h
C content leafy litter (g g^{-1}) ³	0.46	g
Annual char input (after initial clearing) ($\text{kg ha}^{-1} \text{yr}^{-1}$) ⁴	536	CI
Annual carbon input to soil during TP	3 146	CIN _t

formation(kg C ha-1 yr ⁻¹) ⁴		
Amount of litter dry biomass (kg ha ⁻¹ yr ⁻¹) of a forest with a standing biomass of 250 Mg ha ⁻¹ ⁵	8 300	LIT
Input of N by deposition and domestic wastes during TP formation (kg ha ⁻¹ yr ⁻¹) ⁴	241	NIN
Input of N by biological fixation during regrowth ⁶ (kg ha ⁻¹ yr ⁻¹)	80	NIN
Nitrogen removal on TP during occupation (kg ha ⁻¹ yr ⁻¹) ⁴	98	NR
