Royal Geographical Society with IBG
Advancing geography and geographical learning

AREA

Area (2011) 43.3, 264–273 doi: 10.1111/j.1475-4762.2011.00999.x

Anthropogenic soils in the Central Amazon: from categories to a continuum

James Fraser*, Wenceslau Teixeira, Newton Falcão†, William Woods††, Johannes Lehmann‡ and André Braga Junqueira†**

*Department of Anthropology, University of Sussex, Falmer, Brighton BN1 9SJ

Email: james.angus.fraser@gmail.com

**Embrapa Solos, Jardim Botânico 22460-000, Rio de Janeiro, RJ – Brazil

†Instituto Nacional de Pesquisas da Amazônia: CPCA, Aleixo, Manaus, Amazonas 69011-970, Brazil

††Department of Geography, University of Kansas, Lawrence, KS 66045, USA

‡Department of Crop and Soil Sciences, Cornell University, Ithaca, NY 14853, USA

Revised manuscript received 6 January 2011

Amazonian Dark Earths (ADE), one of the best-known examples of anthropogenic (man-made) soils, are the result of Amerindian settlements in the pre-Columbian period. ADE are highly variable in terms of their size, shape, depth and physical and chemical make-up. Scholars tend to divide ADE into two categories: terra preta *and* terra mulata*. The former are dark and highly fertile soils replete with ceramic shards, indicating former areas of habitation, while the latter are lighter in colour, less fertile, lacking pottery and thought to be old agricultural fields. While a scientific consensus on the origins of* terra preta *has existed for several decades, the origins of* terra mulata *remain enigmatic and contested. We argue that owing to the overlapping and constantly changing boundaries of agricultural and habitational areas, it is unlikely that there exist two clear soil fertility classes. This article examines the hypothesis that rather than two distinct anthrosol categories, ADE sites should exhibit a highly fertile 'core area', which grades into more subtly modified soils, with a continuum of fertility between them. Using principal components analysis (PCA) and interpolations based on the geographic distribution of the soil samples, we show that ADE along the Middle Madeira, Brazilian Amazon are extremely diverse, but data support more of a gradient between areas of greater and lesser fertility rather than two distinct categories. We also assess local people's perceptions and classifications of anthropogenic and surrounding soils using ethnographic data. Rather than discarding the* terra preta–terra mulata *opposition however, we suggest abandoning only the idea that they are separate categories, and instead emphasise a continuum, the darker, bluff edge 'central' regions with abundant ceramics are consonant with published descriptions of* terra preta, *which grade into surrounding areas with lighter, less fertile soils that better fit* terra mulata *descriptions.*

Key words: *Middle Madeira River, Amazonian Dark Earths, principal components analysis, interpolation,* terra preta, terra mulata

Introduction

The daily activities of rural and forest peoples concentrate organic material and chemical elements in the soil. In areas of habitation, anthropogenic soils emerge through domestic refuse management involving the burning, sweeping and mounding of diverse wastes including fish, turtle and mammal bones, palm fronds, weeds etc. In agricultural fields, soils are enriched by way of in-field burning and mulching. Such processes of anthropogenic soil enhancement have developed independently in several regions across the world (Woods 2003). Among the best known examples of anthrosols are 'Amazonian Dark Earths' (ADE) (Woods *et al.* 2009). The formation of ADE is a legacy of Amerindian populations that reached their height during the late pre-Columbian period (2000–500 BP) (Neves 2008). Today these soils, still highly fertile hundreds or several

ISSN 0004-0894

thousand years after formation, are found at archaeological sites throughout the Amazon basin.

ADE form through the additions of charred and fresh organic material to soils. This initiates a set of biological and chemical processes that lead to increased soil organic matter, microbial biomass and diversity, cation exchange capacity, pH and nutrient retention, all of which are beneficial for agriculture (Lehmann *et al*. 2003; Liang *et al*. 2006 2010; O'Neill *et al*. 2009; Grossman *et al*. 2010). Over time, such practices increase soil fertility and the content of nutrients available for plant growth. This contrasts strongly with highly leached, nutrient poor oxisols and ultisols that typify soils of the Amazonian *terra firme*. The term ADE encompasses a great degree of diversity in size, shape, depth and chemical elements of Amazonian anthrosols. ADEs are typically divided into two categories: *terra preta* and *terra mulata* (Sombroek 1966; Andrade 1986; Kern and Kämpf 1989; Arroyo-Kalin 2008). *Terras pretas* form under sites of domestic inhabitation. They are very dark in colour, replete with broken potsherds and exhibit highly elevated levels of phosphorus (P), calcium (Ca), manganese (Mn), magnesium (Mg), zinc (Zn) and other minerals essential for plant growth. *Terras mulatas* are less well documented and therefore more contentious. These soils, less nutrient rich – with only slightly elevated pH, P, Ca, Mg, Mn, Zn – are light brown or greyish in colour, and have been reported to have been found adjacent to some *terra preta* sites. Various regional scholars have suggested that *terras mulatas* formed through intensive agriculture involving 'cool' burning and mulching, with low oxygen input (Sombroek 1966; Andrade 1986; Woods and McCann 1999; Hecht 2003).

Studies of ADE have typically classified anthropogenic soils as *terra preta* and *terra mulata*. Wim Sombroek first demonstrated the difference between *terra preta* and *terra mulata* chemically at Belterra on the lower Tapajós (Sombroek 1966). Woods and colleagues clearly showed the chemical differences between *terra preta*, *terra mulata* and oxisols (Woods and McCann 1999) and confirmed these differences with near infrared spectroscopy at a number of sites in the lower Tapajós and Arapiuns drainages (McCann *et al*. 2001). Denevan incorporated the *terra preta–terra mulata* opposition into his model of pre-Columbian agriculture (Denevan 2006). Arroyo-Kalin (2008) compared ADE sites at different locations and formed on different parent materials in the Negro-Solimões confluence region. Using geoarchaeological methods he demonstrated that some ADE fit the profile of *terra preta*, while others appeared to be *terra mulata*. However, drawing on recent evidence from extensive soil sampling in contemporary Kuikuro villages and agricultural areas at the upper Xingu River, Schmidt (2010) demonstrated that the pattern of soil fertility enhancement shows a gradient from most fertile areas under home gardens, which grade into more subtle fertility enhancements in outlying fields. Other studies have also demonstrated considerable intra-site chemical diversity in ADE sites (Kern 1996; Rebellato *et al*. 2009).

It is intuitive to think of anthropogenic soils as *gradients* instead of distinct categories of fertility. Even though habitational and agricultural areas might be clearly separated in a given time, these limits tend to change and/or disappear, especially in contexts of long periods of habitation and/or successive re-occupations of the same site, and indeed the areas often overlap, which is what happens to contemporary populations and it has likely happened in the past. Nonetheless, the notion of *terra preta* and *terra mulata* as separate soil categories prevails in scientific literature, and this issue remains still uncritically examined.

Local perceptions of ADE can be highly variable depending on each individual and/or social group life history and the degree of interaction with these environments. Traditional farmers recognise ADE according to several characteristics, including the presence/absence of ceramics, the colour and texture of the soil and the floristic composition (Fraser 2009). Anthropological studies have shown that local farmers recognise diverse stages of forest regrowth on ADE through indicator plant species, even when vegetation is dense (German 2003). Farmers also recognise vegetation structural characteristics associated with ADE, such as lower canopies and denser understories (Woods and McCann 1999), smaller average diameter of adult trees, and a greater abundance of vines and plants with spines (German 2003). Some species from secondary forests on ADE are recognised as ADE indicators, including some domesticated and/or useful species (Junqueira *et al*. 2010). Despite these studies, however, several aspects of the local perceptions regarding ADE, including the ethnotaxonomy of these soils, remain to be investigated.

The objectives of our study, therefore, were to examine the spatial heterogeneity of ADE. Following Schmidt (2010), we hypothesised that patches of ADE form a gradient from high fertility to low fertility, instead of two well-defined classes. Proceeding from the anthropological studies outlined above, we hypothesised that locals would be cognisant of the diversity of ADE and this would be reflected in their classification of soils.

Materials and methods

The Middle Madeira

The River Madeira is the longest tributary of the River Amazon and the sixth biggest river in the world. It is classified as a whitewater river because of the fertile alluvium brought down from the mountains that give the turbulent waters their light brown colour (Sioli 1984). In

ISSN 0004-0894

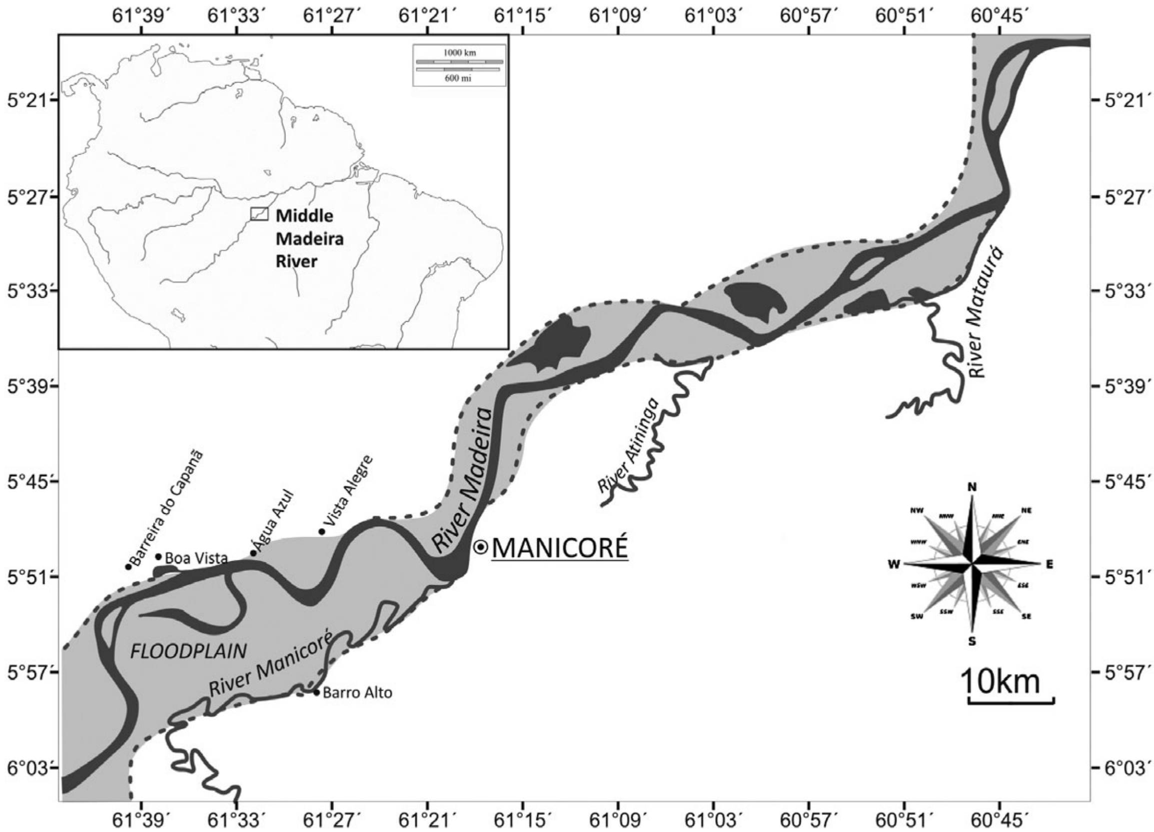

Figure 1 Communities along the Middle Madeira where soil samples were taken and locals were interviewed. Inset: the position of the Madeira River in northern South America
Source: Map by Victoria Frausin

the late pre-Columbian era (AD 500–1500), this rich whitewater environment such as the Madeira supported large and settled Amerindian populations (Neves 2008). During the course of the research described here, 22 ADE sites were visited. In this article we analyse soil samples and GPS data from five of these ADE sites (Figure 1). We also recorded local perceptions of soils and vegetation, through ethnography and participant observation.

ADE sites are extremely variable even within an area of 1 m^2, because of the diversity of pre-Columbian land use and settlement. To capture this great variation even at one site requires thousands of individual soil samples (Schmidt 2010). Given the limited financial resources at our disposal, only enough for the analysis of around 150 samples, we decided instead to use composite samples, which, while losing the accuracy and resolution of individual samples, would allow us to build up a broader, multi-sited and comparative perspective on the variability of ADE, and test our hypothesis. The alternative, a study of 150 individual samples from part of an individual site (a) has been done before (Kern 1996; Rebellato *et al*. 2009), and (b) would not provide us with the comparative material necessary to test our hypothesis.

Soil samples were collected at five ADE sites on the Middle Madeira River (Figure 1), which are currently occupied and used by local residents as habitation and agricultural areas. In total, we collected 142 composite soil samples (Supplementary Material, Tables S1–S5). Each composite sample was made of five simple samples collected from a depth of 0–0.2 m (after removing the litter and superficial roots) in areas ranging from 25 × 10 m (250 m^2) up to 250 × 10 m areas (2500 m^2), depending on land use units being sampled (swidden and home garden samples were taken from smaller areas, fallow samples were taken from larger areas). Sampling avoided freshly burnt fields and paid special attention to areas that were apparently on the transition between ADE and background soils. Qualitative information about the vegetation cover, soil characteristics as colour, texture, ceramic content and brief use-history were recorded for each area sampled. Qualitative data on local knowledge of soils was gathered during long-term ethnography in the region. GPS

ISSN 0004-0894

coordinates were obtained from the centre of each area sampled. Each sample was air-dried, sieved with a mesh of 2 mm, homogenised and analysed at the Laboratory of Soils and Plants (LTSP) of INPA and at the Embrapa Amazônia Ocidental Soil Laboratory, both located in Manaus, Brazil. Results of seven parameters associated with soil fertility were recorded: pH (H_2O), available P, Ca, Zn, Mn (using Melich I as extractor), Ca and Mg (using KCl 1 mol l^{-1} as extractor). The P in the extracts was determined using a colorimeter and for the other minerals by using atomic absorption spectrometry. Details about the methodology used for chemical evaluation of the soil samples are described in EMBRAPA (1997).

The results of the soil chemical analyses were analysed with a principal component analysis (PCA) bi-plot calculated using Pearson's n in the software XLSTAT 2010 (Addinsoft) using the variables pH, P, Ca, Mg, Zn and Mn. The GPS coordinates of each sample were plotted on a georeferenced map, and values for each of the soil variables measured were predicted in space through an interpolation analysis with an inverse-distance weighted procedure with a cell size of 1.15 meters, using the software ArcGis 9.3 (ESRI).

Results and discussion

Local perceptions

Caboclos classify soils according to their colour and texture, floristic composition of secondary vegetation that cover them, and their known history of use. Locals classify non-anthropogenic soils of the *terra firme* based on the amount of sand/clay. Clayey soils are easily recognised and called *barro amarelo*, *barro vermelho* or *barro branco/tabatinga*, depending on yellow, red or grey colouring. The residents also recognise that soils may be a mixture of these types, such as sand mixed with clay. In this folk taxonomy *terra preta* is unmistakable owing to its very dark colouring, pottery shards, different successional vegetation and distinct suite of volunteer species associated with it. Texturally *terra preta* is designated as either *solta* (loose) or *dura* (hard), or somewhere in between. Some plant species, such as the palms Caiaué (*Elaeis oleifera*), Urucuri (*Attalea phalerata*) or a weed locally known as *Maria-preta*, *Marmeleiro* or *Rabo-de-gato* (*Acalypha brasiliensis*), are recognised as being strongly associated with ADE (Junqueira *et al*. 2010). Locals also recognise a transitional gradient between *terra preta* and background soils, which they refer to by saying the *terra preta* is 'mixed with' sand or clay in these areas. According to locals, the further away from core areas of *terra preta* one moves, the amount of sand or clay in the 'mix' increases, and the amount of *terra preta* in the mix decreases.

Local farmers of the Middle Madeira River recognise that vegetation burning is related with the formation of ADEs and are also aware that the ADE expanses farmed by their communities mark the places where Indians used to reside. *Caboclos* recognise processes of ADE formation in the outcomes of three sets of practices (a) sweep and char in the home garden, (b) infield burning (known as *queima de coivara*) and (c) burning fallow. The changes they typically report include a darkening of the soil, an improvement in crop performance and also that soil becomes 'sandier', all features they also recognise in ADEs, which are perceived as sandier and fluffier (*mais fofa*) compared with adjacent soils. Several individuals also say that their grandparents or other elders told them that *terras pretas* formed at the sites of Indian villages. These observations constitute a local folk model that explains the formation of ADEs in the landscapes they inhabit. It extends to fine distinction between different types: one individual noted that some parts of *terra preta* are darker with potsherds, while other parts are lighter and without potsherds. This person hypothesised that the former are the locations where the Indians lived and the latter is where they planted. Along the Middle Madeira River therefore, some locals describe ADE in ways that resemble scientific definitions of both *terras pretas* and *terras mulatas*, and attribute to them origins similar to those proposed by scientists. If individuals today can become aware of processes of ADE formation, then it seems reasonable to assume that Amerindians would also have become aware, which then raises the possibility that intentionality may have begun to play a role in ADE formation as Amerindians became conscious of how their actions transformed the landscape.

Soil analyses

Barro Alto Barro Alto is one of the largest communities in the department of Manicoré, with over 500 residents (Figure 1). The cultivation of bitter manioc is the main land-use in all kinds of soil. ADE stretch from the edge of the bluff back to where nutrient levels suggest little enhancement. The whole community and adjacent cultivation area are located on ultisols, probably the original soils on which ADE have formed. The ADE at Barro Alto conformed to a simple, circular, bluff-edge pattern, located at a strategic outer bend in the River Manicoré (Figure S1). Closest to the bluff we see fertility levels that are consonant with published *terra preta* soil samples characterised by elevated pH and much higher levels of P, Ca, Mg, Zn and Mn than surrounding soils (Smith 1980; Teixeira and Martins 2003; Falcão *et al*. 2003) (SM2, Supplementary Table (ST) I).

Further behind, we encounter ADE with high P levels, but lower levels of Ca, Mg, Mn, Zn. Interestingly, these samples seem to form a continuous area from the south of Barro Alto (Figure S1, Table S1, samples 14, 38, 37) across

ISSN 0004-0894

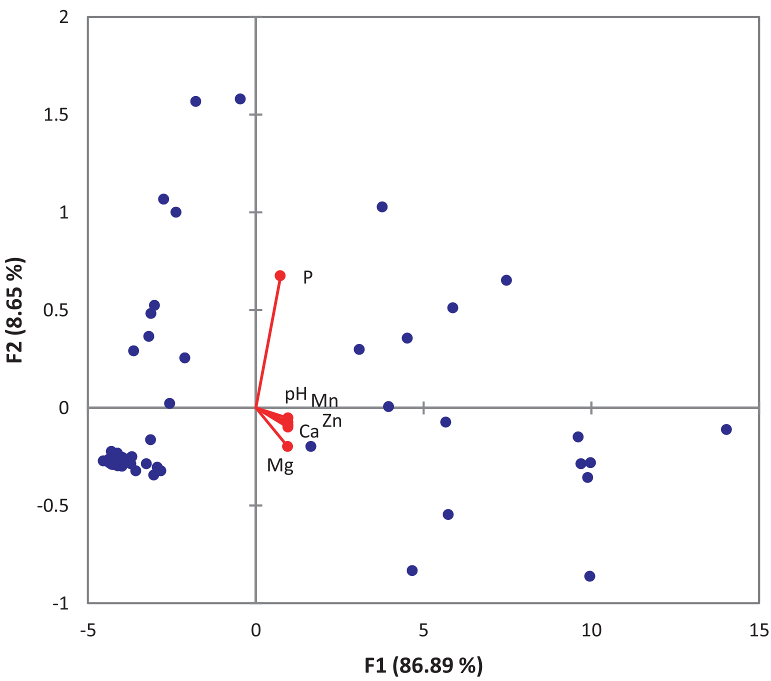

Figure 2 Principal components analysis for pH (H_2O) and available P (mg kg^{-1}), Ca (cmolc kg^{-1}), Mg (cmolc kg^{-1}), Zn (mg kg^{-1}), Mn (mg kg^{-1}) in 52 composite soil samples collected at the Barro Alto community

Note: Sample 7 (Table S1) was removed as an outlier. Each point represents a composite soil sample and the percentages between brackets show the percentage of explanation of each axis. The direction of the lines represents the direction to which variable is contributing to the distribution of the points, and the length of the lines represents the magnitude of the contribution of each variable to the spatial configuration of the points

the river to the adjacent landholding known as Liberdade (Figure S1, Table S1, samples 6, 9, 10, 12).

Much of the P and Ca in ADE come from biogenic apatite (fish and animal bones) (Schaefer *et al*. 2004), but there are many other sources of P and Ca, and depending on the mass of the materials added there may be other important contributors. Given the high P levels, it is very unlikely these are agricultural ADE. It was suggested by W Teixeira that these may be older occupations, where the main minerals in the cationic form (Ca, Mg) have been leached to deeper layers and the predominant anionic form of P and the high specific adsorption of it to the clay oxides have contributed to P being kept nearer the soil surface. Some recent research has shown that biogenic P and Ca can disappear from soils within 2000 years (Sato *et al*. 2009), but it depends on many factors such as leaching rate, source of the minerals, soil texture, pH and predominant charges of the soil.

In various locations further inland there are samples that exhibit more subtle modifications than those closer to the bluff (Figure S1, Table S1, Samples 2, 5, 8, 17, 18, 19, 35, 36), are lighter in colour, and with much lower levels of P, Ca, Mg, Mn, Zn, but higher than those of surrounding ultisols. Further behind we encounter ultisols. These soils, with available P of only 2 mg kg^{-1} and Ca of as little as 0.07 cmolc kg^{-1} and high Al and Fe contents, are extremely infertile. The PCA clearly shows these differences. Firstly, the ultisol samples are shown to be very homogenous and cluster to the bottom left of Figure 2. The ADE samples, by contrast, are diverse. The ADE samples with high P, but without enhanced pH, Ca, Mg, Mn, Zn are located above the ultisols. ADE samples with high P and higher pH, Ca, Mg, Mn, Zn fall to the top right of the axes, while samples with only more subtle fertility enhancements fall to the bottom right of the figure. Hence, the only soils at Barro Alto that form a homogenous category are ultisols. ADE are more accurately represented as a continuum of fertility.

Barreira do Capanã Barreira do Capanã is located in what was once a highly strategic location, at the outer curve of what was until 30 years ago one of the longest bends in the Middle Madeira (Figure 1, SM1, SM3). Today the main ADE site is occupied by various families inhabiting long-term landholdings. Both these families and relatives in the village cultivate the ADE. The ADE at Barreira

ISSN 0004-0894

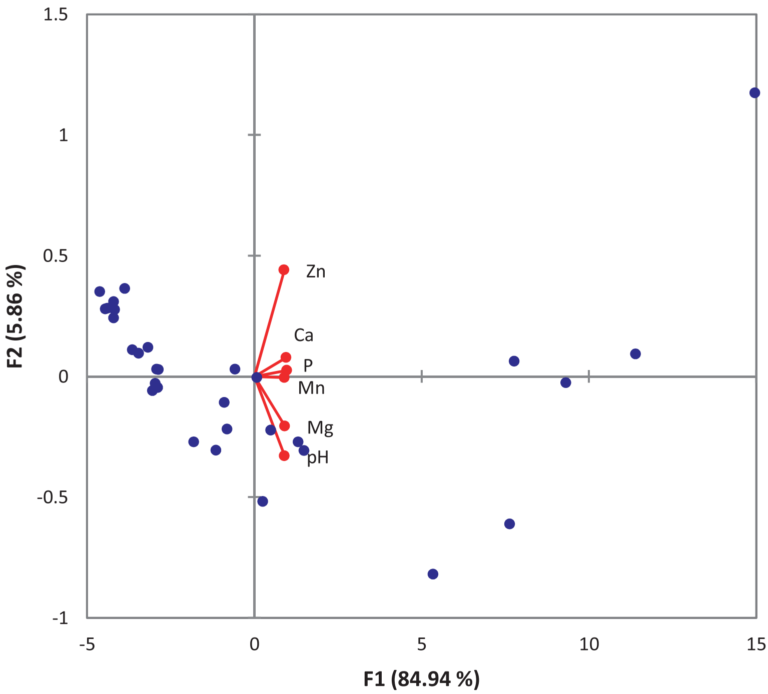

Figure 3 Principal components analysis for pH (H_2O) and available P (mg kg^{-1}), Ca (cmolc kg^{-1}), Mg (cmolc kg^{-1}), Zn (mg kg^{-1}), Mn (mg kg^{-1}) in 31 composite samples collected at the Barreira do Capanã community
Note: Sample 27 (Table S2) was removed as an outlier

do Capanã is clearly strung along the bluff edge (Figure S2). There is no evidence of the high P, low Ca, Mg, Mn, Zn, samples found at Barro Alto, though there was at neighbouring Boa Vista (next section). The most fertile ADE are marked by the soil samples all closest to the bluff edge, with some areas of intermediate fertility between and behind them (Figure S2, Table S2).

The PCA shows that, like Barro Alto, only background soils could be described as a 'category'; oxisols cluster to the top left of Figure 3. There are no samples with high P and low levels of other parameters, as there were at Barro Alto. Rather, to the left of the figure, but to the right of the oxisols, there are ADE with more subtle fertility enhancements, with fertility increasing as we move towards the right of the figure.

Boa Vista The Boa Vista site neighbours the Barreira site (Figure 1). Today it is occupied by four households, and land is used for home gardens, swiddening of manioc and other crops, and pasture for several cattle. The Boa Vista site follows the pattern of the most fertile area of ADE being closest to the bluff (Figure S3, Table S3). Behind and to the side lies one area of high P, low Ca, Mg, Zn, Mn and TM, with oxisols being located further behind that (Figure S3). The high P, low Ca, Mg, Zn, Mn area (Figure S3, Table S3, soil sample 17) was lighter in colouring and exhibited ceramics. Further back from the bluff there were other areas of intermediate fertility that were also lighter but without ceramics. The PCA, like the previous two communities, shows that the only soils that form a homogenous category are oxisols (top left of Figure 4). ADE samples, like those at the other communities, are much more diverse. Two lie close to the oxisols, with only very subtle fertility enhancements (Figure 4).

Água Azul Água Azul is a small site, around 10 ha in size, located east 10 km along the bluff from Boa Vista (Figure 1). It is occupied by several families, with home gardens, manioc fields and fallow. The most fertile areas follow the established pattern in that they are located closest to the bluff (Figure S4, Table S4). These soils were very dark and replete with ceramics. ADE of lesser fertility (Table S4, samples 4 and 5) is located behind the home gardens in an area that has been the focus of intensive manioc cultivation for 30 years. These soils were lighter, with abundant ceramics. There is less evidence of ADE with more subtle fertility enhancements at Água Azul, with only two samples (11 and 13) having chemical profiles similar to those at other communities. Two samples, 6 and 8, have high P, low Ca, Mg, Zn and Mn. The PCA,

Area Vol. 43 No. 3, pp. 264–273, 2011
ISSN 0004-0894

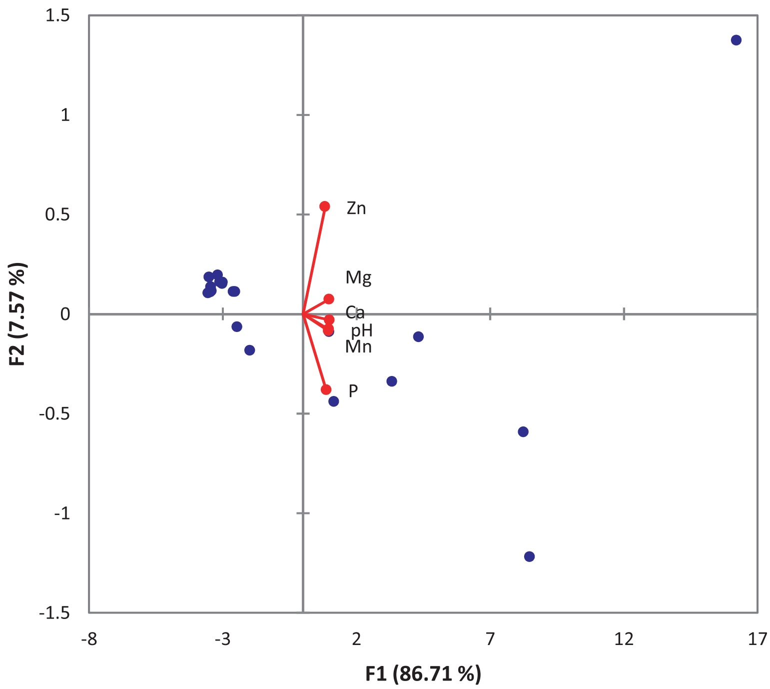

Figure 4 Principal components analysis for pH (H_2O) and available P (mg kg^{-1}), Ca (cmolc kg^{-1}), Mg (cmolc kg^{-1}), Zn (mg kg^{-1}), Mn (mg kg^{-1}) in 21 composite soil samples collected at the Boa Vista community

like the others shows that oxisol samples cluster at the bottom left of the figure, while as fertility increases samples move to the right of Figure 5. The two ADE samples with high P, low everything else are positioned at the bottom right, while most of the ADE samples tend to range along a continuum towards the top right of Figure 5.

Vista Alegre Vista Alegre is located on *terra firme* behind a high floodplain forest that forms a bend in the Madeira (Figure 1). Apart from a brief strip of oxisols at the bluff edge, most of the area is formed from ultisols. Today it is the site of a relatively large community and the ADE has been intensively farmed over the last 30 years, after many people moved in from the disintegrating floodplain. During the 1980s watermelon was intensively farmed on the site. Today bitter manioc and watermelon are planted in the ADE. Locals complain of reduced fertility, referring to the ADE as *terra fraca* (weak land). This case is instructive because it shows what happens to *terra preta* when it is intensively cultivated. We see a reduction in values of P, Ca, Zn and Mn compared with higher fertility ADE of other communities. This supports the notion that the samples with high P but low amounts of other elements is something other than (recently) degraded *terra preta*. The ADE of highest fertility stretches along the bluff (Figure S5, Table S5, samples 3, 4 and 17). The area occupied by samples 1, 2, 5 and 6 was identified as an area of intermediate fertility: lighter colouring than other ADE, but darker than surrounding oxisols, no ceramics, but yielding watermelon and maize, plants that demand higher fertility to be cultivated,and do not yield in oxisols (Figure S5, Table S5).

As with the other communities, the PCA shows that oxisols cluster together to the bottom left of the figure, with samples of slightly elevated fertility located directly above them. Samples of higher fertility lie towards the top and right of Figure 6.

Conclusions

Our results show that ADE on the Middle Madeira are extremely diverse and support a fertility gradient rather than two soil categories. Both the interpolations and the PCAs show similar patterns of a continuum of fertility between ADE and adjacent soils. Interviews with locals demonstrated that they too recognise a fertility gradient, which they express as *terra preta* becoming progressively 'mixed with' background soils as one moves away from areas of core fertility. The diversity of pre-Columbian land use is likely responsible for the heterogeneity of anthropogenic soils. The diversity of Amazonian dark earths along the Middle Madeira does not fit into the separate soil categories *terra preta* and *terra mulata*. Biophysical and social data from the Middle Madeira river suggest that ADE are better conceived of as a continuum of fertility

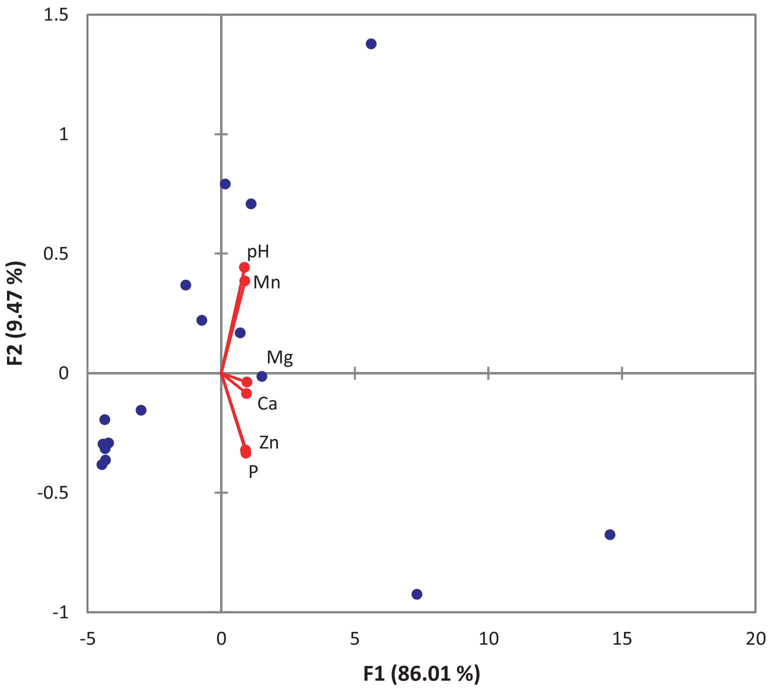

Figure 5 **Principal components analysis for pH (H_2O) and available P (mg kg^{-1}), Ca (cmolc kg^{-1}), Mg (cmolc kg^{-1}), Zn (mg kg^{-1}), Mn (mg kg^{-1}) in 16 composite soil samples collected at the Água Azul community**

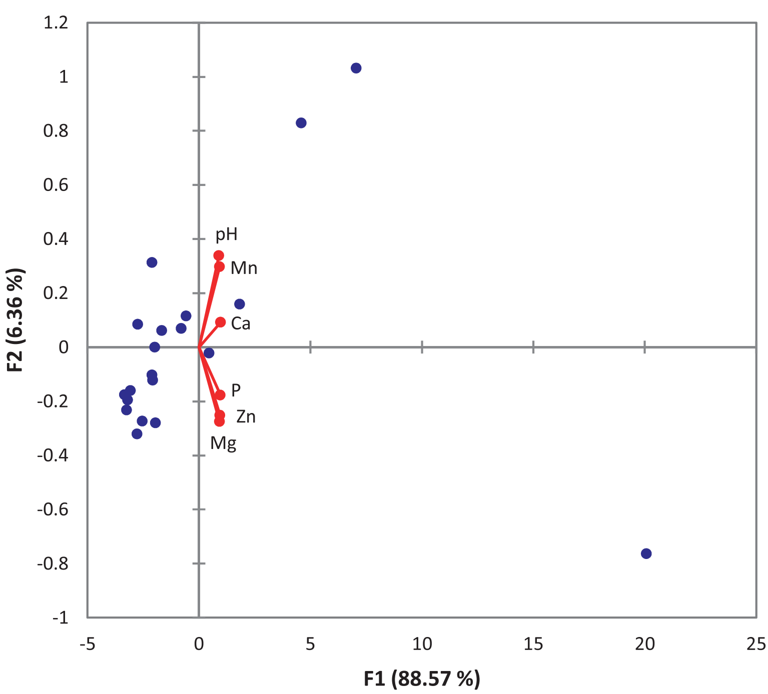

Figure 6 **Principal components analysis for pH (H_2O) and available P (mg kg^{-1}), Ca (cmolc kg^{-1}), Mg (cmolc kg^{-1}), Zn (mg kg^{-1}), Mn (mg kg^{-1}) in 20 composite soil samples collected at the Vista Alegre community**

ISSN 0004-0894

ranging from areas of central fertility that grade into less intensively managed peripheral areas. We propose, therefore, that the terms *terra preta* and *terra mulata* should be used to describe directions along a fertility gradient within Amazonian Dark Earths.

Acknowledgements

We thank the residents of the Middle Madeira for their participation and friendship. We thank the technicians Jonas Filho (INPA) and Estevão Santos (EMBRAPA) for conducting the soil analyses. Fraser thanks the Leverhulme Trust for funding (Grant F/00 230/W) and the CNPq (Brazilian National Research Council) for granting research permission (EXC 022/05). Junqueira thanks the CNPQ for his graduate scholarship and The Brazilian International Institute of Education (IIEB)/The Moore Foundation who also provided financial support, and IdeaWild who provided equipment for his fieldwork. We thank two anonymous reviewers who improved earlier versions of this manuscript.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figures S1 to S5 Interpolations based on the levels of (a) pH (H_2O), (b) Phosphorous ($mg \cdot kg^{-1}$), (c) Calcium ($cmolc \cdot kg^{-1}$), (d) Magnesium ($cmolc \cdot kg^{-1}$), (e) Manganese ($mg \cdot kg^{-1}$) and (f) Zync ($mg \cdot kg^{-1}$) measured on soil samples collected at the communities Barro Alto (S1), Barreira do Capanã (S2), Boa Vista (S3), Água Azul (S4) and Vista Alegre (S5), municipality of Manicoré, Amazonas, Brazil (pdf format).

Tables S1 to S5 Levels of pH (H_2O), Phosphorous ($mg \cdot kg^{-1}$), Calcium ($cmolc \cdot kg^{-1}$), Magnesium ($cmolc \cdot kg^{-1}$), Manganese ($mg \cdot kg^{-1}$) and Zync ($mg \cdot kg^{-1}$) measured on soil samples collected at the communities Barro Alto (S1), Barreira do Capanã (S2), Boa Vista (S3), Água Azul (S4) and Vista Alegre (S5), municipality of Manicoré, Amazonas, Brazil (pdf format).

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

References

Andrade Á 1986 Investigación arqueológica de los antrosolos de Araracuara (Amazonas) *Arqueología Colombiana* 31 1–101

Arroyo-Kalin M 2008 Steps towards an ecology of landscape: a geoarchaeological approach to the study of anthropogenic Dark Earths in the Central Amazon region Unpublished PhD thesis University of Cambridge

Denevan W 2006 Pre-European forest cultivation in Amazonia in **Balée W and Erickson C** eds *Time and complexity in historical ecology: studies in the neotropical lowlands* Columbia University Press, New York 153–63

EMBRAPA 1997 *Manual de métodos de análise de solo* CNPS/EMBRAPA, Rio de Janeiro

Falcão N, Comerford N and Lehmann J 2003 Determining nutrient bioavailability of Amazonian Dark Earth soils – methodological challenges in **Lehmann J, Kern D, Glaser B and Woods W** eds *Amazonian Dark Earths. Origins, properties and management* Kluwer Press, Dordrecht 255–70

Fraser J A 2009 Amazonian Dark Earths and *Caboclo* subsistence on the Middle Madeira River, Brazil Unpublished PhD thesis University of Sussex

German L A 2003 Ethnoscientific understandings of Amazonian Dark Earths in **Lehmann J, Kern D, Glaser B and Woods W I** eds *Amazonian Dark Earths: origin, properties and management* Kluwer, Dordrecht 179–201

Grossman, J, O'Neill B E, Tsai S M, Liang B, Neves E, Lehmann J and Thies J E 2010 Amazonian anthrosols support similar microbial communities that differ distinctly from those extant in adjacent, unmodified soils of the same mineralogy *Microbial Ecology* doi: 10.1007/s00248-010-9689-3

Hecht S B 2003 Indigenous soil management and the creation of Amazonian Dark Earths: implications of Kayapó practices in **Lehmann J, Kern D C, Glaser B and Woods W** eds *Amazonian Dark Earths: origin, properties, management* Kluwer Academic, Dordrecht 355–72

Junqueira A B, Shepard, G H and Clement C R 2010 Secondary forests on anthropogenic soils of the middle Madeira River: valuation, local knowledge and landscape domestication in Brazilian Amazonia *Economic Botany* doi: 10.1007/s12231-010-9138-8

Kern D C 1996 Geoquímica e pedogeoquímica em sítios arqueológicos com terra preta na floresta nacional de Caxiuanã (Portel-PA) Unpublished PhD thesis Universidade Federal do Pará, Belém

Kern D C and Kämpf N 1989 Antigos assentamentos indígenas na formação de solos com terra preta arqueológica na região de Oriximinã, Para *Revista Brasileira de Ciência do Solo* 13 219–25

Lehmann J, da Silva J P, Steiner C, Nehls T, Zech W and 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* 343–57

Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, Skjemstad J O, Thies J, Luizao F J, Petersen J and Neves E G 2006 Black Carbon increases cation exchange capacity in soils *Soil Science Society of America Journal* 70 1719–30

Liang B Q, Lehmann J, Sohi S P, Thies J E, O'Neill B, Trujillo L, Gaunt J, Solomon D, Grossman J, Neves E G and Luizao F J 2010 Black carbon affects the cycling of non-black carbon in soil *Organic Geochemistry* 41 206–13

McCann J M, Woods W I and Meyer D W 2001 Organic matter and anthrosols in Amazonia: interpreting the Amerindian Legacy in **Rees R M, Ball B C, Campbell C D and Watson C A** ed *Sustainable management of soil organic matter* CABI, New York 180–9

Neves E G 2008 Ecology, ceramic chronology and distribution, long-term history, and political change in the Amazonian floodplain in **Silverman H and Isbell W H** eds *Handbook of South American archaeology* Springer, New York

ISSN 0004-0894

O'Neill B, Grossman J, Tsai M T, Gomes J E, Lehmann J, Peterson J, Neves E and Thies J E 2009 Bacterial community composition in Brazilian anthrosols and adjacent soils characterized using culturing and molecular identification *Microbial Ecology* 58 23–35

Rebellato L, Woods W I and Neves E G 2009 Pre-Columbian settlement dynamics in the Central Amazon in **Woods W I, Teixeira W G, Lehmann J, Steiner C, WinklerPrins A M G A and Rebellato L** eds *Amazonian Dark Earths: Wim Sombroek's vision* Springer, New York 15–31

Sato S, Neves E G, Solomon D, Liang B and Lehmann J 2009 Biogenic calcium phosphate transformation in soils over millennium time scales *Journal of Soils and Sediments* 9 194–205

Schaefer C E G R, Lima H N, Gilkes R J and Mello J W V 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* 42 401–9

Schmidt M J 2010 Reconstructing tropical nature: prehistoric and modern anthrosols (*Terra preta*) in the Amazon Rainforest, Upper Xingu River, Brazil Unpublished PhD thesis University of Florida

Sioli H 1984 The Amazon and its main affluents: hydrography, morphology of the river courses, and river types in **Sioli H** ed *The Amazon: limnology and landscape ecology of a mighty tropical river and its basin* Junk, Dordrecht 127–65

Smith N J H 1980 Anthrosols and human carrying capacity in Amazonia *Annals of the Association of American Geographers* 70 553–66

Sombroek W G 1966 *Amazon soils: a reconnaissance of the soils of the Brazilian Amazon region* Centre for Agricultural Publications and Documentation, Wageningen

Teixeira W G and Martins G C 2003 Soil physical characterization in **Lehmann J, Kern D C, Glaser B and Woods W I** eds *Amazonian Dark Earths: Origin, properties, management* Kluwer Academic Publishers, Dordrecht

Woods W I 2003 Development of anthrosol research in **Lehmann J, Kern D, Glaser B and Woods W I** eds *Amazonian Dark Earths. Origins, properties and management* Kluwer Press, Dordrecht 3–14

Woods W I and McCann J M 1999 The anthropogenic origin and persistence of Amazonian dark earths *Yearbook, Conference of Latin Americanist Geographers* 25 7–14

Woods W I, Teixeira W G, Lehmann J, Steiner C, WinklerPrins A M G A and Rebellato L eds 2009 *Amazonian Dark Earths: Wim Sombroek's vision* Berlin, Springer

ISSN 0004-0894