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Logo on back cover: Symbol of the Terra Preta Nova group designed by Wim Sombroek.
Picture on front cover: Wim examining a house garden on the Rio Negro, July 2002.

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Dr Wim G. Sombroek

He had a passion for land as we know
Fueled by the Amazon where jungles grow
A flame that didn't flicker or even go out
His last endeavour Terra Preta still to shout[1]

Wim Sombroek joined the International Soil Museum in Wageningen as a Director in 1978. Long before that, we knew him as a respected soil scientist, who obtained a Ph.D. in Wageningen for his thesis on the Amazon soils, and had carried out extensive soil surveys in Kenya. These illustrated his enthusiasm for field work and for building upon these primary data – the basis for the establishment of the International Soil Museum as a link with the Soil Map of the World project carried out at FAO in Rome.

We remember his many new ideas to make our institution more widely known under the new banner of International Soil Reference and Information Centre (ISRIC). He had an enormous drive to implement new projects. It was a wise decision to accept the task of Secretary-General of the then International Soil Science Society (ISSS), now International Union of Soil Sciences (IUSS). Through this combination of functions over twelve years, he was able to carry out innovative ISSS activities at ISRIC, and play a prominent role internationally, in particular directed to the needs of developing countries.

Wim initiated activities in the further development of a world soil classification system, which finally resulted in the *World Reference Base for Soil Resources* (WRB); the Laboratory Exchange project (LABEX) to improve the performance of soil laboratories in developing countries, in which more than 100 labs participated; the *National Soil Reference Collection* (NASREC) project to develop national soil profile collections in more than 30 countries; and not least the *Soil and Terrain digital database program* (SOTER), which started in 1986 and has carried the initiative of the FAO-Unesco Soil Map of the World through to the twenty-first century,

[1] Excerpt from a poem entitled "Thanks, Wim!" by Richard W. Arnold.

and the framework of the *World Inventory of potential Soil Emissions* (WISE) a unique soil data set that is still used by many researchers.

Wim left ISRIC to become Director of the Land and Water Development Division of FAO, where he was also active in land use issues related to climate change in the framework of the International Panel of Climate Change. His ties with ISRIC were not severed and, after his tenure in Rome, he returned to the Amazon where his heart was, but one foot in an office at ISRIC. He worked on the economic zoning of the Brazilian Amazon, to safeguard parts of this huge but threatened forested region as protected reserves, and develop economical viable systems of sustainable land use.

Thirty years after his thesis, in which he discussed the importance of the *Terra Preta*, he showed the relevance of this pre-Colombian agricultural technique for the development of enhanced carbon sequestration in agricultural land – the *Terra Preta Nova*.

The Terra Preta network has developed enormously in recent years, and includes more than 100 scientists. Two books on the Terra Preta have been published in the meantime, and a symposium on these soils during the 18th World Congress of Soil Science in 2006 was dedicated to his memory.

We, at ISRIC and within the IUSS, are proud that Dr. Wim G. Sombroek has been our Director and friend, and that the work he initiated continues and develops – in the field, in laboratories, institutes and museums, carried out by dedicated researchers in so many disciplines.

On behalf of retired and present ISRIC staff members,

Hans van Baren

Thanks, Wim!

Each of us has a story to tell this day
Of meeting Wim Sombroek along the way
He touched our lives in ways oft untold
And helped us become ‘champions with gold’

He had a passion for land as we know
Fueled by the Amazon where jungles grow
A flame that didn’t flicker or even go out
His last endeavour Terra Preta still to shout

What made this man a man to remember?
Dedication from January to December?
Ready zeal to impart his vast knowledge
To those who never had seen a college?

Perhaps it was the breath of his interests keen
Archaeology nearby, within, without – to be seen
And wild orchids gardened in an exotic place
In his green house always finding space

Was it not the pillars there at home?
Wife Willemijn and four girls that led him roam
Whose constancy supported his very being
Welcomed his return late in the evening?

What do you recall when you hear his name?
A towering presence with moustache and mane
Blue eyes twinkling through gold-rimmed glasses
A fat little notebook shock full of addresses

Or may be the pause as he ‘rolled’ his own
Smoke rising gently as softly it was blown
Or the patient way he slightly leaned over
Catching our phrases like blossoms of clover

I, too, have a special way to recall –
Several clusters of Dutch bulbs one fall
He planted along my garden maze
Now each spring he brightens my gaze

I hear his laughter, feel his handshake
I treasure the moments we dared to take
To dream our dreams, to vision the future
Returning to Pedology, our souls to nurture

Are we mourning – never; rejoicing – ah, yes, ever
Along with insights, strength, and wisdom so clever
There was gentleness, love, and tenderness, too
Wim Sombroek, our hearts give thanks to you.

Richard W. Arnold 1-15-04

A Few Words About Wim Sombroek

The first time I met Wim Sombroek was actually the second time I met him, though I didn't realize it till later. I also didn't realize that in both cases Wim was doing something he had been doing his whole life: trying to attract the world's attention to soil, and to soil science. I am a journalist, and both times I was introduced to Wim I had a notebook and pen in my hand and wanted to talk to him about his research on *terra preta do índio* – anomalously rich, charcoal-thick soils, created by native peoples in the Amazon Basin. Eventually we became friendly and I learned how many and various his interests were. But it was only after he passed away that I fully grasped what he was trying to accomplish. He wanted to change and expand the discipline of soil science itself, with *terra preta* as a hortatory example.

This second time when I met Wim (or, as I thought, the first time) was at a *terra preta* conference at a hotel in Manaus. Someone I was talking to pointed at a silver-haired man with an impressive moustache who was nursing a beer at a table in the lobby bar. "That's Wim Sombroek," I was told. "You ought to talk to him." I went over and introduced myself. One thing led to another, and many hours later we were drinking beer with a large group in another part of Manaus. I asked how long he had been interested in *terra preta*. "A few years," he said, or something to that effect. The amused glint in his blue eyes suggested to me that he was understating the case, an impression that was confirmed when he told me about the soils at his parents' home in the rural Netherlands.

He was ten years old during the Hongerwinter — the Dutch famine of 1944–45, in which more than 10,000 people died. Sombroek's family survived on the harvest from a tiny plot of *plaggen* soil: land enriched by generations of careful fertilization. His parents further improved their land, he told me, by scattering the ash and cinders from their home fireplaces. In the 1950s, Wim went to Brazil and encountered more charcoal-filled earth: *terra preta*. Naturally, it reminded him of the *plaggen* in his parents' yard, and he paid attention. His book, *Amazon Soils*, included the first sustained study of *terra preta* and a map of its distribution along the lower Rio Tapajós.[1]

[1] Sombroek WG (1966) Amazon Soils: A Reconnaissance of the Soils of the Brazilian Amazon Region. Wageningen, the Netherlands: Center for Agricultural Publications and Documentation (map on p. 175).

As Wim told this story I suddenly realized that I had met him almost a decade before, in the early 1990s. At that time two groups of researchers were embroiled in a lengthy fight over the extent and cost of soil degradation. One side, led by entomologist David Pimentel, of Cornell University, charged that "nearly one-third of the world's arable land has been lost by erosion" since the 1950s. Soil loss, Pimentel and his collaborators said in 1995, already cost the world "$400 billion per year, or more than $70 per person per year."[2] The other side, often identified with economist Pierre R. Crosson of the Washington environmental-research group Resources for the Future, responded that Pimentel's figures had "such thin underpinnings that [they] cannot be taken seriously." The annual toll of erosion-induced on-farm productivity losses in the United States was, in Crosson's estimation, no more than $600 million.[3] (Off-farm costs might well be higher, he said, but neither Pimentel nor he had tried to assess them.)[4] The debate spilled outside academia – Crosson, as I recall, once found himself on National Public Radio, trying to explain the Universal Soil Loss Equation to a bewildered interviewer.

For a long time, one of the more striking features of the debate was the near-absence of soil scientists themselves from the discussion. Indeed, almost 20 years passed between the time soil-degradation fears first stirred alarm and the first published estimates of global soil degradation. In 1990, the International Soil Reference and Information Center (ISRIC) in Wageningen, the Netherlands, finally filled the gap, releasing the Global Assessment of Soil Degradation. This major effort was undertaken at the initiative of Wim Sombroek, then ISRIC's director (and, simultaneously, Secretary General of the International Society of Soil Science).[5]

When I learned about GLASOD, as the assessment was called, I contacted Wim. We met when he came to the United States for, I believe, a meeting in Washington, D.C. GLASOD, he told me, was a first step toward answering an urgent question in soil science — the size, location and character of degraded soils around the world. But the assessment also had a second purpose. All soil scientists know that, as Will Durant said, "Ultimately every civilization is based upon the soil."[6] But all

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[2] See, e.g., Pimentel D et al. (1976) Land degradation: effects on food and energy resources. Science 194:149–55. Pimentel D et al. (1995) Environmental and economic costs of soil erosion and conservation benefits. Science 262:1117–1123 (quotes on 1117, 1120)

[3] See, e.g., Crosson PR (1986) Soil erosion and policy issues. In: Phipps TT, Crosson P and Price KA (eds) Agriculture and the Environment. Washington, DC: Resources for the Future.,pp. 35–73; Crosson PR (1995) Soil erosion estimates and costs. Science 269:461–64 (quote on 461)

[4] Crosson PR (2003) The Economics of Soil Erosion and Maintaining Soil Biodiversity. Discussion paper for OECD Expert Meeting on Soil Erosion and Soil Biodiversity Indicators, Rome (unpublished manuscript)

[5] Sombroek WG (1985) Establishment of an International Soil and Land Resources Information Base. Discussion Paper for the ISSS Working Group on Digital Mapping of Global Soil Resources. Wageningen: ISRIC (unpublished manuscript); Oldeman LR, Hakkeling RTA and Sombroek WG (1990) World Map of the Status of Human-Induced Soil Degradation. Wageningen: ISRIC/UNEP

[6] Quoted in Preston RJ (1939) Soil erosion. The significance of the problem and its attempted control. Journal of Geography 38:308. See also the widely cited Howard A 1940. An Agricultural Testament. London: Oxford

too often, Wim said, they act as handmaidens to agronomy and crop science, rather than environmental scientists who should use their specialized knowledge about a critically important resource to work with ecologists, economists, and political scientists to help humankind through these ecologically parlous times.[7] GLASOD was an attempt to show "policy-makers and decision-makers" how soil science could inform the fight against "declining food productivity by conserving and restoring our natural resources."[8]

Ultimately, Wim told me in Washington, he had been disappointed by GLASOD's lack of larger impact, as well as ISRIC's failure to improve on it.[9] But even as he was finishing GLASOD he was turning his attention to another means of elevating the profile of soil science: *terra preta* — or Amazonian Dark Earth,[10] as it has been renamed. Found in patches along almost all of the major rivers in the Amazon basin, Amazonian Dark Earth is, unlike typical tropical soils, rich with phosphorus, nitrogen, zinc, and magnesium. More important, it is full of carbon – as much as 70 times the level of neighboring soils—in the form of "bio-char," a charcoal-like residue created when organic matter is burned at a low temperature.[11]

As far back as the 1960s, Wim had wondered whether scientists could reconstruct the techniques by which Indians had made *terra preta* in the past. If so, he now argued, contemporary tropical farmers might create their own *terra preta — terra preta nova*, as he dubbed it — to help forestall soil degradation. Because soil degradation is an enormous limiting factor in tropical agriculture, *terra preta nova* could not only boost yields but also reduce the amount of tropical forest that had to be cleared for farms. Much as the Green Revolution dramatically improved the developing world's crops, resilient *terra preta nova* could unleash a "black revolution" for the developing world's soil.[12]

In addition, Wim argued, manufacturing large swathes of Amazonian dark earth would require so much biochar that these regions would act as enormous carbon

[7] This is not a new complaint. See, e.g., Kellogg CE (1961) A challenge to American soil scientists: On the occasion of the 25th anniversary of the soil science society of America. Soil Science Society of America Proceedings 25:419–23

[8] Oldeman LR, Hakkeling RTA, Sombroek WG (1991) World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note. Den Haag: CIP-Gegevens Koninklijke Bibliotheek, 2nd ed.: 21

[9] GLASOD is not even mentioned in Pimentel et al. (1995), a widely publicized study in a major journal that appeared just 5 years afterward

[10] This term was coined by Woods and McCann to encompass the wide range of variability of dark anthropogenic soils in Amazonia [Woods WI, McCann JM (1999) The anthropogenic origin and persistence of Amazonian dark earths. The Yearbook of the Conference of Latin American Geographers 25:7–14]

[11] Lehmann, J, Kern DC, Glaser B, Woods WI (eds). 2003. Amazonian Dark Earths: Origin, Properties, Management. Dordrecht: Kluwer; Glaser, B, and Woods WI (eds) 2004. Amazonian Dark Earths: Explorations in Space and Time. Berlin: Springer.

[12] I take the phrase "black revolution" from Marris, E 2006. Black is the new green. Nature 442:624–26.

sinks, counteracting global warming.[13] In theory, the potential for carbon storage is huge: according to a 2006 estimate in the journal *Mitigation and Adaptation Strategies for Global Change*, more carbon could be stored in *terra preta nova* every year than is released by the entire world's fossil-fuel use, at least at current levels of consumption.[14]

The possibilities of Amazonian dark earth obviously thrilled Wim. In Manaus, I was not the only person to be startled during the conference tour of *terra preta* sites when the former Secretary General of the International Society of Soil Science scrambled into archaeological trenches and began taking measurements with his soil-color chart. But what I only realized later, talking to Wim, is that he hoped that the *Terra Preta Nova* project would, even more than GLASOD, serve as an example of how soil science might reorient itself.

Between 1992 and 2004, enrollment in North American soil-science graduate programs fell by about 40%; Europe apparently experienced similar declines. The drop occurred despite "a continuous increase of the interest manifested by the scientific community in soils-related issues," at least as measured by scientific publications in the field.[15] Amazingly, it occurred despite the enormous global boom in organic farming, with its emphasis on protecting the soil. One common explanation for the decline is the tendency of soil-science schools to treat soil science, in isolation, as a vehicle to increase crop production, even though students increasingly view soil through the lenses of environmental and social sciences. To Wim's way of thinking, the *Terra Preta Nova* project was an example of the way to go.

Wim's hopes will not be easy to fulfill. It has become increasingly clear that much of the resilience in Amazonian dark earth derives from its ability to support soil ecosystems; the microbiota of *terra preta* are both more numerous and more diverse than that of surrounding areas.[16] Unfortunately, identifying precisely what is living in these soils will be difficult. As is well known, researchers can cultivate only a small fraction of rhizospheric species in petri dishes. Equally important, nobody knows how much carbon can be stored in soil. Preliminary studies suggest

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[13] Sombroek WG 1992. Biomass and carbon storage in the Amazon ecosystems. Interciência 17:269–72; Sombroek

WG, Ruivo ML, Fearnside PM, Glaser B, Lehmann J (2003) Amazonian Dark Earths as carbon stores and sinks. In: Lehmann, J, Kern DC, Glaser B, Woods WI (eds). 2003. Amazonian Dark Earths: Origin, Properties, Management. Dordrecht: Kluwer, pp 125–139

[14] Lehmann J, Gaunt J, and Rondon M (2006) Bio-char sequestration in terrestrial ecosystems: A review. Mitigation and Adaptation Strategies for Global Change 11:403-27. Lehmann, Gaunt and Rondon predicate their estimates on a sharp rise in biofuel use, with the biofuels being produced by processes that generate bio-char.

[15] Baveye P, et al. (2006) Whither goes soil science in the United States and Canada? Soil Science 171:501–18 (quote on 506).

[16] Ruivo ML, Cunha ES, Kern DC (2004) Organic matter in archaeological black earths and yellow latosol in the Caxiuanã, Amazônia, Brasil. In: Amazonian Dark Earth: Explorations in Space and Time. Berlin: Springer, pp. 95–108.

that at least in some soils' soil-carbon content may not increase linearly with carbon inputs but reach some limiting value.[17]

But in another sense Wim's dream has already been realized. The *Terra Preta Nova* project, with its vision of the soil as a key element in our common future, has attracted enormous public attention to soil science. On a professional level, the scientific collaboration links soil scientists, archaeologists, geographers, microbiologists, engineers, ecologists, economists, and atmospheric scientists around the world in a common project that promises to reveal much about the workings of soil, may have an enormous impact on agriculture and could even play a role in climate change. This book, and all it represents, is more than a tribute to Wim Sombroek's legacy—it is a way forward.

Charles C. Mann

[17] Stewart CE, et al. (2007) Soil carbon saturation: Concept, evidence and evaluation. Biogeochemistry 86:19–31.

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Chapter 1
Amazonian Dark Earths: The First Century of Reports

WI Woods and WM Denevan

1.1 Introduction

Amazonian dark earths are anthropogenic soils called *terra preta de índio* in Brazil, created by indigenous people hundreds, even thousands, of years ago (Smith 1980; Woods and McCann 1999). *Terra preta* proper is a black soil, associated with long-enduring Indian settlement sites and is filled with ceramics and other cultural debris. Brownish colored *terra mulata*, on the other hand, is much more extensive, generally surrounds the black midden soils, contains few artifacts, and apparently is the result of semi-intensive cultivation over long periods. Both forms are much more fertile than the surrounding highly weathered soils, mostly Ferralsols and Acrisols, and have generally sustained this fertility to the present despite the tropical climate and despite frequent or periodic cultivation. This fertility probably is because of high carbon content, which retains nutrients and moisture, and an associated high and persistent microbial activity.

The high concentrations of pyrogenic carbon in *terra preta* come mainly from charcoal from cooking and processing fires and settlement refuse burning, and in *terra mulata* the carbon probably comes from in-field burning of organic debris. Low intensity "cool" burning, what has been called slash-and-char, resulting in incomplete combustion, can produce carbon in high quantity which can persist in soil for thousands of years. Dated carbon in dark earths is as old as 450 BC (Hilbert 1968; Petersen et al. 2001:100). In contrast, slash and burn shifting cultivation fires today tend to be "hot" fires, set at the end of the dry season, which produce large releases of carbon dioxide to the atmosphere and more ash of brief persistence than charcoal.

Denevan (2001:116–119) has argued that in pre-Columbian times the use of stone axes made long-fallow shifting cultivation very inefficient, and as result probably uncommon until the European introduction of metal axes. Previously, soil fertility must have been maintained and improved by frequent composting, mulching, and in-field burning, making semi-permanent cultivation possible with only brief fallowing. Over time these activities could have produced fertile, self-sustaining dark earths.

Dark earths may occupy 0.1% to 0.3%, or 6,000 to 18,000 km^2, of forested lowland Amazonia (Sombroek and Carvalho 2002:130). Because their densities vary

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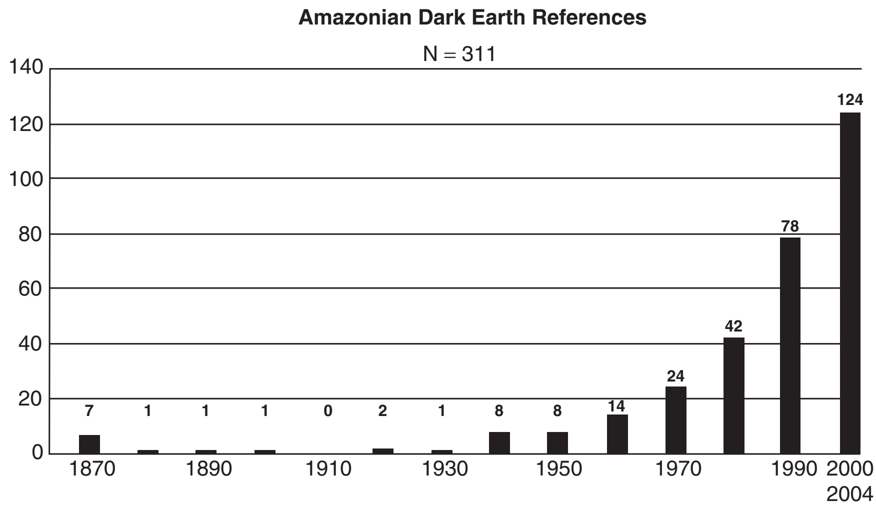

Fig. 1.1 Amazonian dark earth references by decades, 1870–2004 (n = 311)

greatly within subregions and almost no systematic survey has been accomplished within Amazonia, variations in density projections of an order of magnitude are to be expected. The dark earths occur in a variety of climatic, geologic, and topographic situations, both along river bluffs and in the interior, with depths sometimes exceeding 2.0 m. Individual patches range from 1 ha or so to several hundred hectares.

It has only been since about 1980 (Fig. 1.1) that these soils have received intensive scholarly attention. Recent research has been multidisciplinary and international, especially by soil scientists, archaeologists, and geographers from Brazil, Colombia, Germany, and the United States. Independent work in these disciplines and countries came together in three international conferences in 2001–2002 in Benicassim in Spain (CLAG) and in Rio de Janeiro and Manaus in Brazil, resulting in two important collections of *Amazonian Dark Earths* papers (Lehmann et al. 2003; Glaser and Woods 2004). The topic is now of major scientific interest, of relevance both to prehistory and to agricultural development and global climate change today; hence the value of this historical survey.

When Woods began seriously looking at the phenomenon of the Amazonian dark earths in the early 1990s, a first step of course was to acquire as much of the previous literature as possible, review it, and begin a bibliography. Subsequently the bibliography has grown and has become a resource in itself that could be queried for substantive data on the development of and trends in dark earth studies. Toward that end he sent out a draft compilation to over three dozen other interested researchers asking them for comments, corrections, and additions, and he asked them to pass the bibliography on to others who might be able to contribute. Many responded, and the result reflects the combined efforts of numerous individuals.

1.2 The Bibliography

The bibliography through 2004 contains 311 items. All have been examined to determine that they have specific references to dark earths. Not included are newspaper stories, unpublished reports, letters, notes, and abstracts. Included are theses and dissertations and expanded abstracts published in conference proceedings. There are some additional unchecked references that may be included in future revisions of the bibliography. Undoubtedly there are other items, but we believe that these are few. This document is intended to be a work in progress which will be continually updated and distributed to interested parties (copies are available from William Woods, wwoods@ku.edu). Following are some general comments and then a review of early observations and studies.

An overwhelming proportion of the entries are relatively recent (Fig. 1.1). Since the 1960s there has been roughly a doubling in new entries every decade. Indeed, 202% or 65% of the entries have been published since 1990 and 124% or 40% since 2000. About two thirds of the entries are in English, 21% in Portuguese, 5% each in Spanish or German, and less than 2% in French. We should note that many of the Brazilians, Germans, and Colombians often have been publishing in English for over 20 years, so these figures do not truly reflect the linguistic origin of the authors. For example, the majority of the 55 authors and co-authors of the two recently published *Amazonian Dark Earths* volumes are non-native English speakers, and of the four editors Woods is the only one whose native language is English. Finally, 19 of the entries are either theses or dissertations from universities in Germany, Brazil, the United States, the Netherlands, Canada, and Great Britain.

The full bibliography is too long to include here. Thus in "The Bibliography, 1874–1977" that follows, we only list items for the period during which the initial discoveries and studies were made (61 items). The period of modern scientific research properly begins in 1978–1980, although one might be able to argue that both Katzer (1903) and Sombroek (1966) could well fit into the modern scientific period. Most of the publications on Amazonian dark earths from 1980 to 2004 are either in Lehmann et al. (2003) and Glaser and Woods (2004) or are listed in the bibliographies in those collections. The bibliography here through 1977 does not include some publications in which the information about dark earths is not substantial, with the exception of the earliest reports.

1.3 Initial Discoveries and Early Studies

All the entries are dated since 1874. This is extremely curious, since there are numerous explorers', travelers', and scientific reports about Amazonia beginning in the sixteenth century, and one would have expected that someone would have noted, if only in passing, so common and distinctive a phenomenon. However, searches of the literature and archives by numerous people have come up empty. The common settlement place name "*Terra Preta*" isn't even mentioned. Soils in general are rarely referred to, and when they are it is in dubious sources such as the 1809 geography by Jedidiah Morse who merely says that "The soils are extremely fertile …" in Amazonia (p. 242). Perhaps this lack of interest in aboriginal resources stems from the Eurocentric view of the economic superiority of Old World technologies coupled with the prevailing idea of Amazonia as an unsullied wilderness. Not all shared this viewpoint including von Humboldt who admired the achievements of both the pre- and post-colonial Indians and said that "Every tropical forest is not primeval forest" in the neotropics (1869:193).

Ignorance of *terra preta* changed as an indirect result of the ending of the American Civil War. Many in the South decided to migrate to Latin America rather than to be re-Unionized (Dawsey and Dawsey 1995). The leader of one such group, Lansford Hastings, surveyed the Amazon Valley from Santarém to Manaus in 1866 and decided to establish a colony on the Belterra Plateau south of the city of Santarém. Selection of some of the richest dark earth lands in the lower Amazon could not have been a coincidence, but had to have resulted from local knowledge. Enormous dark earth sites at Panema, Diamantina, Taperinha, and Marurú all became plantations for the so-called "Confederados" in 1867 or shortly thereafter.

The first to note this correspondence in print was the geologist Charles Hartt (1840–1878) in his publications (1874a:227; 1874b:36–37; 1885:3, 12–16) describing the lower Tapajós based on his work there in 1870 and 1871, including excavations of the famous Taperinha site.[1] Both Hartt and his assistant Herbert H. Smith (1851–1919) in his book *Brazil: The Amazons and the Coast* (1979a) and in an article "An American Home on the Amazons" (1879b) clearly made the connection between the dark earths and prior Indian villages. Hartt (1874b:5, 7) used the term "kitchen middens" to describe these soils. He was the first to report modern Indian cultivation of *terra preta* (Hartt 1885:13). Smith (1879a:145, 168) said that "Strewn over it everywhere we find fragments of Indian pottery … the bluff-land owes its richness to the refuse of a thousand kitchens for maybe a thousand years." The British geologist C. Barrington Brown (1839–1917) made similar observations at about the same time when describing the black soils along the New River in Guyana: "In two places also, in the forest, were the sites of ancient villages, marked by a deep black soil mixed with broken pottery" (Brown 1876:339); and on the bluffs along the Amazon near Óbidos: "undoubtedly of artificial origin … highly prized as agricultural grounds, owing to their fertility; and they bear the name of "Terras pretas" (black earths)" (Brown and Lidstone 1878:270–271). In this publication Brown and Lidstone were apparently the first to use the term *terra preta* ("*terras pretas*") in print.

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[1] Hartt's history has recently been described by Brice and Figueirôa (2003), who call him "one of he great explorer-geologists of the nineteenth century." He initially went to Amazonia in 1865–1866 with Louis Agassiz on the Thayer Expedition. (Agassiz in his famous book *A Journey in Brazil* [1868] makes no mention of dark earth during his travels between Belém and Tefé.) A respected scholar, Hartt was a correspondent with Charles Darwin. He founded the Geological Commission of Brazil in 1875. He was a professor of geology at Cornell University from 1868 to 1878, when not on leave in Brazil. Interestingly, Cornell is now one of the centers of Amazonian dark earths research, under soil scientist Johannes Lehmann. Hartt died in Rio de Janeiro in 1878 at the age of only 37 after contracting yellow fever in Amazonia.

Another early observer of the dark earth phenomenon was the geologist, clergyman, and explorer James Orton (1830–1877) who visited the Santarém area in 1868. The third edition of his book *The Andes and the Amazon* (1875:368) tells us that "The soil is black and very fertile. It beats South Carolina, yielding without culture thirty bushels of rice per acre." No indication was given by Orton that these soils might be anthropogenic. It is curious that neither of Orton's earlier two editions (1870, 1871) of this volume mention the dark earths and, indeed, they say that in the country surrounding Santarém "the soil is poor" (Orton 1870:251). Perhaps Orton's third edition was rewritten and expanded in response to Hartt's evidence to the contrary and his disparaging comments on Orton's earlier reports (Hartt 1872:243).

Hartt, Smith, Brown and Lidstone, Orton, Orville A. Derby (1851–1915), and J. B. Steere (1842–1940) (see below) in the 1870s were all English speaking and most mentioned the Confederados. It would have been natural for them in their travels in the Santarém region to visit the English speaking American colonists and observe their crops of rice, sugar cane, and tobacco on *terra preta* soils. These settlers undoubtedly had learned about the merits of the black earth soils from Indian and Brazilian farmers.

A posthumous monograph by Hartt was published in Brazil in 1885; however, with the exception of a note by Derby in the late 1890s about *terra preta* soils in the Trombetas region (Derby 1897–1898:374), nothing else on the dark earths was forthcoming until 1903 when Friedrich Katzer's (1861–1925) classic volume on the geology of the Amazon region was published in Leipzig. Based on his 3 years of fieldwork (1895–1898), Katzer (1903:64–70) recognized the fertility of these soils in the lower Amazon. He (1903:64, 67) stated that the region's "more distinguished wealth lies in its soil" and estimated that there were over 50,000 ha of *Schwarze Erde* immediately south of Santarém between the Tapajós and the Curuá Una rivers. Subsequent research has confirmed the extensive amount of dark earth there. Katzer conducted pioneering analytical work on these soils, and as a result concluded that they had a completely different origin from the Chernozems he knew in central Europe in that the former were cultural in origin. He found that these soils consisted of an intimate blending of mineral residuum, charred plant materials, and decomposed organics. Three dark earth samples were subjected to loss-on-ignition testing with results indicating high organic matter content, in stark contrast to soils from surrounding locations. Based on his analyses, Katzer suggested that because of their fertility the dark earths were cultivated in ancient times when the region was more or less densely populated, a prescient assertion. His would be the last published chemical analyses of dark earths until Sombroek in 1966.[2]

[2] Upon returning from Brazil in 1898, Katzer focused his research on the geology of Bosnia-Herzegovina and ultimately became the Director of the Geological Institute in Sarajevo. He authored over 140 scientific works, including his major book *Geologie Bosniens und der Hercegovina* published posthumously in 1925 (Ćorić 1999:131). Almost all of Katzer's collections were destroyed with the national museum during the tragic Bosnian war of the 1990s.

Thus, by the end of the nineteenth century several scientists had reported the presence of dark earths at various locations within Amazonia. They made the connection between Indian artifacts within the dark earth soils and an anthropogenic origin. The link between prior burning activities and charcoal as a major feature of these soils was made, and it was established that these soils were highly fertile and productive and probably used for agriculture in the pre-European past. However, very little further progress was made during the first half of the twentieth century.

There were no other publications on the dark earths until the 1920s. One was by the anthropologist William Farabee (1921:156–157), based on a trip to the Santarém area in 1915. On the northern edge of the Belterra Plateau on bluffs overlooking the Amazon he found that black earth marked ancient Indian settlements. The black earth was 1 to 2 ft deep and covered, in some places, as much as 10 acres of surface. In 1927, Steere (p. 24), a professor and traveler from Michigan, reported briefly on 1870 excavations and observations of dark earths on the plateaus to the east and south of Santarém, "…which were, no doubt, sites of ancient towns."

Sponsored by the Ethnographical Museum of Göteborg, Sweden under the direction of Erland Nordenskiöld, between 1923 and 1925 the German-naturalized Brazilian anthropologist Curt Nimuendajú (1883–1945; Curt Unkel before 1922) conducted excavations and surveys of dark earth sites within the lower Tapajós region and adjacent Amazon bluffs. Like Katzer, Nimuendajú (2004:122) believed that the dark earths had developed from Indian habitation activities associated with permanent settlements and that the resultant fertile soils were then used for crop production. He produced a manuscript in 1925 entitled "Die Tapajó" and beginning in 1923 a number of maps showing locations of *terra preta* sites, with relevant publications not until after his death (Nimuendajú 1948:216; 1949; 1952; 1953; 2004). The latter publication is the result of the efforts of several individuals, most notably the editor, Per Stenborg. It consists of comprehensive translations to English with interpretation of Nimuendajú's manuscripts, notes, and correspondence held at the Göteborg Museum. An editor's preface and introductions by Eduardo Góes Neves and Stig Rydén, coupled with further commentary by these individuals, provide the necessary background for placing Nimuendajú's work in its full historical and contemporary scholarly context. A total of 67 figures, 200 plates, and 21 maps illustrate the wealth of the materials collected by Nimuendajú, give accurate representations of his sketches and plans, and provide through historical and modern photographs the settings for his investigations.

The decade of the 1930s is marked only by the 1933 posthumous publication of a Portuguese translation of Katzer's 1903 book. The lack of dark earth publications in the 1920s and 1930s is puzzling. This was the period of the failed Fordlandia rubber-plantation venture, initiated in 1927 along the upstream Tapajós, with most of the production activities subsequently transferred in 1934 downstream to the much better setting at Belterra. Significantly, the Belterra Plateau has an exceptional density of dark earths, and the zone centered on the town of Belterra is especially rich in these soils. However, no special mention seems to have been made of them in the literature or to the fact that rubber trees grow especially well on them (W Sombroek 2002, personal communication, Manaus). In an effort to investigate further the possibility that dark earths were a major factor in the decision to move production, Woods conducted archival research at the Benson Ford Research Center on records relating to Fordlandia and Belterra. This research indicates that the level terrainof the latter and its position at the head of year round access by deep water ships were considered to be much more significant than any differences between thetwo tracts' soil properties.[3] Equally curious is the failure of Marbut and Manifold to mention dark earths in their classic 1927 *Geographical Review* article on the soils of Amazonia. They clearly conducted soil survey and sampling in the heart of the dark earth country, but seem to have ignored the presence of this unique soil.

In the 1940s, 1950s, and 1960s various observers reported and described dark earth soils. However, rather than analytical research, attention was more focused on possible natural origins of the soil, in contrast to the earlier belief that the soil was of human origin (Glaser et al. 2004:10; Myers et al. 2003:23). The Brazilian agronomist Felisberto Camargo (1941) believed that *terra preta* came from volcanic ash. Archaeologist Barbosa de Faria (1944) and pedologists Cunha Franco (1962) and Ítalo Falesi (1965; 1967; 1972; 1974:210–214) argued that *terra preta* was formed by the accumulation of organic material in past lakes and ponds, and that such sites attracted Indian settlement, which explained the cultural midden material present; therefore a mixed natural and anthropogenic origin. Ítalo Falesi (2002, personal communication, Manaus) now believes that these soils resulted from human activity. In 1949 the French geographer Pierre Gourou reviewed various origin theories and concluded that the soil he had observed was probably "archaeological" (1949b:375–379), as did Hilbert (1968). In 1944 an extract from Katzer's 1903 geology book was published in Brazil as "A Terra Preta." This was the first article specifically on *terra preta* and is frequently cited.

The Brazilian-American geographer Hilgard Sternberg described *terra preta* soils in his 1953 dissertation (Universidade do Brasil, presently Universidade Federal do Rio de Janeiro) on Careiro Island east of Manaus, published in 1956 (new edition in 1998, see pp. 107–110)). Sternberg (1960:417, 419) radiocarbon dated ceramics in *terra preta* soil on Careiro in order to determine the antiquity of the migration and stability of Amazon channels. Later, he pointed out that: "It is remarkable that in an environment such as Amazonia, whose potentials have been judged insufficient to support large concentrations of population or stable settlement (Meggers 1954), indigenous settlements should have been so large and persistent" (Sternberg 1975:32–33).

For the 1960s the soil studies by Franco, Falesi, and Hilbert are mentioned above. Falesi (1967) believed that *terra preta* was so common that he recognized it as

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[3] An April, 1935 photograph (Benson Ford Research Center #0–7672) of the 121 acre *Hevea brasiliensis* nursery at Belterra shows two men in the foreground standing at the edge of a large level field with pottery sherds lying on the bare black soil literally at their feet. This photograph has been published in Bryan (1997:159).

Fig. 1.2 Wim Sombroek at the Hatahara site, July 2002. (Photograph taken by Johannes Lehmann)

a taxonomic unit. In 1966 Dutch soil scientist Wim Sombroek (Fig. 1.2) based on his earlier dissertation published his classic *Amazon Soils*, which includes descriptions and lab analyses of dark earths on the Belterra Plateau (Sombroek 1966:174–176, 252–256, 261). He made a distinction between black *terra preta* proper derived from village middens and brownish *terra mulata*, a term he introduced to the literature, which be believed "obtained its specific properties from long-lasting cultivation." He was the first to suggest this as far as we know. And he mapped the distribution of dark earths along the bluffs of the lower Rio Tapajós (p. 175). In 1966 he questioned whether it was "economically justifiable," in his words, to create and cultivate such soil today (p. 261). However, more recently, he promoted the idea of developing new dark earth as carbon stores and sinks for intensive cultivation, what he called "*Terra Preta Nova*" (Sombroek and Carvalho 2002; Sombroek et al. 2003:136; Madari, Sombroek and Woods 2004). In recognition of his enormous contributions to *terra preta* research, the two recent *Amazonian Dark Earths* books and this one are all dedicated to Wim, "The Godfather of Amazonian Dark Earths," who passed away in 2003.

In the 1970s, reports of Amazonian dark earths are scattered and uneven. They include, among others, Falesi (1970; 1972:33–39; 1974:210–214), Klinge et al. (1977), Ranzani et al. (1970), and Simões (1967, 1974). Botanists Prance and Schubart (1977:569; 1978:61–62) in the lower Rio Negro region examined *campina* forest on fertile *terra preta* in contrast with surrounding open *campina* scrub. Archaeologist Betty Meggers in her 1971 bestseller book on Amazonia (pp. 132–134) brought *terra preta* to the attention of a wide audience outside Brazil, but she failed to realize the significance for prehistoric cultivation either then or in the revised edition 25 years later (Meggers 1996:132–134). Meggers (e.g. 2001:310–319) attributes the development of these distinctive soils to recurrent short-term occupations of the same general site over long periods of time. The archaeologically demonstrated presence of large, planned, and persistent pre-European settlements associated with dark earths in the lower Negro and upper Xingu regions (Heckenberger 1996:2005; Heckenberger et al. 1999; Neves et al. 2003; Petersen et al. 2001) strongly suggests that the Meggers' view is in need of serious reconsideration (Fig. 1.3).

Fig. 1.3 Archaeologists Eduardo Neves and Betty Meggers meeting for the first time and discussing *terra preta at* the XI Congresso da Sociedade de Arqueologia Brasileira, 24 September 2001, Rio de Janeiro, Brasil. (Photograph taken by William Woods)

1.4 Conclusion

The first century of publications about Amazonian dark earths, involving discovery and initial descriptions, properly ends in the late 1970s. The modern period of scientific study can be identified as beginning with the soil science publications by the Japanese Renzo Kondo in 1978 and by the Germans Wolfgang Zech et al. and Gerhard Bechtold in 1979. Then, in 1980 Nigel Smith's influential survey article was published in the *Annals of the Association of American Geographers*.[4] The number of publications with reference to dark earths increased from 24 in the 1970s to 42 in the 1980s to 78 in the 1990s to 124 from 2000 through 2004 (Fig. 1.1), an indication of the dramatic explosion of dark earth research and commentary since 1980 and particularly since 1990. Thus, the topic of Amazonian dark earths is finally receiving focused scientific attention following a century of inattention to the reporting by perceptive observers such as Hartt, Katzer, Nimuendajú, Sombroek, Falesi, and a few others.[5]

[4] Nigel Smith was a doctoral student of Hilgard Sternberg.

[5] Internet search engines provide another measure of spectacular growth in interest in the dark earths. A 2008 query at google.com using the entry "*terra preta*" yielded over 600,000 internet site links; the same entry in 2000 would have provided at most a few dozen. Some of this difference is certainly due to the greater efficiency of the search engine, but most of the entries are post-2000. There is some duplication and many items which are not for Amazonian *terra preta*. Nevertheless, amazing!

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The Amazonian Dark Earth Bibliography, 1874–1977 (n = 61)

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Chapter 2
Pre-Columbian Settlement Dynamics in the Central Amazon

L Rebellato, WI Woods, and EG Neves

2.1 Introduction

During the past decade, integration of anthropology, archaeology, biology, ecology, geography, and soil science has brought important results in the development of an overview of the formation processes of Amazonian Dark Earths (ADE). These interdisciplinary efforts have provided significant information about the genesis, use, and re-use of these soils; moreover, this research is producing important information about pre-Columbian societies and the cultural behaviours that could start the ADE accretion in Amazonia (e.g. Lehmann et al. 2003; Glaser and Woods 2004; Rebellato 2007: Arroyo-Kalin, this volume; Schaan et al., this volume). An archaeological effort directed toward understanding the past socio-cultural processes responsible for the origin of these soils and the subsequent use is presented in this chapter. Evidence for continuity and change in settlement patterns during pre-Columbian times at the Hatahara archaeological site in the Central Amazon of Brazil is reviewed (Fig. 2.1). Soil analysis results correlated with archaeological artifacts excavated in that site provide interpretation of cultural changes, the consequences of these in village morphologies, and advance the interpretation of the region's indigenous history.

Located on a bluff top parallel to the left bank the Solimões/Amazon River, near to the confluence of the Negro and Solimões rivers, the Hatahara site has natural protection against attack due its 40 m high location. The scarp of this bluff surrounds ca. 60% of the site area leaving only a narrow entrance in the northeast. The secure location of the site was enhanced by access to a wide range of resources that allowed the population to survive by fishing, hunting, gathering, and farming (Fig. 2.2). The Hatahara site is an example of the Bluff Model described by Denevan (1996), who understood that pre-Columbian settlements in Amazonia were often located on bluffs adjacent to major river channels and their floodplains. These settlements, consequently, were not subject to the annual floods that cover the lowlands, but still had ready access to the fertile soils of the floodplain. Hatahara contains pottery from three different archaeological phases (the Açutuba – *c*.300 BC–*c*. AD 360; Manacapuru *c*. AD 400–800; Paredão *c*. AD 700–1200; and, the Guarita Subtradition *c*. AD 900–1600) (Heckenberger et al. 1999; Hilbert 1968).

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

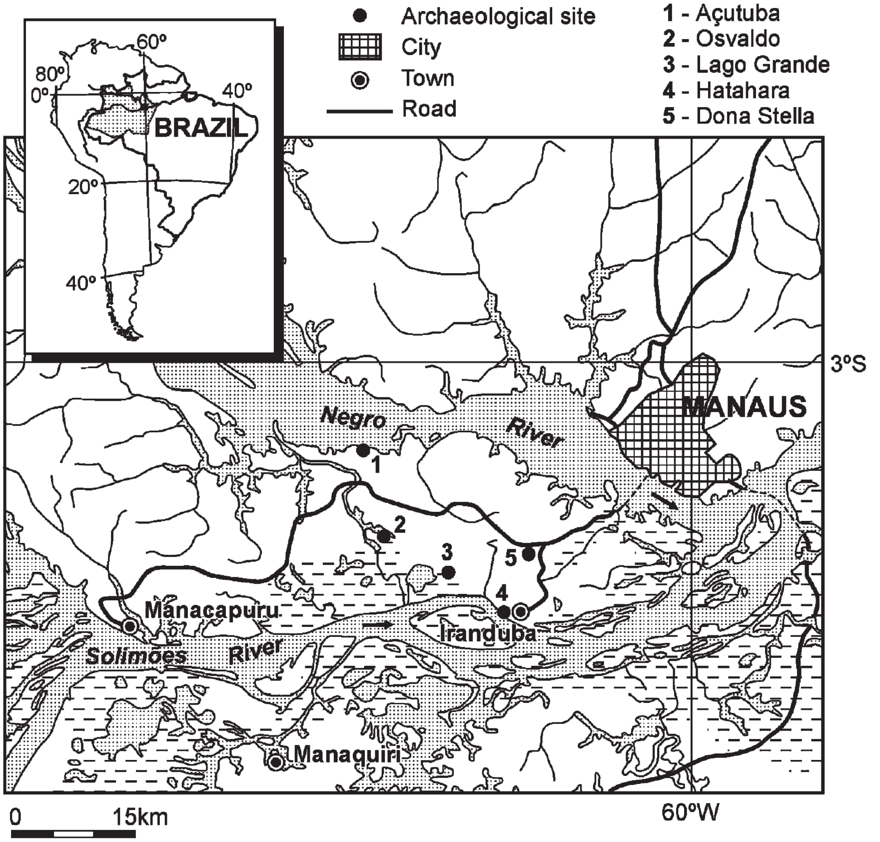

Fig. 2.1 Central Amazon locator map with the Hatahara and other archaeological sites investigated by the Central Amaz on Project indicated

Fig. 2.2 Aerial photograph of the Hatahara Site. It is possible see the scarp of the bluff and the Solimões River. The irregular oval line delimits the habitation zone of the site (Photo by E. Neves 1999) (*See Color Plates*)

It presents a complex stratigraphy with deep and extensive black and brown colored anthropogenic soil layers with high and low pottery concentrations, respectively.

2.2 Archaeology and Procedures

Archaeological research has been pointed out as a key to understanding the ADE formational process. These soils were generated by both intentional and unintentional cultural landscape management. In order to develop the relevant data for interpretation archaeologists must address some basic questions:

1. What did the people do? In other words, what activities did they engage in?
2. What were the material results in a chemical-physical depositional sense of each of these activities?
3. What was the intensity of each activity and the amounts of different materials deposited over a unit area per unit time?
4. What were the patterns of disposal and how did these relate to the morphology of the contemporary settlement and its diverse activity areas?
5. What was the duration of each activity?
6. What was the duration of each settlement?

To fully consider these questions and try to understand the Hatahara archaeological site formation process and its association with the ADE it was necessary to conduct extensive fieldwork across the site. Three field seasons of excavations and a period of intensive laboratory analysis were carried out (Fig. 2.3 shows each year's activity at the site). The topographic mapping helped to identify on the south side a group/assemblage of small mounds (ca. 1.5 m high and 2.5 m long) that together exhibit a horseshoe-like shape. A grid was plotted to carry out a systematic program of auger testing to find out the specifics about the ADE and pottery distributions (horizontally and vertically) throughout the site and their correlation with the mounds.

In the past it has been difficult to recognize individual structures that show clearly the village morphology at Central Amazonian archaeological sites; this is mainly due to conditions of poor visibility within the thick vegetation on these sites (Siegel 1995). The Hatahara group/assemblage of the six little mounds arranged in a semicircular shape was the first evidence that this could possibly be accomplished. Furthermore, through the correlation of soil signatures, pottery, and topography, it was possible to distinguish two distinct village morphologies mainly related to the last two occupations at the site (Paredão phase and Guarita subtradition). Both of these were identified by Hilbert (1968) in the Central Amazon. In addition, Hilbert also associated the Paredão phase with the Incised Rim tradition (according to Meggers and Evans 1961)[1] and the Guarita subtradition with the Amazon Polychrome Tradition.

[1] The Incised Rim Tradition was not accepted by Lathrap who agreed with previous research in Venezuela carried out by e.g. Cruxent and Rouse (1958) and termed this ceramic complex the Barrancoid or Modeled-Incised Tradition. Here, we are following Lathrap's interpretation (1970:113).

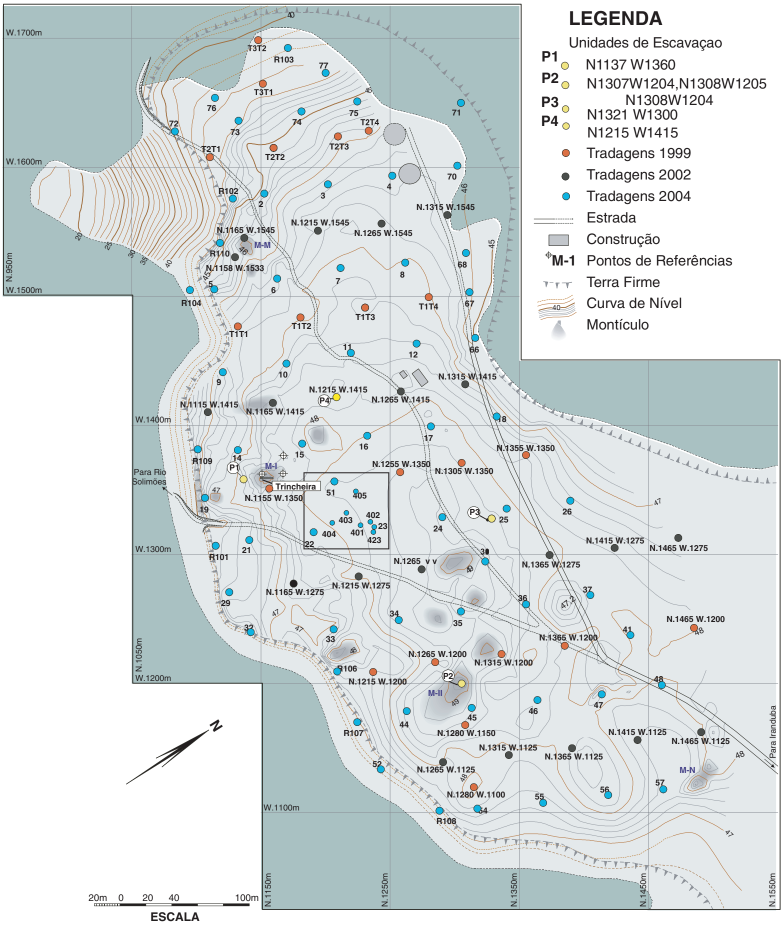

Fig. 2.3 Fieldwork at the Hatahara site. The 103 auger pits are shown in red (recollected in 1999), blue (2002), and black (2004). The yellow indicates units excavated (*See Color Plates*)

Although a battery of soil chemical analyses was also conducted (Grosch 2005 and Rebellato 2007), here we will concentrate on some of the soil physical characteristics identified at the site and correlate them with the pottery distribution.[2] The soil physical

[2] Many soil physical parameters can be examined productively for the analysis of ADE. Unfortunately, very little work has been done with these to date. One insight from such analyses concerns the action of fire on soil particles. Soil aggregates are very important to proper movement of air, water, and roots within the soil body. Due to a fusion of particulates and organic matter these aggregates are increased as a result of burning as pointed out by Teixeira and Martins (2003). ADE contains higher degrees of aggregation than adjacent soils and as such points in part to a relatively higher degree of human manipulation by fire and perhaps intentionality.

analysis allowed the identification of aspects of site formation processes, an interpretation of the use of ADE, and the correlation of these soils with different social groups through time. Through correlation of the distribution of aspects of the soil physical composition areas were identified with intense, medium, and low human interference, respectively, and some of the human behavioural variables that may have started the ADE formation process were able to be isolated. As will be shown, the soil physical signatures also revealed places of specific activities and structures within the site. The correlation between the variables topography, pottery, and soil signature allowed the identification of domestic areas, possible agricultural fields, public areas, places of refuse disposal, and other human altered zones through time.

It is felt that more widespread application of this methodology can contribute to the development of an overview of the diachronic, pre-Columbian settlement variability and differential environmental management by past societies. Through the knowledge of the morphology (form and structure) and function of these sites we can understand the different uses of space and, as a consequence, the different cultural groups that inhabited a specific area. This kind of analysis also helps to establish relationships between the distinct ceramic groups and the morphology of their settlements. The settlement is the primary ingredient of the cultural landscape and it includes the economically used areas (such as hunting and fishing zones, fields, etc.), living areas (seasonal or permanent), burial sites, paths and passageways, and defensive structures, among other features (Eidt and Woods 1974:3). A settlement's structure reveals an internal organization and preserves records of economic, social, and historical events. Because of this and due to the fact that they are located within a physical and cultural landscape, settlements also reflect the interrelationships between economic factors (such as production, transport and consumption of food, raw materials, and other objects), social and historical factors, and physical factors (such as climate and vegetation) (Eidt and Woods 1974:3).

2.3 A Brief Background

Until the last decade a dichotomous view provided two opposing models concerning the density, size, shape, and duration of Amazonian pre-Columbian settlements. One group of scientists believed that environmental conditions in the Amazonian region inhibited the social and cultural development of its populations and posited soil exhaustion and the low available protein as principal limiting factors (Steward 1948, 1949; Meggers 1954, 1971, 1991, 1995; Gross 1975). The second view presented the Amazonian region as a cultural innovation center; especially the Central Amazon, where the oldest pottery was created and the first wild plant domestication for agricultural systems in South America occurred (Lathrap 1970, 1977; Brochado 1984, 1989).

While archaeological work carried out by Meggers (1954, 1971, 1991, 1995) espoused cultural conservatism as the norm with the aboriginal village structure and complexity, subsistence patterns, and low population densities of the present serving as a model for the past; Lathrap in total disagreement, hypothesized that the Central Amazon region was a center for cultural innovation. Based on differences between ecosystems found in Amazonia, including *terra firme* (uplands) and *várzea* (floodplains), Lathrap set up distinctions of natural resource availability which caused social and economic differences between cultural groups. The enhanced fertility of the floodplains of white water rivers (e.g. the Solimões and the Madeira) results from glacial sediments originating in the Andes. This fertility provided increased agricultural productivity that promoted population growth and the creation of large settlements. Due to the resultant demographic pressure a centrifugal movement developed that spread human populations and associated ceramic styles, languages, and agricultural systems to different areas of South America.

Lathrap (1970), followed by his Brazilian PhD student Brochado (1984), believed that the Central Amazon was settled by manioc agriculturalists *c*.3000 BC. Lathrap set up two groups in the area (proto-Tupi and proto-Arawakan linguistic stocks), that subsequently migrated in different directions through the major Amazon tributaries. Lathrap also suggested that there was settlement continuity in the Central Amazon for millennia before European contact. Subsequently, his hypotheses have been reviewed and recent archaeological data in the Central Amazon have shown that Barrancoid or Modeled-Incised Tradition ceramics associated with early radiocarbon dates (*c*.500 BC to *c*. AD 1000) and stratigraphic positions are superimposed by Polychrome ceramic layers dating to after *c*. AD 1000 (Heckenberger et al. 1998; Petersen et al. 2001; Neves et al. 2003a, b, 2004; Neves and Petersen 2006).

2.3.1 ADE Formation Through Time

Chronologically, the ADE formational process in the Brazilian Amazon region minimally begins at the onset of the Christian era (Petersen et al. 2001). However, there is a great deal of variation in the specifics. Examples include the Paredão archaeological site near Manaus where a date of 450 BC was reported (Hilbert 1968:256); a buried ADE site on the Jamari River in Rondônia which dated *c*. 2500 BC (Miller 1992); another site in the Hupa-iya and Yarinacocha area of the Ucayali River in Peru exhibited ADE dating to *c*.200 BC (Eden et al. 1984:126); on the Rio Caquetá in Colombia in the Araracuara region the ADE is dated at *c*. AD 384 (Mora et al. 1991); and, finally, the Upper Xingu River presents the beginning of the process of ADE formation at *c*. AD 950 (Petersen et al. 2001). The 'Period of Regional Integration' (Petersen et al. 2001:99; Heckenberger 2002:104–107) with circular villages and long-term habitation is clearly associated with the development of ADE. This first period of ADE formation (*c*.1000 BC–*c*. AD 1000) in the central Amazon may have been associated with the arrival and spread of Arawak speaking peoples.

To understand how the ADE initially developed it is necessary to consider subsistence practices and refuse disposal patterns (Woods et al. 2007). Practices included hunting, harvesting, fishing, and gathering of many products which were then brought to the place of habitation for direct consumption as food or for use as construction materials or fuel. Byproducts such as feces and urine, charcoal, ash, and other organic materials accumulated at the locus of use or were disposed in specific waste areas. This refuse appears to be mainly responsible for the genesis of these distinctive anthrosols at the places of habitation (Woods 1995). Only later were these soils utilized for food production.

The empirical results from the Hatahara site compare favourably with this scenario for ADE formation and use presented above. Physical and chemical soil signatures at the Hatahara site show a long period of ADE genesis in disposal/waste areas. As a result a few hundred years after the initial occupation a valuable resource, a rich anthrosol that was extremely fertile for agricultural use developed in the former disposal areas of the settlement and began to be utilized. How is this demonstrated through the archaeological research?

According to Denevan (1996:669–670, 2004) *terra preta* and *terra mulata*[3] are an indirect evidence of intensive *terra firme* cultivation in permanent or semi-permanent fields, and, undoubtedly, cultivation with fruit orchards, managed fallows, house gardens, and brief bush fallows with semi-permanent settlements, some numbering thousands of people, surrounded by zones of modified forest manipulated by hunting and gathering activities (Denevan 2001:102–132). This viewpoint expresses a very different vision than that of Meggers who argues for settlement discontinuities due to soil exhaustion and continual reoccupations of the same site through time (e.g. Meggers 1971:12–14). In support of Denevan's stance, research carried out in the lower Tapajós and Arapiuns drainages has identified very large ADE sites with different densities of archaeological materials whose distribution is suggestive of habitation middens associated with areas formed by a long-term agricultural activities (Woods and McCann 1999) and similar results have been found in the Central Amazon.

Results from the Central Amazon Project show that over time soils at choice settlement locations are not necessarily degraded, but can become even more desirable through intentional modification and unintentional alterations resulting from human occupation (Heckenberger et al. 1999:372). The hundreds years of occupation by people related with the Manacapuru and Paredão phases at the Hatahara site clearly made this location significantly more fertile and the ADE are just one example of modification that increased the value of settlement areas. Charles Clement has pointed out improvements in the zones surrounding habitation sites through the process of *landscape domestication*. This was defined by him as a conscious process by which the human management of plants and animals increases the food variability and nutritional quality (Clement 1999:190; 2005:165).

The correlation between cultural systems and the intensive use of the ADE for food production is a point that is stressed in this work. The physical analysis of the soils related to the first occupations of the Hatahara site, especially during the Manacapuru and Paredão phases, strongly suggests permanent use of the space

[3] Wim Sombroek (1966:175) defined the term *terra mulata* (TM). These are dark, organic-rich soils that do not contain quantities of ceramics or the high concentrations of plant nutrients found in the classic *terra preta* (TP). He mapped an extensive area of TM extending inland from a ca. 10 km long zone of TP along the bluff edge in the vicinity of Belterra. Sombroek suggested that the TP represented former habitation waste disposal areas and that the TM zones were pre-Columbian agricultural fields. Subsequently, Woods and McCann (1999) proposed an *intentional* improvement of these TM soils by past societies and that their high fertility provided the basis for a productive agricultural system.

mainly around the circular plaza (Heckenberger 1996, 2002, 2005). Although it was possible to identify a later change in the distribution of *terra preta* and *terra mulata* in the Hatahara site profiles, the switch identified is not associated with the abandonment of the site and a subsequent reoccupation by another group after some time (as suggested by Meggers 1971, 1995). Rather, the precious ADE probably were the object of warfare and social conflict during *c*. AD 900–1000, which resulted in the takeover of the site by another cultural group.

This can be confirmed through the change of land use (Fig. 2.3), where it is possible see sudden rearrangement of the soil characteristics within the upper portions of the ADE profiles. The pottery analysis also shows a switch in ceramic traditions around the 50 cm depth whereby the new ceramics are associated with the Amazonian Polychrome Tradition that was locally defined by Hilbert (1968) as the Guarita.

The linear village shape found in the Hatahara site suggests not just a cultural change, but also a different way to exploit resources by the new pre-Columbian "settlers".[4] Descriptions made by the first European travelers, who in 1542 observed a continuous and almost continuous linear occupations along sections of the Amazon (Friar Gaspar de Carvajal 1934) support the interpretation of the village morphology at Hatahara. Porro (1996) associated a linear pattern for this population with an economy basically associated with the water resources, which is completely understandable. Results presented also furnish one more reason for this shape; namely, better use of the ADE area for food production. Where formerly much of the deposits were contained within the plaza or under structures, with the houses tightly distributed along the bluff edge these rich interior areas were now open for cultivation. Indeed, in addition to distributing their refuse more widely on the site's interior, it even seems that the new inhabitants moved dark earth around within the settlement area to produce a more even distribution of nutrients. Figure 2.4 shows an extensive area with ADE in the last period of the site's pre-Columbian occupation at 30 and 10 cm depths. This area had clearly changed form from a circular shape with a plaza without ADE formation for centuries to, suddenly, a more homogeneous ADE distribution.

2.3.2 A New Perspective

For some time environmental determinism has been put to the test by theories that deal with the Amazonian environment as a social construction and not as a culturally defining element (Descola 1986; Balée 1989 Heckenberger et al. 1999; Woods and McCann 1999; Petersen et al. 2005). These two approaches represent distinct ways of interpreting cultural diversity and, as a consequence, the way of explaining the variability of the archaeological record. The recent perspective proposes a vision that goes beyond

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[4] Another consequence of the linear village shape is the loss of ability to build an effective defensive enclosure or palisade. This suggests that the Guarita inhabitants of Hatahara and other line settlements along the Amazon did not need such a structure because of the lack of advisories or because of a sense of overwhelming strength. Alternatively, warfare could have been institutionalized and ritualized to the extent that it was both temporally and spatially predictable with damage restricted only to the combatants.

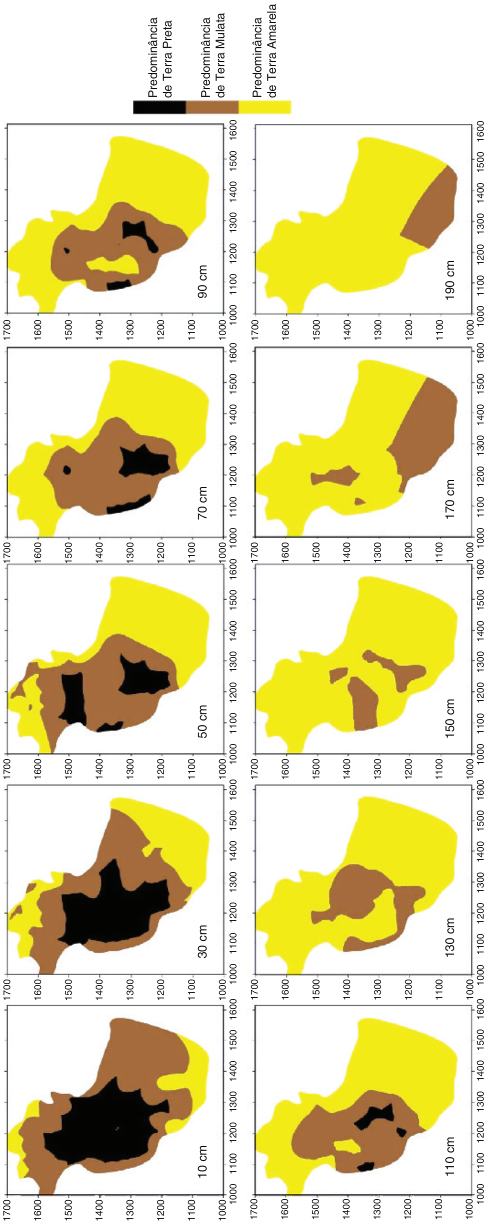

Fig. 2.4 Hatahara site soil color distribution. Soil color behavior through the artificial levels (*See Color Plates*)

the dichotomy between human societies *and* environmental determinism – in which the human being is not considered a passive agent who simply reacts to stimuli (Balée 1989:2). Thus, this approach highlights the importance of the environment in relation to the structuring of indigenous social life and it has been shown in different forms of integration between society and environment, as well as techniques of socialization of nature carried out by these individuals (Descola 1986). This shift in focus presents humans as agents who transform the landscape through the use and manipulation of resources (e.g. Denevan 1966, 1976, 1992a; Woods 1995; Balée 1989; Heckenberger et al. 1999; Woods and McCann 1999; Neves et al. 2004) and takes into consideration the investigative character of the human being. This new perspective has put forward the genesis of the ADE as the mark of the cultural changes which are associated with intensive environmental management, including agriculture (Petersen et al. 2005).

An additional consideration for this scenario is the great difficulty of cutting down enormous trees with stone axes in the rainforest as shown by Carneiro (1974, 1979a, b) and discussed by Denevan (1992b, 2001, 2004, 2006). These authors have stressed that the historical *coivara* (slash and burn) system was made possible by efficient metal axes introduced by Europeans. Carneiro (1960, 1961) also pointed out that the semipermanent settlement, currently practiced by Kuikuro (an ethnic group located along the Kuluene River, a tributary of Xingu River in central Brazil) could be attributed to supernatural factors, rather than soil poverty. Carneiro (1960:231) demonstrated that slash and burn cultivation in that region could be conducted continuously without decreasing the fertility of the soil around a village with a population of around 2,000 people. Denevan (1992b, 1996, 2001, 2004, 2006) added that clearings produced by natural tree falls were exploited agriculturally and that these initial clearings were enhanced and expanded through time. Denevan (2001:40) suggested that a mixed cropping system (*Polyculture*) was the technique used by past societies to combat pests and weeds and to protect the soil from sun and rain. This technique when associated with charcoal additions, such as those found abundantly in the ADE, could produce a synergic effect against depletion of the soil. Recent research has shown that charcoal retains soil moisture, helps to reduce nutrient leaching, and combats disease and pests (e.g. Steiner et al. 2004:188). The fertility of these open areas was probably also maintained and enhanced through organic input from domestic refuse (Hecht and Posey 1989; Hecht 2003). Woods (1995), and later, Oliver (2001, 2008) and Petersen et al. (2005) suggested that ADE started by accident through domestic waste accumulations (see below), but that after some time, the useful properties of these materials for agricultural soil fertility were discovered by pre-Columbian societies who then began to produce ADE intentionally.

2.4 Methodology

Determining the morphology of archaeological sites in Amazonia has been a difficult task. In addition to the problems of visibility in heavily vegetated areas, conditions of prior weathering and pedoturbation can greatly change the site context. Therefore, archaeologists need to work with scientists from other disciplines to understand these processes and how they have affected the specific site situation and its included cultural remains. Soil science methods can provide information applicable to the interpretation of pre-Columbian societies due to field observations and determinations and a variety of subsequent laboratory analyses. Color will be variable utilized here to be compared with the recovered archaeological evidence as an aid to interpretation of the village morphologies and ADE formation processes and uses through time.

In the field, the investigation included emplacing a topographic network with intersection points of the coordinate axes, already consolidated with the help of total station surveying instrument. Systematic surveys have been done at many archaeological sites by the Central Amazon Project (Heckenberger et al. 1999; Neves 2000; Neves et al. 2003a, b, 2004; Neves and Petersen 2005; Neves 1999; Costa 2002; Donatti 2003; Grosch 2005; Lima 2003; Petersen et al. 2005; Machado 2005; Chirinos 2007; Moraes 2007; Rebellato 2007; Arroyo-Kalin, this volume). Generally, test points are determined in transects which receive auger pits each 25 m. A total of 103 auger pits were made in the Hatahara site. Soil and artifact samples, mainly pottery, were collected through arbitrary 20 cm levels until the culturally sterile subsoil was reached and in many cases samples were collected below this point. Soil samples of ca. 300 g were collected from each level, as was all archaeological material. Each level was described on forms with information about debris pottery quantity, soil texture and color (Munsell), bones, charcoal, and lithic presence in the sample. Soil and archaeological remains samples were placed into plastic bags, each one with provenience number (PN).

Physical soil signatures such as color and texture were described in the field. Color was described with the aid of a Munsell Soil Color Chart, while samples were moist. The texture was estimated in the field through hand-texturing and judging the approximate proportions of sand, silt, and clay. Nevertheless, to assign whether a sample is TP or TM, beyond its color, it must be further analysed for features such as phosphorus concentration (in this case determined by Mehlich 3) and the quantity of archaeological remains, that is, ADE contain a high levels of both and TM shows a lower concentration of them. To produce the soil color map it was necessary to merge chromas into three colors: yellow, brown, and black. In this way, each color category had specific characteristics (Table 2.1). Thus, this simple technique applied in the fieldwork can bring consistent data for interpretation.

Table 2.1 Physical characteristics of the soil samples

Color (hue)	Pottery (quantity)	Phosphorus (ppm)	Chroma (10 and 7.5YR)	Texture
Black	Very high (>10 debris)	Very high (>300 ppm)	2/1, 3/1, 3/2 4/1	Sandy, sandy loam, & clay loam
Brown	Low (<10 debris)	Medium (<300 ppm)	4/2, 4/3, 4/6, 5/6, 5/4, 3/3, 5/8	Sandy, sandy loam, & clay loam
Yellow	Zero	Very low (<50 ppm bottom <5 ppm on surface)	6/6, 6/8, 7/8	Sand loam, loamy clay, & clay

Color results were recorded in Excel and compared with both archaeological remains and phosphorus and calcium concentrations. This permitted a correlation between these elements and the establishment of intervals of concentration for each level. After that, the results were plotted on a map, showing its behaviour through the profile (but just color will be shown here). The software used (Surfer 7.0) allowed the extrapolation of results from samples and their projection to nearby areas. Table 2.1 shows soil color, pottery, and texture categories for the Hatahara site.

2.4.1 Soil Color

The yellow color represents the natural Latosol that appears in the deepest layers, where the anthropic interactions were little or none. However, the brown coloring can also be deep, as shown in the East Zone at 190 cm depth; but here it is treated as an exceptional occurrence, a natural A horizon buried by subsequent cultural sediments (Fig. 2.3, 190 cm). But, this same argument can explain the brown soil in the site center at 170–150 cm; unfortunately, there is no pottery in these levels that provides an association between this phenomenon and a specific cultural group. So, further research has to be done to explain this conclusively.

At the 130 cm depth, it is possible to observe the beginning of a circular area of brown earth surrounding a yellow center. This phenomenon reaches its best expression at 110 cm with its shape more clearly outlined and the first signs of black earth at three distinct points. This suggests a positive correlation between ethnographic examples with remains found in the site. For instance, some ethnoarchaelogical research shows that public areas such as plazas in current villages are constantly swept (Heckenberger 2002, 2005; Silva and Rebellato 2004). It is possible to infer similar behavior during this past occupation through the color soil results. The yellow center in the site surrounded by brown soil suggests a constant cleaning of this area. This social behavior slows down the soil color change process in the plaza for some period so that it is not seen until the 90 cm depth.

The next level (70 cm) shows an increase of both types of ADE; for instance, TM expands toward the central and periphery and the TP increases its area at the same three points until 50 cm depth when there is a high increase of ADE in the west. Soil mapping shows another possible correlation with past and present, now associated with waste areas. Domestic waste production from a sedentary occupation can be the key for this issue. Both brown and black soils come from incomplete combustion of the plant materials, mainly woody. Black soils though are more closely associated with charcoal resulting from domestic fires used for cooking, repelling mosquitoes and animals, firing pottery, other processing, and also burning miscellaneous organic refuse, as well as depositions of organic and inorganic wastes from habitation activities and subsequent development of biota within the enriched soils.

In this way, waste areas over time received inputs of organic matter and, especially, charcoal and fish bones. These components had interacted with the natural soil and the charcoal gave darker coloration and increased moisture retention, while the fish bones increased phosphorus and calcium quantities. Other component materials from gathering, hunting, and construction were also integrated into the soils at the site and started the ADE formation process. The map shows the increase of these soils in the same three places for a long time and, rapidly, on the more superficial layers (0–40 cm). Woods et al. (2007) argue that change comes from different agricultural use of these soils. Indeed, it is possible to see a large area for crops; but how to explain the fast spreading? There are two possibilities; (1) there were earthworks, that is, people move these soils and spread them out on the surface to improve the fertility of the area for crops; and/or, (2) this fast increase of ADE was due to population growth, that also increased the waste areas and, due to the linear arrangement of the houses the dispositions in the waste areas behind them was also linear. It is the areas behind the houses that became garden areas. Both possibilities show a change of pattern, both cultural as well as territorial.

Although the map with the pottery distribution does not show the shape of past villages, it is important to relate ADE distribution and ceramic groups. In this way, through the pottery analysis it was possible to correlate the Paredão phase with a circular village pattern and Guarita Subtradition with a linear shape. The switch of village shape associated with pottery also points to cultural change.

Through these results it is completely coherent to think about the chroniclers' descriptions and compare them with the Guarita occupation in the Hatahara site. The results of this work confirm their descriptions; moreover, it is possible to affirm that the population had a productive agricultural system and its expansion through the Amazon could have been propelled by exploitation of the rich soils of the ADE areas, *built* by other groups (Paredão and Manacapuru phases). Neves et al. (2004) stressed the constant warfare in this region and Woods et al. (2007) associate it with the protection of such a rich resource as ADE.

2.5 Conclusion

This chapter has described distinct aspects of the Hatahara archaeological site. Through an interdisciplinary investigation it was possible to understand some of the occupational dynamics of the site's history. This study provided empirical results with which to test theories concerning the settlement of the site and the results will lead to a better understanding of issues related with formation process and use of the site area, including the ADEs. An important point to stress is the connection between divergent theories. The settlement was occupied for a long period during the Paredão phase and the structure of this occupation is comparable to current villages in Amazonia, except for the long period of occupation. The Guarita linear shaped village occupation is more consistent with the settlements present on the Amazon bluffs as described in the early European accounts. These agricultural societies maintained the earlier production strategy of exploiting the rich floodplain soils, but also developed an intense use and production of the ADE on the uplands. This coupled agricultural base could both support more people and support them more sustainably with decreased risk.

Although more research is needed, as a result of this interdisciplinary investigation the management of resources by past Amazonian societies is starting to be better understood. The archaeological record associated with pedological methods revealed an interesting picture about ADE formation processes and their use by past societies.

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Chapter 3
Steps Towards an Ecology of Landscape: The Pedo-Stratigraphy of Anthropogenic Dark Earths

M Arroyo-Kalin

3.1 Introduction

A posthumous *festschrift* to a bold mind is an apposite context to celebrate the role that research into pre-Columbian anthropogenic dark earths has played in a momentous paradigm shift in Amazonian scholarship. This shift – imprinted in the reciprocal intersections, synergies, and oppositions of a long history of intellectual contributions – calls for caution in addressing past and present environments exclusively as self-regulating and equilibrium-seeking systems to which individuals or cultures adapt or adapted to. Instead it encourages a consideration of the biotic and abiotic components of landscapes inhabited by human communities as historically contingent outcomes of niche-building, past and present. From an archaeological standpoint, it invites a sharpening of focus to behold 'past environments' as open-ended and non-deterministic evolutionary trajectories of material transformation within which the emergent surrounding-worlds that have structured the lifeways of past human communities have been crafted step by step. Some of these steps are evident to the learned eye, others remain to be unveiled by future research, and yet others, it is argued below, can be ascertained in subtle material signatures that exist in anthropogenic dark earths.

3.2 The Development of Anthropogenic Dark Earths

The majority of *terra preta* expanses in the central Amazon region are open air archaeological sites that track the location of pre-Columbian settlements on relatively flat, mostly non-flooding landforms in the immediate vicinity of rivers, lakes and streamlets (Hilbert 1968; Simões 1974; Heckenberger et al. 1999; Neves 2003). The distinctively dark topsoil at these locales often includes abundant charcoal and archaeological artefacts. Vertical exposures through 'flat' areas reveal an A horizon of deeper reach than the surrounding soil mantle in which it is generally possible to distinguish one or more subhorizons – A1, A2, A3 and so forth – based on subtle contrasts in soil structure, texture, colour and inclusions. The transition from A to underlying B horizon sediments, in turn, oftentimes appears as an AB, A/B and/or

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

B/A sequence that shows down-mixing of enriched A horizon material into deeper B horizon sediments. These characteristics appear to be shared by many exemplars of anthropogenic dark earths in the tropical lowlands of northern South America (e.g. Mora 1991; Kern 1996; Vacher et al. 1998; see Kämpf et al. 2003 for an overview).

Although it cannot be doubted that the A horizon of artefact-rich anthropogenic dark earths, or *terras pretas*, is a result of the deposition and/or decomposition of debris associated to pre-Columbian settlement dynamics (Sombroek 1966; Smith 1980; Kern and Kämpf 1989; Kern 1996; Kern et al. 2004; Woods 1995; Woods and McCann 1999; Woods and Glaser 2004; see also Erickson 2003), to characterise the dark and organic-rich sediments of these soils as thick A horizons that have expanded downwards understates the exact nature of the processes that resulted in their formation. Over 35 years ago, Lathrap (1970) vehemently defended the suggestion that stratigraphic distinctions were visible or inferable in vertical sections of Amazonian open air sites and advocated their study as an integral part of reconstructions of pre-Columbian history (see also discussions in Eden et al. 1984; Lathrap and Oliver 1987; Myers 2004). Echoing his remarks over two decades later, excavations by the Central Amazon Project (Heckenberger et al. 1999; Petersen et al. 2001; Neves 2003) show that ceramic shards found embedded in expanses of *terras pretas* can be classified into distinct phases, complexes and/or traditions. Importantly, radiocarbon dates show that ceramic phases are constrained chronologically to a few hundred years yet, with some important gaps in the early part of the first millennium AD, span in excess of 1,000 calendar years (Neves 2003; Petersen et al. 2003; Petersen et al. 2004; Lima et al. 2006; Moraes 2006; Arroyo-Kalin 2008).

Archaeological investigations of *terra preta* expanses demonstrate that single-phase sites show a relatively thin and less strongly melanised A horizon compared to multi-phase sites. In the latter, archaeological remains are deposited within often thicker and darker A horizon sediments in generally 'good' stratigraphic order, i.e. older artefacts are generally found underlying younger ones (Hilbert 1968; Donatti 2003; Machado 2005; Moraes 2006). It is important to highlight that the stratigraphic integrity of these remains cannot be explained by invoking their concerted sinking as a result of faunally-induced gravitational displacement (Darwin 1881; Johnson 1990): not only do vertical exposures of anthropogenic dark earths lack horizontally-transgressive alignments of ceramic shards that could be interpreted as analogues of biotically-produced stone lines, but carefully-controlled excavations also frequently record archaeological features – pits, post hole negatives, and the like – whose very presence and edge definition contradicts the suggestion that these deposits have been reworked by soil fauna to the point of obliterating stratigraphic distinctions. In addition, a growing body of evidence shows that broad stratigraphic contiguity can be ascertained at the level of the expanse in different *terra preta* deposits (Heckenberger et al. 1999; Rebellato 2007, and this volume Chapter 2; Arroyo-Kalin 2008).

In another chapter, my colleagues and I have summarised a series of findings, questions and hypotheses about the composition of anthropogenic dark earths in the central Amazon region (Arroyo-Kalin et al., this volume). In this complementary contribution, I examine the development of these soils as an outcome of the progressive burial of subsequent land surfaces, i.e. the build-up of the soil mantle over time (Woods 1995; Vacher et al. 1998; see also Kemp et al. 1994). I first examine in some detail a vertical *terra preta* exposure from the Hatahara site to illustrate that these deposits can, and indeed need to be understood in light of both sedimentary and horizonation processes, i.e. using a pedo-stratigraphic perspective. I next use this perspective to supplement present understandings of settlement-related *terras pretas* at the Lago Grande site and, with this background in place, problematise the more complex record of past landscape domestication represented by off-settlement *terras mulatas*.

3.3 Archaeological Context Material and Methods

3.3.1 Ceramic Chronology

Chronological evidence produced by archaeological investigations is a useful means to examine the development of dark earths over time (Neves et al. 2003, 2004; Myers 2004). However, understandings of the chronology of any regional archaeological sequence constantly evolve as a result of new research. The chronology of ceramic phases in the central Amazon region constitutes no exception (Hilbert 1968; Heckenberger et al. 1998, 1999; Neves 2003; Petersen et al. 2003, 2004; Neves 2005; Machado 2005; Lima et al. 2006; Neves and Petersen 2006; Moraes 2006). Although a full discussion of this body of evidence is beyond the scope of this contribution (see Neves 2003; Lima et al. 2006; Arroyo-Kalin 2008) it is pertinent to the argument presented below to outline how the chronology of this sequence is understood, especially in light of radiocarbon dates on ceramic artefacts and human bone collagen that can be associated to the Guarita, Paredão, Manacapuru and/or perhaps Açutuba phase occupations (Table 3.1).

Table 3.1 AMS dates on shards and human bone from the central Amazon region (a. Moraes 2006, Arroyo-Kalin 2008; b. Hilbert 1968; c. Machado 2005; d. Heckenberger et al. 1999)

Site	Assay	Age	SD	Phase	Cal. Age
Lago do Limão[a]	OxA-15502[a]	1,660	28	Manacapuru	AD 340–430
Manacapuru[b]	P-409[b]	1,525	58	Manacapuru	AD 430–600
Hatahara[c]	β-145484[c]	1,390	40	Manacapuru	AD 610–670
Hatahara[c]	β-145483[c]	1,580	40	Manacapuru (Açutuba?)	AD 430–540
Hatahara[c]	β-145486[c]	1,130	40	Paredão	AD 880–990
Antônio Galo[a]	OxA-15505[a]	1,216	27	Paredão	AD 770–870
Lago do Limão[a]	OxA-15503[a]	846	27	Paredão	AD 1160–1230
Lago do Limão[a]	OxA-15504[a]	625	26	Guarita	AD 1290–1400
Açutuba[d]	β-90009[c]	980	60	Guarita	AD 990–1160
Açutuba[d]	β-97530[c]	690	40	Guarita	AD 1270–1390
Açutuba[d]	β-97529[c]	790	40	Guarita	AD 1210–1270

[a] = AMS date on ceramic shard.
[b] = conventional date on ceramic shard.
[c] = AMS date on bone collagen.

In this chapter, the modeled-incised Açutuba phase (Lima et al. 2006) is considered to begin towards the beginning of the first millennium AD and to overlap the also modeled-incised Manacapuru phase, defined by Hilbert (1968) and re-examined by Lima et al. (2006), towards the fifth century AD. The Manacapuru phase, which can most likely be segmented into earlier and later moments, extends the presence of Barrancoid-affiliated potters in the Central Amazon region at least until the eighth century AD, when it abuts, precedes by a small time lapse, or overlaps the onset of the Paredão phase. The latter, defined by Hilbert (1968) and refined in the context of the Central Amazon Project (Donatti 2003; Machado 2005; Moraes 2006), reaches at least until the late twelfth or early thirteenth century AD, overlapping occupations of the Amazonian Polychrome tradition-affiliated Guarita phase, defined by Hilbert (1968). The Guarita phase include earlier events of 'contact' with Paredão phase potters (see β-90009 in Table 3.1, also Moraes 2006), but appears to span more clearly from the twelfth–thirteenth century AD and to continue – maximally – until the fifteenth century AD (see also Simões and Corrêa 1987; Boomert 2004).

3.3.2 Geoarchaeological Methods

The data discussed in this contribution was collected and analysed as follows: undisturbed soil blocks were carved at clean vertical exposures in the field; made into cover-slipped mammoth-sized thin sections; studied using optical microscopes with plain (PPL), polarised (XPL), oblique (OIL) and ultraviolet (UVL) light sources; and described qualitatively following the recommendations of Kemp (1985), Bullock et al. (1986), FitzPatrick (1993), and Stoops (2003). Quantification of specific features (porosity, particulates, and surface area of the clayey material) relied on the analysis of high resolution digital images using the NIH ImageJ software. Interpretations are based on the broader literature on soil micromorphological analysis in soil science and archaeology (Babel 1975; Eswaran and Stoops 1979; Stoops and Buol 1985; Courty et al. 1989; Valentin and Bresson 1992; Davidson and Carter 1998; Lima et al. 2002; French 2003, and others referenced below).

The soil micromorphological data is supplemented by the analysis of bulk samples collected from sediment columns using a 10 cm interval, sub-sampled from 1 L Constant Volume Samples bagged during stratigraphic excavations, or – in one case – obtained in the field using a Dutch auger. Bulk samples were air dried; ground lightly with a ceramic pestle; rid of visible archaeological artefacts, charcoal and plant fragments; and sieved to obtain the <2 mm fraction. This fraction was then employed to obtain a number of parameters, as follows: pH and electrical conductivity (EC) were measured with a well-calibrated hand-held meter on a paste made of 1 part soil, 2 parts de-ionised water; low frequency magnetic susceptibility (MS) was measured using a Bartington MS2/MS2B dual frequency sensor on 10 cc of sample; total carbon (Ct) was measured using a Leco induction furnace (1,350°C, released CO_2 measured by IR absorption) and a muffle furnace (Loss on ignition after 12 h of combustion at 550°C); organic carbon (Co) was measured using a Leco induction furnace with samples pre-treated with dilute HCl to remove inorganic carbon and residual carbonates; and total Al, Ba, Ca, Cu, Fe, K, Mg, Mn, P, Na, Sr, and Zn were measured by ICP-AES on samples previously digested with *aqua regia*.

3.3.3 Archaeological Context

Soil samples discussed in this study come from two archaeological studies investigated by the Central Amazon Project. The Hatahara site (Fig. 3.1) is a 16 ha *terra preta* expanse located on a high riparian bluff that overlooks the left margin of the

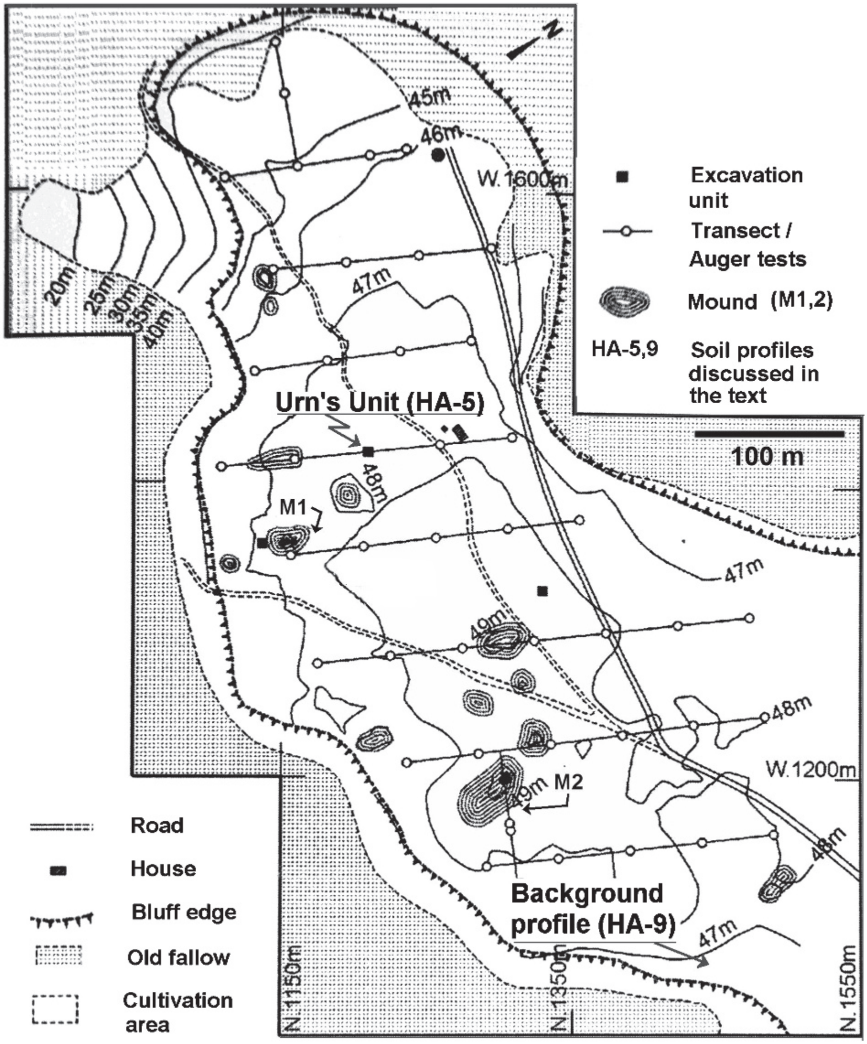


Fig. 3.1 The Hatahara site (adapted from Neves and Petersen 2006; Rebellato 2007)

Solimões River, in the vicinity of the town of Iranduba (Neves 2003; Machado 2005; Rebellato 2008, this volume). The bluff is flanked by relatively abrupt drops on either side, the result of the dissection of the *terra firme* by nearby streamlets that drain into the Solimões. Soils at the site have been examined by pedologists using a host of different techniques, including soil micromorphology (Lima et al. 2002). Detailed maps of variation in the colour and chemical properties of the soil mantle at the site have also been produced through auger surveys. Among others, these maps show that ADE concentrations reach deep into the landform and outline a pattern which resembles a circular ring village (Rebellato 2007, and in this volume). This pattern spatially overlaps a dozen meter-tall earth mounds that circumscribe an oval area with strong topsoil melanisation and is surrounded by less strongly melanised soils, or *terras mulatas*. Beyond this site core, the soil mantle is characterised by shallower, grey-coloured *terras mulatas* with small fragments of charcoal and gravel-sized rubified clay aggregates (Arroyo-Kalin, 2006, personal observation, Iranduba).

Stratigraphic excavations provide a basic archaeological sequence for the site (Neves 2003). Test pits through two earthworks (Mounds 1 and 2, see Machado 2005) show that the bulk of recovered shards in the strongly-melanised dark soil matrix buried by these features is made of Paredão phase pottery. Paredão remains overlie small densities of Manacapuru phase pottery that reach down to the AB horizon of the soil mantle. The mound 'overburden' includes pottery of Paredão, Manacapuru, and Guarita phases, the latter mainly near the surface. This sequence is extended by excavations in a flat area without mounds, the Urn's Unit (Rebellato 2007), where sparse Guarita, abundant Paredão, and common Manacapuru phase remains in good stratigraphic order are found within the strongly melanised sediments of an anthropogenic A - AB horizon sequence. These remains, however, are underlain by nine large, upright-standing *in situ* Manacapuru and/or Açutuba phase burial urns (Neves, 2007, personal communication, Iranduba) embedded in sediments that today appear as a B/A horizon. Some of these urns; deep pit features infilled with loose dark soils and Paredão phase pottery; and less well-defined but clearly intrusive concentrations of Manacapuru phase pottery embedded within non-strongly melanised sediments, cut pits with Açutuba phase and other Barrancoid tradition pottery located deeper in the deposit, i.e. the upper part of the B horizon (Neves 2003; Rebellato 2007; Arroyo-Kalin et al. 2007). Radiocarbon evidence for the Hatahara site is presented in Table 3.2.

The Lago Grande site (Fig. 3.2) is a ~3.1 ha *terra preta* expanse with abundant pottery remains on a peninsula-shaped *terra firme* bluff that overlooks the L. Grande lake, an extensive (40 km^2) but seasonally drying alluvial water body that is part of a cut-off meander of the Solimões River system (Donatti 2003; Neves 2003; Neves et al. 2004; Neves and Petersen 2006). This peninsula, connected to the rest of the *terra firme* by a 3 m wide isthmus-like land bridge flanked by abrupt gullies, is characterised by a horse shoe-shaped complex of earth mounds which circumscribes a round area with a low density of archaeological artefacts. Auger transects and excavations through the mounds show that the vast majority of remains at the site are Paredão phase shards embedded in a strongly melanised, relatively thick anthropogenic horizon. Like Hatahara, however, excavations record scant Guarita

Table 3.2 Hatahara: ^{14}C dates on charcoal (Neves 2001; Machado 2005; Arroyo-Kalin 2008)

Assay	^{14}C	SD	Depth (cm)	Dated material	Provenience	Cal range 66.8%
β-143582	350	40	29	Charcoal[a]	Mound 1 N1152 W1360	AD 1470–1640
β-143583	1,010	80	30–40	Charcoal[b]	Mound 1 N1152 W1360	AD 900–1160
β-143584	1,250	70	40–50	Charcoal[a]	Mound 1 N1152 W1360	AD 670–870
β-143585	980	40	58	Charcoal[c]	Mound 1 N1152 W1360	AD 1010–1160
β-143586	960	30	60	Charcoal[a]	Mound 1 N1152 W1360	AD 1020–1160
β-143587	570	40	65	Charcoal[c]	Mound 1 N1152 W1360	AD 1310–1420
β-143588	1,000	40	80	Charcoal[c]	Mound 1 N1152 W1360	AD 980–1130
β-143589	1,000	40	84	Charcoal[c]	Mound 1 N1152 W1360	AD 980–1130
β-143591	1,250	80	100–110	Charcoal[b]	Mound 1 N1152 W1360	AD 670–870
β-143592	910	40	121	Charcoal[c]	Mound 1 N1152 W1360	AD 1040–1170
β-143593	1,070	50	130	Charcoal[a]	Mound 1 N1152 W1360	AD 890–1020
β-143594	890	120	140–150	Charcoal[b]	Mound 1 N1152 W1360	AD 1020–1230
β-143595	960	40	155	Charcoal[c]	Mound 1 N1152 W1360	AD 1020–1160
β-143596	1,070	70	160–170	Charcoal[b]	Mound 1 N1152 W1360	AD 880–1030
β-143597	2,310	120	170–180	Charcoal[a]	Mound 1 N1152 W1360	750–150 BC
β-143598	1,080	40	180–190	Charcoal[c]	Mound 1 N1152 W1360	AD 890–1020
β-143599	1,300	40	192	Charcoal[c]	Mound 1 N1152 W1360	AD 660–770
β-178914	970	40	108	Charcoal[c]	Mound 1 N1155 W1360	AD 1010–1160
β-178915	880	40	146	Charcoal[c]	Mound 1 N1155 W1360	AD 1040–1220
β-178916	1,150	40	180	Charcoal[c]	Mound 1 N1155 W1360	AD 810–970
β-178917	1,000	40	123	Charcoal[c]	Mound 1 N1155 W1360	AD 980–1130
β-178918	940	40	172	Charcoal[c]	Mound 1 N1155 W1360	AD 1030–1160
WK-16222	2,269	42	60–65	Charcoal[c]	Mound 2 N1308 W1204	400–220 BC
WK-16223	1,105	37	105–110	Charcoal[c]	Mound 2 N1308 W1204	AD 890–990
WK-16224	1,191	38	165–170	Charcoal[c]	Mound 2 N1308 W1204	AD 770–890

[a] = conventional.
[b] = conventional date with extended counting.
[c] = AMS date.

phase shards in the upper centimetres of the soil mantle; small quantities of Manacapuru phase pottery, either in the lower part of deposits or in-mixed with majority Paredão wares; and *in situ* Açutuba phase remains covered by archaeologically-sterile sediments underlying the Paredão phase occupation (Donatti 2003; Tamura 2005; Lima et al. 2006).

Archaeological survey of the isthmus-like land bridge connecting the *terra firme* and peninsula side of the site identifies pairs of linear promontories located on either side of each gully. An excavation cross cutting these promontories shows that they are artificially-constructed; bury a dark brown, relatively shallow, organic horizon with small quantities of archaeological remains and charcoal; and flank an artificially-constructed trench which has been interpreted as a defensive ditch (see Neves and Petersen 2006). The buried horizon shows stratigraphic contiguity with the upper surface of the soil mantle on either side of the gully. On the *terra firme* portion of the site, auger surveys and a test pit show an unusually deep A horizon that can be characterised as a brown *terra mulata*. Radiocarbon evidence for the Lago Grande site is presented in Table 3.3.

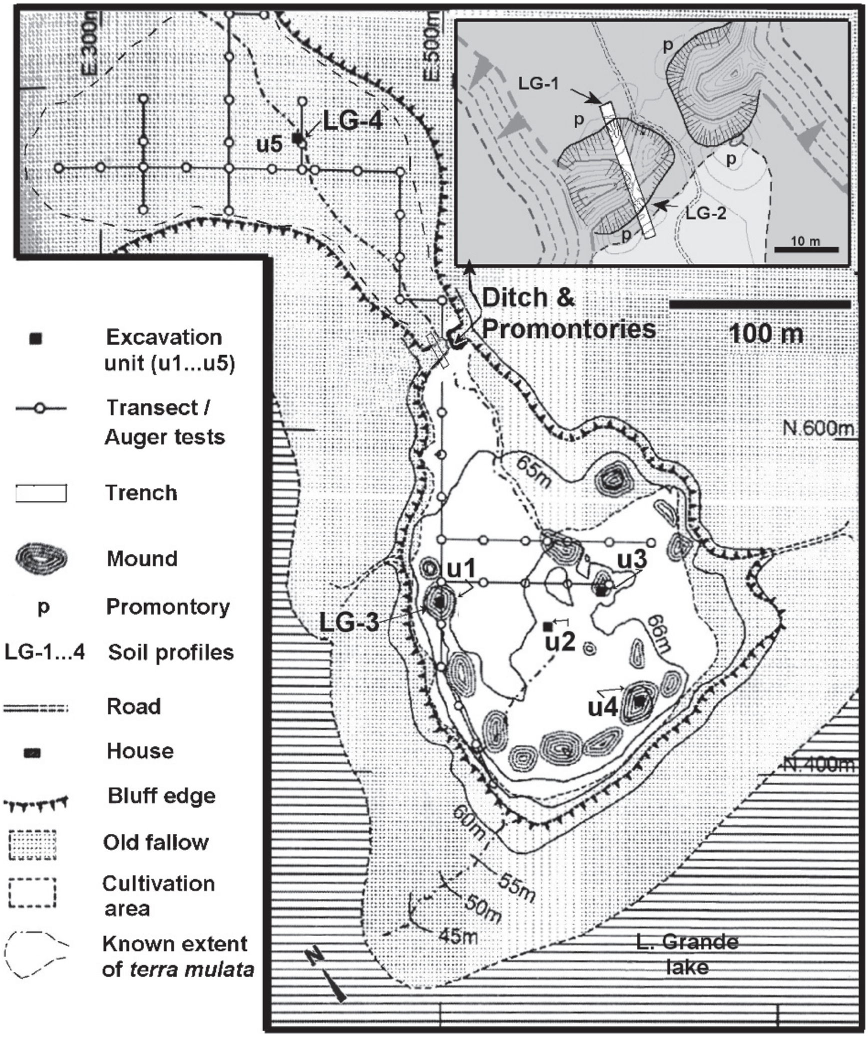


Fig. 3.2 The Lago Grande archaeological site (adapted from Neves and Petersen 2006; Donatti 2003)

3.4 Hatahara: The Pedo-Stratigraphy of *Terra Pretas*

The modal characteristics of 'background' Oxisols at Hatahara have been studied by sampling an exposure located at the point where the *terra firme* bluff falls towards one of the deep ravines that flank the landform (Profile HA-9). This exposure, located a few hundred meters from the core of the archaeological site, lacks any evidence of archaeological artefacts but, as is discussed below, records evidence of burning during sub-recent times (Table 3.3). In the field, the soil profile shows a relatively

Table 3.3 Lago Grande: ^{14}C dates on charcoal (Neves 2003; Donatti 2003)

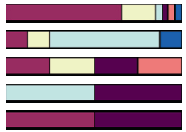
Assay	^{14}C	SD	Depth (cm)	Dated material	Provenience	Cal range 66.8%
β-143600	1,050	40	36	Charcoal[a]	Unit 1 N500 E500	AD 900–1030
β-143601	950	40	75	Charcoal[b]	Unit 1 N500 E500	AD 1020–1160
β-143602	950	30	83	Charcoal[b]	Unit 1 N500 E500	AD 1020–1160
β-143607	960	30	89	Charcoal[b]	Unit 1 N500 E500	AD 1020–1160
β-143604	1,130	40	118	Charcoal[b]	Unit 1 N500 E500	AD 880–990
β-143603	1,150	40	123	Charcoal[b]	Unit 1 N500 E500	AD 810–970
β-143605	1,100	30	142	Charcoal[a]	Unit 1 N500 E500	AD 890–990
β-143606	1260	40	158	Charcoal[b]	Unit 1 N500 E500	AD 670–780
β-178921	910	40	37	Charcoal[b]	Unit 3 N508 E596	AD 1040–1170
β-178919	910	50	50	Charcoal[a]	Unit 3 N508 E596	AD 1040–1180
β-178920	1,920	60	110	Charred seeds[a]	Unit 3 N508 E596	AD 0–210
β-178922	1050	40	47	Charcoal[b]	Unit 4 N443 E 618	AD 900–1030
β-178925	1,000	40	56	Charcoal[b]	Unit 4 N443 E 618	AD 980–1130
β-178923	1,150	40	94	Charcoal[b]	Unit 4 N443 E 618	AD 810–970
β-178924	1,140	40	105	Charcoal[b]	Unit 4 N443 E 618	AD 860–980
β-178928	1,240	40	157	Charcoal[b]	Unit 4 N443 E 618	AD 680–860
β-178926	mod.	–	36	Charcoal[a]	Unit 5 N772 E415	AD 1890–1910
β-178927	1,070	40	113	Charcoal[b]	Buried soil, trench	AD 890–1020

[a] = conventional.
[b] = AMS date.

thin A horizon that grades into a thinner AB horizon, below which a BE horizon is observed overlying the upper part of a B horizon.

From a micromorphological perspective, the organisation of A and AB horizon sediments can be characterised as a composite, decreasingly faunally-reworked, granular to massive microstructure formed by irregularly-shaped peds resulting from the coalescence of subangular to rounded aggregates of different sizes (50–200 µm; 500–1,500 µm; 2–7 mm), most likely produced by ants, termites and earthworms (see Barros et al. 2001). Larger, more organically-stained (PPL) aggregates are more common in the A than the AB horizon. In the A horizon, the clayey material that makes up aggregates expresses an undifferentiated b-fabric (XPL), and include remains of 'fresh' plant matter such as rootlets and tissue, common gravel to silt sized charcoal fragments, common phytoliths showing weak auto-fluorescence under ultra violet light (UVL), and rare silt-sized burnt soil fragments. AB horizon sediments show only light organic staining, about half the microscopic charcoal (Table 3.4), and lack all but very rare plant fragments. BE and B horizon sediments are organised as poorly separated continuous zones of slightly vughy, massive, limpid yellow clay (PPL), the BE showing depletion of iron (OIL) and a speckled b-fabric (XPL), the Bt showing more intense impregnation with iron sesquioxides (OIL) and a striated b-fabric (XPL). Both the BE and the B show zones with fine sand-sized faecal pellets whose optical features are identical to the surrounding matrix, i.e. can be considered as relict evidence for a granular fabric (Schaefer 2001; Lima et al. 2002). Both horizons also show isolated particulate

Table 3.4 Summary of micromorphological observations: HA-9 (background yellow latosol)

Thin section	Depth[a]	Hor. Lay	Micro-artef[b]	Pott-ery[c]	Sponge Spicules[c]	Burnt soil[c]	Rubif. agg[c]	Bone[c]	Microscopic bone % size classes[d]	Micr. char[d]	Microscopic charcoal % size classes[d]	Grav char[c]	PPL[e]	OIL[e]	Org. stain.[e]	b-fabric[e]	Phytho-liths[b]
HA-9.1	5	A				•			----------------	4.5		••			3	u	•
HA-9.2	20	AB				(•)			----------------	2.6		•			1	S(u)	(•)
HA-9.3	36	BE							----------------	1.0					L	S	(•)
HA-9.5	60	Bt1							----------------	0.3					L	S	(•)
HA-9.5	90	Bt2							----------------	0.2					L	S	

[a] = depth of the top of undisturbed block used for thin section manufacture.
[b] % of total solids in thin section.
[c] relative abundance in thin section.
[d] % of fine mineral fraction. Size classes for bone: coarse silt, very fine sand, fine sand, medium sand, coarse sand, very coarse sand (see Stoops 2003).
n/m = not measured. Size classes for charcoal from fine silt to very coarse sand (see Stoops 2003). Relative abundance (•) = marginal; • = rare; •• = common; ••• = very common.
[e] optical properties of the fine mineral fractions: L = limpid, 1 = organic punctuation; 2 = lightly stained; 3; medium stained; 4; strongly stained; d. u = undifferentiated; s = speckled; S = striated; (s,u,S) = marginally s, u or S.

material of organic origin – mainly charcoal – that is either isolated in intrapedal position or embedded within small faunally-produced clayey aggregates whose degree of organic staining suggests an origin higher in the profile. Generally fine sand-sized typic iron nodules increase in frequency from the AB to the B horizon. Common illuvial clay coatings identify a Bt horizon.

Table 3.5 summarises available physical and chemical data for the HA-9 profile. Sediments from the A horizon are characterised by higher MS, Ct, Co, LOI, P, Mn, and Cu as well as slightly higher pH values compared to sediments lower in the profile (Fig. 3.3). The presence of phosphatised plant fragments, organic punctuations and organic staining of the clayey fraction suggest that the most likely source of higher C, P, Mn, and Cu is the decomposition or mineralization of plant matter. A sharp rise in MS values from 50 to approximately 130 si units towards the surface, coupled with observations of charcoal fragments, auto-fluorescent phytoliths and burnt soil fragments suggest this locale has experienced near surface burning, most likely associated to sub-recent clearance and agricultural activities. Although a shallow fall-off pattern characterises most variables, LOI shows higher values down to the bottom of the AB horizon, pointing to a combination between the contribution of not infrequent gravel-sized charcoal down to 35 or so cm and interferences in the technique expected in Fe-rich clayey soils (Vogel 1997). Leco furnace data corroborates much higher organic carbon in the A compared to the Bt horizon.

This backdrop and previous research (Lima et al. 2002; Schaefer et al. 2004) provides a solid comparative basis to examine a vertical exposure through anthropogenic dark earths. Discussion below centres on the profile exposed through excavations of the Urn's Unit (Profile HA-5, see Fig. 3.4). This profile fits the description of a *terra preta* profile presented in the opening discussion of this paper. Archaeological Layer IV is equivalent to an Ap horizon; Layer III identifies an A2-A3 sub-horizon sequence; Layer II, which can be divided into IIb and IIa, approximately maps onto an AB and a BA horizon; Layer I is a B/A and the upper part of the B horizon.

From a micromorphological perspective the microstructure of the A horizon of HA-5 varies from a complex assortment of irregularly-shaped microscopic peds resulting from the coalescence of faunally-produced aggregates (thin section HA-5.1) to irregular, massive, slightly vughy continuous clayey zones with little evidence of faunal reworking (thin section HA-5.2). The fine mineral fraction of this clayey material shows very dark brown colours (PPL), a dark 'opaque' grey colour (OIL), and a completely undifferentiated b-fabric (XPL). Aside from channel/chambers deriving from rootlets and perhaps faunal action, peds are fractured post-depositionally by thin planar voids (especially thin section HA-5.2), pointing to compaction and desiccation (also noted during excavations, see Rebellato 2007:107). Unusually for A horizon sediments, dusty illuvial clay coatings with low interference colours are observed (see Arroyo-Kalin et al. 2008, this volume, Fig. 3.6, left) on planar voids and vughs, suggesting the deposition of ash (Slager and van der Wetering 1977; Courty et al. 1989; Macphail 2003). Embedded intrapedally are silt to sand-sized quartz grains; abundant fine sand to silt-sized charcoal

Table 3.5 Physical and chemical parameters: HA-9 (background yellow latosol)

Horizon or layer	Depth[a]	pH[b]	EC[c]	LOI[d]	Co[e]	Ct[f]	MS[g]	Al[h]	Fe[h]	P[h]	Ca[h]	Mn[h]	Ba[h]	Cu[h]	K[h]	Mg[h]	Na[h]	Sr[h]	Zn[h]
A	5–7	4.1	19	7.76			118.7	22000	39300	250	<100	23	<10	3	50	50	50	1	1
AB	15–17	4	21	7.76	.8	1.75	50.8	19400	40500	200	<100	17	<10	1	50	50	50	1	1
AB	25–27	4	26	7.74			35.5												
BE	35–37	4	26	7.7			29.6												
BE	45–47	4	26	7.39			26	22100	46500	170	<100	19	<10	4	50	50	50	1	1
Bt	55–57	4	31	6.9	.2	.74	25.1	21900	47300	180	<100	19	<10	2	50	50	50	1	1
Bt	65–67	3.9																	
Bt	75–77	4																	
Bt	85–87	3.9	43	6.9			11.8	19800	49000	160	<100	17	<10	1	50	50	50	1	1
Bt	95–97	4.0	61	6.87			10.2												

Sampling. Horizon (A, B, E) or Archaeological layer (I-V).

[a] = depth of sampling from the surface (cm) representing a 15 × 15 × 2 cm block of soil from the indicated depth.

Parameters:

[b] pH, 1: 2 soil to d.i. H_2O.

[c] Electrical conductivity: 1:2 soil to di H_2O (µS).

[d] Loss on Ignition, 12 h, 550°C (%W).

[e] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption (%W).

[f] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption after HCl treatment (%W).

[g] Low Frequency magnetic susceptibility, Bartington MS2/MS2B dual frequency sensor (si units).

[h] ICP-AES on samples pre-treated with *aqua regia* (ppm).

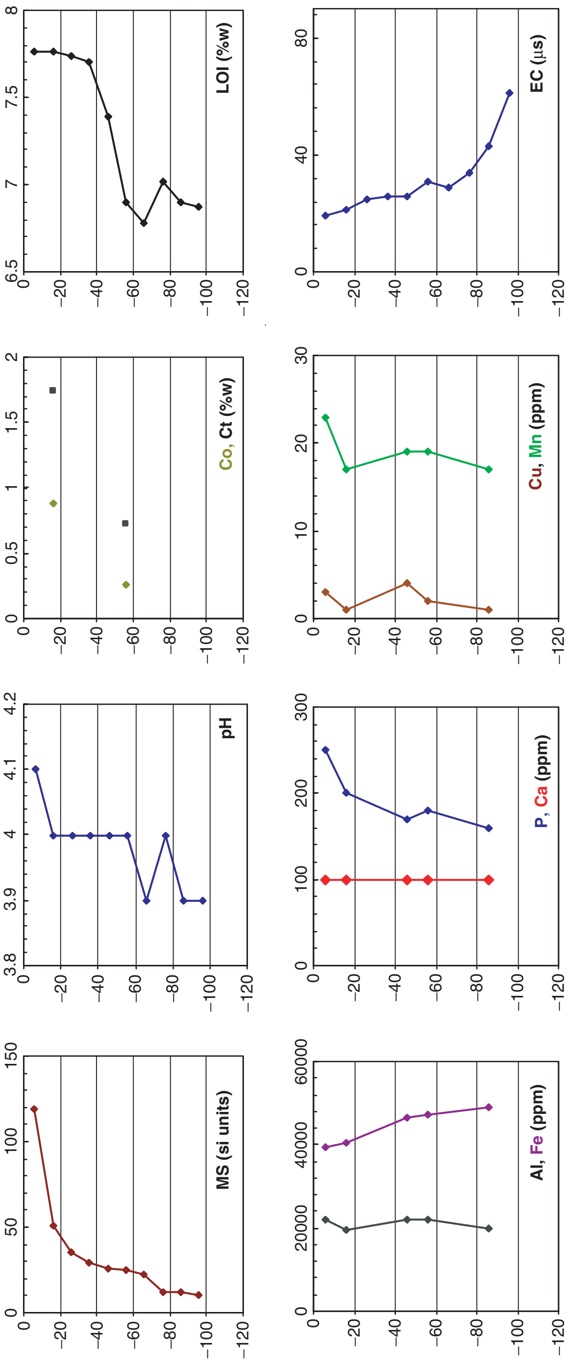


Fig. 3.3 HA-9 (background Yellow Latosol). Physical and chemical parameters. Y axis = depth (cm)

Fig. 3.4 Photographic mosaic of the 2006 excavations at the Urn's Unit, Hatahara. Each section of the ranging rod (right) is 25 cm long. Green dotted line: approximate position of column used to collect bulk samples. Orange dotted lines: approximate position of undisturbed blocks used for thin section manufacture, from top to bottom HA-5.1, HA-5.2 and HA-5.3

fragments; common microscopic pottery fragments; common fine sand to coarse silt-sized rubified clay aggregates; common auto-fluorescent sponge spicules; common, generally medium to fine sand sized, phosphatic (UVL) fragments of microscopic bone; common auto-fluorescent silica phytoliths; and rare burnt soil fragments (Table 3.6).

AB horizon sediments show some remarkable differences. Noteworthy is the fact that the density of microscopic charcoal is not only lower than overlying, strongly melanised sediments but also shows a better representation of size classes between silt and gravel, including more frequent charred plant organs and tissue. Thin section HA-5.3 (90–100 cm), in addition, evidences two contrasting fabrics in terms of texture, abundance of microartefacts and microscopic charcoal fragments (Fig. 3.5). Whilst both fabrics include in-mixed peds from each other (as well as from higher in the profile and the lower B horizon) they are separated by a clear microscopic unconformity that indicates a sharp truncation of the deposit during pre-Columbian times. A long planar void in which dusty illuvial clay coatings accumulate runs slightly above this unconformity. This arrangement can be interpreted as evidence that a re-organised, better sorted, artefact- and charcoal-rich clayey sediment resembling the A horizon of the background Oxisol has been re-deposited on a truncated but relatively *in situ*, faunally reworked AB-like sediment in which low densities of microscopic charcoal fragments, sponge spicules, pottery fragments and bone are present. It most likely represents the bottom of a pit-like feature that is no longer visible to the naked eye but has survived reworking by soil fauna.

The full import of these observations emerges when data from physical and chemical analyses is examined (Table 3.7). Al concentrations of 30,000 ppm below about 35–7 cm are markedly higher than the background soil profile, showing a decrease to about 25,000 ppm towards the surface. Fe concentrations show important fluctuations with depth, shifting from ~44,000 ppm at 125–7 cm to ~52,000 ppm at 105–7 cm, decreasing above this in a similar fashion to the background soil profile up to 35–7 cm, and above this decreasing further to lower levels of ~32,000 ppm.

Table 3.6 HA-5 (Urn's Unit profile). Summary of micromorphological observations

Thin section	Depth[†]	Hor. Lay	Micro-artef	Pott-eryc	Sponge spicules	Burnt soil	Rubif. agg	Bone	Microscopic bone % size classesb	Micr. char	Microscopic charcoal % size classes[a]	Grav char	PPL	OIL	Organic staining	B-fabric	Phytho-liths
HA-5.1	20	Ap	10	••	••	•	••	4.5		8.5		••			4	u	••
HA-5.2	55	A2	15	••	••	•	•••	4		8.2		••			4	u	••
HA-5.3[5%]	95	AB1	5	••	••	•	•	<1	n/m	4.1		•			3	(s)	
HA-5.3[95%]	97	AB2	<2	(•)	•	(•)	•	0.9		1.0		•			1	(s)	•

[a] = depth of the top of undisturbed block used for thin section manufacture.
[b] % of total solids in thin section.
[c] relative abundance in thin section.
[d] % of fine mineral fraction. Size classes for bone: coarse silt, very fine sand, fine sand, medium sand, coarse sand, very coarse sand (see Stoops 2003).
n/m = not measured. Size classes for charcoal from fine silt to very coarse sand (see Stoops 2003). Relative abundance (•) = marginal; • = rare; •• = common; ••• = very common.
[e] optical properties of the fine mineral fractions: L = limpid, 1 = organic punctuation; 2 = lightly stained; 3; medium stained; 4; strongly stained; d.
u = undifferentiated; s = speckled; S = striated; (s,u,S) = marginally s, u or S.

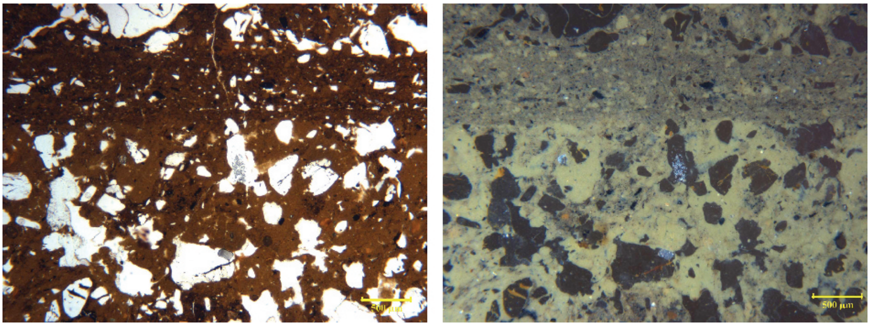


Fig. 3.5 AB horizon truncation and redeposited relict A horizon sediments (PPL/OIL). Urn's Unit, Hatahara (Thin section HA-5.3)

But it is the trends in pH, LOI, P, Ca, Mn, Ba, Cu, K, Mg, Na, Sr, Zn, and MS values (Fig. 3.6), in all cases much higher than those recorded at the background soil profile, that require special attention. Depth-wise trends in these variables do not show the pattern of consistent decrease from the present surface that might be expected from a 'down-mixing model', but instead evidence a series of distinctive inflections, especially in MS and LOI values (no Leco furnace data is available for profile HA-5), below which fall-off patterns can be readily observed.

The lowermost of these inflections, at 115–7 cm, not only shows levels of enrichment/enhancement that are higher than under and overlying sediments but the fall-off pattern of most measured variables with increasing depth immediately recalls the transition from an A to an AB horizon. Importantly, MS values at 115–7 cm exceed those construed as a benchmark of near surface burning in the background soil profile, suggesting that recorded at this depth in the deposit is a buried land surface which was minimally cleared through burning. The depth of the reconstructed land surface is consistent with that of archaeological remains found in stratigraphic excavations: pits with pottery classified as Açutuba phase, as well as other wares that can be classed as modeled-incised or Barrancoid, reach down maximally to 135 cm but are not found higher than 120 cm except in higher pit features. These remains most likely date to the first half of the first millennium AD (Tables 3.1 and 3.2; Machado 2005; Lima et al. 2006) and can be assumed to have been buried from the reconstructed land surface recorded at 115–7 cm.

Above 115–7 cm, a shift towards higher MS and LOI only takes place between 97 and 85 cm. As noted previously, however, micromorphological data (thin section HA-5.3, 90–100 cm) suggests that sediments at this depth constitute an AB horizon which has been truncated prior to deposition of non-strongly melanised, organic-rich A-like horizon material. An obvious corollary is that somewhere above 85–7 cm a surface with an A horizon existed in the past. MS values, which are relatively stable between 85–7 and 75–7 cm, suggest this A horizon might be recorded at 75–7 cm, where substantial enrichment with P, Ca, Mn, Ba, Cu, K, Mg, Na, Sr, Zn, and a slightly higher pH are observed, in effect identifying a second surface of

Table 3.7 HA-5 (Urn's Unit profile). Physical and chemical parameters

Horizon or layer	Depth[a]	pH[b]	EC[c]	LOI[d]	Co[e]	Ct[f]	MS[g]	Al[h]	Fe[h]	P[h]	Ca[h]	Mn[h]	Ba[h]	Cu[h]	K[h]	Mg[h]	Na[h]	Sr[h]	Zn[h]
IV (Ap)	−6	6.3	78	9.16			250.6	CHECK											88
IV (Ap)	−16	6.3	5	8.08			278.6	24900	31900	6880	14300	725	200	47	500	700	100	88	88
III (A2)	−26						267.5												
III (A2)	−36	6.5	5	8.25			255.1	31000	40000	8010	16200	488	160	42	500	600	200	98	98
III (A3)	−46						227.0												
III (A3)	−56	6.3	14	8.25			250.6	29700	39700	7400	14600	408	120	46	400	500	200	84	84
III (A3)	−66		30				193.4												
IIb (AB1)	−76	6.1	43	7.98			173.9	31400	45400	5050	9900	289	90	28	300	400	100	60	60
IIa (AB2)	−86		91				170.1												
IIa (AB2)	−96		80				149.6												
I (B/A)	−106	6.1	35	7.84			118.1	30200	51900	3320	5800	200	50	16	200	200	50	34	34
I (B/A)	−116		19				213.6												
I (B/A)	−126	6.2	6	7.61			164.1	31800	43700	5880	11200	373	110	34	400	500	100	72	72
I (B/A)	−136	6.0	109	7.54			75.7												

Sampling. Horizon (A, B, E) or Archaeological layer (I-V).

[a] = depth of sampling from the surface (cm) representing a 15 × 15 × 2 cm block of soil from the indicated depth.

Parameters:

[b] pH, 1:2 soil to d.i. H_2O.

[c] Electrical conductivity: 1:2 soil to di H_2O (μS).

[d] Loss on Ignition, 12 h, 550°C (%W).

[e] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption (%W).

[f] Leco Induction furnace, 1,350°C, released CO_2 measured by IR absorption after HCl treatment (%W).

[g] Low Frequency magnetic susceptibility, Bartington MS2/MS2B dual frequency sensor (si units); [h] ICP-AES on samples pre-treated with *aqua regia* (ppm).

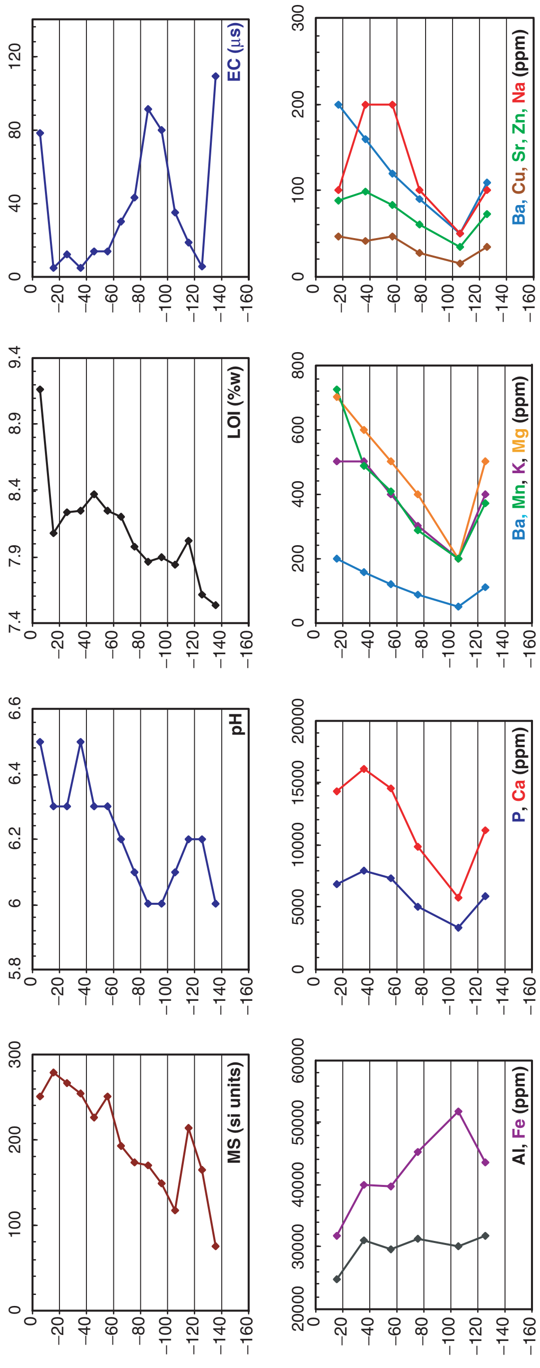


Fig. 3.6 HA-5 (Urn's Unit profile). Physical and chemical parameters. Y axis = depth (cm)

accumulation in the deposit. The land surface recorded at 75–7 cm seems congruent with the depth of some of the burial urns unearthed during excavations, which as noted previously have been suggested to reflect the transition between Açutuba and Manacapuru phases (Neves, 2007, personal communication, Iranduba).

Above this, a dramatic increase is observed in all measured variables prior to a new inflection in MS at 55–7 cm, the approximate depth of thin section HA-5.2 (50–60 cm). Like the 115–7 cm land surface, the shape of the MS and LOI curves from 55–7 cm to 75–7 cm recalls the transition from an A to an AB horizon, i.e. suggests down-mixing of anthropogenically-enriched sediments from a further land surface recorded at about 60 cm. Rebellato (2007:132–133) reports that only Manacapuru phase pottery is recorded below 60 cm whilst both Manacapuru and Paredão phase material occur above this depth. Considered from a pedo-stratigraphic perspective, this implies that the surface recorded at 55–7 cm in the profile is a significantly enriched/enhanced A horizon that most likely dates, going by the radiocarbon chronology produced during excavations of Mound 1, to Manacapuru occupations of the fifth–seventh century AD (Table 3.1, see also Machado 2005). A significant rise in Mn concentrations above this depth is noteworthy in light of discussions about factors that impinge on melanisation of these soils (see Arroyo-Kalin et al., this volume).

Although no ICP-AES data exists for 45–7 cm, an inflection in MS between 55–7 and 45–7 cm and a shift in LOI values suggests a brief ‘hiatus’, most likely pointing to burial of a surface by conveyor up-mixing (Vacher et al. 1998; Johnson et al. 2005) that is subsequently followed by intense accumulation of debris associated to settlement activities. The latter is indicated by a sharp rise in the density and weight of ceramic shards (Rebellato 2007:118–119), previously mentioned micromorphological observations (abundance of microartefacts and charcoal fragments), and a consistent rise in concentrations of P, Ca, Mn and others from 55–7 cm and upwards. A peak at 35–7 cm, which approximately maps onto the boundary between the A2 and A3 horizon, should not detract attention from the fact that measured concentrations above and below are equivalent. The presence of Paredão phase pottery above 60 cm and up to 16 cm suggests that strongly melanised dark earths can be associated to this context and occupation of the locale. Chronological evidence from Mounds 1 and 2 (Table 3.2) suggests Paredão phase occupations take place between the nineth–twelfth century AD. On the other hand, it cannot be overruled – especially in view of low EC and high pH values – that recorded above 35–7 cm is yet another surface of accumulation. The presence of grooving and incised decoration towards the upper part of the deposit (Rebellato 2007:115, Gráfico 5.1.4.) may indicate that this surface is related to Guarita phase occupations at the site, which takes place after the Paredão occupation and reach approximately to the fifth century AD (Neves 2003; Machado 2005; Arroyo-Kalin 2008). Be that as it may, depth-wise trends in physical and chemical data for sediments between 55–7 and 15–7 cm suggest that this sediment zone needs to be understood as an outcome of build-up of the deposit (Woods 1995; cf. Vacher et al. 1998).

Above 15–7 cm, finally, near surface sediments record sharp increases in LOI, EC, and pH coupled with a drop in MS, the latter most likely tracking a decrease in sustained burning over time. In general, these values reflect the compounded effects of more intense faunal activity, plant nutrient uptake, incorporation of organic matter, and sub-recent agriculture. It needs to be emphasised, however, that these trends overrule the suggestion that the proximity of near surface processes affects the properties of sediments below 15–7 cm. For instance LOI weight loss values, which should theoretically record down mixing of organic matter and charcoal from the present surface, are actually lower at 15–7 cm than between 25–7 and 65–7 cm. Whilst this could point to a thin, near surface eluvial horizon, the consistence between archaeological artefacts and the sediment zones previously discussed is sufficiently overwhelming to question this interpretation.

3.4.1 Discussion

The preceding analysis shows that even if specific vertical exposures of anthropogenic dark earths appear to show a thick A horizon that has expanded downwards, the latter can be argued to have developed as a result of net positive sedimentation, in effect raising the overall elevation of surfaces at which pedogenetic processes took place (Woods 1995). Given that *terra preta* expanses such as Hatahara are located on flat landforms that lack sedimentary sources in the immediate vicinity, it can be suggested that accretion results from a combination of factors, including here faunally-induced burrowing, wriggling, mixing and/or churning of soil material (Johnson et al. 2005); the upwards or ‘conveyor' translocation of sediments from lower in the deposit (Vacher et al. 1998); and the accumulation and decomposition of debris associated to settlement dynamics (Lima et al. 2002; Hecht 2003; Erickson 2003; see also Arroyo-Kalin et al. this volume).

Micromorphological observations provide a number of additional and important insights about this build-up. First, the presence of a more diverse range of charcoal size classes and, especially, clear evidence for non-strongly melanised peds in AB horizon sediments together suggest that in addition to sediments down-mixed from the overlying, strongly melanised, chemically-enhanced and magnetically-enriched anthropogenic A horizon (Kämpf et al. 2003), the AB horizon of the studied exposure records relict evidence of a significantly-enriched, now buried and partially reworked Oxisol A horizon. Second, aside from ash-related dusty illuvial clay coatings and common microscopic pottery fragments, rubified clayey aggregates, and bone fragments, it has already been mentioned that the microstructure of characteristics around 56 cm point to compaction and desiccation of sediments. These characteristics could resonate with a specific ethnographic analogue: the interior of long houses with earthen floors. Accounts from the northwest Amazon (Koch-Grünberg 1995 [1909]; Rice 1910; Hugh-Jones 1979) highlights that their interiors were swept regularly (resulting in size sorting of particulate debris) and that abundant fires were always kept burning (resulting in the production of charcoal and ash). Ethnoarchaeological research in the Ecuadorian Amazon (Zeidler 1983; Stahl and Zeidler 1990) highlights the potential of houses as sediment traps, especially of ashy deposits, small-sized food debris, and charcoal. I have personally witnessed the formation of accreting house floor deposits inside recently-built long houses not used for habitation purposes (Arroyo-Kalin 2001, personal observation, upper Tiquié River). Woods (2007, personal communication, Iranduba) has also documented similar examples among present day rural inhabitants in the Santarém region. In a parallel contribution, my colleagues and I highlight the importance of the deposition of ash, the production of *caraipé,* and the decomposition of pottery as significant factors for the formation of anthropogenic dark earths. In the present context I will add that the concentration of soot particles inside residential structures, both accumulating on the underside of roof thatching and/or being trampled into earthen floors (Hugh-Jones 1979; Arroyo-Kalin 2001, personal observation, upper Tiquié River), may be linked to the density and size class distribution of microscopic charcoal observed in thin sections.

3.5 Lago Grande: The Pedo-Stratigraphy of *Terras Pretas*

Many of the *terra preta* expanses with Paredão phase pottery in the central Amazon region are characterised by one or more circular arrangements of often meter-tall earth mounds. Whilst it is increasingly clear that these arrangements track the position of plaza-centred villages, different hypotheses have been advanced in the Central Amazon Project to interpret the construction process and make-up of these features, for instance that some are special purpose funerary constructions; that others represent deliberate-constructed house platforms; that others are middens associated to residential structures; and that sedimentary facies within some of them may represent accreting house-floor deposit (Heckenberger et al. 1999; Neves 2003; Donatti 2003; Machado 2005; Neves and Petersen 2006; Moraes 2006; Arroyo-Kalin 2006; Rebellato 2007).

At the Lago Grande archaeological site, excavation of Unit 1 samples one such feature, Mound 1 of the peninsula side of the site (Fig. 3.2). The darker coloured sediments within Unit 1 occur below about 100 cm (Fig. 3.7, left), an observation that has been interpreted as evidence for an old land surface characterised by a *terra preta* A horizon that was buried by construction or accumulation of the mound 'overburden' (Donatti 2003; Neves et al. 2004). Radiocarbon evidence from this part of the deposit has been marshalled to suggest a scenario for rapid formation of *terra preta* soils (Neves et al. 2003, 2004). The fact that these sediments include a minority of Manacapuru phase together with a majority of Paredão phase pottery has been considered as evidence for Manacapuru 'tradeware' at the site (Neves 2003; Donatti 2003; see chronological implications in Lima et al. 2006:46).

Sediment samples collected during excavations of Unit 1 (Profile LG-3, see Fig. 3.7, right) and analysed in the same fashion as the Hatahara Urn's Unit profile, provide support for some of the preceding inferences and a basis to offer a number of supplementary interpretations (Table 3.8, Fig. 3.8). First, the fact that Layer II (170–180 cm) shows pH values higher than immediately overlying sediments, low but important levels of enrichment in especially P and Ca, and levels of MS comparable to near surface burning, suggests that the stratigraphic boundary between it and the overlying Layer III identifies the burial of an old land surface characterised by

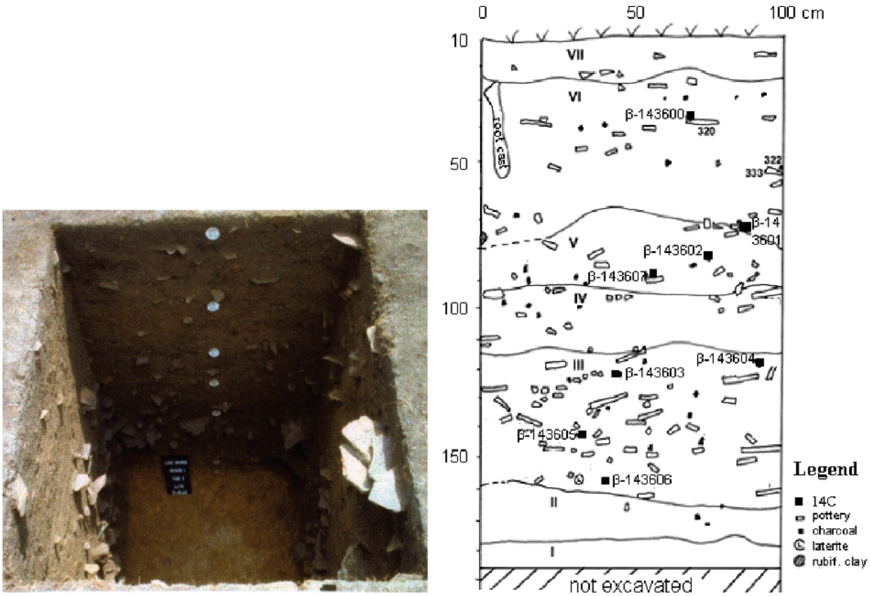


Fig. 3.7 Unit 1, Lago Grande (Profile LG-3). Left: photograph of Unit at the end of archaeological excavations. Right: stratigraphic profile showing layer designations and charcoal fragments dated by ^{14}C, (photo and profile drawing from Donatti 2003)

some soil enrichment but no clear soil melanisation. If broad stratigraphic contiguity exists at the scale of the landform, as noted a premise that obtains at other sites in the region (Heckenberger et al. 1999; Machado 2005; Rebellato 2007; Arroyo-Kalin 2008), it is likely that this record can be related to the Açutuba phase occupation identified some 100 cm below the surface in Unit 3 (Fig. 3.2), which dates to the beginning of the first millennium AD (Table 3.2). These characteristics support Lima et al. (2006) suggestion that Açutuba phase occupations did not result in strongly melanised *terra preta* soils (cf. Myers 2004).

Second, focusing on Layer III, a peak in pH and a marked rise in MS values at around 130–140 cm suggests the convenience of distinguishing two 'facies' within this part of the deposit. The lower IIIa is characterised by constant Ba and Na, a decrease in Fe, and rising concentrations of Mn, P, and Ca. The higher IIIb is characterised by stable Fe concentrations but sharply rising P, Ca, Mn, Ba, Cu, Na, Sr, Zn, K, and Mg. Concentrations of these elements peak towards the upper part of Layer III (IIIb). Inflections in pH delimiting both facies suggest acidification of sediments as a result of up-mixing from lower in the deposit. Contrasts between IIIa and IIIb, which can be observed in profile drawings (Fig. 3.7, right, note much smaller shards in the lower part of Layer III), extend to the ceramic assemblage and radiocarbon evidence. As regards pottery, the popularity of Manacapuru with respect to Paredão phase rim fragments is much higher in the proposed Layer IIIa

Table 3.8 LG-3 (Mound 1). Physical and chemical parameters

Horizon or layer	Depth[†]	pH[a]	EC[b]	LOI[c]	Co[d]	Ct[e]	MS[f]	Al[g]	Fe[g]	P[g]	Ca[g]	Mn[g]	Ba[g]	Cu[g]	K[g]	Mg[g]	Na[g]	Sr[g]	Zn[g]
VII (^A1b)	0–10	6.4	36	11.32			615.5												
VII (^A1b)	10–20	6.1	18	9.75	2.46	3.25	572.5	29000	49500	6630	11800	617	90	36	100	600	100	89	89
VI	20–30	5.9	22	10.1			605.7												
VI	30–40	6.1	16	9.87			563.2	33400	60100	9150	13000	610	90	38	200	400	100	108	108
VI	40–50	6	19	9.16			551.2												
VI	50–60	6.1	10	8.81			515.5	36800	60600	11950	18000	671	90	50	200	400	200	167	167
VI	60–70	6.1	11	8.23			461.7												
V	70–80	5.6	68	6.72	2.66	3.09	397	31900	52800	12000	19900	492	70	37	200	300	100	171	171
V	80–90	6	19	7.4			394.3												
IV	90–100	5.7	22	7.46			385.2												
III (A1b)	110–20	6	20	7.61	3.1	3.49	496.7	33200	53800	12550	22300	881	50	35	200	200	100	114	114
III (A1b)	120–30	5.8	15	7.86			422												
III (A1b)	130–40	6.3	21	7.57			342.9	28600	53200	7380	14600	571	50	21	100	100	100	60	60
III (A2b)	140–50	6.2	30	7.43			263.4												
III (A2b)	150–60	5.8	35	7.32	2.12	2.41	234.4	25900	57200	3930	7000	119	20	12	100	100	50	29	29
III/II (A3b)	160–70	5.6	58	7.65			208.8												
II (ABb)	170–80	5.9	150	7.96	1.03	1.24	149.1	26400	63200	2140	2800	50	90	36	100	600	100	89	89

Sampling. Horizon (A, B, E) or Archaeological layer (I-V). Note buried and remobilized horizon designation (Ab = buried A, ^A = remobilized A).

[†] = depth of sampling from the surface (cm) representing constant volume samples collected during excavations every 10 cm at the indicated depth.

Parameters:

[a] pH, 1:2 soil to d.i. H_2O.

[b] Electrical conductivity: 1:2 soil to di H_2O (µS).

[c] Loss on Ignition, 12 h, 550°C (%W).

[d] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption (%W).

[e] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption after HCl treatment (%W).

[f] Low Frequency magnetic susceptibility, Bartington MS2/MS2B dual frequency sensor (si units).

[g] ICP-AES on samples pre-treated with *aqua regia* (ppm).

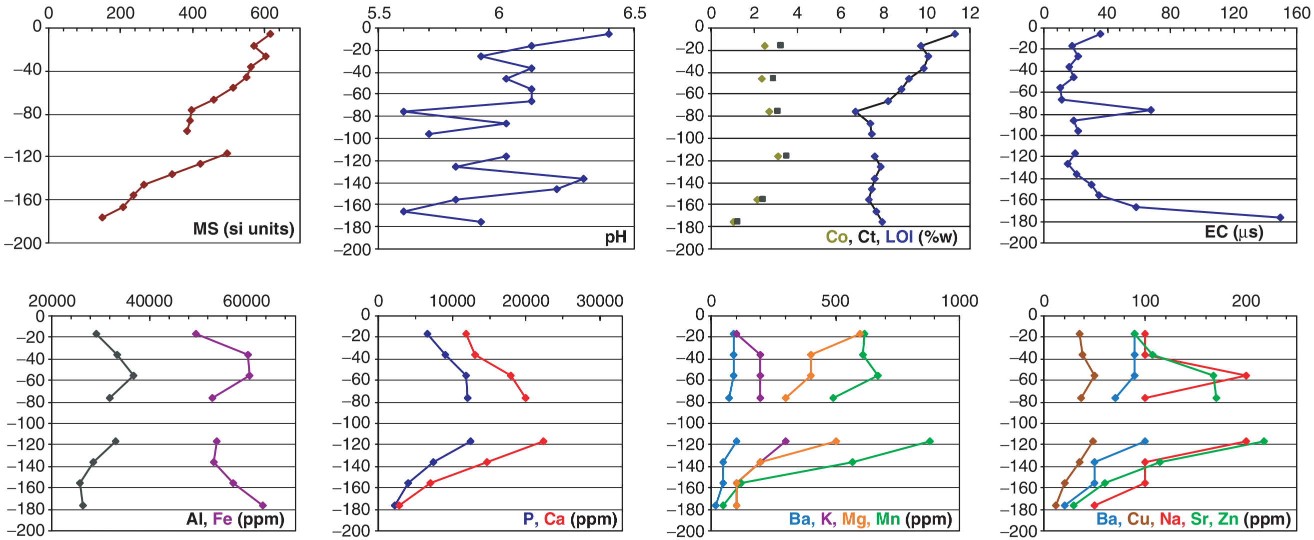


Fig. 3.8 LG-3 (Mound 1). Physical and chemical parameters. Y axis = depth (cm)

(10:31 fragments) compared to IIIb (10:104 fragments, shard counts based on Donatti 2003:94). As regards radiocarbon evidence, a charcoal fragment from Layer IIIa (β-143606) provides an age range of AD 670–780, which is consistent with the chronology for the later part of the Manacapuru phase at the Osvaldo site (Neves 2000; Lima et al. 2006; Chirinos 2007) and also congruent with the Manacapuru occupation at the Hatahara site (Table 3.2, Neves 2003; Machado 2005). In contrast, three dates from the proposed Layer IIIb (β-143603, 4 and 5) calibrate to the 9–tenth century AD, consistent with Paredão phase dates at Hatahara (Table 3.2; Neves 2003; Machado 2005; Arroyo-Kalin 2006) and Antônio Galo (Table 3.1; Moraes 2006; Arroyo-Kalin 2008). These observations suggest that some in-mixed Manacapuru phase pottery represents a Paredão phase reworking of a prior (Manacapuru phase) occupation, i.e. highlights an occupational hiatus that cannot be readily ascertained by comparison of radiocarbon dates (the oldest Paredão Layer IIIb dates are barely statistically indistinguishable from the Manacapuru date in Layer IIIa (X2-Test on β-143603 and 143606: df = 1 T = 3.8(5% 3.8), see Table 3.3), but which resonates with the pedo-stratigraphic interpretations presented in the analysis of the Hatahara Urn's unit.

Third, patterns in MS data identify a relatively sharp inflection located at around 110 cm in the deposit (Table 3.8, Fig. 3.8). This inflection is subtly echoed in other variables such as Co, Ct, LOI, pH, and EC, and underscores that very high values of P, Ca and especially Mn, Ba, K, Sr, and Zn at 100–110 cm (top of Layer III) and 70–80 cm (top of Layer V), cannot be assumed in the intervening sediments (Layer IV and lower part of layer V). In other words, physical and chemical data support the suggestion that the upper part of Layer III constitutes a buried anthropogenic dark earth with significant levels of enrichment (Neves et al. 2004). In addition, physical and chemical data, including here inflections in pH, MS, LOI, and EC values, provides some sense that a distinction between layers IV and V is reflected in sediment composition, and highlights potential stratigraphic discontinuity suggested by available radiocarbon evidence: three radiocarbon dates (β-143607, 2, and 1, see Table 3.3 and Fig. 3.7) from Layer V and the contact with overlying layer VI indicate that these sediments begin to accumulate towards the eleventh–twelfth century AD. These dates *can* be distinguished statistically from Layer IIIb dates [X2-Test on β-143605 and 143602: df = 1 T = 12.5(5% 3.8)] although not construed as evidence of site abandonment.[1] The shift to high EC, lower pH, relatively low Mn, and low LOI recorded in the upper part of the more brown-coloured sediments of Layer V is noteworthy and will be discussed in more detail in the following section.

Fourth, micromorphological, physical and chemical data for Layers VI and VII show that sediments which constitute the mound 'overburden' are significantly

[1] Dates from the upper part of layer III, Mound 1 (β-143603, 4 and 5) cannot be distinguished statistically from dates from the upper 60 cm of Unit 4 (β-178922 and 5, see Table 3.3), especially if the most proximate are considered [X2-Test on β-178922 and β-143605: df = 1 T = 1.0(5% 3.8)]. The dates from the upper part of Unit 4 (recorded by excavators as dark terra preta soils with abundant Paredão remains Donatti 2003; Neves 2003), cannot be distinguished statistically from dates from Layer V and the lower part of Layer VI at Mound 1 [X2-Test on β-178925 and 143601, 2, or 7: df = 1 T = 1.0(5% 3.8)].

Table 3.9 G-3 (Mound 1). Summary of micromorphological observations

Thin section	Depth[†]	Layer/ horizon	Micro- artef	Pott- eryc	Sponge spicules	Burnt soil	Rubif. agg	Bone	Microscopic bone % size classesb	Micr. char	Microscopic charcoal % size classes[a]	Grav char	PPL	OIL	Organic staining	B- fabric	Phytho- liths
LG-3.1	10	VII/Ap	15	•••	•••	••	•••	6.2		8.5		••			4	u	••
LG-3.2	35	VI/A2	15	••	•••	•••	•••	4.1		8.2		••			4	u	••

Key: see Table 3.4
[a] = depth of the top of undisturbed block used for thin section manufacture.
[b] % of total solids in thin section.
[c] relative abundance in thin section.
[d] % of fine mineral fraction. Size classes for bone: coarse silt, very fine sand, fine sand, medium sand, coarse sand, very coarse sand (see Stoops 2003).
n/m = not measured. Size classes for charcoal from fine silt to very coarse sand (see Stoops 2003). Relative abundance (•) = marginal; • = rare; •• = common; ••• = very common.
[e] optical properties of the fine mineral fractions: L = limpid, 1 = organic punctuation; 2 = lightly stained; 3; medium stained; 4; strongly stained;
d. u = undifferentiated; s= speckled; S = striated; (s,u,S) = marginally s, u or S.

enriched by settlement-related activities. Thin sections from the upper part of Layer VI and Layer VII (Table 3.9) show very abundant microscopic bone, pottery, rubified clay, and charcoal embedded intrapedally in Type I (layer VI) to Type II (layer VII) texturally 'clayey' sediments, the latter contrast mapping onto macroscopic colour differences. Thus, in spite of colour contrasts recorded by excavators, high MS values and concentrations of P, Ca, Mn, and other elements can be associated to the deposition and/or decomposition of debris associated to pre-Columbian settlement dynamics, with lower concentrations of P, Ca, Mn and other elements in Layer VII with respect to Layer VI, on the one hand, and higher Al and Fe in Layer VI with respect to layer VII, on the other, possibly indicating different sources for the sediments that make-up the mound 'overburden'. In this regard, similarities in chemical data and recorded colour between Layer IIIb and VII, coupled with the fact that charcoal at 35 cm (β-143600) dates older than underlying Layer V/VI sediments, suggests remobilisation of anthropogenically-enriched soils from the immediate vicinity of the site. The uninterrupted increase in MS values in Layer VI up to approximately 30–40 cm, at the same time, strongly resonates with the suggestion that build-up of the deposit up to this depth is characterised by intensive *in situ* burning at progressively higher surfaces.

To summarise, it is clear that much like the Urn's Unit at Hatahara, settlement-related *terra preta* soils from the peninsula-side of the Lago Grande site (1) record net positive sedimentation; and (2) show evidence of buried land surfaces. Layer IIIa of Unit 1 may record an occupation that results in some modification of the soil mantle that is subsequently reworked during a more intense occupation that builds-up Layer IIIb, triggering the development of strong melanisation and much more significant soil enrichment/enhancement. Both occupations are preceded by the imprint of less intense inhabitation events starting in the first half of the first millennium AD. The mound 'overburden' records evidence of deliberate events of sediment deposition as well as possible profile build-up as a consequence of habitation. Clearly further research and comparative examination of earth mounds from other sites (Machado 2005; Moraes 2006; Arroyo-Kalin 2008) is needed to elucidate the matter more fully. However, it is interesting to note that the stratigraphic position of Layers IV and V suggests that the topsoil at the Lago Grande peninsula was not a uniformly dark earth about 1,000 years ago *because* dark *terra preta* soils (Layer III) were buried by deposition of brown coloured sediments (Layer V) before the construction or build-up of the earthworks we presently recognise as mounds. Analysis of the soil mantle beyond the peninsula side of the site offers some intriguing clues about the processes responsible for these characteristics of the soil mantle.

3.6 Lago Grande: The Pedo-Stratigraphy of *Terras Mulatas*

The study of four separate profiles located outside the core area of the Lago Grande site offers a glimpse into differences between clayey oxisols developed under forest vegetation, thick brown *terras mulatas* on the *terra firme* side of the site, and the settlement-related *terras pretas* discussed in the preceding section.

Profile LG-5 samples an Oxisol A horizon under forest vegetation located some 3 km north of the Lago Grande archaeological site. A horizon samples shows physical and chemical data comparable to the Hatahara background (Profile HA-9) except as regards Fe and MS values (Table 3.10). Higher Fe concentrations reflect the fact that the soil mantle of this sub-region has formed much closer to laterite exposures (see also Donatti 2003; Moraes 2006; Arroyo-Kalin 2002–2006, personal observation). Lower MS values, on the other hand, can be considered as levels of magnetic enhancement in Oxisols which have not seen recent burning. These two observations bear on some of the interpretations of anthropogenic soils offered below.

Profile LG-2 samples the buried organic horizon (Layer II), overlying B horizon sediments (Layer I), and underlying redeposited B horizon sediments (Layers IA and III, the latter being a new A horizon forming on redeposited Layer I sediments) of the *peninsula*-side promontory at the isthmus portion of the Lago Grande site (Figs. 3.2, 3.9). Important contrasts are observed in micromorphological, chemical and physical data between Layers I, II, IA, and III (Table 3.11). From a micromorphological perspective, Layer IA and Layer I sediments are organized as continuous, massive vughy zones, varying from a limpid yellow (PPL/OIL) clay with a striated b-fabric (Layer I) to a slightly organically-stained dark yellowish brown clay with a marginally speckled b-fabric (Layer IA). Layer II sediments, on the other hand, are organised as matrix-supported clayey irregular peds resulting from the coalescence of different-size aggregates, showing a strongly organically-stained dark yellowish brown (PPL) and gray (OIL) fine mineral fraction, and expressing a marginally speckled b-fabric (XPL). The latter sediments have low but significant frequencies of microartefacts (1%), including small quantities of mostly coarse silt-sized bone, as well as a very high density (max 12.5% FMF) of mostly fine-silt sized charcoal fragments (Table 3.10). The contact between Layers II and I (thin section LG-2.4) appears as a sharp unconformity describing a more or less irregular contour. Sectioned illuvial clay coatings on Layer I sediments at this unconformity (Fig. 3.10), coupled with an almost complete lack of indications for down-mixing of Layer II sediments into the upper part of Layer I (thin section LG-2.7) strongly suggests the latter is not an *in situ* buried A horizon but instead a redeposited organic- and charcoal-rich sediment placed on a truncated B horizon. This observation accords well with the recording of a sharp boundary between Layers I and II by site excavators in 2001 (Fig. 3.9) and is also congruent with descriptions of the profile at the time of geoarchaeological sampling in 2002.

Data from physical and chemical analyses for Profile LG-2 (Table 3.12) shows much higher values in virtually all measured variables in Layer II compared to samples from the background profile (LG-5, Table 3.10) but levels of enrichment/enhancement that are much lower than peninsula-side *terras pretas* (LG-3, Table 3.8), including here a much smaller pool of organic carbon. At the level of the profile (Fig. 3.11), Layer II values also depart significantly from under and overlying sediments (Layers I and IA). Differences include much lower Al and Fe concentrations, higher P, Mn, K, Mg, Na, and MS, yet lower LOI values, suggesting moderate anthropogenic enrichment/enhancement and/or inputs from other sources. As regards MS measurements, it is noteworthy that Layer II shows values between

Table 3.10 LG-5 (background yellow latosol). Physical and chemical parameters

Horizon	Depth[a]	pH[b]	EC[c]	LOI[d]	Co[e]	Ct[f]	MS[g]	Al[h]	Fe[h]	P[h]	Ca[h]	Mn[h]	Ba[h]	Cu[h]	K[h]	Mg[h]	Na[h]	Sr[h]	Zn[h]
A1	–6	4.1	26	7.77			66.1												
A2	–16	3.4	168	6.63			56.5	25200	79600	350	<100	36	<10	4	50	50	50	3	7
A2	–26	3.6	146	6.10			52.8												

Sampling. Horizon (A, B, E).
[a] = depth of sample from surface (cm), collected using a dutch auger.
Parameters:
[b] pH, 1:2 soil to d.i. H_2O.
[c] Electrical conductivity: 1:2 soil to di H_2O (μS).
[d] Loss on Ignition, 12 h, 550°C (%W).
[e] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption (%W).
[f] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption after HCl treatment (%W).
[g] Low Frequency magnetic susceptibility, Bartington MS2/MS2B dual frequency sensor (si units).
[h] ICP-AES on samples pre-treated with *aqua regia* (ppm).

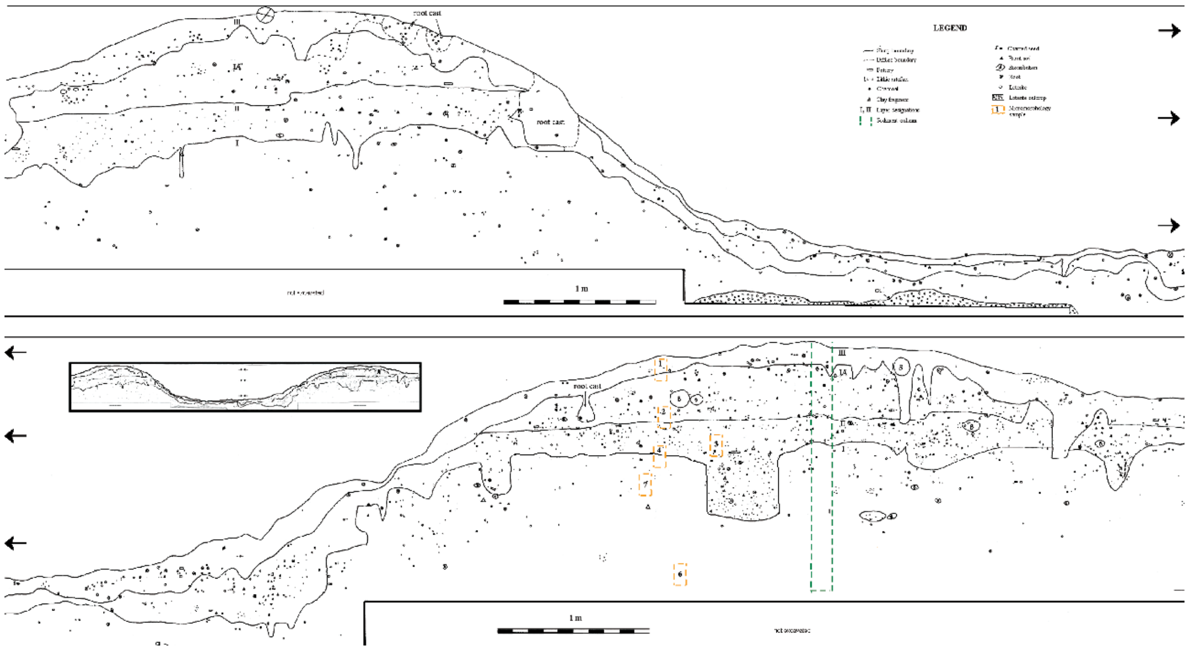


Fig. 3.9 Promontories flanking an artificially-constructed ditch and burying a *terra mulata* horizon. Layer I is a B horizon. Layer II is a *terra mulata* horizon. Layer IA are redeposited Layer I-like sediments. Layer III identifies a shallow A horizon forming on top of Layer IA. The stratigraphic contiguity of Layer II between both sides suggests that Layer IA sediments have not been sourced directly from the excavation of the ditch. Note sampling for geoarchaeological analyses on the peninsula side of the feature (profile drawing adapted from Donatti 2003:61, Figure 19)

Table 3.11 LG-2 (buried *terra mulata*). Summary of micromorphological observations

Thin section	Depth[†]	Layer/ horizon	Micro-artef	Pott-ery[c]	Sponge spicules	Burnt soil	Rubif. agg	Bone	Microscopic bone % size classes[b]	Micr. char	Microscopic charcoal % size classes[a]	Grav char	PPL	OIL	Organic staining	B-fabric	Phytho-liths
LG-2.1	10	III /Ap (^Bt)							----------------	3.5		•			1	(s)	••
LG-2.2$^{50\%}$	50	IA: ^Bt							----------------	0.2		•			L	s	(•)
LG-2.2$^{25\%}$	55	IA: A2/ A3	<1				•		----------------	5.0		•			2	s	•
LG-2.2$^{25\%}$	55	IA: (^Ab)	1	(•)	••	••	•	<0.1	n/m	10		••			4		••
LG-2.3	65	II (^Ab)	1	•	•	••	••	0.2	n/m	12.5		••			3	(s)	••
LG-2.4$^{50\%}$	75	II (^Ab)		•	(•)	•	•	<0.1	n/m	7.5		(•)			2	(s)	••
LG-2.4$^{50\%}$	80	I/Bt1							----------------	0.2		(•)			L	(s)S	•
LG-2.7	85	I/Bt1							----------------	0.2					L	S	(•)
LG-2.6	135	I/Bt2							----------------	3.5		•			L	S	••

[a] = depth of the top of undisturbed block used for thin section manufacture.
[b] % of total solids in thin section.
[c] relative abundance in thin section.
[d] % of fine mineral fraction. Size classes for bone: coarse silt, very fine sand, fine sand, medium sand, coarse sand, very coarse sand (see Stoops 2003).
n/m = not measured. Size classes for charcoal from fine silt to very coarse sand (see Stoops 2003). Relative abundance (•) = marginal; • = rare; •• = common;
••• = very common.
[e] optical properties of the fine mineral fractions: L = limpid, 1 = organic punctuation; 2 = lightly stained; 3; medium stained; 4; strongly stained;
d. u = undifferentiated; s = speckled; S = striated; (s,u,S) = marginally s, u or S.

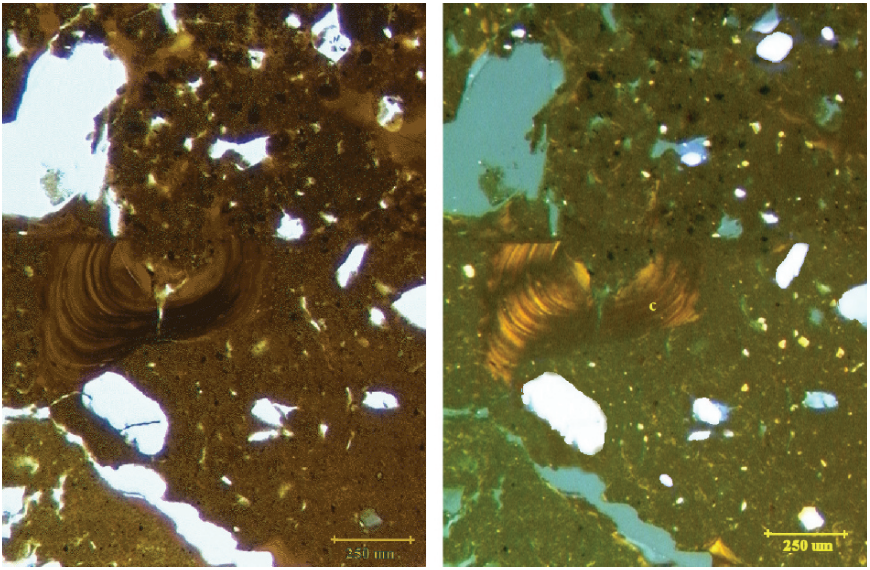


Fig. 3.10 Truncation with sectioned illuvial clay coatings (c) at the boundary between the lower part of Layer II (^Ab *terra mulata*) and underlying Layer I. Thin section LG2.4, Profile LG-2 (PPL/XPL)

145 and 165 si units, higher than the benchmark for near surface burning derived from the HA-9 background profile at Hatahara. As regards LOI, whilst it is surprising to record an inflection towards lower values given the abundance of microscopic charcoal and strong organic staining observed in thin section, it supports the interpretation of a truncated Layer I and a redeposited Layer II, followed by burial with Layer I-like sediments. Inflections in the values of other properties, including pH and EC, also underline sharp shifts between Layers I, II, and IA.

Profile LG-1 samples a soil profile whose A horizon is stratigraphically contiguous with Layer II (the buried organic horizon) in LG-2 but which is located on the *terra firme* side of the artificially-constructed ditch feature, immediately behind the promontory. Macroscopically, the A horizon of LG-1 can be clearly subdivided into three sub-horizons (A1, A2 and A3) followed by a thin AB horizon that is underlain by a B/A horizon. Micromorphological observations reflect these contrasts as follows: A-horizon sediments are similar in texture and optical features of the fine mineral fraction but show more granular peds, increasingly more abundant illuvial clay features, and different overall proportions of intrusive clayey aggregates in A2 and A3 sediments compared to A1. All A horizon sediments show marginal to rare microartefacts and microscopic charcoal in small size classes, with peak concentrations in A2 (Table 3.13). More common gravel-sized limpid yellow clayey aggregates towards the bottom of A3 indicate 'up-mixing' (tree throws, digging?) of B horizon sediments. B/A horizon sediments appear as a massive vughy limpid brownish yellow

Table 3.12 LG-2 (buried *terra mulata*). Physical and chemical parameters

Horizon or layer	Depth[†]	pH[a]	EC[b]	LOI[c]	Co[d]	Ct[e]	MS[f]	Al[g]	Fe[g]	P[g]	Ca[g]	Mn[g]	Ba[g]	Cu[g]	K[g]	Mg[g]	Na[g]	Sr[g]	Zn[g]
III /Ap (^Bt)	5–7	5.4	28	12.19			53												
IA (^Bt)	15–17	5.2	27	12.07			46.9	32200	74700	1460	400	27	10	4	50	100	100	9	9
IA (^Bt)	25–27	5	24	11.54			38												
IA (^Bt)	35–37	5	27	11.32			40.5												
IA (^Bt)	45–47	5	27	11.29			42.7												
IA/II (^Ab)	55–57	5	21	11.01			64.1	35400	79800	1930	200	31	10	6	50	50	50	9	9
II (^Ab)	60–62	4.9	16	9.60			151.6												
II (^Ab)	70–72	5	27	9.75	1.31	1.71	165.1	31400	67500	2540	200	143	10	11	100	100	100	8	8
II (^Ab)	75–77	5	27	9.86			145.9												
I/Bt1	85–87	5	23	11.24			68.6												
I/Bt1	90–92	5	20	11.03			62.9	33500	79200	1730	200	24	10	5	50	50	100	7	7
I/Bt2	105–7	5	29	10.82			49.9												
I/Bt2	135–7	5	40	10.60			31.1	36000	80000	1750	100	18	10	3	50	50	100	8	8
I/Bt2	145–7	5	58	10.83			30.6												

Sampling. Horizon (A, B, E) or Archaeological layer (I-V). Note remobilized horizon designation (^A = remobilized A).

[†] = depth of sampling from the surface (cm) representing constant volume samples collected during excavations every 10 cm at the indicated depth.

Parameters: [a] pH, 1: 2 soil to d.i. H_2O.

[b] Electrical conductivity: 1:2 soil to di H_2O (µS).

[c] Loss on Ignition, 12 h, 550°C (%W).

[d] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption (%W).

[e] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption after HCl treatment (%W).

[f] Low Frequency magnetic susceptibility, Bartington MS2/MS2B dual frequency sensor (si units).

[g] ICP-AES on samples pre-treated with *aqua regia* (ppm).

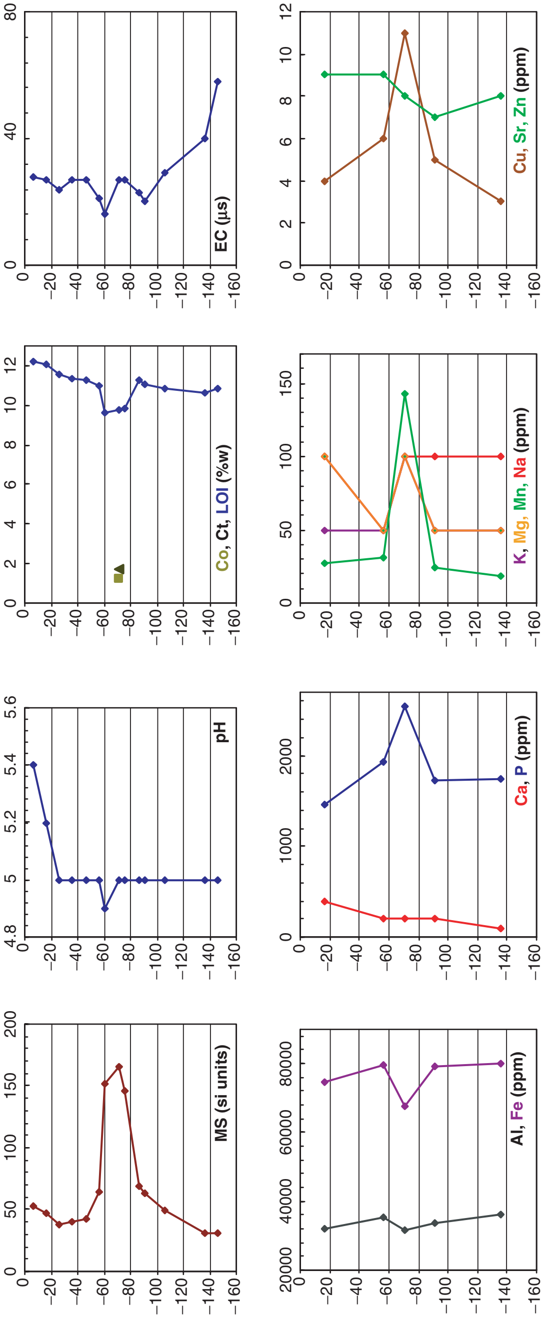


Fig. 3.11 LG-2 (buried *terra mulata*). Physical and chemical parameters. Y axis = depth (cm)

Table 3.13 LG-1 (*terra mulata*). Summary of micromorphological observations

Thin section	Depth†	Layer/ horizon	Micro-artef	Pott-ery[c]	Sponge spicules	Burnt soil	Rubif. agg	Bone	Microscopic bone % size classes[b]	Micr. char	Microscopic charcoal % size classes[a]	Grav char	PPL	OIL	Organic staining	B-fabric	Phytho-liths
LG-1.1	10	A1	<1		•	•			----------------	7.5		••			3	(s)	••
LG-1.2$^{50\%}$	30	A2	1	(•)	•	•	•		----------------	10.0		•			3	(s)	••
LG-1.2$^{50\%}$	35	A3	1		•	•	•		----------------	5.0		•			2	(s)	••
LG-1.3$^{90\%}$	55	B/A: B						<0.1	----------------	1.5		(•)			1	S	

[a] = depth of the top of undisturbed block used for thin section manufacture.
[b] % of total solids in thin section.
[c] relative abundance in thin section.
[d] % of fine mineral fraction. Size classes for bone: coarse silt, very fine sand, fine sand, medium sand, coarse sand, very coarse sand (see Stoops 2003).
n/m = not measured. Size classes for charcoal from fine silt to very coarse sand (see Stoops 2003). Relative abundance (•) = marginal; • = rare; •• = common; ••• = very common.
[e] optical properties of the fine mineral fractions: L = limpid, 1 = organic punctuation; 2 = lightly stained; 3; medium stained; 4; strongly stained; d. u = undifferentiated; s = speckled; S = striated; (s,u,S) = marginally s, u or S.

clay with a striated b-fabric (XPL) within which are embedded isolated charcoal fragments, as well as intrusive and faunally-reworked peds of A2 or A3-like material.

Data from physical and chemical analyses for LG-1 (Table 3.14) show much higher values in virtually all measured variables than the A horizon of the LG-5 background profile (Table 3.10). Particularly noteworthy (Fig. 3.12) is a rise in MS from low levels at 46 cm to values that are equivalent to near surface burning at the HA-9 background profile at around 36 cm. Above this MS remains constant at around 138 si units between 16–26 cm before rising towards the surface. pH values, significantly higher than measured in background soils, show an inflection at 36 cm that is echoed by LOI and EC, together recalling the transition between Layers I and II in Profile LG-2. These trends are accompanied by lower Al and Fe and a sharp rise in Ca and Mn from at least 36 cm.

Profile LG-4 samples the west profile of Unit 5, a test pit on the *terra firme* portion of the Lago Grande site (Fig. 3.2). Macroscopically, the profile shows a dark brown and deep reaching A horizon that is underlain by an AB and a B/A horizon sequence (Fig. 3.13). The A horizon can be subdivided into two sub-horizons (A1 and A2) that map onto layers IV and III recognised by excavators. Micromorphological data (Table 3.15) reveals that the A horizon is a porous matrix-supported 'clay' organised as massive, irregular, peds formed from the coalescence of different size aggregates of faunal origin. The fine mineral fraction appears as a strongly organically-stained, dark yellowish brown (PPL) and brown (OIL) clay with an undifferentiated b-fabric (XPL). Peds include small quantities of microartefacts in densities comparable to A2 and A3 horizon sediments at LG-1 (<1% of the fine fraction), including marginal fine sand-sized or smaller pottery fragments, marginal to rare sponge spicules, marginal to rare silt-sized burnt soil fragments, and marginal fragments of fine sand-sized bone. Microscopic charcoal is very abundant (10.5% in LG-4.1 and 12.5% in LG-4.2) but more common in gravel to coarse sand size in A1 (Layer IV, i.e. LG-4.1) and in fine sand to silt size in A2 (Layer III, LG-4.2), in effecting peaking in density in the A2 horizon (Table 3.15). The lower 1 cm of thin section LG-4.2 appears as a zone of lightly organically stained yellow clayey (PPL/OIL) with a marginally speckled b-fabric (XPL) well above the AB or B horizon, an observation that resonates with gravel-sized limpid yellow clayey aggregates in the A3 of Profile LG-1. Within this secondary fabric, charcoal in the same size classes as LG-4.2 is present (3.5% FMF).

Data from physical and chemical analyses for the LG-4 profile (Table 3.16) reveals that A horizon sediments show much higher values in virtually all measured variables compared to the LG-5 background soil (Table 3.10). Most noteworthy is the fact that, like LG-1, a sharp rise in MS above the near surface burning benchmark (HA-9) is recorded as deep as 56 cm, in parallel with a consistent trend towards higher pH (Fig. 3.14). An inflection in EC values at this depth suggests discontinuity in profile build-up from 46 cm. Like LG-1, Al and Fe values are much lower towards the surface. Mn, K, Mg, and Na are higher at the surface but P, Ba, Cu, Sr, and Zn are higher at 36 cm, co-patterning with high MS values, microartefacts and silt-sized charcoal.

Table 3.14 LG-1 (*terra mulata*). Physical and chemical parameters

Horizon or layer	Depth[†]	pH[a]	EC[b]	LOI[c]	Co[d]	Ct[e]	MS[f]	Al[g]	Fe[g]	P[g]	Ca[g]	Mn[g]	Ba[g]	Cu[g]	K[g]	Mg[g]	Na[g]	Sr[g]	Zn[g]
A1 (II)	5–7	5.7	46	10.51			146.4												
A2 (II)	15–17	5.6	50	10.13			138.5	23600	53400	1240	1900	261	20	12	50	100	50	13	13
A2 (II)	25–27	5.6	54	9.55			137.6												
A3 (II)	35–37	5.4	102	10.34			110.8	27800	65700	1430	1300	63	10	9	50	100	50	12	12
AB (I)	45–47	5.6	107	10.51			72.8												
B/A (I)	55–57	5.6	107	10.76			52.4	41000	93400	1700	800	25	10	6	50	100	50	13	13
Bt (I)	115–7	5.4	115	10.68			31.7	33700	78300	1340	400	16	10	3	50	100	100	10	10

Sampling. Horizon (A, B, E) or Archaeological layer (I-V). Note remobilized horizon designation (^A = remobilized A).

[†] = depth of sampling from the surface (cm) representing constant volume samples collected during excavations every 10 cm at the indicated depth.

Parameters:

[a] pH, 1: 2 soil to d.i. H_2O.

[b] Electrical conductivity: 1:2 soil to di H_2O (µS).

[c] Loss on Ignition, 12 h, 550°C (%W).

[d] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption (%W).

[e] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption after HCl treatment (%W).

[f] Low Frequency magnetic susceptibility, Bartington MS2/MS2B dual frequency sensor (si units).

[g] ICP-AES on samples pre-treated with *aqua regia* (ppm).

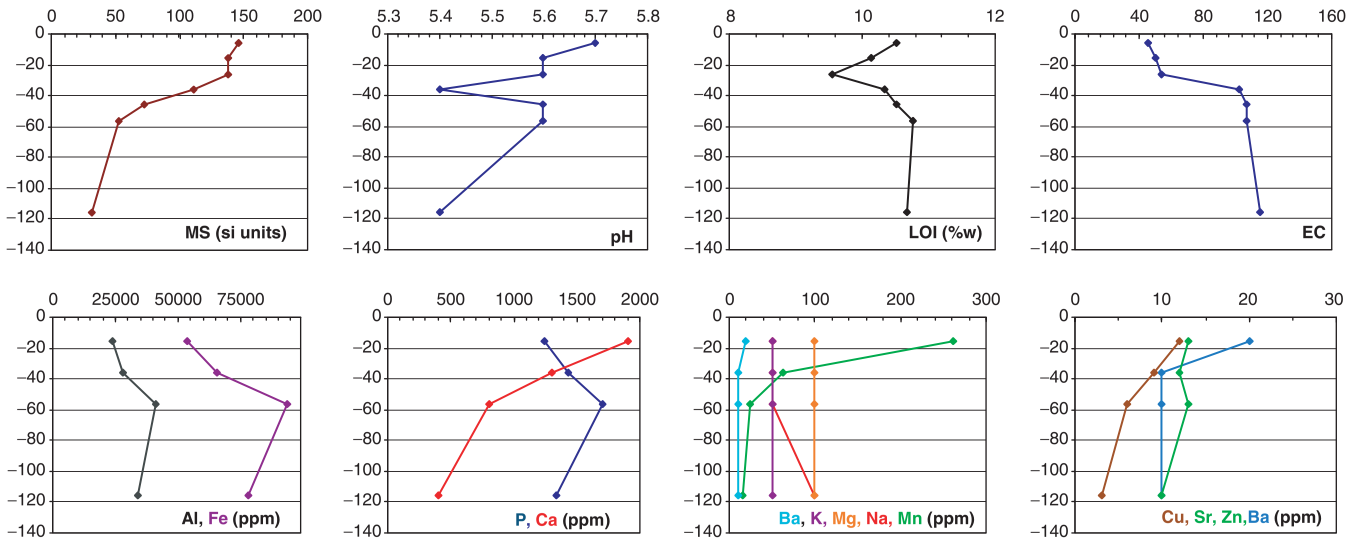


Fig. 3.12 LG-1 (*terra mulata*). Physical and chemical parameters. Y axis = depth (cm)

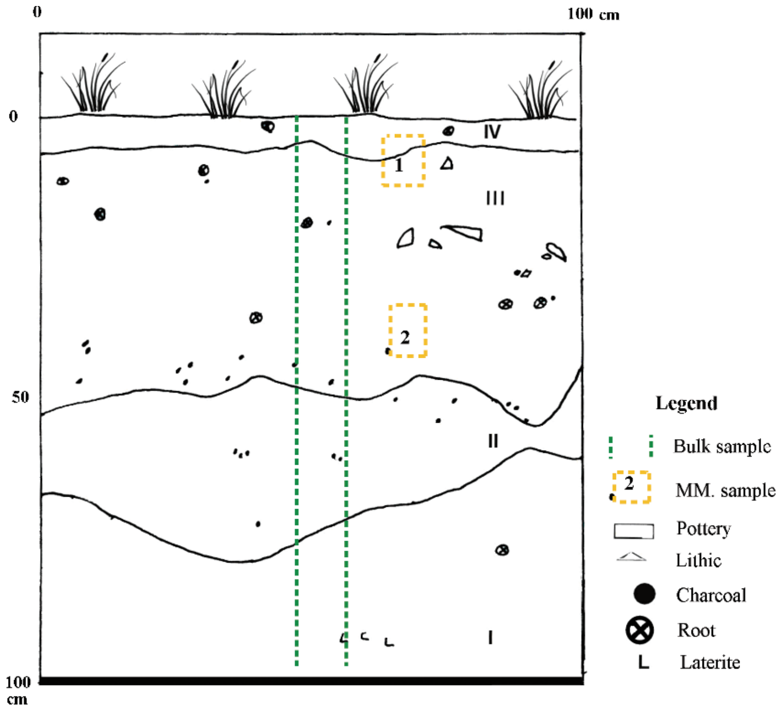


Fig. 3.13 Profile LG-4. Note sampling for geoarchaeological analyses (redrawn from Donatti 2003)

3.6.1 Discussion

The analysis of profile LG-2 shows that the main characteristics of the buried organic horizon (Layer II) differ markedly from *terras pretas* that have been studied at Mound 1 of the site (Profile LG-3): settlement-related anthropogenic dark earths show much higher abundance of microscopic ceramic artefacts, rubified clayey aggregates, and bone fragments. At the level of the Profile, micromorphological evidence shows that the transition from Layer II to Layer I is not equivalent to an *in situ* A + B sequence but instead resembles a redeposited, organic-rich sediment placed on a deliberately truncated surface. Similarities between Layer II sediments from LG-2 and A2-A3 sediments from LG-1, including here overall concentrations of Al and Fe, small but significant quantities of microartefacts, dense silt-sized charcoal peaking with microartefacts, and slightly lower pH underlined by inflections in EC and LOI values (at about the same elevation as the contact between Layers II and I in LG-2) extend the inference of a redeposited sediment to the *terra firme* side of the gully immediately behind the promontories. Similarities between Layer II and the A horizon of LG-4, including here markedly different Al and Fe concentrations, a high density of silt-sized charcoal, marginal quantities of microartefacts, and an inflection in LOI values, extend this interpretation to the

Table 3.15 LG-4 (*terra mulata*). Summary of micromorphological observations

Thin section	Depth[†]	Layer/ horizon	Micro-artef	Pott-ery[c]	Sponge spicules	Burnt soil	Rubif. agg	Bone	Microscopic bone % size classes[b]	Micr. char	Microscopic charcoal % size classes[a]	Grav char	PPL	OIL	Organic staining	B-fabric	Phytho-liths
LG-4.1	5	IV/A1	<1	(•)	(•)	(•)		<0.1	----------------	10.5		••			3	u	••
LG-4.2	30	III/A2	<1		•	•	(•)	<0.1	----------------	12.5		•			3	u	•

[a] = depth of the top of undisturbed block used for thin section manufacture.
[b] % of total solids in thin section.
[c] relative abundance in thin section.
[d] % of fine mineral fraction. Size classes for bone: coarse silt, very fine sand, fine sand, medium sand, coarse sand, very coarse sand (see Stoops 2003).
n/m = not measured. Size classes for charcoal from fine silt to very coarse sand (see Stoops 2003). Relative abundance (•) = marginal; • = rare; •• = common; ••• = very common.
[e] optical properties of the fine mineral fractions: L = limpid, 1 = organic punctuation; 2 = lightly stained; 3; medium stained; 4; strongly stained; d. u = undifferentiated; [s] = speckled; S = striated; (s,u,S) = marginally s, u or S.

Table 3.16 LG-4 (*terra mulata*). Physical and chemical parameters

Horizon or layer	Depth[†]	pH[a]	EC[b]	LOI[c]	Co[d]	Ct[e]	MS[f]	Al[g]	Fe[g]	P[g]	Ca[g]	Mn[g]	Ba[g]	Cu[g]	K[g]	Mg[g]	Na[g]	Sr[g]	Zn[g]
IV/A1	5–7	5.6	30	8.98			214.6	19200	42000	1260	400	326	10	8	100	100	50	7	7
III/A2	15–17	5.2	26	8.6			239.6												
III/A2	25–27	5.1	23	8.87			236.3	27800	61000	1780	400	156	20	12	100	100	50	8	8
III/A2	35–37	5.0	30	8.43			236.1												
II/AB	45–47	5.0	28	8.01			143.8												
I/B/A	95–97	4.9	33	7			51.8	28900	70700	1360	200	22	10	2	50	50	50	7	7

Sampling. Horizon (A, B, E) or Archaeological layer (I-V). Note remobilized horizon designation (^A = remobilized A).

[†] = depth of sampling from the surface (cm) representing constant volume samples collected during excavations every 10 cm at the indicated depth.

Parameters:

[a] pH, 1: 2 soil to d.i. H_2O.

[b] Electrical conductivity: 1:2 soil to di H_2O (µS).

[c] Loss on Ignition, 12 h, 550°C (%W).

[d] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption (%W).

[e] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption after HCl treatment (%W).

[f] Low Frequency magnetic susceptibility, Bartington MS2/MS2B dual frequency sensor (si units).

[g] ICP-AES on samples pre-treated with *aqua regia* (ppm).

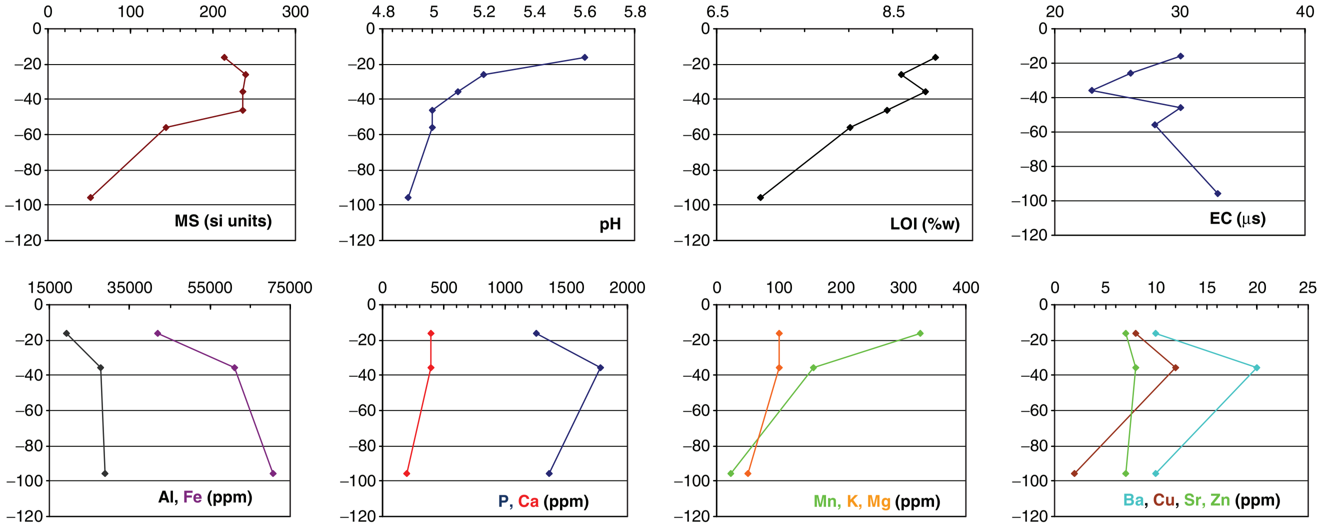


Fig. 3.14 LG-4 (*terra mulata*). Physical and chemical parameters. Y axis = depth (cm)

deep-reaching A horizon of LG-4. In the latter, rising trends in MS values from 56 cm and upwards suggest that the thick A horizon at this part of the site is an accreting deposit that has been enriched by incorporation of sediments which produce physical and chemical signatures analogous to those observed in LG-2 and LG-1 (Fig. 3.15, top).

An economical explanation for these observations is that some form of compost or mulch constituted by large amounts of microscopic charcoal, abundant organic matter, and marginal quantities of settlement debris has been redistributed over the surface of at least the *terra firme* portion of the Lago Grande site prior to consistent near surface burning as the soil mantle builds up from 46 cm (LG-1) and 56 cm (LG-4). This interpretation not only resonates with previous suggestions that *terras mulatas* reflect semi-intensive or even intensive pre-Columbian cultivation practices (Sombroek 1966; Andrade 1988; Denevan 1992) but is also in line with suggestions that organic amendments and consistent in-field burning characterised past land use of these soils (Hecht and Posey 1989; Hecht 2003; Denevan 2004). The fact that these sediments show inflections towards *lower* LOI values (Fig. 3.15, bottom), an evident paradox given high quantities of microscopic charcoal in thin section, suggests that the recipe for these amendments may include sediments with a lower inherited pool of mineral carbon, for instance clayey material from the nearby, seasonally drying lake bed.

Chronological data for these modifications is sparse but significant. Whilst a radiocarbon date on charcoal from LG-4 returned a 'modern' age (β-178926, Table 3.3), the scant ceramic remains at the exposure include an *adorno* fragment of a Paredão burial urn (Donatti 2003), minimally suggesting that inhabitants related to this or later occupation were responsible for the practices of soil management reconstructed on the *terra firme* portion of Lago Grande. The suggested timing is confirmed by the calibrated age of a charcoal fragment from the buried horizon (Layer II) in LG-2, which points to a death event around AD 890–1020 (β-178927). This age range is not only congruent with the Paredão occupation of the peninsula side of the site but, interestingly, closes the chronological gap left by radiocarbon dates from Layer IIIb and Layer V/VI at Mound 1 on the peninsula side of the mound. This provides a tentative basis to suggest that shifts in LOI, MS, pH and EC values in Layer V at Mound 1 may be related to deposition of the same type of material on the substantially-enriched *terras pretas* that make up the core of the site. Since, as discussed previously, co-eval radiocarbon dates from strongly melanised *terras pretas* from the immediate vicinity (Unit 4) weaken any suggestion that site abandonment has taken place in this time range, if Layer V represents deposition of organic amendments as submitted herein, it can be construed as evidence for an occupational episode characterised by the implantation of a house garden (Lathrap 1977; Oliver 2001; Hecht 2003) on the peninsula side of the site.

Although very different interpretations of the dataset discussed above can undoubtedly be entertained, it is worth pointing out that the hypotheses enunciated previously strongly resonate with archaeological interpretations offered by Colombian researchers for approximately the same time range in the Araracuara plateau, including here the presence of brown anthropogenic soils; shifts in land-use

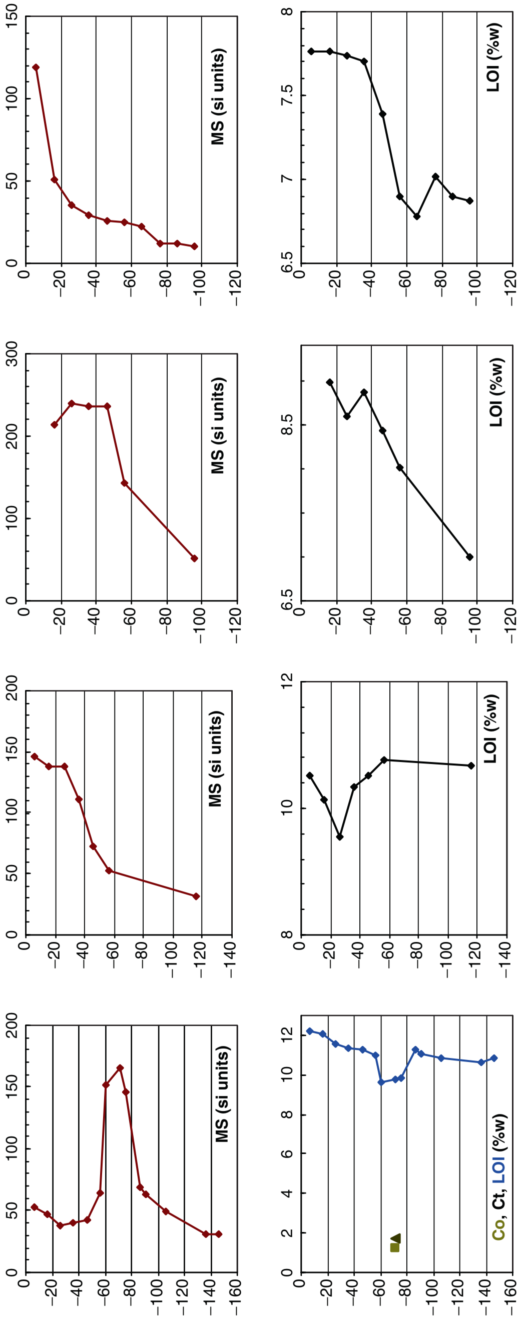


Fig. 3.15 MS/LOI values (top/bottom) in *terras mulatas* and a background soil profile. From left to right: LG-2, LG-1, LG-4 and HA-9

patterns of specific locales; and evidence for intentional soil modification using alluvial sediments (Andrade 1986; Mora 1991; Herrera et al. 1992a; see also Erickson 2003; Denevan 2004:140). The Colombian research also highlights pollen evidence for a diversification in the crop repertoire, more open conditions, and possible intensification of palm trees (Mora 1991; Herrera et al. 1992b). Emerging plant fossil evidence from the Hatahara site – which like the Araracuara research shows more open conditions (abundant grass phytoliths), a wider range of cultivars, and some evidence for the use of *Bactris gasipaes* (see Bozarth et al., this volume) – appears to point in the same overall direction. Research on clay mineralogy and aquatic plant microfossils (Mora 2003), coupled with a better understanding of the geomorphic evolution of the L. Grande lake (see also Latrubesse and Franzinelli 2002), will be crucial to evaluate these suggestive parallels.

3.7 Summary

The preceding analyses illustrate that a pedo-stratigraphic perspective, as coherently argued by Woods (1995), is important to understand the historical development of Amazonian anthropogenic dark earths. By examining exposures from two sites in some detail I provide geoarchaeological data that corroborates Lathrap's (1970) prescient suggestion that not all stratigraphic resolution in these soils is obliterated by pedogenetic processes. By reconstructing a series of land surfaces in *terras pretas* – invisible steps that track the *tempo* of their development – I demonstrate that faunal mixing and illuviation, both important for a better understanding of these soils (Vacher et al. 1998), understate the up-building dynamics that result in their formation. By highlighting specific micromorphological characteristics that can be construed as evidence for the concentration of inputs within roofed and walled structures, I suggest that houses with earthen floors – together with middens and gardens (Andrade 1986; Mora 1991; Hecht 2003; Erickson 2003) – may constitute crucial *loci* for the formation of settlement-related anthropogenic dark earths (see also Kern 1996; Kern et al. 2004). By pointing out stratigraphic overlaps that can be associated to specific ceramic phases at both Hatahara and Lago Grande, I suggest that a model for rapid formation of anthropogenic dark earths (Neves et al. 2003, 2004) requires qualification: at both sites putatively Paredão-age anthropogenic dark earths have formed on an anthropogenically-modified soilscape, the legacy of a less intense Manacapuru occupation. The latter has been preceded by events of clearance, less intense occupations, and most likely moments of re-vegetation since at least the beginning of the first millennium AD (Arroyo-Kalin 2006). An inference of similar effect can be drawn from the distribution of radiocarbon dates from other sites investigated by the Central Amazon Project (Arroyo-Kalin 2008). Lastly, by examining the micromorphology and pedo-stratigraphy of *terras mulatas* I angle on the actual differences that exist between these soils and *terras pretas* (Sombroek 1966; Woods and McCann 1999; McCann et al. 2001) and endorse previous suggestion that this variability – reflective of distinct constituents and inputs – tracks different dimensions of pre-Columbian land use.

Amazonian anthropogenic soils are unlikely to have a unique, basin-wide interpretation. However, exemplars from the central Amazon region can be associated to increasingly more sedentary ceramic groups of the second half of the first millennium AD (Neves 2005; Lima et al. 2006; Arroyo-Kalin 2008). Within the strictures that geoarchaeological data impose, the interpretations I present provide indirect but tangible evidence that the formation of anthropogenic dark earths track longer term processes of landscape domestication (Balée 1989; Clement 1999; Erickson 2006). As various authors have suggested (Andrade 1988; Herrera et al. 1992a; Mora 1991; Denevan 1992, 2004) one dimension of these processes in pre-Columbian times comprises more intensive forms of agriculture that rely on organic amendments and the systematic use of fire. At a more fundamental level, however, my sense is that these processes on the one hand constitute a *continuum* with older histories of vegetation disturbance, forms of managed succession, and a set of biotic legacies 'in the landscape' (Denevan and Paddoch 1988; Saldarriaga et al. 1988; Piperno and Pearsall 1998; Balée 1989; Clement 1992; van der Hammen and Rodríguez 1996; Rival 1998; Politis 1999; Heckenberger et al. 2007) and, on the other, become amplified with the introduction, domestication and/or intensification of particular *terra firme* cultivars (Carneiro 1983; Heckenberger 1998; Arroyo-Kalin 2008).

The trans-generational dynamics of landscape transformation have deeper and broader implications, both for understandings of the pre-Columbian history of the central Amazon region (Arroyo-Kalin 2006) and more broadly for the archaeological record of the Neotropical lowlands (e.g. Piperno and Pearsall 1998; Gnecco and Aceituno 2004; Clement 2006; Arroyo-Kalin 2008). For this very reason, and in closing, I pay homage to the late Wim Sombroek, who first identified and named *terras mulatas*, hypothesised correctly the processes that lead to their formation, and in my opinion climbed one of the first tall steps towards understanding the historical ecology of pre-Columbian landscapes in the Amazon basin.

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Chapter 4
Phytoliths and *Terra Preta*: The Hatahara Site Example

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4.1 Introduction

In this chapter analyses the results from soils sampled in the Hatahara archaeological site. The first objective of this proposal was to determine if the Hatahara had an agricultural field during the pre-Columbian times and, if validated the agricultural use of the land, to identify the plants that were cultivated in the past. The general site characteristics and location were presented in earlier chapters (see Rebellato et al. Chapter 2 in this volume; Arroyo-Kalin Chapter 3 in this volume). The samples were collected from a ca. 1.5 m column through one of the site's mounds (M-I; see Fig. 2.2 this volume). The mound is associated with the Paredão phase occupation of the site. The mound was constructed with dark earth soil from the surrounding area that had developed during the previous Manacapuru occupation (see Machado 2005). Consequently, the archaeological materials, including the phytoliths, found within it are not *in situ* and are from the disturbed context developed by this earthmoving operation ca. 1,000 years ago. Even the terra preta below the mound is not in primary context. It was disturbed by a burial program that occurred during Manacapuru phase *c*500 years before the construction of the mound. A total of 22 skeletons was recovered from the submound context. So, there are basically two contexts represented by these samples: (1) The redeposited materials from within the mound; and (2) The turbated materials found below the mound. The latter are at least close to their original place of deposition and were sealed by the mound. Within the mound the materials are most likely in inverse stratigraphic/temporal position and come from a much wider area. In spite of the disturbed context for these samples it is felt that the study was available one in that it demonstrated the array of useful plants found in association with the occupations of the Hatahara site. As will be seen the phytolith data derived from this study (one of the very few so far in Amazonia) are in conformance with the stance of that a broadly-based subsistence strategy was operant in the Central Amazon during the pre-Columbian period.

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

4.1.1 Phytolith Formation

Growing plants typically absorb water containing dissolved silica. Microscopic silica bodies are then formed by the partial or complete silicification of plant cells, cell walls, and intercellular spaces. The resulting silica bodies which have characteristic shapes and sizes are called *opal phytoliths* (Wilding and Drees 1971). The term phytolith is derived from the Greek words *phyton*, meaning plant, and *lithos*, meaning stone. Opal is the common name for amorphous, hydrated silica dioxide.

Phytoliths form in most plants and are produced in a multitude of shapes and sizes. They are diagnostic when their shapes and/or sizes are specific to a particular plant taxon. Fortunately, many phytoliths are resistant to weathering and are preserved in most soils and sediments for long periods of time.

4.2 Taxonomic Classification of Cultigen Phytoliths

4.2.1 Maize

Much of the early archaeological phytolith research on cultivated plants in the New World has focused on maize because of its importance in many pre-Columbian cultures and the abundance of distinctive phytoliths produced. Cross-shaped phytoliths are commonly produced in maize, but they are also formed, although less commonly, in the Panicoid subfamily of grasses and a few species in the Bamboo subfamily. This type of phytolith consists of three or four lobes attached to a central body and is easy to identify (Piperno 1988).

Research by Pearsall (1982) on an extensive reference collection of Panicoid grasses (62 species) native to southwestern Ecuador demonstrated that only five taxa produce large (16.0–20.5 μm) cross shaped phytoliths, and that they were produced in low frequencies. Four varieties of maize, in contrast, produced relatively abundant large and a few extra large crosses (20.6–25.2 μm). Measurements were based the on short-axis dimensions (width). Cross-shaped phytoliths were defined as those that are not more than 9 ∝m longer than wide.

A comparative analysis by Piperno (1984) on maize and grasses native to lower Central America and northern South America demonstrated that a classification system based on criteria of three-dimensional morphology, in addition to size, should be used to identify cross-shaped maize phytoliths in archaeological sites. It was also shown that Variant 1 (mirror image) extra-large (20.6–25.2 μm) cross-shaped phytoliths were absent from, and Variant 1 large cross-shaped phytoliths occurred only rarely in the many wild grass species studied. Identifying cross-shaped maize phytoliths should not be applied to areas where teosinte (*Z. mays* spp. *mexicana*), a wild ancestor of maize, is native because certain races of teosinte produce maize-like phytoliths (Piperno 1991).

Husks produce cross shapes that are predominately Variant 6 (irregularly trapezoidal to rectangular). These Variant 6 cross shapes are larger than those from leaves and are extremely thick, averaging about 10.8 µm. Husk phytoliths may be identifiable when isolated from sediment if recovered in number (Piperno 1988).

Cobs are a particularly important part of the maize plant to study in most archaeological investigations. Following removal of the grain, cobs would have been either discarded or used as a fuel source. Therefore, cob phytoliths should be present in various pre-Columbian contexts in Amazonia if maize was grown by the culture being studied.

A comparative study of phytoliths formed in traditional non-hybrid maize varieties from the Great Plains and grasses native to the region demonstrated that cobs produce numerous diagnostic phytoliths which have been identified at prehistoric sites in the Great Plains (Bozarth 1989, 1993a). Taxonomic classification by Bozarth (1994) in the American Southwest showed that cobs of all five types of maize (flint, flour, dent, sweet, and pop) produce diagnostic phytoliths. Moreover, cob phytoliths are generally well-preserved and have been recovered from several prehistoric sites in the Southwest (Bozarth 1994, 1997, 2000, 2003).

A recent study by Bozarth (2001b) demonstrates that the same types of phytoliths are formed in a variety of popcorn from Mexico (PI 217409); PI #'s denote plant introduction #'s of the USDA. Piperno et al. (2001) report similar phytoliths in cobs of other maize varieties from Central America. Archaeological cob phytoliths have been identified at Nakbé, Guatemala (Bozarth and Hansen 2001; Hansen et al. 2002) and Blue Creek, Belize (Bozarth and Guderjan 2004).

Other taxonomically valuable phytoliths are also formed in maize. A particular type of ridged bilobate common in the aerial portion of maize, one with round and/or pointed ends and distinctly notched sides, is diagnostic of maize in Arizona (Bozarth 1994). As with cob phytoliths, ridged bilobates are well-preserved in most sediment and have been identified in various sites in the American Southwest (Bozarth 1994, 1997, 2003). The same type of ridged bilobate was recently found in husks from a variety of popcorn from Mexico (PI 217409) and was identified at Blue Creek (Bozarth 2001b).

4.2.2 Squash

The first phytolith study of squash fruit was on rinds of selected varieties of *Cucurbita maxima* and *C. pepo,* in addition to *C. foetidissima* (wild buffalo gourd). Analysis of the rind phytoliths demonstrated that spheroidal phytoliths with deeply scalloped surfaces of contiguous concavities are produced in much higher frequencies in squash than in the wild buffalo gourd and could be used as indicators of squash in the central United States (Bozarth 1987).

Subsequent phytolith research demonstrated that a variety of *C. mixta* (Hopi cushaw squash, Native Seed/SEARCH #182) also produces the distinctively scalloped spheroidal phytoliths in their rinds. Squash rind phytoliths have been recovered from sediment samples collected in several prehistoric sites in the American Southwest (Bozarth 2000, 2003).

Distinctive scalloped phytoliths are also produced in squash varieties from northern Belize (Bozarth 2001b). Varieties studied include *C. argyrosperma* (PI 438546), *C. moshata* (PI 438553), and *C. pepo* (PI 438696). A comparison of phytoliths formed in the rinds of these domesticated *Cucurbita* spp. with those formed in *C. lundelliana*, the only wild *Cucurbita* native to Belize (Balick et al. 2000), demonstrates that the later can be differentiated by their asymmetrical morphology, which consists of a hemisphere and a low dome. The domesticated *Cucurbita* rind phytoliths are more symmetrical, i.e., spherical. Squash phytoliths were identified in late pre-Classic and Classic contexts at Blue Creek (Bozarth 2001a, b; Bozarth and Guderjan 2004) and archaeological sites in Panama and Equador (Piperno and Pearsall 1998; Piperno et al. 2000).

4.2.3 Gourds

A comparative phytolith analysis of a variety of bottle gourd (*Lagenaria siceraria*) from the Southwest with many reference materials from the region demonstrated that large, distinctively scalloped, flat to globular phytoliths are unique to bottle gourd rinds. They differ from diagnostic squash phytoliths in they are not spherical and the scalloped areas are larger. Flat grainy plates with angular-curvilinear edges are also formed in bottle gourd rinds (Bozarth 1994). Scalloped *Lagenaria* phytoliths have been identified at Nakbé, Guatemala (Bozarth and Hansen 2001; Hansen et al. 2002), and Equador (Piperno et al. 2000). Taxonomically valuable segmented hair cell phytoliths are formed in the leaves of bottle gourds and squash. However, none are solidly silicified, indicating that they may not preserve in soil (Piperno 1988).

4.2.4 Beans

Cultivated beans (*Phaseolus* spp.) were a significant part of Prehispanic diets in many areas. Distinctive hooked-shaped silicified hairs are produced in pods of common beans (*P. vulgaris*) and lima beans (*P. lunatus*). Statistical analysis demonstrated that many of these phytoliths are significantly wider near the tip than similar silicified hairs produced in species native to the Great Plains (Bozarth 1990). Bean phytoliths have been identified in several archaeological sites in the Great Plains (Bozarth 1989, 1990) and the American Southwest (Bozarth 1997) based on this distinguishing characteristic.

Similar phytoliths are formed in leaves and pods of domesticated varieties of *P. vulgaris* from Mexico (PI 533312) and Guatemala (PI 163584), as well as a wild variety of *P. vulgaris* from Guatemala (W 620509) (Bozarth 2001b). *Phaseolus* phytoliths have been identified at Blue Creek (Bozarth 2001a). The similarity of hook-shaped phytoliths formed in domesticated and wild *P. vulgaris* does not necessarily present an archaeological problem in distinguishing one from the other because wild *P. vulgaris* does not occur in much of the area in which it was grown prehistorically (Gentry 1969).

4.2.5 Palms

Palms produce abundant distinctive phytoliths that are readily identifiable in the phytolith record. The Arecaeae (palms) is unique in producing the same kind of phytolith in all of its plant structures (Piperno 1988). Two different types of phytoliths are formed in palms, "hat-shaped" and spinulose spheres. Several palm genera produce hat-shaped phytoliths in their leaves (Tomlinson 1961). Species in those genera that occur in the study area include *Astrocaryum acaule, A. aculetum, A. gynacauthum, A. jauari, A. murumuru, Bactris acanthocarpa, B. balanophora, B. bidentula, B. brongniartii, B. concinna, B. elegans, B. gasipaes, B. gastoniana, B. hirta, B. killipii, B. macroacantha, B. major, B. maraja, B. oligocarpa, B. riparia, B. simplicifrons, B. tomentosa, B. trailiana, Desmoncus polyacanthos, Hyospathe elegans, Iriartella setigera,* and *Socratea exorrhiza* (Henderson et al. 1995).

Edible fruit is produced in nine palm species which form hat-shaped phytoliths, including Astrocaryum acaule, A. aculetum, A. gynacauthum, A. murumuru, Bactris brongniartii, B. concinna, B. gasipaes, B. major, and B. maraja Astrocaryum jauri produces palm hearts as does B. gasipaes. Bactris gasipaes is not known as a wild plant but is widely cultivated throughout humid areas of Central America. Leaves of A. murumuru and stems of S. exorrhiza are used in construction. Desmoncus polyacanthos stems are used for making baskets (Henderson et al. 1995).

Several other palm genera produce another archaeologically important type of phytolith: the spinulose sphere (Tomlinson 1961). Several species in these genera are native to the study area, including *Attalea maripa, Euterpe longebrateata, E. precatoria, Geonoma baculifera, G. deversa, G. leptospadix, G. macrostachys, G. maxima, G. stricta, Lepidocryum tenue, Manicaria saccifera, Mauritia carana, M. flexuosa, Mauritiella aculeata, M. armata, Oenocarpus bacaba, O.* bataua, and *O. minor* (Henderson et al. 1995).

Edible fruit and oil is produced in *M. flexuosa*. Beverages are made from fruits of *E. precatoria*, *O. bacaba*, and *O. bataua*. A high quality oil is also made from fruits of *O.* bataua. Palm starch is made from stems of *M. saccifera*. Thatch is made from *A. maripa, G. baculifera, G. deversa, G. leptospadix, G. macrostachys, G. maxima, G. stricta, L. tenue, M. carana,* and *M. saccifera*. Leaves of *A. murumuru* and stems of *S. exorrhiza* and *E. precatoria* and are used in construction. Fiber is made from leaves of *M. flexuosa* (Henderson et al. 1995).

4.2.6 Bromeliads

Bromeliads produce spinulose spheres much like those in certain palms, with which there is overlap in size. A study by Bozarth (1993b) demonstrated that pineapple produces spinulose spheres that range up to 10 μm in diameter.

4.2.7 Other Food Producing Plants

In addition to palms, there were many other cultivated and wild fruits, nuts, leaves, and tubers important in the Prehispanic diet in Central and South America. Distinctive phytoliths formed in the fruits and seeds of many dicotyledon families provide a promising area of research, as none have been found in leaves and many appear unique to genera and even species. These phytoliths usually have a stippled surface and protuberance emanating from the center of the bottom of the cell. Furthermore, production of fruit and seed phytoliths can be quite high (Piperno 1988).

Four Neotropical plant species domesticated for their roots or tubers produce taxonomically significant phytoliths: achira (*Canna edulis*), arrowroot (*Maranta arundinaceae*), chufa (*Cyperus esculentus*), and llerén (*Calathea allouia*). Evidence suggests that achira may have been important in South American prehistory. Arrowroot and chufa are minor cultigens in indigenous economies of Central and South America (Piperno 1991). Llerén was cultivated prehistorically in South America (Chandler-Ezell et al. 2006).

Taxonomically useful phytoliths are formed in chufa seeds (Piperno 1991). Achira leaves produce numerous spherical rugulose phytoliths that range in size from 9–30 μm (Piperno 1988). Rugulate-nodular spheres and regulate conical phytoliths are formed in the leaves of arrowroot. The later type may be unique to arrowroot leaves. More importantly, very distinctive, and probably diagnostic, large globular bodies with branching processes are formed in arrowroot seeds. Recent research shows that *C. allouia* produces distinctive flat domed rhizome cylinders diagnostic of the genus (Chandler-Ezell et al. 2006).

4.2.8 Fiber Plants

Fiber plants were also important prehistoric cultigens. Two species of cotton were domesticated prehistorically in the New World: upland cotton (*Gossypium hirsutum*) in Mesoamerica and North America and Sea Island cotton (*G. barbadense*) in South America (Harland 1992). Non-diagnostic phytoliths are formed in leaves of *G. barbadense*. Phytoliths have not been found in its pods or fiber (Piperno 1988).

4.3 Methodology

Fifteen sediment samples were analyzed for phytoliths and other biosilicates. Five gram samples were processed based on a heavy-liquid (zinc-bromide) flotation and centrifugation procedure. The extraction procedure consists of seven basic steps: (1) removal of carbonates with dilute hydrochloric acid; (2) removal of colloidal organics, clays, and very fine silts by deflocculation with sodium pyrophosphate, centrifugation, and decantation through 7-µm filter; (3) oxidation of sample to remove organics; (4) introduction of spike spores for the calculation of phytolith concentration; (5) heavy-liquid flotations of phytoliths from the heavier clastic mineral fraction using zinc bromide concentrated to specific gravity of 2.4; (6) washing and dehydration of phytoliths with butanol; and (7) dry storage in 1-dram vials.

After thorough mixing, a representative portion of the isolate was mounted on a microscope slide in immersion oil under 24 × 40 mm cover glasses and sealed with clear nail lacquer. A minimum of 200 phytoliths were taxonomically classified at the finest level possible with a Zeiss microscope at a magnification of 625X. Other biosilicates (sponge spicules, diatoms, algal statospores, and other algal bodies) were also counted. At least 25,000 additional phytoliths were then scanned for economic species.

Phytoliths were taxonomically classified based on phytolith systematics reported by Piperno (1988) and analysis of the University of Kansas phytolith reference collection of Central and South American flora. This reference collection currently consists of 47 arboreal spp. and 22 herbs for a total of 114 reference slides of leaves, fruits, and tubers.

Calculation of microfossil concentrations were made using a method based on a known number of spike spores, in this case *Lycopodium*, being added to each sample before flotation. The concentration of microfossils/gram was computed as follows: *microfossil concentration = no. of microfossils counted x (total no. of exotics added/ no. exotics counted/10*. Concentration permits an evaluation of the phytolith production and preservation for a given sample interval. Biosilicate frequencies and culturally significant data found in the scanning beyond that encountered during the classification were presented with Excel software (Table 4.1).

4.4 Results and Discussion

Biosilicates were well-preserved and highly concentrated in all 15 samples analyzed. Maize cob phytoliths were identified in all but three samples. Large (16–20.5 microns) Variant 1 cross-shaped phytoliths were found in 11 samples, three of which also yielded ridged bilobates. Moreover, spherical scalloped phytoliths diagnostic of *Cucurbita* fruit rinds were discovered in three samples. Their symmetry shows that they were produced in squash. In addition, *Lagenaria* (domesticated gourd) phytoliths were identified in two samples. The identification of *Calathea* rhizome

Table 4.1 Phytolith Frequencies and Scanning Data for the Hatahara Site, Central Amazon (N1158 W1360) (Hatahara)

Sample depth (cm)	30–40	40–50	60–70	70–80	80–90	90–100	100–110	110–120	120–130
Sample number	05–16	05–17	05–18	05–19	05–20	05–21	05–22	05–23	05–24
Phytolith sum	206	217	235	232	230	219	227	231	247
Phytolith concentration	3,226,550	2,527,888	2,269,594	2,201,845	1,901,208	1,617,509	1,583,635	1,575,166	1,147,500
Shrubs and trees									
Rugulose spheres ≤10 u	31.8	38.1	48.8	46.7	46.5	51.3	43.5	41.6	40.9
Smooth spheres ≤10 u	0.5	2.6	1.6	1.6	–	2.6	2.5	2.9	3.9
Polyhedral/anticlinal	1.8	0.4	1.2	–	0.4	0.4	0.8	–	0.4
Bactris-type palms (“Hat-shaped”)	9.5	10.8	9.7	9.9	9.9	4.4	5.6	6.9	5.5
Other palms (Spinulose spheres ≥10 u)	1.8	–	–	–	–	–	0.4	0.4	0.4
Other palms and Bromeliads (S. S. 5–10 u)	5.5	4.3	5.6	7.9	8.6	8.3	6.3	7.3	11
Native Grasses, subfamilies (short cells)									
Panicoid-type (bilobates and crosses)	5.5	3.4	3.2	3.7	4.1	3.9	6.3	1.2	3.1
Chloridoid-type (saddles and spools)	15	6.5	1.6	1.2	2.1	2.2	1.7	4.1	2
Pooid-type (trapezoids)	0.9	0.9	1.2	0.8	0.8	1.3	0.8	0.4	–
Native Grasses, other phytoliths									
Long cells	5	5.2	4.4	4.1	2.1	2.2	4.2	6.1	4.7
Bulliforms	3.6	4.3	1.6	0.8	3.7	1.8	0.4	2	0.8
Trichomes	–	2.2	0.4	0.8	0.4	0.4	–	0.4	0.8
Cyperaceae	–	0.4	–	–	–	–	–	–	–
Cyperaceae – inflorescences	–	(2)	–	–	–	–	–	–	–

Other monocots									
Rugulose spheres >10 u	8.2	11.3	13.7	15.7	12.8	14.5	19.2	16.7	18.5
Smooth spheres >10 u	–	–	0.8	–	0.4	1.3	0.4	1.6	1.6
Helicona	–	–	–	–	–	–	–	–	0.4
Marantaceae (nodular spheres)	1.8	–	–	–	1.2	–	0.4	0.4	1.6
Cultigens									
Calathea	–	(3)	–	–	–	(1)	–	(2)	(2)
Cucurbita	–	(1)	–	–	–	–	–	–	(1)
Zea mays-cob types	(3)	(1)	(1)	(1)	(2)	(4)	(2)	(5)	(1)
Z. mays-large (16–20.5 u)									
Var. 1 crosses	(5)	–	(2)	(1)	(1)	(1)	0.4 (2)	(1)	(1)
Z. mays-ridged bilobes	(1)	–	–	–	(1)	–	–	(1)	–
Unidentified phytoliths	2.7	3.5	0.8	2.5	1.6	1.3	1.7	2	1.6
Other biosilicates									
Sponge spicules	2.3	4.3	0.8	1.7	2.9	1.8	1.3	2.5	1.2
Algal statospores	–	–	0.4	–	0.4	–	–	0.4	–
Other algal bodies	4.1	1.7	4	2.5	2.1	2.2	3.8	2.9	1.6

Note: u represents microns; ( ) represents taxa identified during scanning; S.S. represents Spinulose Spheres.

Table 4.2 Phytolith frequencies and scanning data for the Hatahara Site, Central Amazon (N1159 W1360) (Hatahara 2)

Sample depth (cm)	120–130	130–140	140–150	150–160	160–170	170–180
Sample number	05–25	05–26	05–27	05–28	05–29	05–30
Phytolith sum	219	202	208	237	224	229
Phytolith concentration	1,093,566	1,027,500	873,000	589,500	600,390	387,000
Shrubs and trees						
Rugulose spheres ≤10u	39.6	34.3	40.6	49.4	38.9	40.7
Smooth spheres ≤10u	7.4	5.6	10.1	7.5	7.9	3.8
Polyhedral/anticlinal	–	–	–	–	1.3	1.3
Hairs	–	–	–	–	–	0.4
Disks	–	–	–	–	–	0.8
Bactris-type palms (“Hat-shaped”)	5.7	1.5	3.7	5.4	0.8	3.4
Other palms (spinulose spheres ≥10 u)	0.4	–	–	0.4	0.4	0.4
Other palms and Bromeliads (S. S. 5–10 u)	7.8	4.5	10.1	10	7.1	9.7
Native Grasses, subfamilies (short cells)						
Panicoid-type (bilobates and crosses)	1.3	3.5	3.7	2.1	1.3	–
Chloridoid-type (saddles and spools)	–	2.5	0.9	2.9	1.7	0.8
Pooid-type (trapezoids)	0.4	–	0.9	–	–	–
Native Grasses, other phytoliths						
Long cells	2.2	5.6	3.7	1.7	9.6	9.3
Bulliforms	1.3	2.5	3.7	1.2	4.6	2.5
Trichomes	0.9	1	–	0.4	0.4	0.4
Cyperaceae	–	–	–	–	–	–
Cyperaceae – inflorescences	(3)	(4)	(6)	(3)	(4)	(2)
Other monocots						
Rugulose spheres >10 u	26.5	29.8	16.1	15.8	15.1	19.5
Smooth spheres >10 u	0.4	2	0.9	0.4	–	0.8
Helicona	–	–	(1)	(2)	–	–
Marantaceae (nodular spheres)	0.4	1.5	–	0.4	–	–

Cultigens						
Calathea	–	–	(2)	(1)	(2)	(1)
Cucurbita	–	–	(1)	–	–	–
Lagenaria	(2)	–	–	(1)	–	
Zea mays-cob types	(2)	–	(1)	(4)	–	–
Z. mays-large (16–20.5 u) Var. 1 crosses	(1)	–	–	(1)	0.4	–
Z. mays-ridged bilobes	–	–	–	–	–	–
Unidentified phytoliths	0.9	2	1.4	0.8	4.2	3.4
Other biosilicates						
Sponge spicules	3.9	2.5	1.4	0.8	4.6	2.1
Diatoms	–	0.5	–	–	–	–
Algal statospores	–	–	–	–	–	–
Other algal bodies	0.9	0.5	2.8	0.8	1.7	0.8

Note: u represents microns; ( ) represents taxa identified during scanning; S.S. represents Spinulose Spheres.

phytoliths in eight samples shows that at least one species in this genus was utilized for edible tubers.

The presence of phytoliths diagnostic of maize cobs, squash fruit rinds, and domesticated gourds suggest that the sediment samples originated in a refuse disposal area. The identification of other types of maize phytoliths (large Var. 1 crosses and ridged bilobates) indicates that other parts of the plant were also present, suggesting that the maize was grown on-site. *Calathea* may also have been cultivated at the site based on rhizome phytoliths diagnostic of the genus. It is interesting to note that maize was generally more common in the upper eight samples within the mound, whereas *Calathea* was more frequent in the lower seven submound samples.

Heliconia leaf phytoliths were found in three samples and may be from discarded food wrappings because *Heliconia* produces banana-like leaves used for that purpose (Stiles 1983). However, *Heliconia* is also an excellent indicator of disturbed plant associations in the humid, lowland tropics and therefore may have occurred naturally.

There was abundant evidence of disturbance in the phytolith record. The frequency of native grass phytoliths ranged from 6.1% to 30%. Other monocots ranged in frequency from 10% to 33.1%. The overall frequency of monocots (excluding palms) was 24.9% to 40%. These high frequencies of monocots are most likely the result of disturbance from cultivation as herbaceous plants were nearly absent at a non-archaeological site located 70 km north of Manaus, Brazil in the Central Amazonian *terra firme* forest (Piperno and Pearsall 1998). The two uppermost samples (30–40 and 40–50 cm) had high frequencies of native grass phytoliths, 30% and 22.9%, respectively, compared to 6.1% to 17.6% for the other samples, indicating utilization of native grass.

The dominance of arboreal phytoliths in all samples suggests that certain trees were cultivated or managed. Palms were evidently more utilized in later occupation based on the higher frequency of *Bactris*-type phytoliths in the upper five samples. Of the nine species that produce hat-shaped phytoliths and edible fruit, *B. gasipaes* is the most likely species as it is the only one that is cultivated for its fruit (Henderson et al. 1995).

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Chapter 5
Anthropogenic Dark Earths of the Central Amazon Region: Remarks on Their Evolution and Polygenetic Composition

M Arroyo-Kalin, EG Neves, and WI Woods

5.1 Introduction

"On the Amazons the clay intended for the manufacture of pottery is mixed with the ash of the Caraipé tree"

(Hartt 1879:81)

Anthrosols are soils whose formation and characteristics have been enduringly influenced by the material effects of human action (Limbrey 1975; Eidt 1984; Woods 2003). Among others they include those whose surface horizon has been modified by topsoil disturbance and/or irrigation associated to different types of agriculture; those which have formed on human-transported, -manufactured or -mobilised sediments, including here landforms created or altered by humans; and soils whose surface horizons have become significantly transformed as a result of human-induced inputs (see also Dudal 2005). Anthrosols are ubiquitous on a planetary scale (FAO 1998): they vary in spatial extent from compost heaps that concentrate organic matter in the backyard of households to entire landscapes modified by agricultural or industrial activity. Below we focus on anthrosols variously known as *terras pretas de índio* or Amazonian Dark Earths (Sombroek 1966; Hilbert 1968; Woods and McCann 1999; Lehmann et al. 2003; Glaser and Woods 2004). We examine these soils from a geoarchaeological perspective because we believe that important aspects of the dynamics of past anthropogenic landscape transformations are recorded in them. Our approach focuses on relict signatures of past human agencies (e.g. French 2003; Davidson and Simpson 2005) in a soilscape that we understand as a 'moving target', i.e. one whose variability is dictated by its position in specific landscape evolutionary pathways.

From this vantage point, with a sincere hope of contributing to the broader enterprise of understanding past anthropogenic landscape transformations in the Amazon basin, and in fond memory of Wim Sombroek, undoubtedly a pioneer in investigations of these soils, we offer below two interlinked sets of remarks about the physical and chemical characteristics of anthropogenic dark earths. We focus first on dimensions of the variability and evolution of the soil mantle of the central Amazon region that clearly impinge on the physical and chemical properties of these soils and, therefore, affect the nature of archaeological inferences that can be drawn from them.

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

We next offer a discussion of chemical and physical properties of these soils from the perspective of soil micromorphological characteristics at different *terra preta* expanses. Our remarks constitute a summary of findings, questions and hypotheses that emerge from ongoing geoarchaeological research (Arroyo-Kalin et al. 2004; Arroyo-Kalin 2006, 2008) and double as an important cornerstone for interpretations about the historical processes that resulted in the formation of these soils. We discuss aspects of the latter processes in another contribution (see Arroyo-Kalin, this volume), which reciprocally underwrites some of the interpretations presented below.

5.2 Archaeological Context Material and Methods

5.2.1 Sampling Locales

The dataset discussed in this chapter consists of micromorphological, physical, and chemical data used to characterise soil profiles exposed during archaeological excavations of the Hatahara, Lago Grande, Osvaldo, Açutuba, and Nova Cidade archaeological sites (Neves 2003). These sites sample an important range of landscape positions. The Hatahara site is 16 ha clayey *terra preta* expanse located on a high riparian bluff that directly overlooks the whitewater Solimões River (Neves et al. 2003; Machado 2005; Rebellato 2007). The Lago Grande site is a ~3.1 ha clayey *terra preta* expanse located on the *terra firme* margin of the seasonally-drying L. Grande alluvial lake, which is part of a relict meander system that is connected to, but is some kilometres distant from the Solimões River (Donatti 2003; Neves et al. 2004). The Osvaldo site is a 4 ha clayey *terra preta* expanse located on the margin of the L. Limão lake, a fluvial ria in the vicinity of the Colonia Lago do Limão village (Petersen et al. 2001; Neves et al. 2003; Chirinos 2007). This lake is part of the blackwater *igapó* riverscape during the better part of the year but is seasonally enriched by whitewaters from the Solimões during flooding highs, resulting in an ecosystem that is teeming with aquatic fauna during most of the year (Neves 2000). The Açutuba site is a 3 km long sandy *terra preta* expanse which overlooks the right hand margin of the Negro River, approximately 50 km upstream from its confluence with the Solimões River (Heckenberger et al. 1999). Finally, the Nova Cidade site was a minimally 6 ha sandy *terra preta* expanse located at the outskirts of Manaus, some 15 km from the left bank of the Negro River (Neves and Costa 2001, 2004).

The Hatahara, Lago Grande, and Açutuba sites include ceramic remains of the Açutuba, Manacapuru, Paredã,o and Guarita phases, suggesting long histories of human inhabitation (Heckenberger et al. 1999; Petersen et al. 2001, 2003; Neves 2003; Lima et al. 2006). The Osvaldo site is characterised mainly by ceramic remains of the Manacapuru phase but small quantities of Paredão phase material are also found and available radiocarbon dates point to either occupations or burning events in the early part of the first millennium AD (Neves et al. 2003, 2004; Chirinos 2007). Knowledge of the Nova Cidade site is limited due to its almost complete destruction during building of a housing compound. Salvage operations recorded important concentrations of Manacapuru, Paredão, and Guarita phase ceramic remains, including here numerous burial urns with human bones, and an important array of lithic artefacts (Neves and Costa 2001, 2004).

5.2.2 Geoarchaeological Methods

The dataset discussed in this chapter was produced using the following sampling and analytical procedures: undisturbed soil blocks were carved at clean vertical exposures in the field; made into cover-slipped mammoth-sized thin sections; studied using optical microscopes with plain (PPL), polarised (XPL), oblique (OIL) and ultraviolet (UVL) light sources; and described qualitatively following the recommendations of Kemp (1985), Bullock et al. (1986), FitzPatrick (1993), and Stoops (2003). Quantification of specific features (porosity, particulates, and surface area of the clayey material) relied on the analysis of high resolution digital images using the NIH ImageJ software. Interpretations are based on the broader literature on soil micromorphological analysis in soil science and archaeology (Babel 1975; Eswaran and Stoops 1979; Stoops and Buol 1985; Courty et al. 1989; Valentin and Bresson 1992; Davidson and Carter 1998; French 2003, and others referenced below).

The soil micromorphological data is supplemented by the analysis of bulk samples collected from sediment columns using a 10 cm interval, sub-sampled from 1 litre Constant Volume Samples bagged during stratigraphic excavations, or obtained in the field using a Dutch auger. Bulk samples were air dried; ground lightly with a ceramic pestle; rid of visible archaeological artefacts, charcoal and plant fragments; and sieved to obtain the <2 mm fraction. This fraction was then employed to obtain a number of parameters, as follows: pH and electrical conductivity (EC) were measured with a well-calibrated hand-held meter on a paste made of 1 part soil, 2 parts de-ionised water; low frequency magnetic susceptibility (MS) was measured using a Bartington MS2/MS2B dual frequency sensor on 10 cc of sample; total carbon (Ct) was measured using a Leco induction furnace (1350°C, released CO_2 measured by IR absorption) and a muffle furnace (Loss on ignition after 12 h of combustion at 550°C); organic carbon (Co) was measured using a Leco induction furnace with samples pre-treated with dilute HCl to remove inorganic carbon and residual carbonates; and total Al, Ba, Ca, Cu, Fe, K, Mg, Mn, P, Na, Sr, and Zn were measured by ICP-AES on samples previously digested with *aqua regia*.

5.3 Soil Mantle Evolution and Its Effects on the Variability of Anthropogenic Dark Earths

Sedimentes from the artefact-rich A horizon of Amazonian Dark Earths at the Hatahara, Lago Grande, Osvaldo, Açutuba, and Nova Cidade sites are characterised by high pH values, very high concentrations of Ct, Co, P, Ca, Mn, Ba, Cu, K, Mg, Na, Sr, and Zn, and, in most cases, high levels of magnetic susceptibility compared to background soil developed on the same landforms (Table 5.1). In good agreement

Table 5.1 Physical and chemical parameters

Prof.	Horizon or layer[a]	Depth[b]	Text.[c]	pH[d]	EC[e]	LOI[f]	Co[g]	Ct[h]	MS[i]	Al[j]	Fe[j]	P[j]	Ca[j]	Mn[j]	Ba[j]	Cu[j]	K[j]	Mg[j]	Na[j]	Sr[j]	Zn[j]
HA-1	V (Ap)	5–7	C	6.6	70	9.44			433.6	25,200	26,600	10,400	22,200	1,315	230	62	800	1,200	200	133	133
	V	15–17	C	6.5	50	8.69	3.76	4.33	486.7	31,400	31,500	15,700	30,800	1,530	330	80	1,200	1,500	200	209	209
	IVb	45–47	C	6.5	61	8.07	2.55	3.13	409	29,500	30,400	16,600	33,500	1,280	260	73	1,100	1,500	200	193	193
	IVb	55–57	C	6.7	31	7.64			372.8	28,000	34,400	16,850	33,800	1,130	210	61	900	1,400	100	173	173
	IVc	85–87	C	6.4	29	7.29	2.14	2.58	292.1	27,200	33,700	14,050	29,600	925	170	58	800	1,100	200	146	146
	III (A1b)	115–7	C	6.5	49	7.05			219.6	25,300	39,500	10,000	21,400	674	150	41	600	800	50	100	100
	III (A2b)	135–7	C	6.5	18	7.1	1.22	1.62	161.4	24,000	39,500	6,470	14,700	453	110	31	400	600	200	72	72
	II (ABb)	165–7	C	6.5	40	7.25			95.7	25,700	46,100	4,630	9,700	282	60	17	300	400	50	47	47
	II (B/Ab)	195–7	C	6.5	42	6.78	.38	.61	42.3	25,800	52,100	2,130	3,700	95	30	8	100	100	100	20	20
	II (B/Ab	215–7	C	6.4	66	6.97			38.6	25,800	51,500	2,140	3,700	87	30	7	100	100	100	20	20
HA-9	A	5–7	C	4.1	19	7.76			118.7	22,000	39,300	250	<100	23	<10	3	50	50	50	1	1
	AB	15–17	C	4	21	7.76	.8	1.75	50.8	19,400	40,500	200	<100	17	<10	1	50	50	50	1	1
	BE	45–47	C	4	26	7.39			26	22,100	46,500	170	<100	19	<10	4	50	50	50	1	1
	Bt	55–57	C	4	31	6.9	.2	.74	25.1	21,900	47,300	180	<100	19	<10	2	50	50	50	1	1
	Bt	85–87	C	3.9	43	6.9			11.8	19,800	49,000	160	<100	17	<10	1	50	50	50	1	1
LG-3	VII(^A1b)	10–20	C	6.1	18	9.75	2.46	3.25	572.5	29,000	49,500	6,630	11,800	617	90	36	100	600	100	89	89
	VI	30–40	C	6.1	16	9.87			563.2	33,400	60,100	9,150	13,000	610	90	38	200	400	100	108	108
	VI	50–60	C	6.1	10	8.81			515.5	36,800	60,600	11,950	18,000	671	90	50	200	400	200	167	167
	V	70–80	C	5.6	68	6.72	2.66	3.09	397	31,900	52,800	12,000	19,900	492	70	37	200	300	100	171	171
	III (A1b)	110–20	C	6	20	7.61	3.1	3.49	496.7	33,200	53,800	12,550	22,300	881	50	35	200	200	100	114	114
	III (A2b)	130–40	C	6.3	21	7.57			342.9	28,600	53,200	7,380	14,600	571	50	21	100	100	100	60	60
	II (A3b)	150–60	C	5.8	35	7.32	2.12	2.41	234.4	25,900	57,200	3,930	7,000	119	20	12	100	100	50	29	29
	I (ABb)	170–80	C	5.9	150	7.96	1.03	1.24	149.1	26,400	63,200	2,140	2,800	50	90	36	100	600	100	89	89
LG-4	IV/A1	15–17	C	5.6	30	8.98			214.6	19,200	42,000	1,260	400	326	<10	8	100	100	50	7	7
	III/A2	35–37	C	5.1	23	8.87			236.3	27,800	61,000	1,780	400	156	20	12	100	100	50	8	8
	I/B/A	95–97	C	4.9	33	7			51.8	28,900	70,700	1,360	200	22	<10	2	50	50	50	7	7
LG-5	A	10–20	C	3.4	168	6.63			56.5	25,200	79,600	350	<100	36	<10	4	50	50	50	3	7
OS-1	IIIb (A2)	20–30	C	5.4	32	17.28	4.9	6.14	402.5	40,800	31,900	15,050	26,500	628	270	58	400	900	200	152	152
	IIIb (A2)	40–50	C	5.4	20	15.93	5.1	5.4	375	44,000	33,100	18,300	31,700	672	260	65	400	900	200	196	196
	IIIa (A3)	60–70	C	5.8	25	13.4	5.1	5.4	331.2	42,900	37,700	12,150	21,600	497	170	47	300	500	100	132	132

	II (A4)	80–90	C	5.5	54	12.56	1.6	2.04	123.5	35,900	40,000	4,740	8,000	203	80	21	200	200	100	58	58
	I (AB)	90–100	C	5.3	38	12.49			72.1	33,100	45,000	2,390	3,200	62	50	10	100	100	100	32	32
AC-1	Ap	15–17	SC	7	30	5.17	1.84	2.52	155.2	13,600	24,700	1,230	2,300	285	40	13	100	300	100	23	31
	A2	25–27	SC	6.4	24	4.51			177.9	18,700	29,400	1,780	1,100	313	50	18	100	200	100	18	32
	A2	35–37	SC	6.4	22	3.82			144.4	11,700	19,200	1,120	800	245	40	13	100	100	100	13	24
	A3	55–57	SC	6.5	15	3.46	1.83	2.29	160.1	12,800	21,000	1,300	1,200	329	60	19	100	100	100	18	34
	AB	75–77	SC	6.4	33	3.39	1.08	1.13	117.6	9,200	19,800	560	700	166	30	11	100	100	100	13	17
	B/A	95–97	C	6.3	30	4.57			87.6	21,300	48,400	1,000	800	127	30	10	100	100	100	18	19
	Bt	115–7	C	5.7	41	4.45	.34	.6	52	19,600	49,000	960	500	45	20	5	50	50	100	13	10
	Bt	165–7	C	6	56	4.62			30.1	20,000	49,800	950	300	26	<10	4	50	50	100	12	7
NC-1	A1	5–7	SCL	4.7	8	9.66			2.2	9,700	5,000	440	300	67	<10	2	50	50	100	4	4
	A1b	15–17	SCL	4.8	9	3.47			2.9	17,000	6,900	560	200	52	<10	1	50	50	50	3	4
	A1b	25–27	SCL	5.7	6	3.38	1.18	1.33	6.2	16,400	6,300	400	300	118	<10	3	50	50	50	4	6
	A2b	65–67	SL	5.6	9	3.13	1.92	2.15	8.1	10,300	4,700	710	200	174	<10	5	50	50	100	2	10
	A2b	75–77	LS	5.2	14	2.62			6.5	10,400	4,700	420	<100	158	<10	2	50	50	100	1	4
	ABb	85–87	LS	5.3	15	2.2			1.5	10,300	5,300	200	<100	29	<10	1	50	50	50	1	4
	ABb	104–6	LS	5.3	13	1.81	0.35	0.79	1.2	11,400	6,000	130	<100	22	<10	1	50	50	50	1	3
	Btb	175–7	SC*	5.2	81	1.47			1.5	18,800	5,500	70	300	12	<10	2	50	50	100	4	4

Sampling. [a] Horizon (A, B, E) or Archaeological layer (I-V). Note use of buried horizon designation (Ab = Buried A horizon) in HA-1, LG-3 and NC-1.
[b] = depth of sampling from the surface (cm). OS-1 and LG-3 are constant volume samples from archaeological excavations; LG-5 collected using a dutch auger. All others represent a 15 × 15 × 2 cm block of soil from the indicated depth.

Parameters:
[c] Texture based on thin section surface area measurement of quartz grains in relation to the groundmass, USDA standard, except ([a], see text): C = clay; SCL = Sandy clay loam; SL = Sandy loam; LS = Loamy sand; SC = Sandy clay.
[d] pH, 1: 2 soil to d.i. H_2O.
[e] Electrical conductivity: 1:2 soil to di H_2O (µS).
[f] Loss on Ignition, 12 h 550°C (%W).
[g] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption (%W).
[h] Leco Induction furnace, 1350°C, released CO_2 measured by IR absorption after HCl treatment (%W).
[i] Low Frequency magnetic susceptibility, Bartington MS2/MS2B dual frequency sensor (si units).
[j] ICP-AES on samples pre-treated with *aqua regia* (ppm).

Profiles: Clayey *terras pretas*: Hatahara: HA-1: Mound 1, HA-5: Urn's Unit; Lago Grande: LG-3: Mound 1; Osvaldo: OS-1: unit S710 E1966. Sandy *terras pretas*: Açutuba: AC-1: Açutuba IA; Nova Cidade: NC-1: surviving monolith. Clayey *Terra mulata*: Lago Grande; LG-4: Unit N772 E415. Background samples: Hatahara: HA-9: Yellow Latosol, vegetation cleared sub-recently; Lago Grande: LG-5: Yellow Latosol, old secondary forest vegetation.

Table 5.2 Abundance of particulates of archaeological origin in thin section

Thin section	Depth	Horizon/ layer	Microartef[a]	Pottery[b]	Spicules[b]	Burnt soil[b]	Rubified Aggregates[b]	Bone[c]	Microscopic bone % size classes[c]
HA-1.1	25	V	10	••	••	•		5.5	
HA-1.2	50	IVb	15	•••	•••	••	•••	6.3	
HA-1.4	115	III	10	••	••	(•)	•••	3.9	
HA-1.5	140	II/AB1	5	••	••	••	••	3.8	
HA-1.7	210	II/B/A	<1	(•)	(•)			<0.2	————
HA-9.1	5	A				•			————
HA-9.2	20	AB				(•)			————
HA-9.5	90	Bt2							————
LG-3.1	10	VII/Ap	15	•••	•••	••	•••	6.2	
LG-3.2	35	VI/A2	15	••	•••	•••	•••	4.1	
LG-4.1	5	IV/A1	<1	(•)	(•)	(•)		<0.1	————
LG-4.2	30	III/A2	<1		•	•	(•)	<0.1	————
AC-1.1	12	Ap	<1			•			————
AC-1.1	18	A2	2	•	•••	•	(•)	0.2	n/m
AC-1.2	35	A2	2	••	•••	•		<0.1	n/m
AC-1.3	75	AB	<1	•	•	•	(•)	0.1	n/m
AC-1.4	110	B/A	<1		(•)				————
AC-1.5	165	Bt	<1						————
NC-1.2	25	Ab1	<1					0.1	n/m
NC-1.4	65	Ab2	<1					0.1	n/m
NC-1.6	95	AB							————
NC-1.8	135	Bt							————

[a] % of total solids in thin section.

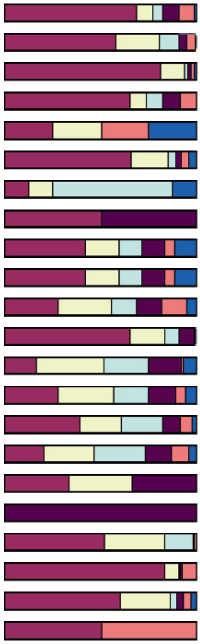
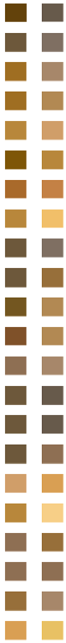
[b] relative abundance. Size classes for bone: coarse silt, very fine sand, fine sand, medium sand, coarse sand, very coarse sand (see Stoops 2003). n/m = not measured.

[c] relative abundance in thin section: (•) = marginal; • = rare; •• = common; ••• = very common. b.% of the fine mineral fraction (%FMF) in thin section.

with previous studies (Lima et al. 2002; Schaefer et al. 2004), micromorphological analysis of thin sections sampling the A horizon of these soils generally shows ubiquitous sand-sized or smaller particulates of archaeological origin (Table 5.2), including here microscopic fragments of bone, pottery, rubified clay, burnt soil; aquatic sponge spicules and silica phytoliths; and very substantial quantities of microscopic charcoal (Table 5.3, see Figs. 5.1, 5.2). Archaeological evidence, the ubiquity of microscopic remains, and high levels of chemical enrichment leave no room for doubt that the enduring transformations that led to the development of these soils resulted from the deposition and/or decomposition of debris associated to pre-Columbian settlement dynamics (see also Sombroek 1966; Smith 1980; Eden et al. 1984; Andrade 1986; Mora 1991; Pabst 1991; Kern 1996; Glaser et al. 1998a; Costa and Kern 1999; Heckenberger et al. 1999; Lima et al. 2002; Lehmann et al. 2004; Rebellato 2007).

Table 5.3 Abundance of charcoal in thin section and optical properties of the FMF

Thin section	Depth	Horizon/layer	Microscopic charcoal[a]	Microscopic charcoal % size classes[a]	Gravel char[b]	PPL	OIL	Org.staining[c]	B-fabric[d]	Phytoliths[b]	Fresh organics[b]
HA-1.1	25	V	11.1		••			4	u	••	(•)
HA-1.2	50	IVb	11.1		••			4	u	••	
HA-1.4	115	III	5.5		••			3	u(s)	••	
HA-1.5	140	II/AB1	3.6		••			3	u(s)	•	
HA-1.7	210	II/B/A	1.0		•			L(1)	S(s)		
HA-9.1	5	A	4.5		••			3	u	•	•r
HA-9.2	20	AB	2.6		•			1	S(u)	(•)	
HA-9.5	90	Bt2	0.2					L	S		
LG-3.1	10	VII/Ap	17.5		••			3	u(s)	(•)	(•)
LG-3.2	35	VI/A2	17.5		•			3	S(u)	••	••
LG-4.1	5	IV/A1	10.5		••			3	u	••	••r
LG-4.2	30	III/A2	12.5		•			3	u	•	•
AC-1.1	12	Ap	9.2		••			4		•	•r
AC-1.1	18	A2	11		••			4	u(s)	••	•r
AC-1.2	35	A2	14		••			4	u(s)	••	
AC-1.3	75	AB	7.4		•			3	U(s)	•	
AC-1.4	110	B/A	0.8		(•)			L	s	(•)	
AC-1.5	165	Bt	0.3		(•)			L	S		
NC-1.2	25	Ab1	12.5		•			4	u	•	(•)
NC-1.4	65	Ab2	17.5		(•)			4	u	•	(•)
NC-1.6	95	AB	3.5		•			2	(s)	(•)	
NC-1.8	135	Bt	0.2					L	S	(•)	

[a] % of the fine mineral fraction (%FMF) in thin section.
[b] relative abundance: (•) = marginal; • = rare; •• = common; ••• = very common; r = rootlets. Size classes for charcoal from fine silt to very coarse sand (see Stoops 2003).
[c] L = limpid, 1 = organic punctuation; 2 = lightly stained; 3 = medium stained; 4 = strongly stained.
[d] u = undifferentiated; s = speckled; S = striated; (s,u,S) = marginally s, u or S.

Very different magnitudes of enrichment/enhancement, however, are apparent in specific exemplars: samples from archaeological sites overlooking the Solimões River and its immediate affluents (Hatahara, Lago Grande, Osvaldo) tend to show much higher values than those which are, broadly-speaking, on *terra firme* reaches drained by the Negro River (Açutuba, Nova Cidade). Given the import that water chemistry has been assigned as a proxy for total biomass in studies of human ecology (Moran 1993), it is tempting to overemphasise these contrasting magnitudes of enrichment. In the present context, however, this emphasis would be misleading: rather than water chemistry in itself, it is the soil mantle at these locales that differs: anthrosols at the Hatahara, Lago Grande, and Osvaldo sites are texturally clayey whilst those at Açutuba and Nova Cidade are texturally sandy.

Textural contrasts are very significant to understand the actual variability of anthropogenic dark earths. Micromorphological observations show that the microstructure

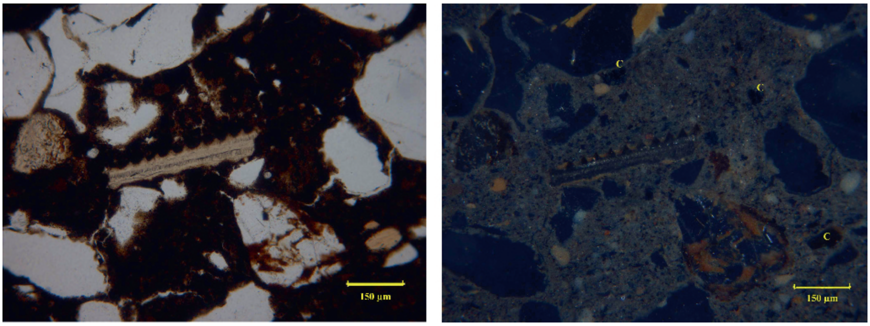


Fig. 5.1 Small bone and charcoal (C) fragments in A horizon sediments of the Lago Grande site. Left: PPL. Right: OIL (*See Color Plates*)

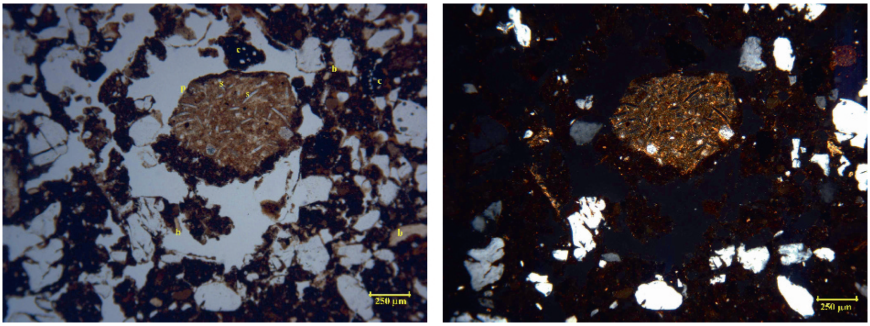


Fig. 5.2 Rounded, sponge-spicule (S) tempered pottery fragment (**p**) from the A horizon of the Hatahara site (Left: PPL; Right: XPL). Note charcoal (C) and bone (B) fragments (*See Color Plates*)

f A horizon sediments of texturally-clayey *terras pretas* is composite. It is generally characterised by irregularly-shaped microscopic clayey peds[1] resulting from the coalescence of aggregates of different sizes (50–200 µm; 500–1500 µm; 2–7 mm), some clearly resulting from soil reworking by ants, termites, and earthworms (see Eschenbrenner 1986; FitzPatrick 1993; Barros et al. 2001). More rarely, sediments are organised as irregular, massive, slightly vughy[2] continuous clayey zones with

[1] According to the online glossary of the Soil Science Society of America (http://www.soils.org/sssagloss/, accessed 01/09/2007), a ped is "a unit of soil structure such as a block, column, granule, plate, or prism, formed by natural processes (in contrast with a clod, which is formed artificially)". The same types are recognised at a microscopic scale by micromorphological analyses although it is often the case that macroscopic 'peds' appear to be constituted by smaller units in thin section (Stoops 2003). Hereinafter, all mentions of peds refers to those ascertained through micromorphological analysis.

[2] According to the online glossary of the Soil Science Society of America (http://www.soils.org/sssagloss/, accessed 01/09/2007), 'vughs' are "relatively large voids, usually irregular and not normally interconnected with other voids of comparable size; at the magnifications at which they are recognized they appear as discrete entities". One frequent use of the term 'vugh' in soil

little evidence of faunal reworking, suggesting some compaction has taken place. In all studied thin sections, inherited particulates of mineral origin (especially quartz grains but also small quantities of other minerals) are found embedded within clayey peds in a matrix-supported or porphyric coarse-to-fine related distribution. Sand-sized or smaller particulates of organic or archaeological origin – discussed in more detail in subsequent sections – are also found embedded in the clayey fraction of the soil. Quartz grains – by far the most important contributors to particle size distribution – show angularity and fracture patterns which suggest that cracking related to the weathering of quartz silica is the main source of textural variation (Table 5.4). This inference is supported by the frequent presence of clayey streaks on sectioned grain surfaces (Eswaran and Stoops 1979; Schnutgen and Spath 1983) and underscores the suggestion that all quartz particles observed in thin section derive from the soil parent material itself. Underlying B horizon sediments are organised as matrix-supported, poorly-separated continuous zones of slightly vughy massive clay with occasional granular fabrics formed by rounded to subangular, often coalescing faecal pellets (<150 µm). In general, they show slightly less frequent silt-sized quartz grains that overlying A horizon sediments.

In contrast, micromorphological analysis of thin sections sampling the A horizon of sandy *terras pretas* (Açutuba and Nova Cidade) show a grain-supported or enaulic microstructure that is primarily composed of silt to sand-sized quartz grains and only secondarily of clayey material, the latter organised as grano-oriented braces (<50 µm in width), small porphyric peds (generally <150 µm in diameter), and rare intergrain rounded pellets (generally smaller than <60 µm). Compared to clayey *terras pretas*, particulates of organic or archaeological origin are rare, most likely because their preservation is dependent on becoming embedded in the clayey fraction of the soil. But interestingly, (1) a thin section from the A horizon at Açutuba shows the presence of a 2 cm long matrix-supported clayey ped in which the size class distribution of quartz grains mimics that observed in the surrounding grain-supported matrix (Fig. 5.3, compare left and right), and (2) A horizon sediments at Açutuba grade into B horizon sediments that are comparable to clayey *terras pretas* in terms of microstructure and texture, i.e. the latter are matrix-supported sediments in which particulates of mineral origin are observed in a porphyric coarse to fine related distribution. Thin sections sampling sediments from the upper portion of the B horizon at Nova Cidade show slightly more clayey material than overlying A horizon sediments (Table 5.4). Field observations suggest this trend is accentuated deeper in the profile, i.e. the soil grades into texturally more clayey sediments in a manner similar to the Açutuba profile.

These preceding micromorphological observations provide a basis to draw a number of important inferences. First, the texture of settlement-related anthropogenic dark earths is determined by (1) the inherited distribution of size classes

micromorphological analyses is to describe irregularly-shaped microscopic pores between coalescing microscopic aggregates that form larger peds. As used in this paper, a vughy massive zone is a structurally massive zone of clayey material in which small pores in thin section can be hypothesised to result from the coalescence of smaller clayey aggregates.

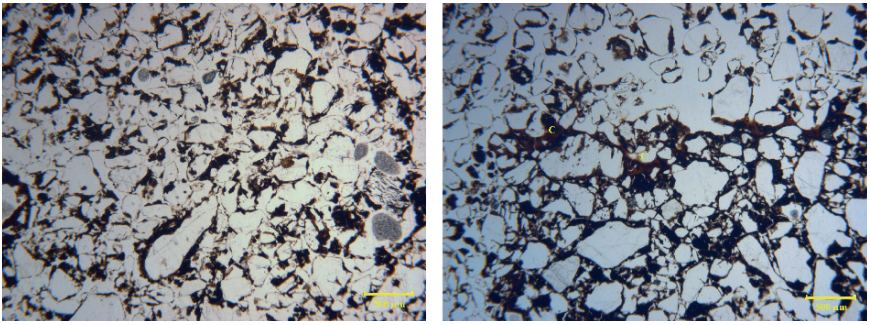


Fig. 5.3 Left: grain-supported microstructure in the A horizon of Açutuba (PPL). Right: matrix-supported ped within grain-supported microstructure in the A horizon of Açutuba. Note illuvial clay coatings (C) on matrix-supported ped (PPL) (*See Color Plates*)

Table 5.4 Textural variation, microartefacts and microscopic charcoal in thin sections

Thin section	Depth (cm)	Horizon or layer	Texture size classes (%)	Fine Fraction[a]	Silt quartz[a]	Sand quartz[a]	Microartef[a]	Charcoal[a]
HA-1.1	25	V		66	1	33	10	11.1
HA-1.2	50	IVb		74	1	25	15	11.1
HA-1.4	115	III		70	1	29	10	5.5
HA-1.5	140	II/AB1		68	2	30	5	3.6
HA-1.7	210	II/B/A		72	1	27	<1	1
HA-9.1	5	A		72	1	27		4.5
HA-9.2	20	AB		76	1	23		2.6
HA-9.4	60	Bt1		80	1	19		0.3
LG-3.1	10	VII/ Ap		74	1	25	15	17.5
LG-3.2	35	VI/A2		72	1	26	15	17.5
LG-4.1	5	III/A1		71	3	26	<1	10.5
LG-4.2	30	III/A2		73	3	23	<1	12.5
AC-1.1	12	Ap		39	1	60	<1	9.2
AC-1.1	18	A2		43	1	56	2	11
AC-1.2	35	A2		44	<1	56	2	14
AC-1.3	75	AB		50	1	49	<1	3.8
AC-1.4	110	B/A		59	3	38	<1	0.8
AC-1.5	165	Bt		58	1	40	<1	0.3
NC-1.2	25	Ab1		23	<1	77	<1	12.5
NC-1.4	65	Ab2		15	<1	85	<1	17.5
NC-1.6	95	AB		10	2	87		3.5
NC-1.7	115	AB		9	5	86		0.2
NC-1.8	135	Bt		16	5	78		0.2

[a] % of total solids in thin section.

[b] % of fine mineral fraction (FMF) in thin section. Size classes for texture: clay (surface area of groundmass excluding quartz grains), quartz in the fine silt, coarse silt, very fine sand, fine sand, medium sand, coarse sand, and very coarse sand size classes.

of mineral particulates (especially quartz grains) vis-à-vis the volume of clayey material; (2) the presence and size of rounded clayey aggregates and pellets that slake to 'pseudo-sands' or 'pseudo-silts' (see also Jungerius et al. 1999; Schaefer 2001); and, (3) the presence of silt to sand sized archaeological or organic particulates, which makes clayey *terras pretas* more silty or sandy. The interplay between these factors is evidently difficult to control across different particle sizing methods.

Second, texturally-sandy *terras pretas* do not necessarily signal sedimentary inputs from other sources (e.g. Heckenberger et al. 1999). We interpret the presence of gravel-sized or larger matrix-supported peds at the Açutuba site as relict evidence for the past presence of a more clayey fabric. We believe that peds such as these (Fig. 5.3, right) are more resistant to degradation than the surrounding sediment matrix as a result of compaction induced by anthropogenic activity. In other words, we regard soils at Açutuba to have undergone processes of regressive erosion in geologically-recent times (Lucas et al. 1984; Chauvel et al. 1987; Righi et al. 1990; Dubroeucq and Volkoff 1998; Horbe et al. 2003). These processes have led to localised depletion of the clayey fraction and attendant shifts from a matrix- to a grain-supported microstructure.

Third, as noted earlier, given that particulates of organic or archaeological origin are mostly observed embedded in clayey peds of *terras pretas*, depletion of the clayey fraction results in less efficient preservation and, therefore, affects physical and chemical parameters (see next section). Given that metals and other compounds are adsorbed onto clay lattices, their measurement in sandy soils are skewed in analogous fashion. Given that known aspects of regressive erosion in these soils include deferralitization (do Nascimento et al. 2004), Fe-dependent signals such as magnetic susceptibility (MS) are also affected. If we examine chemical and physical parameters for the Açutuba site with this background, it can be suggested that levels of chemical enrichment and magnetic enhancement may have been more substantial a thousand years ago.

5.4 Remarks on the Composition of Anthropogenic Dark Earths

An obvious corollary of the fact that the magnitude of enrichment/enhancement in terras pretas at the five sites under discussion depart dramatically from measurements in background soils (Table 5.1, physical and chemical parameters) is that sources for these high values need to be sought in inputs associated to human settlement dynamics. We discuss below the potential relevance of microscopic particulates of archaeological (Table 5.2) and organic (Table 5.3) origin on physical and chemical characteristics of these soils and offer some hypotheses about sources of enrichment that require further attention.

5.4.1 Microscopic Bone and Ceramic Fragments

Microscopic bone fragments are virtually absent in samples from sandy *terras pretas* but are extraordinarily ubiquitous in texturally-clayey A horizon sediments from the Hatahara and Lago Grande sites (Fig. 5.1). Confirming the findings of previous studies, some of these fragments can be taxonomically identify as fish bone (Lima et al. 2002; Schaefer et al. 2004). In thin section, the overwhelming majority are characterised by very low interference colours under XPL, pointing to overall loss of collagen (Jans 2005). However, most fragments also show strong auto-fluorescence under UVL (Fig. 5.9, right), pointing to high retention of phosphorus in bone apatite. Data reported by Schaefer et al. (2004) suggest that microscopic bone fragments at Hatahara are significant sources of Ca and P, an inference that finds support in the high concentrations of these elements that we have measured in bulk samples from clayey *terras pretas* at the site. However, the inference that microscopic bone fragments constitute the most important contributors to measured concentrations of Ca and P is not straightforward: even if ratios between Ca and P in some bulk samples (Fig. 5.4) resonate with the Ca to P ratio of 2.16 to 1 of pristine bone apatite ($Ca_5(PO_4, CO_3)_3(OH)$), Lima (2001) demonstrates that an important part of P in bulk soils samples at Hatahara is Al-extractable, an observation that can be construed as evidence that a significant proportion of P is adsorbed onto clayey material (see also Lehmann et al. 2004). Schaefer et al. (2004) also report low but significant concentrations of P and Ca in faunal channels. In other words, although high P and Ca in these soils are most likely related to the abundance of surprisingly well-preserved microscopic bone fragments and/or their decomposition over time, it is difficult to ascertain conclusively that the latter constitute the most significant pool of P and Ca in these soils. A comparison of elemental concentrations and bone density at sites progressively more distant from sources of aquatic animal protein may be a productive way to assess their relative importance in the future.

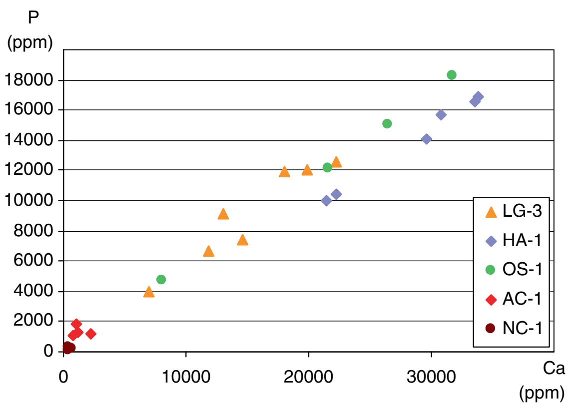


Fig. 5.4 A horizon samples of *terra preta* expanses

Soil micromorphological data also show that thin sections from the A horizon of *terras pretas* at Hatahara, Lago Grande, and to a lesser extent Açutuba embed important quantities of microscopic pottery fragments (Table 5.2). These subangular to rounded inclusions are primarily tempered with aquatic sponge spicules (Fig. 5.2, left), and less frequently with charcoal fragments, grog, and, silt to fine sand-sized quartz grains (see also Lima et al. 2002; Schaefer et al. 2004). We can expect that microscopic pottery fragments will contribute to higher concentrations of particular elements on account of different clay sources, tempering material, and residues associated to their past use. In this regard, Lima et al. 2002; Schaefer et al. 2004 report that shard fragments observed in thin sections are made of illite, which implies inputs of K, Al, Ca, Mg, Fe, and Si into the soil. Other studies, in this case of the actual chemical composition of pottery shards from the lower Amazon basin, identify additional chemical inputs, notably Mn, Zn, Si, Al, Fe, and P (Costa et al. 2004). Trace element research on shards from the Hatahara and Açutuba sites (Neves 2003), on the other hand, highlight the likelihood that a combination of different clay sources, each with potentially different chemical signatures, were used in the past. In this connection, it is important to note that pottery that can be classified into different pottery phases will use different but overlapping tempers (Lima et al. 2006; Moraes 2006). A surprisingly low density of microscopic pottery fragments tempered with organic fibres in thin section could indicate that small fragments of particular ceramic types have decomposed more readily than others into these soils.

The latter point is underscored by the different potential sources for the high MS values measured in most of samples of the dataset discussed in this chapter. Magnetic susceptibility, which primarily reflects the abundance of ferromagnetic minerals, is an expected index of weathering in Fe-rich soils over very long periods of time (Singer et al. 1996). However, these minerals can also form rapidly as a result of near surface burning at relatively low temperatures of 150°C (Le Borgne 1960; Tite and Mullins 1971; Mullins 1977; Allen and Macphail 1987). Heat treatment of Fe-rich clayey material (e.g. pottery, brick), in addition, has been shown to result in high magnetic susceptibility for analogous reasons (Jordanova et al. 2001). On the basis of micromorphological observations, we find no reason to disregard that heat treated clay, including here rubified clay aggregates and pottery fragments (Fig. 5.5, right; Fig. 5.2) are co-responsible for the high MS values measured at Hatahara, Lago Grande, Osvaldo and Açutuba. We consider that low Fe and MS values at Nova Cidade reflect more advanced deferralitization of the soil mantle at the site. However, contrasting MS values (Fig. 5.6) from (1) background samples from the A horizon of a clayey oxisol developed under old secondary forest vegetation some 3 km north of the Lago Grande site (LG-5); (2) A, AB and Bt horizon samples from sub-recently cleared sediments of an artefact-devoid background soil profile at Hatahara (HA-9); and, (3) samples from the A and B horizon of a clayey *terra mulata* soil under young secondary vegetation at the Lago Grande site (LG-4) suggest that MS measurements also identify levels of soil which overlap the magnitudes resulting from the incorporation of fragments of ceramic microartefacts. In other words, near surface burning and the presence of smaller than sand-sized heat-treated particulates contribute to the MS signal in ways that are difficult to disentangle (see also Sergio et al. 2006).

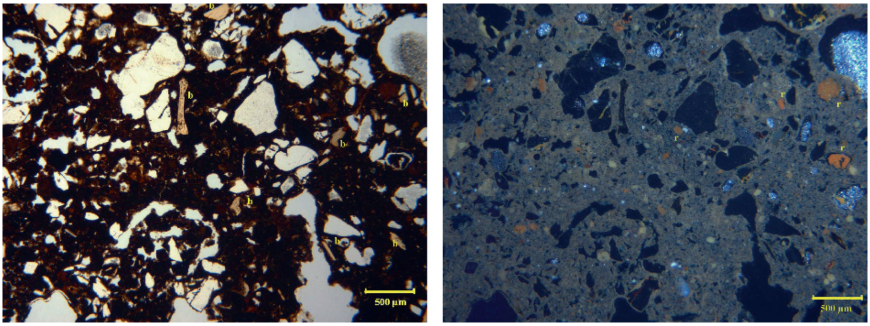


Fig. 5.5 Microscopic bone (**b**) and rubified clay aggregates (**r**) in a Type II clayey fabric. A horizon sample, Lago Grande site (Left: PPL; Right: OIL) (*See Color Plates*)

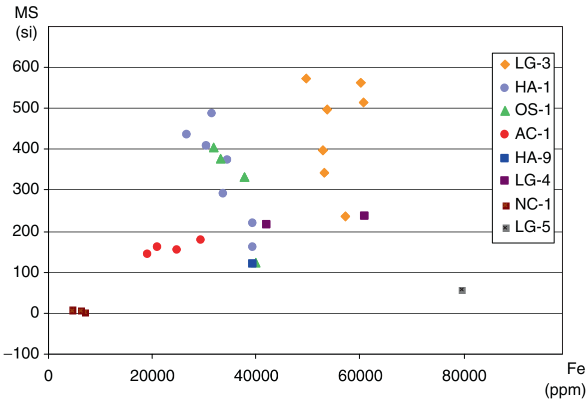


Fig. 5.6 MS and Fe of *terra preta (LG-3, HA-1, OS-1, AC-1, NC-1), terra mulata (LG-4)* and background oxisol (HA-9 and LG-5) A horizon samples. Micromorphological evidence shows important charcoal concentrations and burnt soil fragments in HA-9 and LG-4, pointing to the role of near surface burning of soils

5.4.2 Microscopic Charcoal, Organic Matter Retention, and Soil Melanisation

Micromorphological observations show that microscopic charcoal fragments constitute by far the most significant non-inherited particulate input observed in *terras pretas*. This assessment relies on the quantification of visual estimates from thin sections (Table 5.3). Although we admit that the latter procedure is intrinsically subjective, it provides some sense of overall abundance and also highlights significant contrasts in particle size that bear on other parameters of these soils: at the Nova Cidade site, where the clayey mineral fraction is almost non-existent, the surface area of microscopic charcoal fragments in clayey peds is very high (17.5% of the surface area of the fine mineral fraction, thin section NC-1.4). At Hatahara, the total surface area of microscopic charcoal fragments is 2–3 times higher in *terras pretas* (max 12.7% of the fine mineral fraction, thin section HA-3.2) than background soils (max 4.5% FMF, thin section HA-9.1). The density of microscopic charcoal in the A horizon of the Lago Grande *terra mulata*, however, is also substantial (max 12.5% FMF in thin section LG-4.2, see also Arroyo-Kalin, this volume). More precise comparisons are hindered by a lack of depth-wise resolution in Leco furnace Co data and well-known problems in the use of Loss on Ignition to estimate the carbon pool of clayey, Fe-rich soils (Vogel 1997). However, we can assert that the rising trend with decreasing depth recorded in our estimates of the surface area of charcoal in thin section is in most cases consistent with that observed in available Leco furnace Co data.

The presence and ubiquity of microscopic charcoal is of special relevance because a number of studies (Glaser et al. 1998b; Lima et al. 2002; Glaser et al. 2003; Liang et al. 2006; Solomon et al. 2007) suggest that black carbon increases the cation exchange capacity of these soils and also contributes to higher retention of organic matter. In addition to more overarching concerns about carbon sequestration in these anthrosols, increased retention of organic matter and high inputs of pre-Columbian charcoal are recognised as some of the key factors that underlie the dark colours of anthropogenic dark earths (Smith 1980). Micromorphological analysis provides some important supplementary observations.

First, microscopic charcoal fragments in thin sections sampling the A horizon of *terras pretas* (Fig. 5.1) generally represent poorly size classes between gravel and fine sand, pointing either to very efficient mechanical comminution as a result of faunal reworking or suggesting that a large proportion of the charcoal in the soil has became deposited as very small particles that are equivalent or slightly larger than the reported size of soot particles (Masiello 2004). Thin section from *terra preta* AB horizon samples, *terras mulatas,* and background soils, in contrast, show a more balanced representation of the different size classes between silt and gravel.

Second, aside from thin section representing near surface sediments, *terra preta* A horizon samples for the most part do not evidence organs, tissues, cell fragments, and amorphous fragments of plant matter unless these show evident signs of charring. Soil micromorphologists, however, also subjectively recognise different degrees of staining with organic pigment in the fine mineral fraction as a measure of organic matter retention. These estimates generally rely on the observation of brown or grayish colours under plain polarised light (PPL) and darker colours than organically-depleted material under oblique incident light (OIL). A poor expression of interference colours of the fine mineral fraction under cross-polarised light (XPL), in addition, is often interpreted as the masking effects of humus, impregnation with sesquioxides, and/or isotropy of constituent minerals. Finally, well-expressed speckled and especially striated/strial birefringence fabrics (b-fabrics) generally occur in more weathered sediments that are organically-depleted (Bullock et al. 1986; Courty et al. 1989; Stoops et al. 1994; Stoops 2003).

The occurrence of these characteristics in thin sections from the dataset under discussion highlight some important and intriguing contrasts (Table 5.3): compared to the A horizon of background soil profiles and *terras mulatas*, which show brown hues under PPL/OIL and an undifferentiated to marginally-speckled b-fabric under XPL, the fine mineral fraction of sandy and clayey *terras pretas* varies between two poles: very dark brown colours (PPL/OIL) and a dark undifferentiated to marginally speckled b-fabric (XPL) to very dark brown (PPL), dark 'opaque' grey (OIL) colours with an undifferentiated b-fabric (XPL). In what follows we refer to these two poles as Type I and II optical characteristics of the fine mineral fraction (Fig. 5.7). AB horizon sediments from our background soil profile at Hatahara records a shift to a lightly organically-stained, brownish yellow clay (PPL/OIL) with a marginally speckled b-fabric (XPL), suggesting a gradual decrease in the reach of soil chelates and evidencing shallow-reaching faunal down-mixing. Thin section from *terra preta* AB horizon sediments, in contrast, appear as mixes between clayey peds whose optical characteristics are analogous to those observed in strongly melanised overlying sediments (generally Type I), those observed in A horizon sediments of background soils, and those observed in B horizon sediments. B horizon sediments in all cases show a light brownish yellow colour (PPL/OIL) that we recognise as characteristic of organically-depleted sediments; a speckled to striated b-fabric (XPL), which suggests lack of recent faunal reworking; and low interference colours (XPL) that are consistent with a kaolinitic composition (see also Lima et al. 2002).

These observations support the suggestion that black carbon enhances organic matter retention: all samples with abundant microscopic charcoal – *terras pretas, terras mulatas,* and the A horizon of the Hatahara background soil (HA-9) – show the brown colours that soil micromorphologists generally gloss as organic staining, and some sense of a grading towards lighter colours with decreasing density of charcoal fragments can be ascertained after repeated comparative observations (Table 5.3). However, the darker and generally isotropic (XPL) Type II properties discussed previously do not, in our opinion, indicate more intense staining with organic matter. Thin sections with these optical characteristics do not necessarily reveal a higher density of microscopic charcoal fragments than thin sections with Type I optical properties. Our first inclination has been to relate Type II properties to impregnation with iron sesquioxides. However, thin sections with these properties can occur at depths in profiles where iron concentrations are relatively reduced compared to

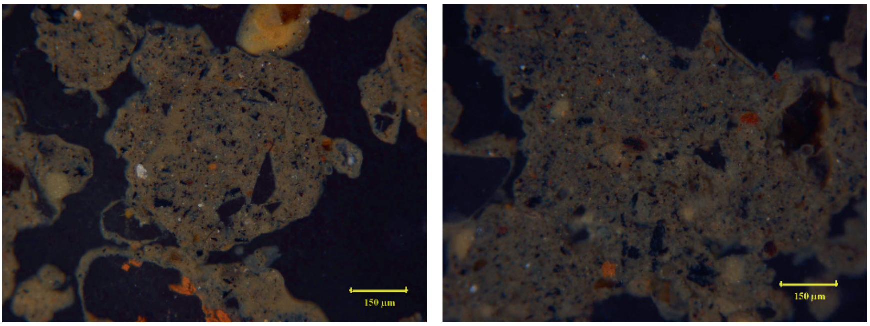


Fig. 5.7 Left: Type I (LG-3.2) and, right: Type II (LG-3.1) fabrics at the Lago Grande site (Profile LG-3, OIL). Note similar density of microscopic charcoal. More opaque grey colours are observed on the right but these are not well expressed in photographs. A higher Mn:Al ratio can be computed for 10–20 cm vis-à-vis 30–40 cm in this profile (*See Color Plates*)

underlying sediments. We therefore cautiously point out that suggestive correlations exist between the depth of the relevant thin sections and high concentrations of Mn in bulk samples, i.e. we submit that these darker characteristics could point to slight impregnation of the fine mineral fraction with Mn oxides. As we argue presently, we are convinced that high concentrations of Mn and other metals need to be sough in organic inputs. We therefore consider it plausible that Mn oxides form as result of the transformation of Mn(II) into Mn(IV) by bacteria and fungi. Given the preceding discussion about the role of charcoal and organic matter as factors contributing to the melanisation of these soils, the well-established ability of Mn oxides to adsorb a wide range of metals (Tebo et al. 2004) deserves to be mentioned.

5.4.3 Plant Matter, Fresh, and Ashed

A noteworthy aspect of the chemical composition of soil samples from settlement-related anthropogenic dark earths is that total concentrations of Ba, Cu, K, Mg, Mn, Sr, and Zn, and to a lesser extent, P and Ca, show strong co-patterning, especially when examined by depth (Fig. 5.8). Aside from the microscopic particulates we have discussed previously, we expect these concentrations to reflect a variety of additional sources, including plant matter, shell remains, urine and excrement (Kern et al. 2004; Woods and Glaser 2004). We also believe additional clues are provided by other researchers, including here suggestions that palm trees actas Mn concentrators and reports that soils at middens and food-processing areas become enriched with K (Kern 1996; Kern et al. 2004; Hecht 2003; Schmidt and Heckenberger 2006). However, aside from research presented by Hecht 2003; Hecht and Posey 1989, the possibility that ash constitutes a significantinput in settlement-related anthropogenic dark earths has been underemphasised in recent investigations: 'Ash' is not even an entry in the index of the two most recent books on anthropogenic dark earths (Lehmann et al. 2003; Glaser and Woods 2004). This lack of attention is somewhat surprising because ash is produced in copious quantities in most kinds of burning activities, including cultivation practices that range from house gardens to slash and burn agriculture (Carneiro 1961; Harris 1971; Carneiro 1983; Hecht and Posey 1989; Texeira and Martins003; Denevan 2004); combustion of middens of various kinds (Hecht 2003), domestic and cooking fires (especially in the processing of bitter manioc and the preparation of *ipadú* Arroyo-Kalin 2001, personal observation, Tiquié River, see also Hugh-Jones 1979; Zeidler 1983); combustion associated to the firing of pottery (e.g. DeBoer and Lathrap 1979); and – of particular relevance from an archaeological point of view – combustion associated to the preparation of specific ceramic tempers (*caraipé* is made by burning the bark of *Licania octandra*, see Hartt 1879 for a detailed description). Ash, in short, must have been one of the most common by-products of pre-Columbian settlement activities in sedentary ceramic age occupations.

Ash is generally an alkaline sediment (pH = 9–13.5) that can at least temporarily raise the pH of the upper centimetres of the soil. Studies of the chemical composition of plant ash in a variety of contexts show that it is rich in Ca, K, Mg, and Si yet also

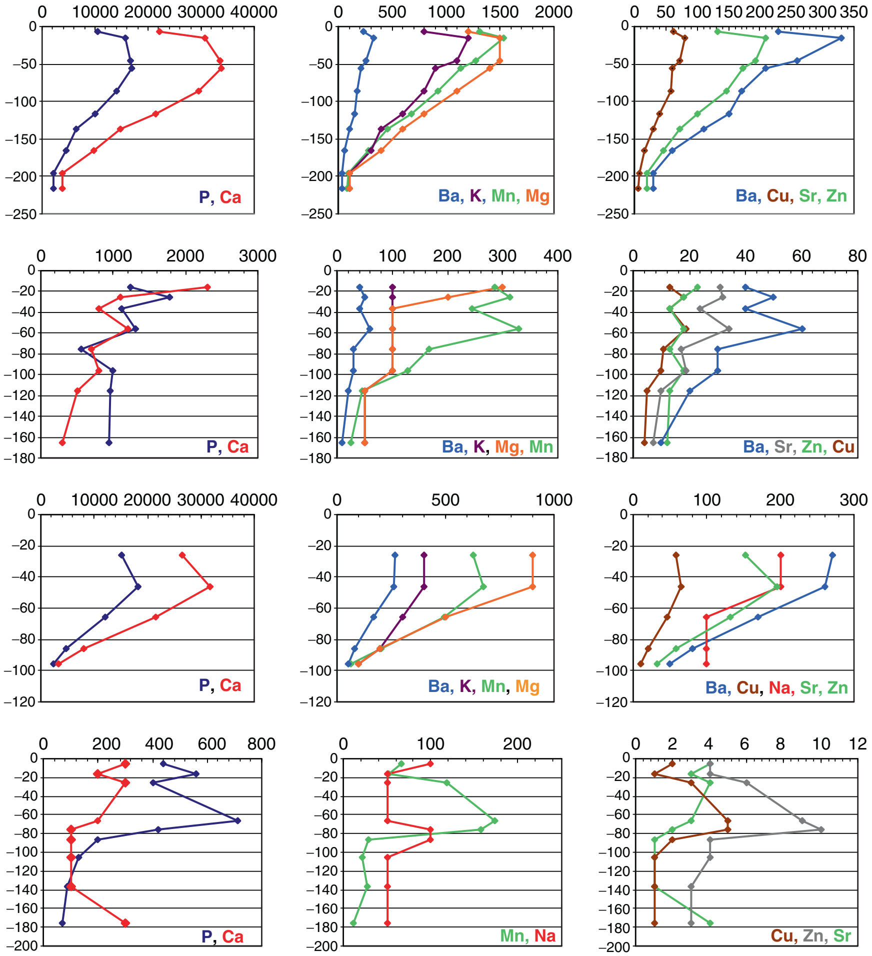


Fig. 5.8 Y = cm from surface; x = ppm of indicated elements

includes significant but varying concentrations of Al, Na, Mn, P, and Fe, and trace quantities of Zn, Na, Ba, Cu, and Sr (Etiégni and Campbell 1991; Pierce et al. 1998). Along similar lines, chemical data presented by Hecht (2003) show different and taxonomically-specific concentrations of Ca, K, Mg, N, and P. Clearly specific elemental signatures reflect nutrient availability in soils, which in turn depend on lithology and factors affecting their solubility. Perhaps of equal importance, specific anatomical parts of particular plant taxa concentrate metals more efficiently than others: in what we consider has an important resonance with the preparation of *caraipé* for the tempering of pottery, Durand et al. (1999) show that concentrations of specific metals are 10 times higher in bark compared to those measured in the sapwood and heartwood of the same tree species at Chaco Canyon, New Mexico.

Microscopic studies of archaeological sediments show that given appropriate preservation conditions pseudomorphs of plant calcium oxalate crystals ($CaC_2O_4.H_2O$ or $2H_2O$) can be readily recognised through soil micromorphological analysis (Courty et al. 1989; Schiegl et al. 1996; Arroyo-Kalin 1999; Canti 2003; Arroyo-Kalin et al. 2007). Notwithstanding, as is highlighted by other studies of strongly melanised anthropogenic soils (Courty et al. 1989:111; Cammas 2004) there exists a low preservation potential in sedimentary contexts without strong stratification (Brochier 2002), intense faunal reworking, and – at least initially – low pH. Unsurprisingly, therefore, we have not been able to observe evidence for ash crystals or other forms of calcium carbonate in any of the thin sections discussed in this chapter. However, we offer a number of arguments that indirectly support the suggestion that ash may have been a significant input in settlement-related dark earths.

First, some anthropogenic A horizon samples evince unexpected concentrations of 'dusty' illuvial clay coatings (Fig. 5.9, left): a number of studies suggest that potassium derived from weathered ash can encourage clay illuviation under moderately acid conditions (Slager and van der Wetering 1977; Courty et al. 1989:113; Macphail 2003) and hence it is not infrequent that soil micromorphologists interpret these illuvial features as evidence of ash. Second, anthropogenic A horizon samples evince common phytoliths that show weak to moderate auto-fluorescence under UVL (Fig. 5.9, right). Auto-fluorescence of silica under UVL has been related to the formation of an Al coating when silica is exposed to high temperatures (Y. Devos, R. Macphail, personal communication 2007 to Arroyo-Kalin) and, indeed, is also observed in pottery- and soil-embedded sponge spicules. Given that both phytoliths and sponge spicules are made of silica, the obvious implication is that phytoliths have been burned at high temperatures. Third, higher Al concentrations than background sediments are measured in all studied exposures of *terras pretas*, with particularly significant increases in earthworks at Hatahara and Lago Grande. The dissolution of Al minerals and their complexation with organic matter (Ritchie 1994; Wong and Swift 1995; Haynes and Mokolobate 2001) is an insufficient explanation for these values given that ICP-AES measurements approximate

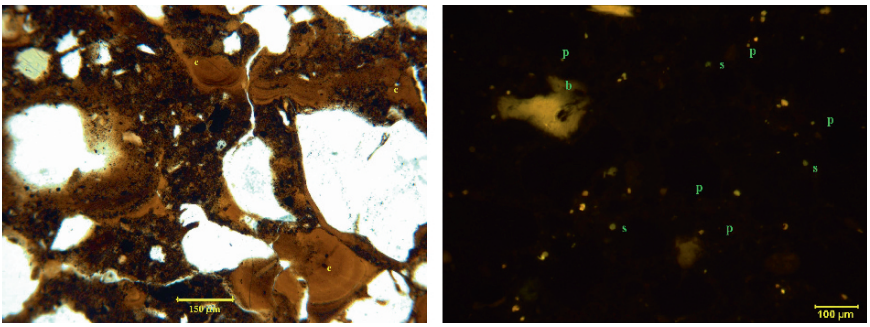
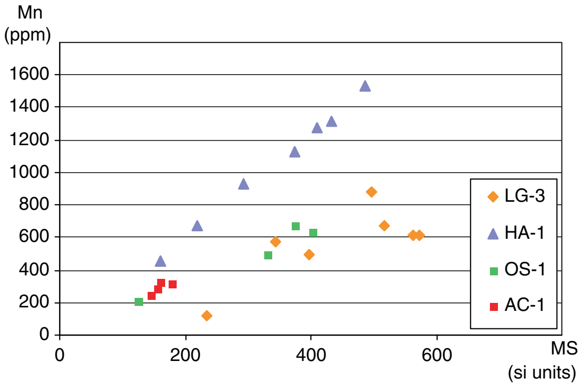


Fig. 5.9 Indirect evidence for ash in A horizon samples at Hatahara. Left: Dusty illuvial clay coatings (**c**) in Profile HA-5 (PPL). Right: auto-fluorescent bone fragments (**b**), sponge spicules (**s**) and silica phytoliths (**p**) in profile HA-3 (UVL) (*See Color Plates*)

Fig. 5.10 A horizon samples from selected *terra preta* expanses



total Al concentrations. Pierce et al. (1998) report that plant ash shows an average ratio of Ca:Al of around 11:1. If most Ca in soils comes from ash, the proportional 'gain' in Al concentrations recorded in clayey dark earth at Hatahara and Lago Grande is commensurate with this ratio.

If ash was consistently deposited on cleared and inhabited soil surfaces in pre-Columbian times, we would minimally expect a systematic rise in soil pH and an *in loco* concentration of plant-borne nutrients and others (e.g. phytoliths). As soil pH increased, we would expect that some of these metals would adopt insoluble forms (Vitousek and Sanford 1986; Burnham 1989; Schaetzl and Anderson 2005), in turn permitting their concentration in the soil. This model obviates the need to suggest a geological origin for high elemental concentrations in anthropogenic dark and also explains the fact that values for Mn, Ba, Cu, K, Mg, Sr, and Zn, and to a lesser degree P and Ca, show strong co-patterning (see also Ruivo et al. 2004). The fact that Mn shows a relatively linear relation to MS values at different *terra preta* expanses (Fig. 5.10), moreover, could indicate that Mn substitutions in otherwise anti-ferromagnetic iron forms, such as haematite (Wells et al. 1999), contribute to overall higher MS values in settlement related dark earths.

5.5 Summary

The preceding remarks aim to contribute to our knowledge of the Amerindian soilscape legacy in the Amazon basin. A brief summary is in order:

We first highlight that textural variation, chemical enrichment, higher pH, and magnetic enhancement need to be examined at the intersection between, on the one had, landscape evolutionary processes that impinge on the characteristics of the soilscape and, on the other, inputs and practices associated to pre-Columbian settlement dynamics. Our understandings of the impact of the former on the physical characteristics of sandy anthrosols diverts us from the pitfalls of suggesting that lower levels of enrichment and enhancement at some of the sites under discussion reflect contrasting intensities of occupation associated with the Solimões and Negro basin, i.e. whitewaters and blackwaters. We do not discount the importance of water chemistry as a proxy for aquatic biomass, but our increasing awareness of the fact that the tempo of landscape evolutionary pathways overlaps that of pre-Columbian human histories leads us to also highlight the potential relevance of recent research suggesting that the water chemistry of the Negro River may have been substantially different in the 1st millennium AD (Latrubesse and Franzinelli 2002).

Second, we confirm previous observations (Lima et al. 2002) about the ubiquity of microscopic bone and pottery fragments, yet caution that the former may not be the only source of P and Ca concentrations measured in these soils and argue that the contribution of the latter to chemical composition of these soils remains to be ascertained. We provide evidence that all settlement-related anthropogenic dark earths show very significant levels of magnetic enhancement but suggest two complementary sources: (1) near surface burning of plant matter; and, (2) microscopic pottery fragments and rubified clay aggregates. Each of these sources potentially contributes to high concentrations of Ca, P, Mn, Ba, Cu, K, Mg, Sr, and Zn, for which clearly polygenetic origins need to be considered (Woods and Glaser 2004).

Third, we are strongly minded to endorse Hecht's (2003) attention to ash as an important, if not crucial, input for the development of these soils. We submit that its consistent deposition may be co-responsible for high pH and, via ash-borne Mn mineralisation, strong melanisation of these soils. In this connection, it is interesting to highlight that more-strongly melanised anthropogenic dark earths in the central Amazon region often embedded ceramic artefacts that can be classified into the Manacapuru, Paredão, and Guarita phases (Hilbert 1968; Neves 2003; Lima et al. 2006), whilst pottery that can be classified into the older Açutuba phase pottery is generally found in soils that do not show strong melanisation. Echoing previous remarks about the importance of pottery manufacture (Lima et al. 2002; Schaefer et al. 2004; Sergio et al. 2006) and recalling Hartt's (1879) characterisation of the ashing of *caraipé* bark, we consider it intriguing that the very dark colours of some *terras pretas* appear to be more than incidentally related to ceramic phases which make use of organic tempers in the production of pottery artefacts.

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Chapter 6
An Assessment of the Cultural Practices Behind the Formation (or Not) of Amazonian Dark Earths in Marajo Island Archaeological Sites

DP Schaan, DC Kern, and FJL Frazão

6.1 Introduction

For many decades, archaeologists working in Amazonia have looked for *terra preta* (black soil) areas in their search for ancient settlements. The typical Amazonian archaeological site is comprised of a combination of black soil, ceramic sherds and some distinct vegetation species, which William Balée calls "cultural forests" (Balée 1989). Sites are usually located in elevated terrains or riverine bluffs, protected from the annual floods when along the major rivers floodplains. Archaeologists also know that there is some correlation between soil color and density of ceramic sherds, both being a sensor for ancient demography patterns.

Ever since Sombroek (1966) and Smith and Nigel (1980) reported the existence of the anthropogenic *terra preta* soils, and especially after several research projects carried out by soil scientists and archaeologists during the last 20 years, research on ADE (Amazonian Dark Earth) sites has drawn much scientific interest. Analysis of ADE samples have demonstrated that such soils present higher levels of chemical nutrients such as C (carbon), P (phosphorus), Ca (calcium), Mg (magnesium), Zn (zinc) and Mn (manganese) when compared to original, background soils, besides presenting superior pH, as well as higher amounts of organic material, which make them particularly fertile (Kern and Kampf 1989; Kern et al. 1999; McCann et al. 2000). Such elements were possibly added to the soils during degradation of organic debris related to human occupation and discarding activities (Eidt 1985; Kern, et al. 1999; Woods and McCann 1999; McCann et al. 2000).

High values of P, Ca and Mg on ADEs can be attributed in part to animal residues, since bones, blood, carapaces and feces are rich in these elements. Zn and Mn might occur as residues of palm trees, whose leaves are commonly employed as construction material for house walls and roofs, beds, hammocks, and basketry (Kern et al. 1999).

Soil chemistry studies directed to solve archaeological problems have increased in number in the last three decades. While physical modifications caused by anthropic factors, such as sediment compression and texture changes can be perceived by an experienced archaeologist, chemistry, although less evident to the naked eye, can contribute to determine boundaries of activity areas, and help to define stratigraphy and function of an archaeological site (Woods 1984). Chemical anomalies coupled to

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

ethnographic data can inform on ancient settlement patterns (Ball and Kelsay 1992; Manzanilla and Barba 1990; Sokoloff and Carter 1952). P can be used to estimate population size, duration and intensity of occupation, determine basic subsistence patterns, define garbage dumps areas and establish relative chronology (Collins and Shapiro 1987; Griffith 1980; Sjoberg 1976). Other authors use chemical analysis in the field in order to obtain quick responses for the differentiation of post molds and rodent holes, and define stratigraphy (Deetz and Dethlefsen 1963; Verwe and Stein 1972). Hence, geochemical studies have demonstrated that chemical signatures caused by anthropogenic activity vary within a site or even residence, and these variations tell us something about human behavior.

ADE sites have a wide-ranging distribution in Amazonia. Some of the largest ADE sites (e.g. in Manaus, Oriximiná, Juruti, Santarém, and Belterra), containing remains of ancestor cult (elaborate ceramics and funerary vessels) and prestige goods were the *loci* of ancient chiefdoms, regional societies that emerged at the end of the first millennium. At the same time, small ADE sites representing autonomous villages dated to the last two millennia are found in diverse ecological settings

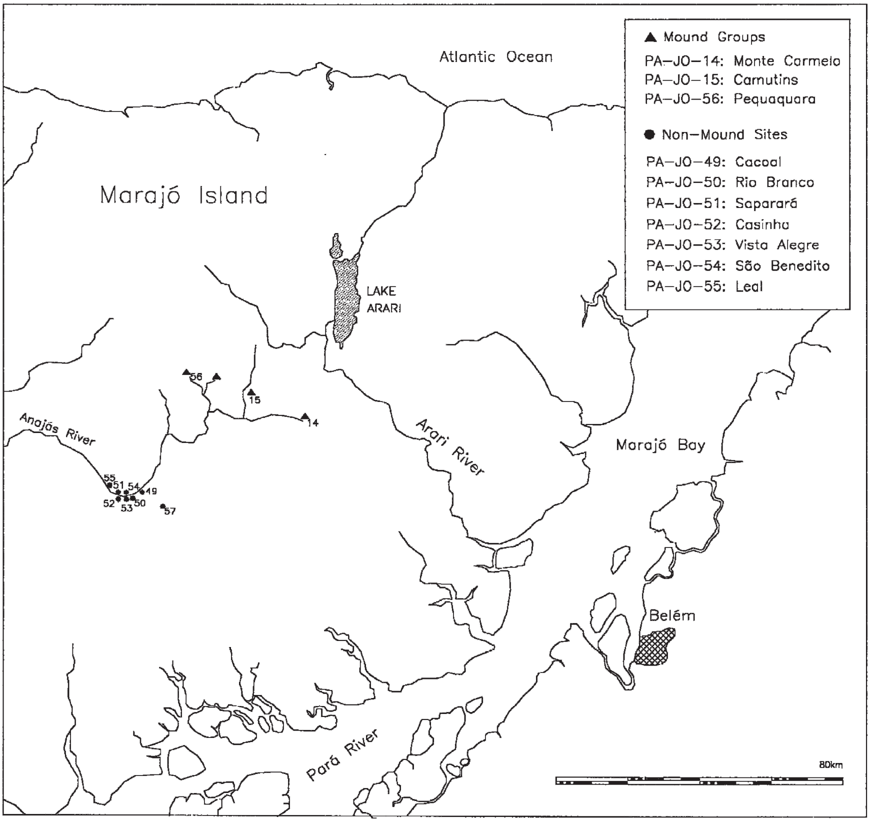


Fig. 6.1 Research area

(Kern et al. 2004). So wherever ADE sites exist, they belong to roughly the same time period, and speak about the emergence of a new way of life. Since ADEs were formed as remains of human activities were incorporated to the soils, the sudden appearance of such soils signals changes in consumption and discard practices.

This chapter discusses the results of geoarchaeological research carried out in three archaeological sites, belonging to different time periods: (1) Rio Branco site, *c*.3500–3000 BP; (2) Camutins site, *c*. AD 700–1100; and (3) Leal site, *c*. AD 1200–1600) (Fig. 6.1). At the Rio Branco and Leal sites it was observed a negative correlation between soil color, ceramic density and chemical content. On the basis of such findings, the presence or not of ADE and its characteristic chemical signatures is explained as caused by diverse spatial organization. Cultural practices, subsistence patterns, as well as certain post-depositional processes might have been responsible for the formation or not of ADE on the Marajó Island sites.

6.2 Pre-Columbian Settlers

Marajó Island is one of the best known archaeological areas in Amazonia. Research there started in the late nineteenth century, due to the special attraction that monumental mounds and exquisite funerary pottery exerted over scientists and the general public. Since then, looting has destroyed many of the most prominent large mounds, but there are still many sites in fair state of preservation.

In the late 1940s, Betty Meggers and Clifford Evans studied several sites located in the center and north of the island, identifying other occupations besides the mound builder culture called Marajoara (Meggers and Evans 1957). The cultural sequence they described, later refined by radiocarbon dates (Meggers and Danon 1988; Roosevelt 1991; Simões 1969), included three ceramic phases that preceded the Marajoara phase (dated to *c*. AD 400–1300), Ananatuba (*c*.3500–*c*.3000 BP), Mangueiras (*c*.3000–*c*.2800 BP), and Formiga (*c*. AD 0–800); and one later ceramic phase: Aruã (*c*. AD 1300–1600), contemporary to European presence during the sixteenth and seventeenth centuries.

Meggers and Evans interpreted Ananatuba, Mangueiras, Formiga, and Aruã as the typical tropical forest phases: semi-sedentary people living on slash-and-burn cultivation, hunting, fishing, and collecting (Meggers and Evans 1957; Steward 1948). In the Marajoara phase, however, they recognized all the characteristic traits of chiefdoms: stratification, occupational division of labor, control of labor, organization, and leadership, "features more closely resembling those of Circum-Caribbean or Sub-Andean cultures than those of the Tropical Forest" (Meggers and Evans 1957:404).

Before the advent of radiocarbon dating, Meggers thought Marajoara was short-lived on the island, attributing its existence to migration from the Andean foothills. Arriving to the Amazon delta, migrants were not able to reproduce intensive agriculture in poor soils, and their fate was to decline and vanish. After radiocarbon dating was available, however, the long endurance of Marajoara culture (*c*.900

years) emerged as a problem, and Meggers was never able to adequately explain it within her theoretical framework.

In disagreement with Meggers' interpretations of the Marajoara culture, Anna Roosevelt carried out, in the 1980s, a comprehensive study of a single Marajoara phase mound, Teso dos Bichos, finding there evidence for sedentary habitation. According to her assessment of human osteology, faunal and botanical remains, she found out that the Marajoara subsistence "was based on annual cropping of seed crops, plant collection, and intensive seasonal fishing" (Roosevelt 1991:405). However, Roosevelt did not really find any evidence for maize consumption and cultivation (Roosevelt 1999).

Disagreeing with both Meggers' theory of foreign origin of Marajoara peoples, and Roosevelt's insistence on intensive agriculture as the basis for social complexity, and aiming to investigate Marajoara social organization and subsistence patterns, the first author carried out, between 1998 and 2002, a research project in the Anajás River basin (central Marajó). Six sites located in the middle Anajás River were mapped and excavated. Seventy five kilometers up river, the largest known mound group on the island, the Camutins site, was surveyed, mapped, and two of the elite mounds were excavated (Schaan 2004).

The Anajás Project made it possible to study sites belonging to different time periods, revealing a long history of cultural change. The chronology of cultural change shows initial occupation by cultivators with a generalized economy living in small autonomous villages. By AD 400, people moved to the headwaters and lakes in order to establish permanent villages and intensively exploit the abundant fish resources. In a few decades, cooperation and competition in such bountiful areas led to the emergence of chiefdoms (Schaan 2004). There is archaeological evidence for water management, with the construction of dams, ponds, and elevated causeways between adjacent mounds. Mound building was in fact a side effect of earthmoving activities aiming to control aquatic fauna. By AD 1100 chiefdoms spread throughout the savannas, and non-mound settlements replicating Marajoara culture also emerge along the major rivers. By AD 1300, chiefdoms collapsed, mounds and water systems were abandoned, and population returned to the autonomous village type of social organization. However, the typical Marajoara material culture still persisted in post-chiefdom villages along rivers.

6.3 The Archaeological Study

Two of the six sites excavated during the Anajás Project were selected in order to conduct geochemical studies: PA-JO-50, the Rio Branco site and PA-JO-55, the Leal site. The Rio Branco site was first investigated by soil coring at regular intervals, in order to assess the depth of archaeological strata. Anthropogenic soils and ceramics spread over a 4,000 m^2 elliptical area, next to the Rio Branco stream, 150 m before its mouth at the Anajás River (Fig. 6.2). The area was previously used for manioc cultivation, but at the time of our research it was occupied by secondary

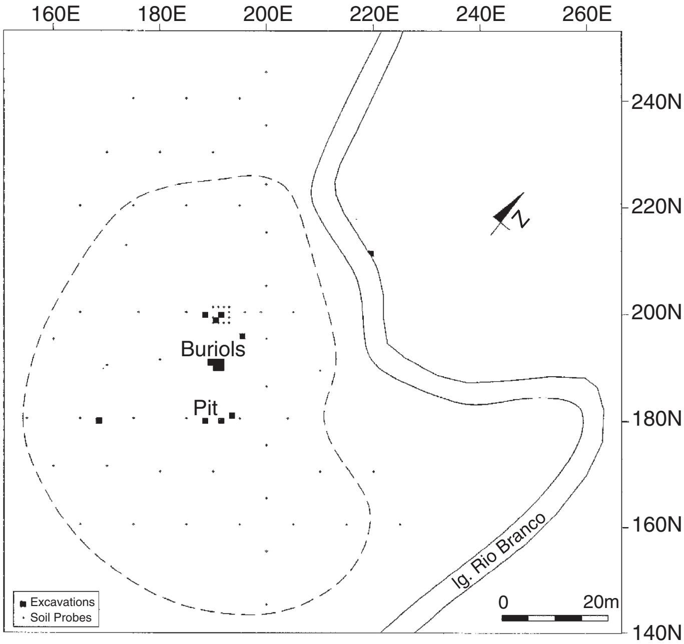
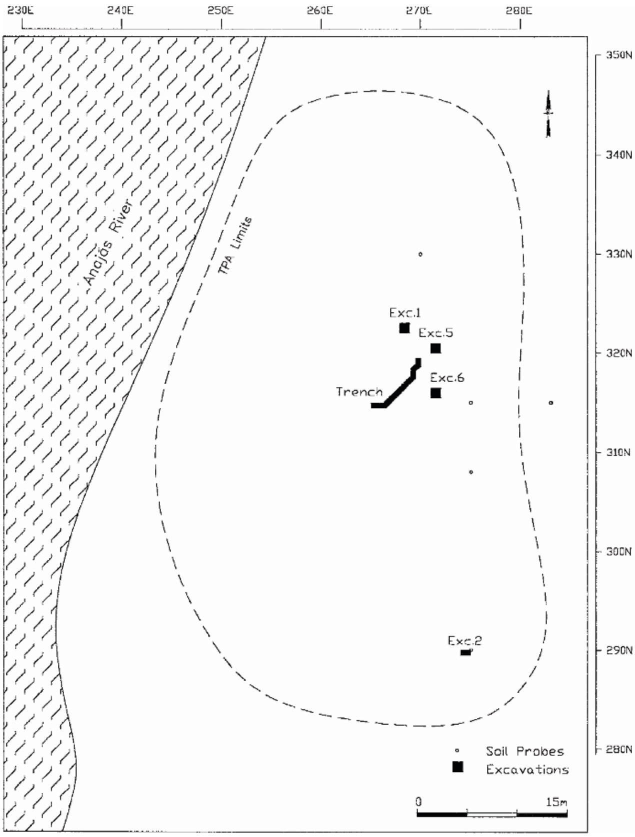


Fig. 6.2 Rio Branco site map

vegetation, including banana trees. The archaeological deposits were buried under 10–20 cm layer of sediment, which was visible in a profile at the eroded stream banks. After mapping, the site was surveyed by geophysical methods, using a proton precession magnetometer and a GPR on a 4 m grid, covering a 6,400 m^2 area. A sample of the anomalous areas was investigated through stratigraphic excavations, resulting in 18.25 m^2 of excavations. The depth of archaeological strata varied from 50 to 80 cm. The investigation of anomalies revealed features such as: (1) clusters of ceramic sherds over ancient surfaces, indicating areas to which the sherds were swept (e.g. DeBoer and Lathrap 1979) (Pits 4, 5, 6 and 7); (2) a hummus and ceramics filled pit, which was interpreted as a garbage dump (Pit 2); (3) two buried broken vessels, covered by a thick layer of sherds (Pit 5). Some 26,000 ceramics sherds belonging to Ananatuba phase were recovered. This phase was dated to 3500–3500 BP in other sites of the island (Meggers and Danon 1988; Simões 1969). The only two radiocarbon dates obtained from the site were too recent to be trusted, probably the result of intrusive recent charcoal, so they were disregarded.

The Leal site occupied a 2,000 m^2 elliptical area (Fig. 6.3). The site was located 5 km downriver from Rio Branco, on the Anajás River right bank. The area was once cultivated, but it was then covered by cocoa trees and secondary vegetation. Geophysical mapping did not reveal any outstanding anomalies. A total of 13 m^2 of non-continuous area was excavated, including 1 × 1 m pits and a trench. The depth

Fig. 6.3 Leal site map



of archaeological strata was about 40 cm. Cultural features consisted of small clusters of ceramic sherds and charcoal, one of which, located 30–40 cm below surface in trench 1, was dated to 730 ± 80 BP (c. AD 1170 to 1400, calibrated, Beta 146,221), which was assumed to represent the initial occupation. Some 7,000 ceramic sherds were recovered from all excavations. There are important changes in ceramic technology as observed for other post-marajoara period sites (Schaan 1999, 2004). Decorated sherds comprise 6.75% of the total, and no burials were found.

The Camutins site was excavated in 2001 (Mound 1) and 2002 (Mound 17) (Fig. 6.4). No chemical studies were performed, but dark earths were observed as a result of post-depositional processes in cemeteries, as well as littering.

P, Ca, Mg, Zn, and Mn were chosen for analysis, because these are chemical elements that better characterize ADE archaeological sites (Kern 1988, 1996). Soil samples were collected from pit walls after archaeological excavations were completed, and the profiles recorded. Lemos and Santos (1984) methodology was employed for soil sampling and description, separating the pedological horizons, and collecting samples every 20 cm. Since excavations were conducted only to the archaeological sterile layer, soil samples

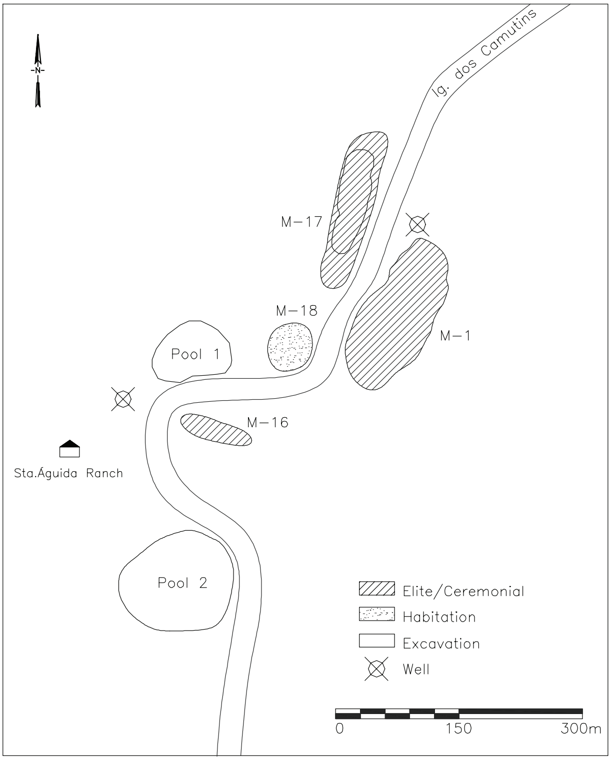


Fig. 6.4 Camutins lower course mounds

were collected even further down, to reach the B horizon, some 50 cm deeper. In each site, one of the pits was excavated one more meter below cultural strata. Control samples of background soil were collected outside both sites (thereafter AA – adjacent areas).

6.4 Results and Discussion

In the Leal and Rio Branco sites horizontal and vertical variation in physical, morphological, and chemical characteristics of the soils was observed. Both sites presented a sequence of horizons A_1, A_2, A_3, AB, BA, and B, for in-site profiles, and A_1, AB, BA, and B, for background soils' (AA) profiles. In-site A horizon was thicker, reaching up to 56 cm in Rio Branco and 30 cm in Leal, while in AA soils they average 10 cm. P_2O_5, Mn, and Zn levels markedly diverge between in-site and AA soils (Figs. 6.5–6.7).

The two sites presented similar data for AA soil samples, which allows for direct comparison. This similarity compensates a possible influence that differences in soil texture must have caused in the retention of chemical nutrients, because Leal soils were much sandier than the clay-rich Rio Branco soils.

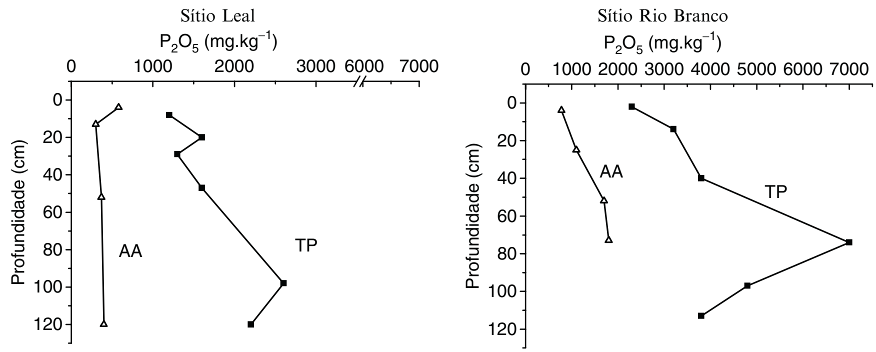


Fig. 6.5 Variation of phosphate according to depth in ADE/*terra preta* (TP) and adjacent area (AA), in Leal and Rio Branco

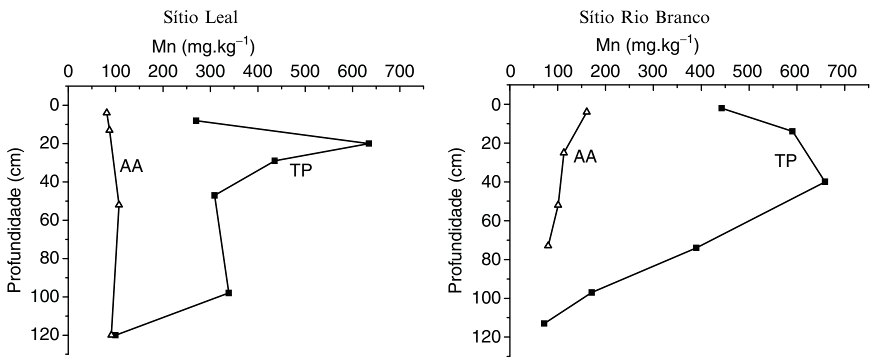


Fig. 6.6 Variation of Mn according to depth in ADE/*terra preta* (TP) and adjacent area (AA), in Leal and Rio Branco

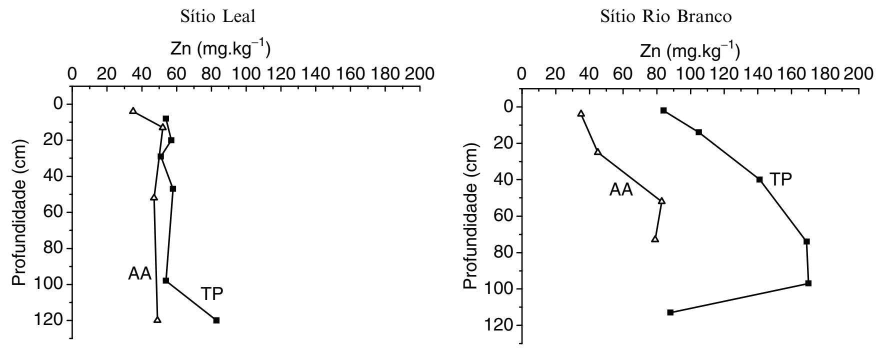


Fig. 6.7 Variation of Zn according to depth in ADE/*terra preta* (TP) and adjacent area (AA), in Leal and Rio Branco

In the Rio Branco site, P_2O_5 levels in horizon A vary from 780 to 7,500 mg/kg^{-1} in the anthropogenic soil and from 410 to 600 mg/kg^{-1} in background soil. This element also presented meaningful horizontal variation. In the Pit 2, horizon AB (56–91 cm deep), P_2O_5 levels (7,000 mg/kg^{-1}) were exceedingly high (Fig. 6.5). Examining a soil sample in a Scanning Electron Microscope, bone fragments were detected. In this excavation, the profile reveals a humus and ceramics filled pit, likely a garbage dump.

Evaluating proportions of ceramic sherds and P_2O_5 levels by layer, it was noticed that there is no correspondence between these two variables. That, in part, may be due to the watering of P to lower levels. However, if Pit 6, where there was a cluster of sherds in horizons BA and B (a total of 3,743 fragments), with P_2O_5 level of 1,800 mg/kg^{-1}, is compared to Pit 3, where sherds are in smaller amount (223 fragments), with P_2O_5 level of 2,800 mg/kg^{-1}, it is clear that these two variable do not co-vary.

Zinc and manganese levels in Rio Branco show different behavior when compared to P_2O_5. For example, in Pits 1, 2, and 5, manganese and P_2O_5 have similar behavior by horizon, with contrary trends in excavations 3, 4, and 6. Since zinc and manganese are elements related to the decomposition of plant matter, higher levels of manganese in Pit 4 and zinc in Pit 3 might mean a higher amount of palms and materials used in the construction of houses at the periphery of the site, while phosphorus predominate in the center, where there would be higher incidence of animal matter (burial, food residues, etc.).

In the Leal site, P_2O_5 levels in A horizons vary from 1,200 to 2,500 mg/kg^{-1} in the anthropogenic soils, but from 300 to 580 mg/kg^{-1} in AA. There is also important in-site horizontal and vertical variation. From horizon A3 to horizon A2, P_2O_5 levels decrease from 2,500 to 1,400 mg/kg^{-1} in Pit 6 and from 2,400 to 1,700 mg/kg^{-1} in the trench, while they increase from 1,300 to 1,600 mg/kg^{-1} in Pit 1. There is an increase in the amount of ceramics of 3.3% in these horizons, at the same time that occurs a dramatic increase in the proportions of caraipé tempered ceramics, which goes from 49% to 62% of the total. The typical Marajoara phase ceramics (grog tempered) decreases 9%. From horizon A2 to A1, soil color gets lighter and P_2O_5 values decrease considerably. At the same time that ceramic proportions decrease around 10%, caraipé tempered ceramics again increases, from 62% to 74% of the total. Comparing geochemical data to the results of ceramic analysis, one sees that important changes were in place. The decrease of P_2O_5 levels from A3 to A2 horizons do not seem to be relate solely to demographic decrease, since ceramics do not decrease as much; therefore chemistry signatures must indicate changes in human behavior.

Although Ca and Mg are important markers for ADE sites, these elements did not provide good results for the Anajás River sites. This is likely due to the seasonal flooding to which many areas are subjected; besides that, some areas are affected by the inversion of the Atlantic Ocean currents that penetrate the island during the dry season, carrying salt water. Normally, Ca levels in soils are higher than Mg, since these are more easily watered. For soils under study, higher levels of Mg indicate influence of salts. The geological, morphological and pedological characteristics of Marajó soils, then, could have affected the absorption of Mg and Ca.

In both sites, P levels in B horizon were also observed to be too high for non-cultural strata, especially when compared to AA soils. That is due to the leaching phosphate, together with the pedological characteristics of both sites. Even though, considering that phosphate might migrate in the whole site, it is still possible to compare between horizons. The correlation between cultural features and phosphate content, for example, is significant in Pit 2, Rio Branco site, so chemical analysis likely confirm that it was a garbage dump. In the same way, high P_2O_5 levels associated to clusters of ceramic sherds on ancient surfaces indicate sweeping of both sherds and biological debris to non-circulation areas.

Data showed a more intense and differentiated occupation at Rio Branco site, where organic matter was disposed in discrete areas, compatible with well-organized social and domestic activities, following cultural patterned behavior. It is possible that houses were disposed in a circle or semi-circle around a central plaza. In Pit 3, for example, P_2O_5 levels are higher than in AA, but lower than in the center of the site; there zinc levels were high, an element associated to degradation of construction materials of organic origin, such as palms, which suggests that was the locus of a house. In Pit 6, lower levels of all elements indicate it was a peripheral area.

Comparing both sites, it is possible to affirm that: (1) Leal is smaller in area and demography than Rio Branco. (2) Activities carried out in Rio Branco involved a greater amount of organic materials, which, contrary to the expectations, did not lead to the formation of the typical ADE, although soil is darker in areas where there are more ceramics and nutrient levels are higher. (3) Geophysical, geochemical, and ceramic analyses suggest that in Rio Branco houses were disposed around a central plaza. (4) The fact that Leal is located next to the river suggests fishing as a primary subsistence activity. Its houses would be aligned along the river, as it has been suggested for other Marajoara phase sites (Schaan 2004). Discarding activities were less organized; garbage would be thrown around the habitation.

In the Camutins site both mounds were artificially build by the accretion of silt brought from adjacent areas. After a layer of silt was added, a period of occupation took place. During the occupation, human debris was consistently swept, so only a thin layer of dark soil was formed (Fig. 6.8). Such layers were comprised of charcoal and a few sherds. After a period of occupation (a year or a couple of years) another layer of silt was added. Silt was constantly being removed from the adjacent lake in order to improve hydraulic works (e.g. Schaan 2004).

Since Mound 1 was largely looted, the frontal part of the mound was covered with dark earth and amazing amounts of broken sherds (Fig. 6.9). These included parts of funerary vessels. Although no bones were found, it is a fact that looters frequently discard bones and broken pottery, taking with them only the best preserved pieces.

In the better preserved Mound 17, ADE was found in the cemetery area and in the back of a house. In the cemetery area it was associated with broken funerary pottery and bones. In excavation 4, it was associated to kitchen dump (charcoal, broken pots, pot stands) and human bones (Fig. 6.10).

Fig. 6.8 Camutins stratigraphy

6.5 Final Remarks

As this paper have tried to demonstrate, diverse lines of evidence (soil cores, excavations, geophysics, and geochemical analysis) can help interpreting pre-Columbian human behavior and settlement patterns. In the Rio Branco site, the study of cultural features and soil analysis permitted to understand spatial organization. In the Leal site, the lower levels of P_2O_5, if compared to Rio Branco, was interpreted as the result of a smaller population, something also supported by the amount of artifacts recovered.

It is important to emphasize that soil color in A horizon at the Leal site is darker than in A horizons of the Rio Branco site. While in the Leal site A horizons present soil colors of 10YR3/2, 3/3 and 2/2, in the Rio Branco A horizon with more intense occupation (A2 and A3) display 10YR4/3 and 4/4 colors. Darker soil in the Rio Branco site is restricted to the A1 superficial layer (3 to 7 cm thick), 10YR 2/1 at Pit 3, but 10YR 4/2 and 4/1 in other pits. An exception is Pit 5, where A2 color is 10YR3/3. Although, the Leal site soil has a typical ADE color, P_2O_5 levels are higher for Rio Branco. It might mean that the formation of ADE was not associated to the intensity of human activities and demographic increase, but to a particular cultural practices, such as a higher dependence on riverine fauna. Future studies,

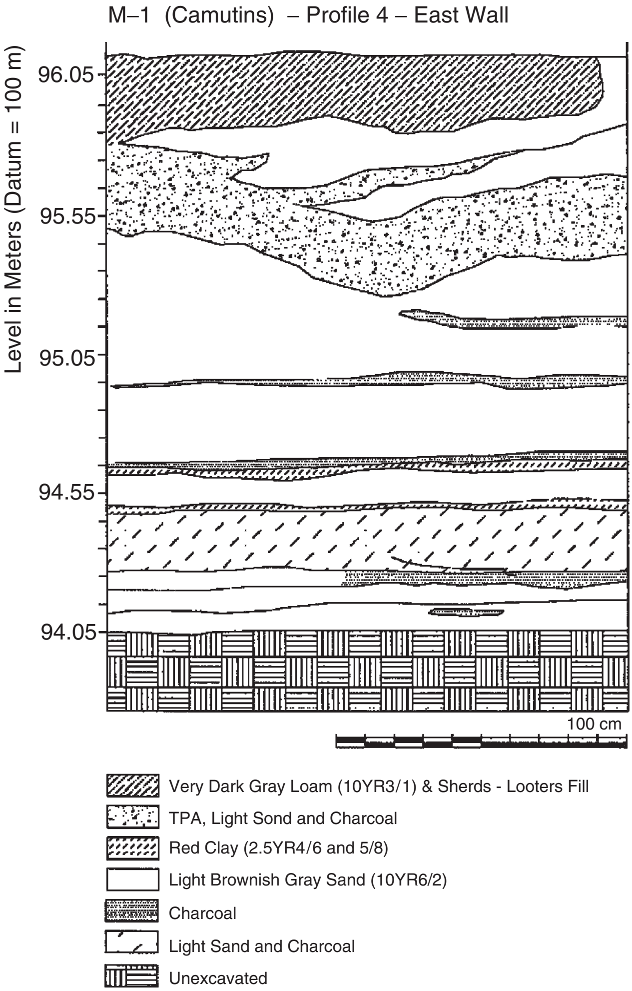


Fig. 6.9 M-1 Excavation 4 showing looters fill

combining studies of faunal and botanical remains associated with soil studies could certainly contribute significantly to our understanding of ADE formation. By now, it is suggested that the solely presence of dark earths, without investigation of archaeological structures, artifact remains, and soil chemistry is not a safe measure for demography and settlement patterns.

Given the special characteristics of Marajó Island hydromorphic soils, subjected to tide regimes and seasonal floods, analysis of Ca and Mg were handicapped. P_2O_5, however, together with manganese and zinc showed to be good indicators of human activity. Their values in both sites seem to be directly proportional to settlement size and quantity of artifacts, despite the fact that artifact amount may exhibit more variation. In the Rio Branco site, P_2O_5 levels indicate the location of garbage pit (clearly seen in the stratigraphy), while at the Leal site there seems to be a disagreement between cultural features (remains of charcoal and ceramics in excavation 6 and trench) and P_2O_5 levels; in Pit 1, where no significant features were found, P_2O_5

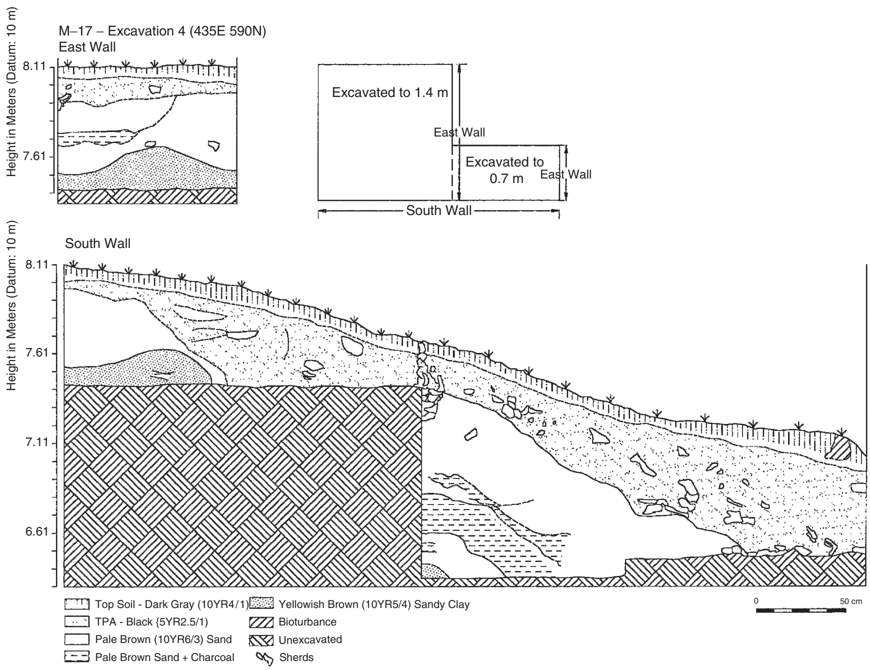


Fig. 6.10 Belém kitchen dump

levels are as high as in other areas of the site. It is likely that the population that lived at the Leal site was less integrated socially, smaller in number and more variable in terms of their discarding behavior. On the contrary, at the Rio Branco site, a larger and socially bounded population developed more intense, constant and ritualized activities.

Finally, populations that inhabited the ceremonial mounds were very concerned with cleaning their living platforms, so dark soils are only found associated to garbage dumps. Post depositional process related to disruption of burials produced very dark sediments, where human bones are assumed to have provided the organic content necessary for soil modification.

It is hoped that this research could, in some way, encourage other archaeologists to carry out geochemical studies in Amazonian archaeological sites, especially if integrated to studies of biological remains. In this way researchers could all have access to more data for comparative studies, in order to refine their methodologies and improve geochemical studies of ancient settlements.

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Chapter 7
Kayapó Savanna Management: Fire, Soils, and Forest Islands in a Threatened Biome

SB Hecht

7.1 Introduction

A great deal of Amazonian research has been devoted to the study of indigenous management of tropical forest resources. Questions of soils research have become particularly significant for understanding the forms of landscape manipulations that could have given rise to large pre-Columbian populations in tropical forest areas, and their implications for sustainable practices today, especially in light of determinist theories that viewed the possibilities of Amazonian cultural evolution as constrained by the general poverty of its upland soils (Denevan 2001; Erickson 2000; Heckenberger et al. 2003; Kim et al. 2007; Lehmann 2003; Peterson et al. 2001).

The analyses of indigenous tropical savanna management, and especially of soils on the other hand, are relatively rare. In part this reflects the reality that "savanna" peoples are also often managers of forests, since savanna ecosystems are usually part of ecotones that include gallery forests and a complex mosaic of lower biomass, semi-deciduous forests and successional systems as well as the open woodlands. Researchers often laid the emphasis on the forest rather than the Cerrado side of the equation, because they themselves were often more interested in the agricultural bases of these societies (Gross, Hames). For funding, it was often convenient to portray such "heterodox" groups as forest dwellers, or ambiguously as "native Amazonians" since such an approach fit in with broader social and scientific concerns about tropical environments and human rights alarms over Amazonian development.

Who were these savanna peoples? For the most part they were speakers of Jê languages, a linguistic group that stretched from the northeast of Brazil well into Western Mato Grosso, down into Minas Gerais and Sao Paulo states (Fig. 7.1). The Northern Jê include such well studied groups as the Xavante, the Xerente, the Krahô, the Apinayé, the Mekrãnoti, the Suya, the Xikrin, the Kreen-Akrore, and, of course, the Gorotire Kayapó.

The research on the Jê populations and their resource management was initially outlined in the early work of the Kurt Nimuendajú on the Krahô, Apinayé, Xerente, and Tapirapé. Later research was shaped by the theoretical concerns of anthropology

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

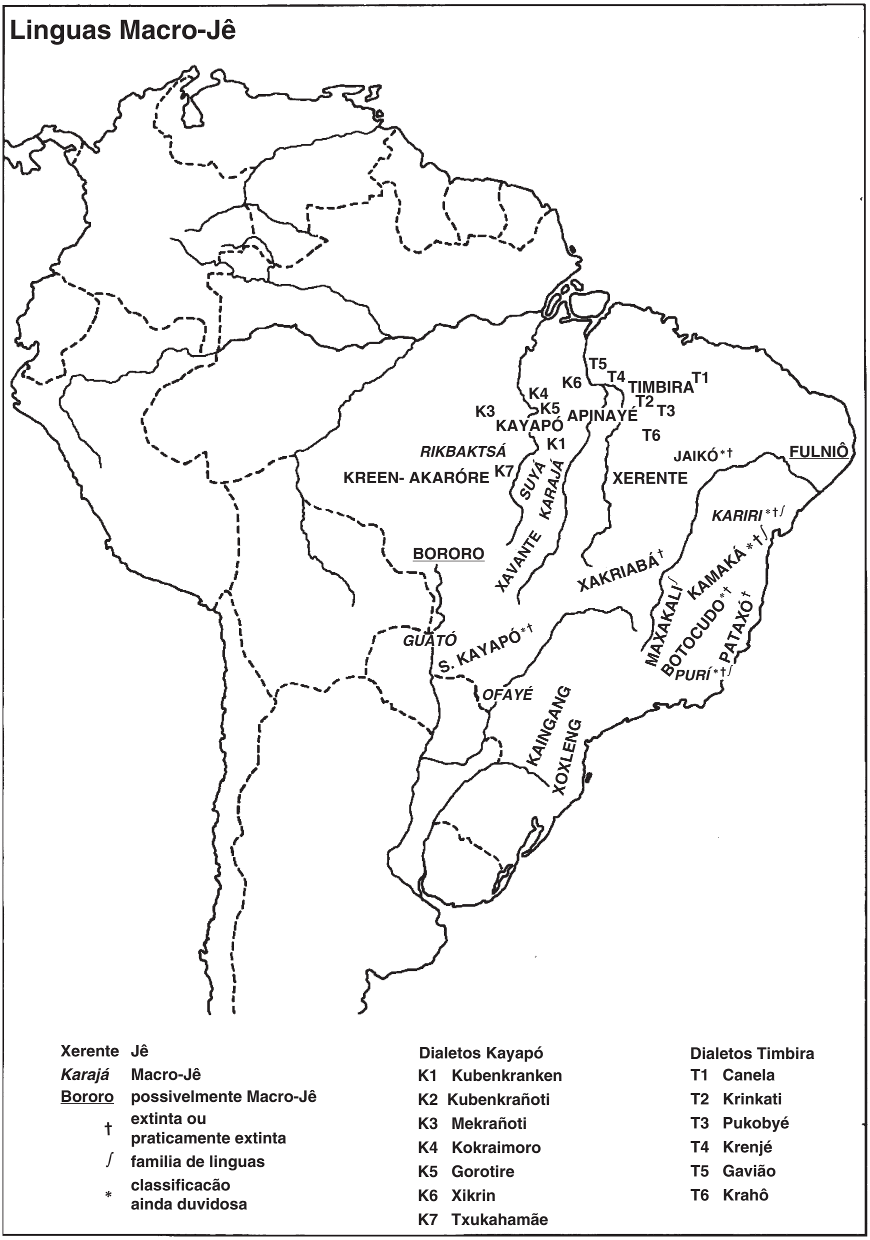

Fig. 7.1 Linguistic and Cerrado map

of the 1960s and early 1970s. These included Harvard scholars of the Jê Central Brazil Project under the direction of social anthropologist David Maybury-Lewis who focused on the political and symbolic structures that underpinned these

"Dialectical Societies" whose extraordinary social complexity appeared at odds with what was presumed to be basically nomadic or semi nomadic cultures (Crocker 1985; Maybury-Lewis 1967; Maybury-Lewis and Bamberger 1979; Turner 1995). Their emphasis was on structures of internal dominance and mechanisms of power as expressed through the complexities of moieties, marriage, nonkin sodalities, and rituals, among other dynamics. The productive base of these societies was understood largely through the control of labor and not assessed through the knowledge about nature or specifics about control over nature held by members of these societies.

Other research among the Jê developed under the leadership of Columbia University Professor, Daniel Gross (Gross 1975; Gross et al. 1979). This was also a comparative exercise, but one that followed the functionalist cultural materialist approaches and was largely informed by the dominant environmental ideas and ideologies about tropical populations and resource limitation that held sway at the time (Meggers 1971; Gross 1975; Gross et al. 1979). These optics viewed tropical populations as basically primitive (just adopting agriculture or otherwise nomadic, for example) with little history other than a kind of stone age imaginary, with isolated villages pitted against the great and determinant powers of nature and modernity to which natives had to adapt. Read today, these ethnographies are striking in their ahistoricism.

Indigenous knowledge systems, native cognition and practices pertaining resources and landscapes began to emerge as historians, cultural anthropologists, and geographers began to recast ideas of the New World tropical demography in light of a deeper reading of the historical record in Amazonia, especially the demographic impact of disease, colonial and indigenous warfare, and slaving. This began to inform the study of large scale landscape modification and the ecological analysis of indigenous production systems not as primitive elements of some stage theories of history, but rather as populations with their own history in complex relation to European colonialism and endogenous dynamics (Whitehead 2003).

Modern Amazonian populations reflected historical holocausts and diasporas, as well as different epistemes. Levi-Strauss, in one of his departures from his stricter forms of structuralism influenced this alternative effort through the classic The *Savage Mind* (1972) that posited that nature was "good to think". In addition there were the famous emic classificatory studies associated with landscape management such as Conklin's *Hananoo Agriculture* (1956) the Berlin's classificatory studies of southern Mexican populations (Berlin 1992; Berlin et al. 1968) and Alcorn's *Huastec Ethnobotany* (Alcorn 1982) among others. These set the stage for a much larger reworking of the "natural" not simply as scientific descriptions, but spaces that were as constructed physically and biotically as ideationally. (Balée 1998; Denevan and Padoch 1987; Descola 1994; Ellen et al. 2000; Posey and Plenderleith 2004; Whitehead 1993, 2003).

The geographer William Denevan's "machine" (and its affines) and the Berkeley School of cultural geography converged with historical ethnobotany and compiled an extensive set of analyses on indigenous resource management systems in Central America, the Andes, and the Amazon, where questions about landscape and ecological histories whose logics, though not divorced from productionist questions (what fed large populations in these difficult montane or tropical environments?) were linked to their historical, agroecological and environmental underpinnings (Balée and Erickson 2006; Denevan 1970, 1976, 1992, 2001; Denevan and Padoch 1987; Erickson 2000; Whitmore and Turner 2001; Zimmerer 2001). It was this framework, as well as pro indigenous activism that gave impetus to other projects, such as Darrell Posey's 12 year Kayapó project, and those spear headed by New York Botanical Garden's Gillian Prance.

Posey's research, along with that of his collaborators from several different disciplines showed that Kayapó landscapes were saturated both with human management and with meaning, a finding echoed elsewhere throughput the tropics (Brosius 1997; Descola 1994; Ellen et al. 2000; Fisher 1994; Franchetto and Heckenberger 2000; Heckenberger 2005; McEwan 2001; Posey and Balée 1989; Rival 2002; Whitehead 2003). That position, though it seems almost banal today, was part of a larger paradigmatic change about the relations of people with nature in the tropics, even as it focused primarily on forest ecosystems.

7.2 The Cerrado Question

The Cerrado, the complex of wooded savannas ranging from almost open grasslands to the mostly closed canopy Cerradão and semi deciduous tropical forests was far more extensive in New World landscapes until about 5,000 years ago when the warmer and moister Holocene climate contributed to the extension of tropical forests into these more open woodland formations (Mayle et al. 2000, 2007). Human occupation within Brazil is thought to be at least 11,000 years old and burning profiles suggest that people have affected this biome since their advent (Miranda et al. 2002). Cerrado vegetation is thought to embrace close to 10,000 species (Ratter et al. 1997; Ratter and Bridgewater 2006) and is composed of very complex patch ecologies and matrices with other forest types (for example, riparian, tropical semi deciduous forests, palm formations, as well as the floras of regional biogeographies) that reflect fire histories, edaphic factors, successions, biogeographies, animal and human interventions, as well as larger scale macro climatic change and disequilibria (Barbosa and Fearnside 2005; Gardner 2006; Hoffmann 1999; Hoffmann et al. 2003; Jepson 2005; Kauffman et al. 1994; Mayle et al. 2007; Oliveira and Marquis 2002; Ramos-Neto and Pivello 2000).

While humid tropical forests have dominated the "Deforestation Story" of the last decades, the Cerrado, semi deciduous transitional forests like the Cerradão, and tropical seasonally dry forests were largely out of the picture. Cerrado in its broadest sense covers almost 2,000,000 km^2 (22% of Brazil) and about 700,000 km^2 are found in legal Amazonia. It has been undergoing rates of deforestation that are often double those of the moist Amazon tropical forests (Klink and Machado 2005; Ratter et al. 1997).

Environmental attention to this biome has been apathetic in spite of the high diversity and complexity of these ecosystems, because they were viewed as less important and more anthropogenic (hence, degraded) than high biomass tropical forest formations. Although there is now significant research in many fields that emphasizes the deeply anthropogenic nature of forested Amazonia (e.g., Lehman et al. 2003; Balée and Erickson 2006; Denevan 1992, 2001; Heckenberger et al. 2001, 2003; Peterson et al. 2001; Posey and Balée 1989; Roosevelt 2001; Glaser and Woods 2004). Not surprisingly, the Cerrado is proportionally among the least conserved of New World biomes (Jepson 2005; Klink and Machado 2005; Ratter and Bridgewater 2006). The Cerrado as a whole has only about 2% of its area slated for conservation. This means that the large swathes of Cerrado and its transitions that stretch from Mato Grosso to Maranhão, including the extremely diverse and highly endemic systems near the Xingu/Araguaia rivers (Bridgewater et al. 2005; Ratter and Bridgewater 2006), are now mostly to be found in indigenous reserves. The processes of native marginalization and the loss of buffer areas around Cerrado native reserves has become especially acute because the expanding soy frontier is so remarkably dynamic (Hecht 2005; Nepstad et al. 2006). In light of the "vanishing biome", the questions of management and Cerrado recuperation are especially urgent, and what information can be culled from indigenous societies could usefully inform the practices of regenerative and landscape conservation management.

7.3 Lost Tribes, Long Treks, Languishing Techniques?

Jê speakers were the largely the masters of the Cerrados since European arrival. The earliest reports of Cerrado societies reported very large populations, central plaza cities, and beautifully flowered open landscapes (Wust and Barreto 1999). The area was known in Colonial Brazil as "The Forbidden Lands". The dry season treks frequently taken by modern observers as complete nomadism were less characteristics of a non-agricultural culture than a seasonal division of labor and certainly part of a military review of traditional territories, a setting for rituals, and resource management.

What is certain is that these native populations in savanna zones traverse substantial areas of the landscape, much of which was Cerrado and much of which they identify as anthropogenic (Cormier 2006; Posey 2004; Heckenberger et al. 2003; Rival 2006). Posey reported that the Gorotire moved plant germplasm through areas the size of France, both in long distance and stepwise transfers, as well as through trading and gifts with kin. The extended travels by natives in the savanna mosaics of the Xingu, Araguaia, the llanos de Moxos, the savannas of Rio Negro, Rio Branco, and the Orinoco confirm that enormous distances were covered (Chernela 1993; Whitehead and Wright 2004).

These travels involved surveillance, ritual, political, trade, and resource management activities, and depended on resource islands that recent research suggests were largely anthropogenic (Balée 1994; Cormier 2006; Posey 2003; Rival 2003). These management activities including maintenance of resource areas, through clearing, planting (intentionally or otherwise) ritual activities, transfer of germplasm, extraction and manipulation of resources such as casual pruning and weeding of resources islands and above all burning (Verswijver 1996). The engagement with savanna landscapes was not an exclusively a male domain associated with hunting, warfare and male ritual, since the purposes, propensities and intensities of savanna interventions would differ closer to villages. Women figure into the management equation of landscapes near the village in more protracted and continuous ways, and with different goals than male hunting treks. The focus of the uses and logics of resources might have a more gendered dimension than the literature suggests. Elaine Elizabetsky, for example points to girl age cohort who manage a Cerrado orchid used as a contraceptive, and there are other similarly gendered management regimes (Balick et al. 1996; Elisabetsky and Posey 1989).

7.4 Kayapó and the Cerrado

The Kayapó are part of the Jê linguistic group who inhabit the southern Pará and northern Mato Grosso in Brazil, and who historically occupied widespread areas of the upper Araguaia and Xingu watersheds. The Gorotirê Kayapó reside on the margins of the Rio Fresco, a tributary of the Xingu. The area is very heterogeneous in terms of vegetation types as a function of relief, forest-savanna dynamics, human manipulation, micro-climates, and burning, and in its geology. This complexity is reflected both in the indigenous classification systems of local vegetation types as well as classification systems for various montane and outcrop vegetation and soils (Hecht and Posey 1989).

The Gorotirê Reserve is located in the Grand Carajas formation that includes acid basement, as well as basaltic parent materials. The complex local geomorphology reflects Precambrian shield formations that contact the basaltic extrusions and recent sedimentary formations and creates a landscape of enormous geological and soil heterogeneity. This complexity was further elaborated through Kayapó impacts on forests and cerrado landscapes. Kayapó managed Cerrados for an array of reasons including anthropogenic of forest islands. This chapter explores the Cerrado management of the Kayapó and reports on some of the burning logics and especially focuses on the soil dimensions associated with anthropogenic forest islands within savanna landscapes. The ethnographic data we report here comes from interviews in the field (that is, in agricultural fields, in savannas and forests) with three adult males (one a vegetation specialist or shaman, another an animal specialist, the other an excellent horticulturalist) and two senior women, one the *capitoa* a kind of female authority, and another an accomplished agriculturalist. These were all from the eldest age classes of the Kayapó Interviews were carried out largely in Kayapó by Darrell Posey, although I posed questions in Portuguese to the adult males. The adult women were unable to speak very much Portuguese and I used my rudimentary Kayapó.

Soil samples were collected to a depth of 5 cm, and ten random samples per site were collected. These samples were not composited, but analysed separately. This study and formed part of more general analysis of Kayapó soils management carried out under the aegis of Dr. Posey's Kayapó Project (Hecht 2003; Hecht and Posey 1989). The samples were transferred from the field and analysed at the Soils Laboratory of Paul Zinke, in the Forestry Department of UC Berkeley.

7.5 Burning Cerrados and the Kayapó

Cerrado systems are the outcomes of natural processes and human manipulation at varying degrees of intensity. A given landscape feature, such forest islands in Cerrados can reflect edaphic features, drainage, laterite, termite ecology, and human actions all within relatively close proximity in the same grass/woodland. Similar formations in the same region can have radically different histories (Mayle et al. 2007; Ratter et al. 1978; Ratter and Bridgewater 2006). It is this complexity that can lead to a great deal of misinterpretation about "savannization" and landscape management. Moreover, the "tame" versus "wild" distinction that so characterizes North American understanding of landscapes (and, indeed, it underpins most of the history of American conservation ideologies) is in many ways an inadequate concept for the Kayapó, who understand nature in much less dichotomous terms. This is hardly unique to this ethnic group, however; one need only cite the recent work of Descola, Rival, Heckenberger, and Posey the idea of being in a "society with nature" is perhaps a more operant concept for much of Amazonia than the sharp northern dichotomies of the wild and the tame.

The Brazilian savannas are the most diverse of any on the planet, and so perhaps it is not surprising that while their soils are not particularly rich, they are not considered an impoverished landscape either. The gallery and other forests provide extensive ecotones that are widely used by animals of all sorts, they are relatively richer in huntable game than forest and especially because many of the predominant species, and, especially, those that profit from ecotones: peccaries, agoutis, capyvara, and brocket deer reproduce rapidly. The much enjoyed armadillo thrive on the termite and ant fauna. Cerrado areas are excellent bee habitat, and honey is one of the most prized of gathered items by men. The region has many creeks and rivers where fishing can also take place. There are numerous food resources as well: more than 25 species of Cerrado fruits are commonly consumed (Coimbra Junior 2004; Santos et al. 1997; Souza 1952). At least eight varieties of wild tubers are also regularly foraged. Geophytes are a feature characteristic of these fire ecosystems with rhizomes, tubers and underground bulbs, many of which are eaten, especially *Dioscorea*, and *Ipomea*, (yams and wild sweet potatoes), as well as some *Marantaceae* (arrowroots). These are recorded for other Jê speaking groups. (Santos et al. 1997; Fabian 1992). The patchy combination of forests with Cerrado means that forest fruits such as cacao and Ingá, (among many others) are also available.

Studies of human intervention in savanna ecosystems in the New World are useful because they reveal the vast extension of human action on landscape. Research on native burning patterns report that cool, frequent burning by natives is an important feature of their savanna landscape management, and many areas are burned on annual and up to 3 year cycles generating low biomass burns (Andersen et al. 2003; Batalha and Martins 2007; Burbridge et al. 2004; Martins 1995; Mayle et al. 2007; McDaniel et al. 2005; Mistry et al. 2005; Ribeiro 2005; Rodriguez 2007). Burning is one of the most powerful management tools available to native peoples, it is the great transformer and unsurprisingly it is widely used for a range or purposes. These are outlined in Table 7.1.

This array of burning rationales is not unique. Native populations throughout the New World in fire adapted ecologies report a complex of technologies and logics (Mistry et al. 2005; Rodriguez 2007). The essential features of fires, especially near settlements, are their frequency, intensity, and timing. Modern analysts of indigenous fire regimes in inhabited savannas repeatedly report continuous burning during the dry season (Mistry et al. 2005; Mayles et al. 2007; Laris 2002; Rodriguez 2007; Hecht and Posey 1989; Hecht 2003). Many ethnographies have also noted the high frequency of small burns during the dry season (Santos et al. 1997). These

Table 7.1 Uses of fires by the Kayapó

Create open places	For agriculture
	In field burning to reduce weeds
	Create campo
	Clean campo
	Clean campsites
	Clean pathways
	Clean a tyk ma and house areas
Renew/help	Infield burning
	Burning campos for sprouting grasses
	Cooking, smoking
	Helps flowering of some trees (*Hymenea, Caryocar, Voyschia*)
	Help other animals hunt
	Help hunt other animals
	Help get honey
	Help ground plants (geophytes) flower
	Help feed other animals
Create forests	Palm (*Astrocaryum; Maritius Orbygnea, Attelea*)
	Successional forests/orchards
	Apêtê
	Tabocal (bamboo stands)
Protect	Fire "breaks" around village
	Early burning grassland near apete; forest edges
	Night fires on treks
	Smokey fires against mosquitos
	Reduce pests, snakes
Territoriality	"We burn on our land"
	Communication among hunting groups
Hunting	Animal drives
	Animals attracted to ash salts
	Animals attracted to green forage
	Smoke away bees to steal honey
Aesthetics	Effect on the night sky
	Stimulates flowering

produce low temperature grass burns that move quickly, do not damage the fire adapted vegetation, provide a short term nutrient subsidy, stimulate flowering and fruit production as well as new shoots of native grasses and the other rhizomatous plants of the Cerrado. Research on Brazilian Cerrados in experimental burns has shown no impact on termite diversity, minimal successional impact on small rodents, no effect on armadillos and anteaters. Such fires cause minimal damage on woody vegetation, which is well adapted to it (Alencar et al. 2004; Briani et al. 2004; DeSouza et al. 2003; Higgins et al. 2007; Hoffmann 1999; Hoffmann et al. 2003; Nardoto et al. 2006; Prada 2001; Prada and Marinho 2004). Importantly, cool fires of this type produce woody clumping versus a more random distribution, as do relatively frequent fires since smaller seedlings are less resistant and can be destroyed even in these "soft" conflagrations (Hoffmann 1999). Thus, the landscape physiography of clumpy forest islands has much to do with the burning regime. In general, Cerrado-dry forests mosaics are increasingly understood as highly resilient ecological systems (Vieira and Scariot 2006; Vieira et al. 2006, 2007). What does have a disastrous effect on the environment are catastrophic fires, such as that recorded for the Parque das Emas where fire suppression led to a conflagration that burned up the entire park and the wildlife in it. Hot fires late in the dry season have a very different dynamic than the dispersed burning system generally practiced by native savanna peoples.

The Kayapó burn the Cerrado systems in many complex ways, although the intentionality of the burning in some cases may be open to speculation. The Kayapó burn throughout the dry season, the burning is usually done early in the day. The spatial mosaic of the burning is very uneven, creating a pattern of burn history of different extent, intensity and age and types of ash depending on the burn temperature. As has been noted elsewhere burning is a constant feature of Kayapó resource management and throughout the dry season one is in a kind of smoldering landscape (Hecht 2003, 2005).

Fire is a dialectical entity: it is the transformer of the wild into the tame, the "raw into the cooked", to quote Levi Strauss, as it takes forests and turns them to gardens and savannas, but it can also become wild and devour villages and fields. The duality that inheres in fire is not itself that unusual as it is after all a tamed primordial force, but its relevance for our Kayapó situation is that fire is both a destroyer of forest in the cerrado and a creator and maintainer of specialized forests of palms, successional forests/ orchards, bamboo forests (*tabocal*) and campo woodland islands (the *Apêtê*).

7.6 Anthropogenic Forest Creation in Cerrado System

Fires are used to create particular kinds of forests within the cerrado landscape. The Kayapó report that campo, the open landscapes near their settlements were created and maintained by them although fire makes open areas (*Kapôt*) it also helps "make" and "help" forests for palms, for secondary/orchards and forest islands.

7.6.1 Palms

Notable among the tropical new world populations are the importance of pyrophilic or fire tolerant palms due to their usefulness for food, animal attractants, building material, salts, and input for artisanal materials. The ethnobotanical importance of palms has been widely noted, and their presence as oligarchic or almost monospecific formations in many tropical ecosystems is often seen as evidence of human influences on landscapes (Henderson 1995; Kahn and de Granville 1992; Peters et al. 1989). The Kayapó are avid users of palms, as are other Amazonian populations (Balée 1994; Coimbra Junior 2004; Crocker 1985; Fabian 1992; Fausto and Heckenberger 2007; Giaccaria and Heide 1975).

Fires are used to maintain particular vegetation formations, such as those of the Tucumã palm (*Astrocaryum* species) that is highly attractive to collared peccaries, and maintenance of such groves relatively close to the village helps lure them into close range of the village. Fires are set in Buriti (*Mauritius flexuosa*) swamp groves when the soil is still moist to reduce litter and stimulate the palm which is valuable for its fruits and especially important as an animal attractant and fish food. Fires are crucial for making Babassu (*Orbignea phalerata*) palm groves, when forests are cleared and then repeatedly burned (Anderson et al. 1991), and within villages and gardens ashes are often placed near small trees to enhance their growth. The palm is prized for its artisanal uses, palm heart, and oil rich fruits and the agoutis, paca and pigs that prey on them. Other palms that are tolerant of fire and that feature in Kayapó ethnobotany and successional management include Inajá (*Maximiliana sp.*) and *Attelea* both resistant to fire. Inajá tolerates the high heat of the formation fire of a swidden plot, and these are almost never cut when a new garden is developed, and remain as markers of previous agricultural sites (and their valuable *terra mulata*) for women and the daughters. Fronds of this palm in particular are also used as mulch. The use of fire for maintaining palm landscapes is not controversial and widely documented for indigenous and peasant communities. Palms are important indicators of anthropogenic landscapes (Balick 1979; Muniz-Miret et al. 1996; Peters et al. 1989).

7.6.2 Successional Forests

Fires, as part of the creation of secondary forests and successional orchards via swidden agriculture has been described widely for Latin American swidden systems more generally (see Denevan 2001; Posey and Plenderleith 2002; among many others). Fires initiate processes that produce orchards and manipulated secondary forests. The use of old successions in the cerrado-forest mosaic among the Jê speaking populations in addition to the Kayapó is described for the Mekronotí (Verswijver), the Apinayé (Nimuendajú et al. 1939), as well as more broadly in other trekking cultures (Balée 1994; Cormier 2006; Rival 2006).

7.6.3 Forest Islands

The role of human agency in the creation of forest islands has been controversial and vexed because of an academic rivalry that was played out in the pages of *American Anthropology* by Eugene Parker who asserted that the data and analysis presented by tropical botanist Anthony Anderson and Darrell Posey was incorrect, and no anthropogenic forces were at play in the formation of forest islands (Parker 1992, 1993). Parker never produced a plant list or any corroborative data, to prove his assertions never deposited his exemplars in any herbaria, and his statement that his single site, located within 2 km of a village that had been continuously occupied for 60 years was a "wild" or "natural" forest island, is hard to sustain in the absence of any verifiable data. The high proportion of named and useful species the Anderson-Posey and alleged for Parker sites argue for a "constructed nature" but in any case he never published again on the Kayapó or even on Amazonia. This highly personal, nasty interchange effectively hindered a more active research on native management of savannas at exactly the moment when cerrado forests were being aggressively converted into pasture, sugar cane and soy.

Anthropogenic forests in savannas are hardly unique to the Kayapó. They are reported as elements of highly anthropogenic landscapes throughout the southern Amazon Basin. The Bolivia Ibibate complex is clearly anthropogenic (Erickson 2006). Ratter and Bridgewater (2006) describe anthropogenic forest mounds near the island of Bananal on the Araguaia, as well as in northeastern Mato Grosso. Cunha (1990) reports large *Capões*, elliptical in shape and 300 m wide and up to 80 m in length. These are called *aterros de bugre*, a derogatory name meaning lands of the ape-men, clearly identifying them with native management and habitation and often include potshards. Other forest island systems are also seen as the outcome of anthropogenic forces (Mayle et al. 2007; Ponce and Dacunha 1993).

There are clearly very different contexts that produce forest islands, and their formation in varying cultural matrices does not require an adherence to a uniform formula or cultural group. But, it is quite likely that they emerge as elements of a larger set of landscape dynamics that mesh both human actions and natural processes that produce formations that integrate human purposes and biotic outcomes. The Kayapó enable and even plant in Apêtê because they find it useful and interesting to do so. But everything in this landscape element is not planted by people, nor are all forest islands the outcome of human agency, although some initial planting of Apêtê does occur. The extensive naming of the species within them, plus the very high degree of plants that are identified as useful (70–98%) suggests more than a peripheral interest in these systems. The Kayapó use these systems in complex ways close to home and on treks. One potential marker of their engagement and of anthropogenic activities is soil differences between sites that are more actively manipulated and those that are less so. In the next section I outline the broader context of anthropogenic forests in savanna sites, and document soil differences in anthropogenic Cerrado forests islands.

7.7 Anthropogenic Forest Islands in Savanna Landscapes

7.7.1 Research Sites

Part of my research on soil dimensions of Kayapó land use examined the outcomes of landscape structures of cerrado vegetation activities on soil properties within the frameworks of control sites or old successions in adjacent forest areas and open campo. Management outcomes were set against this background. The soils that are the subject of our analysis are classified in Brazil as red-yellow dystrophic podzols and yellow dystrophic podzols. Our main research site was about 8 km away from the village, and not far from another former village that had become a "resource island" with its village yards, and adjacent fruit trees now standing in the midst of campo, a very clear and explicit anthropogenic forest island. The use of such sites is not unique to the Kayapó. Nimuendajú cited young Apinayé going off to old villages for fruit collection and hunting (Table 7.2).

7.7.2 Old Village Forests

There are many processes that contribute to the formation of forest islands, but for the sake of clarity, we begin with one forest island that was a former village site and now is an orchard and a resource island in the complex of savanna/forest. This is unequivocally an anthropogenic site, and there is ample reason to believe that many such sites occur throughout the region given the historically large numbers of Kayapó and other Jê groups in this region. The Pao D'Arco settlement had some 4,000–5,000 inhabitants, and fissioning of villages and relocation of villages is common among the Jê. There were several former village sites relatively near to the current Gorotire village itself. While lacking detailed botanical descriptions the old village forest, this anthropogenic forest included *Spondias*, (Taperbá), *Annona*,(Soursop), Piquí (*Caryocar* sp), Guava (*Psidium* sp.), Genipap (*Genipapo americanum*), Urucú (*Bixa orelleana*), Jatobá (*Hymenea* sp. Babassu (*Orbygnea* sp.), and Inajá (*Maximilleana* sp.).

Soils were sampled in the nearby campo as well as adjacent forest about half a kilometre away. It was reported to us that nothing in particular had been done in forest sites and their nearby campo, although surely the campo had burned at one time or another. While as a generalization, forests in cerrado areas are often taken to occur on more nutrient rich soils, those studies usually focus on large scale

Table 7.2 Background soil characteristics of research site (forest and grassland)

Vegetation formation	pH	%C	%N	P (ppm)	Ca (meq)	Mg (meq)	K (ppm)
Campo	4.8	1.76	0.13	0.6	0.20	0.11	107
Adjacent forest	4.8	1.2	0.11	1.3	0.16	0.07	42

Table 7.3 Comparison between village site and background soils

Vegetation formation management	pH	%C	%N	P (ppm)	Ca (meq)	Mg (meq)	K
Campo	4.8	1.76	0.13	0.6	0.20	0.11	107
Adjacent forest	4.8	1.2	0.11	1.3	0.16	0.07	42
Old campos village forest/orchard	4.7	2.53	0.27	19.83	1.56	0.07	234

landscape patterns including gallery forests that often follow geomorphic incisions in the landscape and reflect soil catenas with more active reworking and deposition (Diniz et al. 2004; Furley 1999; Furley and Ratter 1988; Kauffman et al. 1994; Oliveira and Marquis 2002). In many areas of upland soils in this region of the Amazon, where Cerrado and forest both occur on highly weathered granitic upland substrates, the differences in the underlying soils are often negligible (Furley et al. 1988; Ratter et al. 1978). This is the case here. The soils showed very little difference between forest and campo. Their pH levels were comparable, the N and % C levels were not significantly different, nor were they divergent in terms of macronutrients except for the campo which showed higher levels of K, probably an artefact of fire. P levels are higher under forest, but still very low, although not atypical for this Amazonian soil type (Table 7.3).

At the village site however, there are significant differences in the soil elements of this forest island, and the background soil characteristics. This association of this forest resource island was unquestionably anthropogenic, and included sites of dark ash laden areas of incipient *terra preta* or *terra mulata* (cf. Sombroek 1966; Woods and McCann 1999).

The old village/forest site shows higher levels of C perhaps associated with a higher faction of wood ash and char in the samples, double the levels of nitrogen in the forest grassland controls, and especially significantly higher levels of phosphorous, calcium and the marker for management because of its association with ashes and fire, much higher levels of potassium. The site was regularly visited on various travels, was still a foraging/collection site, intermediate camping site and activities supported the site, including casual weeding, pruning, peeing and tossing ashes from campfires and occasional understory burning both by accident and by plan. Clearly, human intervention in this case significantly improved soil properties.

7.7.3 *Unmanaged Apêtê and Its Matrix*

Forest islands (the *Apêtê*) whether they are created by human agency, or opportunistically managed reveal significant levels of useful species (70–98%) and are widely used on both short and long treks. The next comparison we chose was between an Apêtê that was reported to us to be currently unmanaged, although it may have had some attention in the past when the village was occupied. Table 7.4 presents the results.

This site has slightly more acid soils but overall shows little difference from the forest “control”. This site was compared with the soil data of actively managed Apêtê where we also sampled the different inner zones that have variable light regimes. It may be that our site was too small to manifest larger scale soil differences within the Apêtês, but were no significant differences between the internal areas of the Apêtê. Compared with the non managed Apêtê, the managed site showed significantly higher levels of C (about triple), three times higher levels of N, about five times the level of P, significantly greater levels of Ca and Mg, and quadruple the levels of K (Table 7.5).

Some *Apêtê* can also function as camping sites and areas of ritual activities of various types, which could include ritual painting, preparation of weapons, making or weaving of ritual gear, body paints, incense, and the like. Data on such *Apetê* are presented in the Table 7.6.

This site reveals the highest levels of C compared to our other managed sites, significant amounts of P and high levels of K, suggestive of application of ashes or burning within the ritual sites, and charcoal within the samples. The high levels of C reflected the residues of materials used in preparation of ritual artifacts, much of which was palm fibers of various types. Burning and decay of palm fibers may also have contributed to the exceptionally high level of K.

Table 7.4 Soil nutrients in unmanaged *Apêtê*

Vegetation formation management	pH	%C	%N	P (ppm)	Ca (meq)	Mg (meq)	K (ppm)
Nonmanaged Apêtê	4.3	0.9	0.06	1.34	0.14	0.09	50
Campo	4.8	1.76	0.13	0.6	0.20	0.11	107
Adjacent forest	4.8	1.2	0.11	1.3	0.16	0.07	42

Table 7.5 Comparison of managed and unmanaged *Apêtê*

Part of *Apêtê*	pH	%C	%N	P (ppm)	Ca (meq)	Mg (meq)	K
Ira	3.9	3.1	0.19	5.5	0.73	0.75	201
Tree	4.1	3.25	0.18	6.4	0.57	0.79	195
Edge	4.2	3.45	0.17	5.6	0.56	0.79	207
Average values	4.1	3.20	0.18	5.63	0.62	0.77	202
Nonmanaged *Apêtê*	4.3	0.9	0.06	1.34	0.14	0.09	50

Table 7.6 Ritual site *Apêtê*

Vegetation formation management	pH	%C	%N	P (ppm)	Ca (meq)	Mg (meq)	K
Ritual site	4.5	4.7	0.31	13.1	0.77	0.56	477
Apêtê (metoro nin dja)	4.1	8.0	0.27	10.1	0.95	1.27	–
Campo	4.8	1.76	0.13	0.6	0.20	0.11	107
Adjacent forest	4.8	1.2	0.11	1.3	0.16	0.07	42

Table 7.7 Camping site *Apêtê*

Vegetation formation management	pH	%C	%N	P (ppm)	Ca (meq)	Mg (meq)	K
Big trail *Apêtê* (camping site)	4.2	2.54	0.23	12.36	0.81	0.34	114
Campo	4.8	1.76	0.13	0.6	0.20	0.11	107
Adjacent forest	4.8	1.2	0.11	1.3	0.16	0.07	42

Table 7.8 Anthropogenic effects on soil properties in forest islands

Vegetation formation	pH	%C	%N	P (ppm)	Ca (meq)	Mg (meq)	K
Campo	4.8	1.76	0.13	0.6	0.20	0.11	107
Adjacent forest	4.8	1.2	0.11	1.3	0.16	0.07	42
Anthropic forest islands (average)	4.3	3.63	0.24	12.3	0.85	0.64	226

The sample set was taken from an *Apêtê* which was used as a sleeping area on treks, and as a protected camping area. As Table 7.7 shows, the soil C and N levels are roughly double those of the background soils and P, at 12 ppm is dramatically greater than the background soil levels of around 1 ppm. Ca was roughly four times that of the controls, while mg was about triple the levels of the background soils. K was comparable to the campo soil. Except for K, all the differences were significant.

Table 7.8 shows the average values for soil properties from the anthropogenically formed or influenced forest islands. The data clearly show augmented levels of C% that are double those of the background soil, %N which though still low is double that of the controls. Phosphorous is much higher, as is Ca (by a factor of 4), while K averages double the levels of the control sites but with higher variability. As noted, areas such as the ritual site were unusually high in their C, P, and K levels. Such data, especially compared with unmanaged sites and adjacent forest suggest that human nutrient additions through various activities including residues, ashes, waste of various kinds affect soil properties in positive ways. These are not meant as agricultural sites, hence the values are not as elevated as the farm plots (Hecht and Posey 1989; Hecht 2003), but such additions clearly reveal nutrient support for *Apêtê* species which are composed of species from dry forest, Cerradão successions, and open campo plants and cerrado fruits found in these forest islands.

These nutrient additions may enhance productivity for human foods and medicines, but one significant value of these *Apêtê* and the species that compose them are their importance for attracting game. Luring animals into the open to feast on the fruits of forest islands, or providing them with cover within the larger expanse of the savannas may have important effects for maintaining animal biodiversity, especially those favored for game by creating a complex of ecotones over larger areas. Given the importance of vertebrates and their dependence on forest elements the recognized value of attractants by the Kayapó as a "use" of *Apêtê* components is important (Anderson and Posey 1989; Parker 1992). Moreover, compared with other new world savannas, Cerrado has three times the number of mammals that are cerrado dependent, and more recent studies of diversity in Cerrados places their mammal biodiversity above that of tropical forests. Rather than a site of dearth and an impoverished human habitat, a view that prevailed until quite recently about tropical forests, it may be, that like those forests they are far richer than we understand, as greater analysis about these regions unfolds (Bridgewater et al. 2005), especially as we expand our understanding of native techniques of management and *terra firme* history (Wust and Barreto 1999). Recent research suggests that cerrados are much more dynamic than previously thought (Vieira and Scariot 2006; Vieira et al. 2006, 2007), and the forest islands clearly play a role in the larger ecological resilience of these systems by providing nutrient-rich substrates for trees and brush whose role as animal attractants may be a critical element for recuperation of degraded cerrado landscapes that often follow in the wake of careless tropical development.

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Chapter 8
Amerindian Anthrosols: Amazonian Dark Earth Formation in the Upper Xingu

MJ Schmidt and MJ Heckenberger

8.1 Introduction

Amazonia is a region known for large expanses of acid, infertile soils difficult to farm without considerable inputs of fertilizer or long fallow periods. In this same region, scattered patches of fertile black soil also exist that are highly sought after by farmers for planting nutrient-demanding crops. These areas are the result of the activities of prehistoric Amerindians. We know that the black earth is associated with archaeological sites and is, in itself, an archaeological remain that is full of information about past societies and their resource use. Scientists also believe that research on black earth, known as *terra preta de índio* in Brazil, could lead to a better understanding of soils and their management, particularly nutrient-poor tropical soils. Questions remain as to what processes were in action to produce the fertile black soil and what keeps them fertile over long time periods.

The Kuikuro Amerindian word for the black soil is *igepe*, which is also their word for cornfield. They plant fields of their staple crop manioc on the normal red soils but all other crops are planted on patches of deep *terra preta* with abundant ceramic fragments and boasting large prehistoric earthworks that give structure to the sites. They plant banana, corn, squash, sweet potato, papaya, sugarcane, and many other crops that generally would not do well in the natural red soil. The fact that they are willing to travel up to 10 km or more to reach these *igepe* gardens and haul the produce back to the village demonstrates the value of the *terra preta* to the Kuikuro. They are using a resource that was accumulated over decades or centuries by previous inhabitants but, are they also creating it themselves?

The Kuikuro are affecting the soil in their own village much like the prehistoric inhabitants that occupied the large *terra preta* sites. Their activities are creating, within and around the village, a more fertile, less acid soil that is rich in organic matter and has high levels of a wide range of nutrients similar to prehistoric *terra preta*. In their extensive middens surrounding the village they have created a thick (30–40 cm) layer of dark, fertile soil over a substantial area. They use this soil to plant the same crops that they plant on the *terra preta* of archaeological sites. Other actions, besides refuse disposal, appear to have a significant effect on the soil including domestic and ritual activities and cultivation. Soils in village sites that

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

were abandoned decades ago, having been occupied for 10 years or less, also continue to display high pH, high organic matter, and high levels of nutrients, similar to the *terra preta* in the nearby archaeological sites.

Ongoing archaeological research in the Upper Xingu (Fig. 8.1) suggests that Amerindians today continue basic economic forms and settlement patterns from those of the prehistoric inhabitants who left a legacy of large sites with earthworks and abundant *terra preta*. The continuity of Amerindian culture in the region is suggested by evidence from ceramic technology (reflecting manioc agriculture), settlement patterns (circular-plaza villages), and overall use of the landscape (roads, bridges, fish weirs) (Heckenberger 1996, 1998, 2001, 2005; Heckenberger

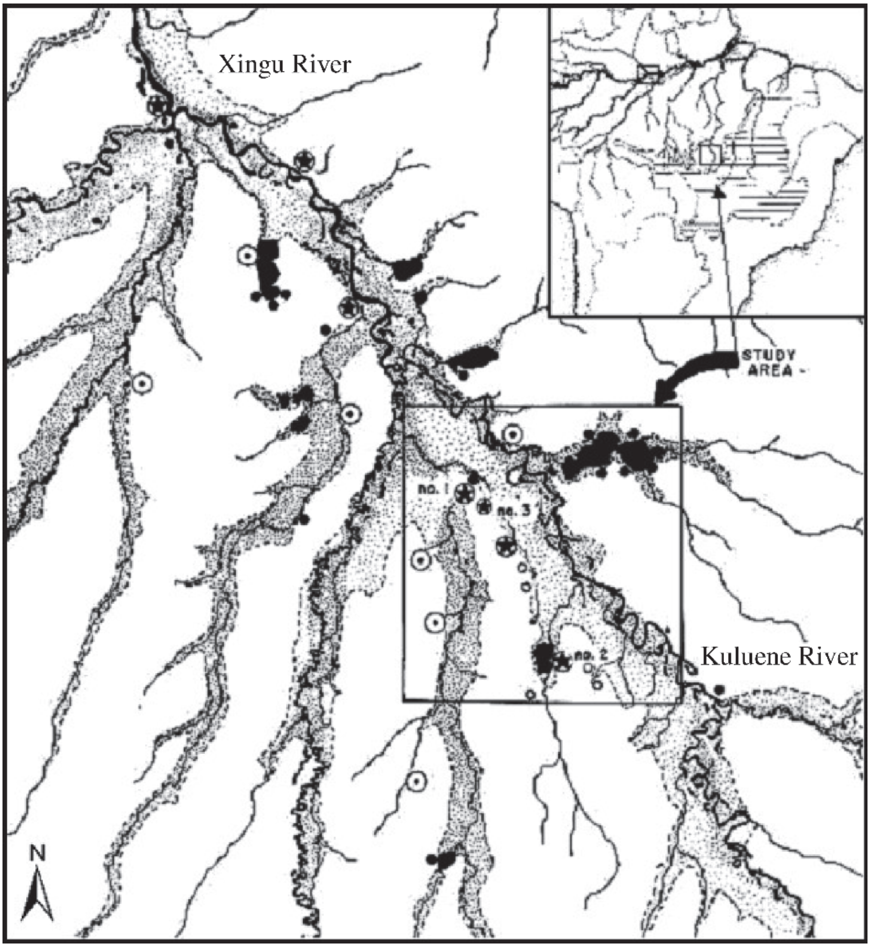


Fig. 8.1 Map of Upper Xingu with box showing study area and inset showing location in Brazil. Black indicates rivers and lakes and shaded areas are floodplain. Circles are the locations of archaeological sites with stars representing major prehistoric settlements

et al. 2003, 2007). The apparent cultural continuity makes an ethnoarchaeological approach (e.g. Silva and Rebellato 2004) even more valuable for understanding the archaeology of the region and presents a unique opportunity to address questions about the range of activities that produced the soil variation found in archaeological sites.

Soil data can provide valuable insights into the use of space in abandoned settlements when combined with other lines of archaeological evidence such as site maps, artifact counts, features, and associations and especially when samples are collected in an ethnoarchaeological context (Barba and Ortiz 1992; Entwistle et al. 1998, 2000; Knudson et al. 2004). Archaeologists have emphasized the utility of soil chemical analysis for understanding the remains of households and outside activity areas particularly where artifacts are lacking (Fernández et al. 2002; Parnell et al. 2002a, b). Soil analysis has the potential of being an efficient tool for further investigation of sites in the Upper Xingu and in the wider Amazon region where *terra preta* is arguably the dominant archaeological remain.

8.2 Amazonian Dark Earths

Patches of Amazonian dark earths (ADE) occur in diverse environments throughout Amazonia and range in size from less than 1 ha to many square kilometers (Woods and McCann 1999). The elevated fertility and stability of nutrients in ADE compared to typical upland soils makes them highly sought after by farmers particularly for the cultivation of nutrient demanding crops and have long captured the attention of scientists (Woods and Denevan, this volume). A number of researchers have stressed that the information 'buried' in dark earth soils can help to develop modern sustainable agriculture in Amazonia and other tropical regions. Fundamental questions of the *Terra Preta Nova* project (Madari et al. 2004:176), created to advance agronomic and agro-ecological research on ADE, are: (1) How were the ADE soils formed? And, (2) Was this an unintentional anthropic or an intentional anthropogenic process, or a combination of these two factors?

ADE are characterized by their dark color, elevated levels of nutrients, and the presence of cultural material remains including ceramics, lithics, and abundant charcoal. Although, in the past, several authors have suggested a natural origin for ADE, there is now little dispute as to the human origin of these soils (Glaser; Woods 2004; Smith 1980). Scholars recognize that ADE soils are archaeological sites significant for their potential to reveal the structure of society, resource use, and social change of prehistoric and post-contact Amazonian communities (Heckenberger et al. 1999; Petersen et al. 2001; Neves et al. 2003, 2004). Numerous studies have demonstrated the extraordinary anomaly that ADE represent within the typically acid and relatively infertile Oxisols and Ultisols that dominate the Amazon region (Kern and Kämpf 1989; Pabst 1991; Smith 1980). ADE typically show significantly elevated levels of N, P, K, Ca, Mg, Mn, Zn, and other nutrients in relation to surrounding soils. They contain abundant charcoal, and pH, organic matter, CEC, and SB are usually higher, providing a better growing environment for many crops. ADE have been shown to be extremely variable within sites due to the differential intensity, duration, and nature of cultural activities that formed them as well as natural processes and post-abandonment activities (Heckenberger et al. 1999; Kern 1996; Kern and Kämpf 1989).

It has been suggested that many dark earth soils are the result of semi-intensive or intensive agricultural practices, reasoning that long-fallow shifting cultivation techniques generally practiced today could not have sustained large settled populations purported to exist in prehistoric Amazonia and that stone axe technology induced farmers to rely on relatively intensive or continuous cultivation (Denevan 1992, 2004; Neves et al. 2003). Direct evidence for prehistoric intensive agriculture in upland forest areas of Amazonia is so far slight. So-called *terra mulata* soil (TM), is hypothetically formed by semi-intensive or intensive agriculture (Sombroek 1966; Woods and McCann 1999). It is sometimes found in a broad band surrounding *terra preta* (TP) and is characterized by having fewer cultural remains, a lighter color (dark brown), elevated levels of organic carbon (including abundant charcoal) but lower levels of other nutrients in comparison with TP. Although relatively intensive agricultural methods such as mulching, in-field burning, soil amendments, and/or repeated cycles of short-fallow slash and burn have been proposed as the origin of TM, this has yet to be demonstrated. Hecht (2003) suggests that these soil management practices as used among the Kayapó may be similar to practices that, in the past, produced ADE (Hecht and Posey 1989).

Some evidence for ADE being formed by cultivation comes from investigations of several sites at Araracuara on the Caquetá River in Colombia and is based on the discovery of algae in the soil profile, reportedly from additions of alluvial silt and organic debris transported by the inhabitants from the nearby floodplain. This provided an interpretation that dark soils found on the site are the result of cultivated plots and pollen analysis revealed a diversification of cultivated plants during occupation of the site, a clear indication for the authors of prehistoric soil fertility management representing a process of agricultural intensification (Herrera et al. 1992; Mora et al. 1991). Some writers caution assuming that ADE was formed by cultivation arguing that modern efforts to modify soils such as charcoal and organic amendments and in-field burning fail to generate lasting changes in the soil (German 2003; Heckenberger 2005; Heckenberger et al. 1999; Smith 1980).

8.2.1 Two Broad Hypotheses for ADE Formation

The two general hypotheses for ADE formation are not exclusive but complementary: (1) ADE was an unintentional outcome of human occupation and discard of waste resulting in TP, and (2) ADE was the outcome of intentional management of the soil for agriculture resulting in a zone of TM surrounding the settlement. In the Upper Xingu, current use of both ADE and backyard middens for the cultivation of crops suggests that the line between these two hypotheses is blurred. Today, Amerindians exploit the developing trash middens in their backyards for planting crops as well as the ADE (prehistoric sites) often many kilometers from home and they have been observed enriching soil in cultivation plots adjacent to the village with organic waste, mulch, and the practice of coivara, or burning of weeds and crop residues. They were also observed spreading organic refuse over a wider area (expanding the middens) with the intention of improving the soil for later cultivation. In a large village setting centuries ago, residents may have exploited middens or intentionally improved soil for planting but activities not directly related to cultivation or waste disposal, such as domestic, economic, and ritual activities, would also conceivably result in a darkened soil with characteristics of TP or TM.

Processes that contributed to the formation of ADE may differ depending on eco-region and cultural practices. As Denevan puts it, "Undoubtedly, there has been considerable variation in Amazonia in the forms of dark earths, the specific processes and histories responsible, forms of land use, and associated settlement patterns" (2004:141). The Upper Xingu case represents one such instance of ADE formation. This research will advance an understanding of ADE by providing information on soils in a current Amerindian village in activity areas within domestic, ritual, refuse midden, and agricultural contexts.

8.3 Field Site and Data Collection

The Upper Xingu basin lies in a unique transitional environment between the Amazon rainforest and the savanna (*Cerrado*) of central Brazil. It is one of the regions of Amazonia hardest hit by deforestation and development. The study area lies in the territory of the Kuikuro community, a Carib speaking Amerindian group inside Xingu National Park, the first indigenous reservation created in Brazil. The sites lie on terra firme on the margin of the extensive floodplain of the Kuluene River that is rich in aquatic resources in the numerous lakes but whose soil is poor for cultivation. There is some indication that the prehistoric inhabitants may have cultivated limited areas of the floodplain based on the presence of possible raised fields. The Kuikuro rely on fishing in the numerous water bodies and farming a range of crops. Bitter manioc, the staple food, is usually grown on the 'weak' red upland soils (*terra firme*) (Carneiro 1983) with characteristic properties of Oxisols in the USDA soil taxonomy or *latossolos vermelhos* in the Brazilian system that are dominant in the region (Ratter et al. 1978) while most other crops are grown either in backyard middens or on the fertile *terra preta* of archaeological sites. The manioc is passed through a labor intensive process to remove the deadly prussic acid and the tough fiber to refine flour that is made into bread resembling tortillas. Bulky waste is generated in the process (peels and fibrous pulp) and deposited in the middens. Large ceramic (and recently aluminum) pots and griddles are used in processing and cooking manioc.

Within 4 km of the Kuikuro village are two prehistoric sites with TP and at least four historically abandoned villages where middens can still be easily identified by walking over the ground. Samples were collected from the current village, historical villages, off-site forest and agricultural contexts and from three prehistoric sites. Results discussed here are from occupational contexts that include the current village and two villages abandoned in the past 100 years and from 'off-site' contexts including forest and secondary forest or grass and scrub fallow.

Samples were collected from 743 locations using a 8 cm bucket auger to extract a core up to 2 m deep. Most samples were collected at 1 m intervals along transects ranging in length from 3 to 52 m. Further samples were collected from activity areas with restricted size such as manioc processing areas that are a few meters across. Each sample location had a minimum of two samples at 0–5 cm and 5–10 cm depths with deeper samples taken at 10 cm depth intervals. Middens were always sampled to greater depths (minimum 60 cm) due to their height (up to approximately 40 cm) above the former soil surface, producing 30 to 40 cm of dark topsoil.

The current and historical villages provide soil samples from known discrete functional zones in an ethnoarchaeological context (Figs. 8.2, 8.3, 8.4, 8.5, 8.6, and 8.7). These zones include: (1) center of plaza in the context of the central men's house and cemetery; (2) midrange area of the plaza; (3) margins of the plaza 0–20 m in front of the houses; (4) house floors; (5) backyard activity areas; (6) refuse disposal areas (middens); and (7) defecation areas in bushes behind houses. Localized areas of specific activities were sampled within these zones including food processing

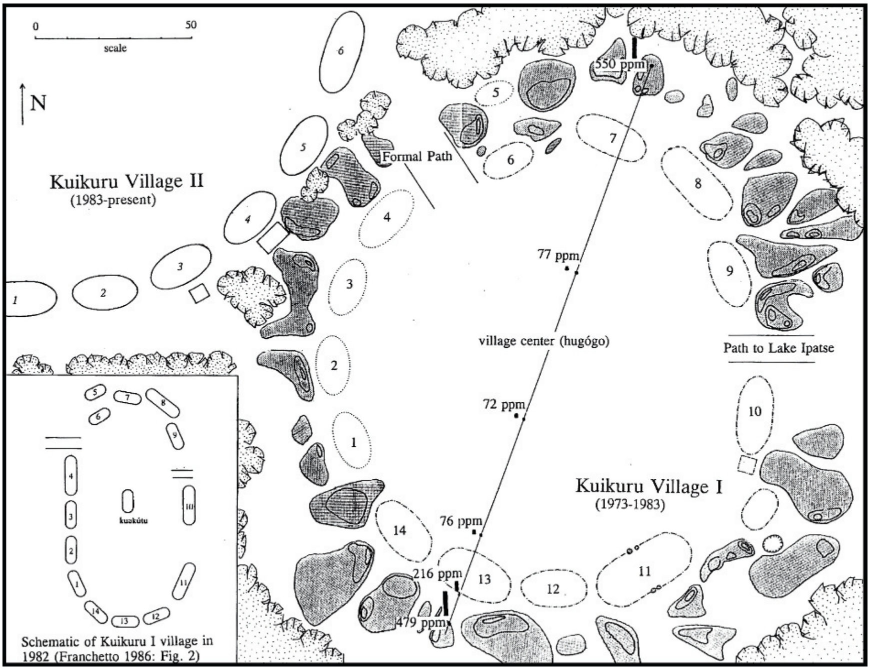


Fig. 8.2 Map of Kuikuru Village I occupied from 1973 to 1983 with phosphate fractionation sums shown. Contours show the varying height of the middens, typically higher at the edge of the backyard and along trails (Heckenberger 1996)

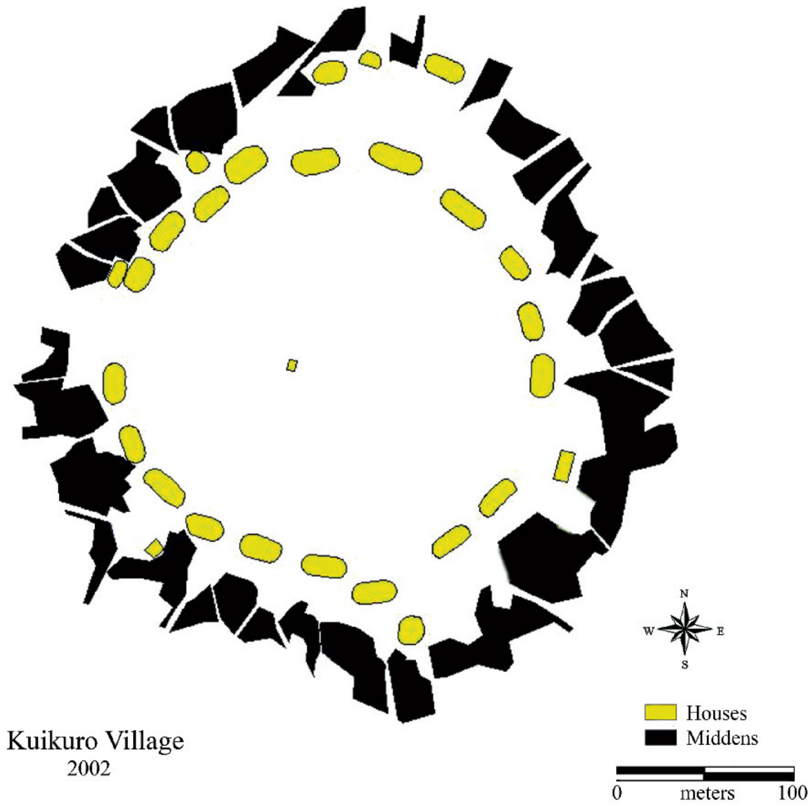


Fig. 8.3 Map of current Kuikuro village. Black represents trash middens or areas of incipient ADE formation separated by trails leading from the backs of houses out of the village. The domestic area lies in and around the houses and the square in the middle is the location of the men's house and ritual center of the village

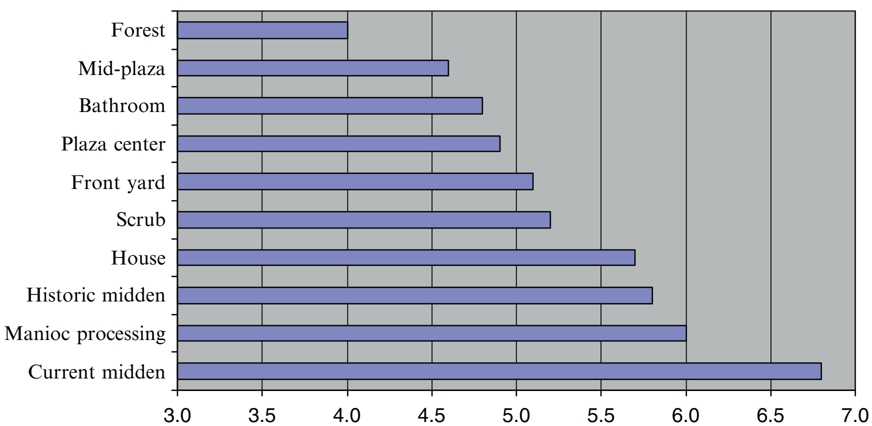


Fig. 8.4 Mean soil pH from level 0–5 cm

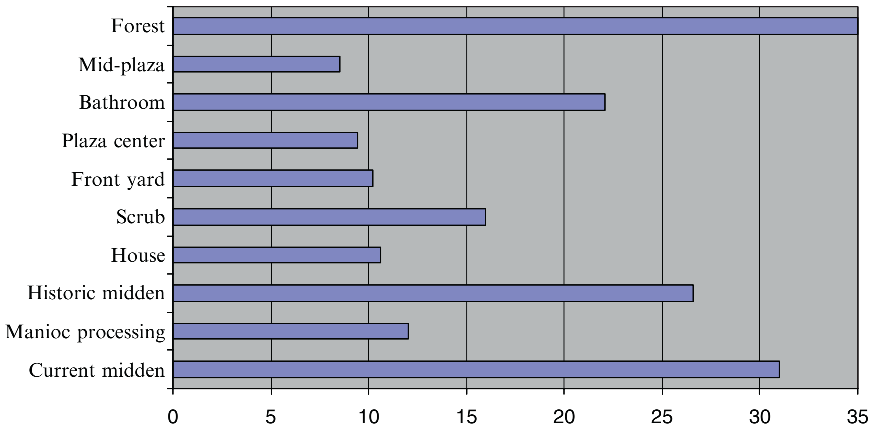


Fig. 8.5 Mean organic carbon (g kg^{-1}) from level 0–5 cm

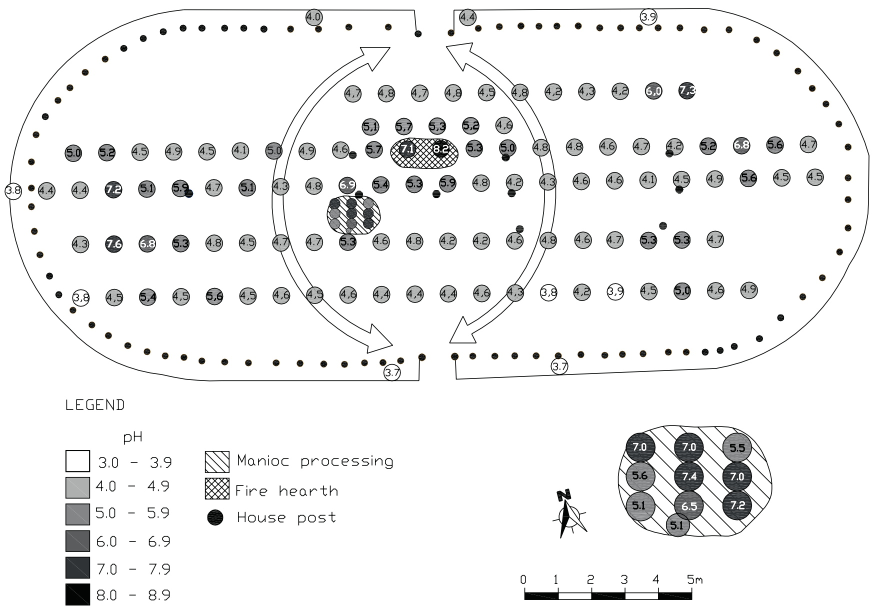


Fig. 8.6 Sketch map indicating pH from the surface level 0–5 cm inside a house. Activity areas in the house include the work area near the front door (in bottom of Figure), cooking and eating area at the back of the house, passage areas (arrows), sleeping areas located on left and right ends, manioc processing, fire hearths, and edge of house in wall recess

(fish butchering, manioc processing, corn grinding), cooking and heating hearths, eating, sleeping, work, and high traffic areas within and around houses that will provide additional detail on soil variation resulting from differing use of domestic space. The four households sampled (in one case the house had burned down

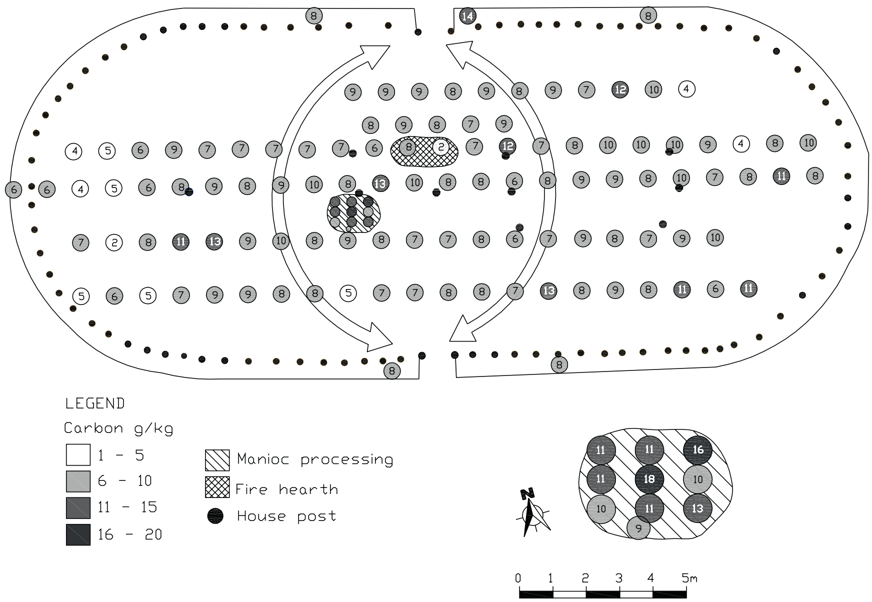


Fig. 8.7 Sketch map indicating OC (g kg^{-1}) from the surface level 0–5 cm inside a house. Activity areas in the house include work area near the front door (in bottom of figures), cooking and eating area at the back of the house, passage areas (arrows), sleeping areas located on left and right ends, manioc processing, fire hearths, and edge of house in wall recess

7 months earlier) were chosen because they are the oldest houses in the village, ranging in age from about 7 to 10 years.

8.4 Laboratory Analyses

Soil sample preparation and analyses were carried out at the Emilio Goeldi Museum (MPEG), Department of Ecology, in Belem, Pará. Samples were air-dried at room temperature in plastic trays in an open air room for 2–3 days. Samples were then prepared for analysis by breaking large soil aggregates when necessary with a wooden rolling pin, however, samples were not ground completely in order not to crush charcoal or ceramic fragments. Samples were screened through 2 mm mesh (wiped with alcohol) and the larger than 2 mm portion was stored in a separate bag. Laboratory analyses followed the methods of EMBRAPA (1997) routinely used at the MPEG soils lab. These include: exchangeable Al, Ca, and Mg by 1 M KCl extraction and extractable P, K, Na, Cu, Fe, Mn, and Zn by Mehlich-1. In order to avoid contamination by filter paper, samples were centrifuged for 15 min at 2,500 rpm and the supernatant transferred into sterile 125 cm^3 Nalgene bottles. Main and trace elements were determined by inductively coupled plasma optical emission spectrometry (ICP OES) (Varian) at Pará State University (UEPA), pH was determined in water 1:2.5 with each sample stirred for 2 min, allowed to set for 20 min, and stirred briefly again before reading. Organic carbon (OC) was determined by Walkley-Black modified.

8.5 Preliminary Results

The preliminary results suggest that all of the soil properties analyzed are sensitive indicators of anthropic modifications to the upland soils in the Upper Xingu. The activity areas in the current and historical villages show marked differences from the forest soil in pH, OC, and available nutrients. Results are presented here for pH and organic C in nine activity areas in the current and historical villages. Available nutrients are presented for three areas that include middens, manioc processing, and forest.

The results indicate that average pH, OC, and available nutrients vary greatly among the activity areas. The data presented in Tables 8.1 and 8.2 show the large

Table 8.1 Mean pH in diverse activity areas in the current village and offsite

		0–5 cm				5–10 cm			
Activity area	n	Mean	Min	Max	CV	Mean	Min	Max	CV
Forest	26	4.0	3.6	4.9	0.06	4.0	3.7	4.3	0.05
Scrub	11	5.2	4.9	5.6	0.04	5.0	4.8	5.5	0.04
Midden	17	6.8	5.8	8.2	0.09	6.7	5.8	7.8	0.08
Historic midden	30	5.8	5.1	6.4	0.06	6.0	5.2	6.4	0.04
Manioc	31	6.0	5.9	7.4	0.13	4.9	4.2	6.4	0.39
House	237	5.7	3.8	8.6	0.17	5.0	3.8	8.3	0.20
Plaza margin	22	5.1	3.7	6.6	0.13	4.3	3.9	5.0	0.07
Mid-plaza	33	4.6	4.3	5.1	0.04	4.4	4.1	4.8	0.03
Plaza center	49	4.9	4.0	6.9	0.10	4.6	3.9	6.1	0.10
Bathroom	37	4.8	4.2	5.3	0.04	4.9	4.7	5.2	0.02

Table 8.2 Mean organic carbon (g kg^{-1}) in diverse activity areas in the current village and offsite

		0–5 cm				5–10 cm			
Activity area	n	Mean	Min	Max	CV	Mean	Min	Max	CV
Forest	26	35.0	18.4	57.4	0.30	23.7	13.8	37.2	0.27
Scrub	11	16.0	10.7	22.9	0.24	12.1	10.3	4.2	0.10
Midden	17	31.0	16.5	48.8	0.30	22.0	8.8	41.4	0.37
Historic midden	30	26.6	11.0	42.7	0.25	25.6	12.2	41.3	0.34
Manioc	31	12.0	4.1	19.4	0.35	9.8	4.7	19.4	0.39
House	237	10.6	1.6	25.5	0.37	9.3	2.4	21.0	0.36
Plaza margin	22	10.2	5.3	20.1	0.32	9.3	5.7	15.2	0.21
Mid-plaza	33	8.5	4.0	18.1	0.32	8.6	4.4	12.9	0.22
Plaza center	49	9.4	3.6	16.6	0.30	9.3	4.2	15.8	0.31
Bathroom	37	22.1	12.7	39.6	0.29	19.1	12.0	40.0	0.29

variations of averages of pH and OC between the different activity areas. In the 0–5 cm level, average soil pH is lowest in the forest (4.0) and highest in the current middens (6.7). Average OC from the surface level (0–5 cm) is lowest in the mid-plaza (8.5 g kg^{-1}) and highest in the forest (35 g kg^{-1}). Available nutrients also display marked differences in their concentrations between the three areas tested. Available phosphorous, for example, averages only 8.9 mg kg^{-1} in the upper 5 cm of forest soil and 1,394 mg kg^{-1} in the same level in middens. In the manioc processing areas average available P is 35 mg kg^{-1} at the surface level and rises to 108 mg kg^{-1} at 20–30 cm depth. These marked differences bode well for further research that will attempt to correlate soil signatures to activity areas using multi-variate statistics.

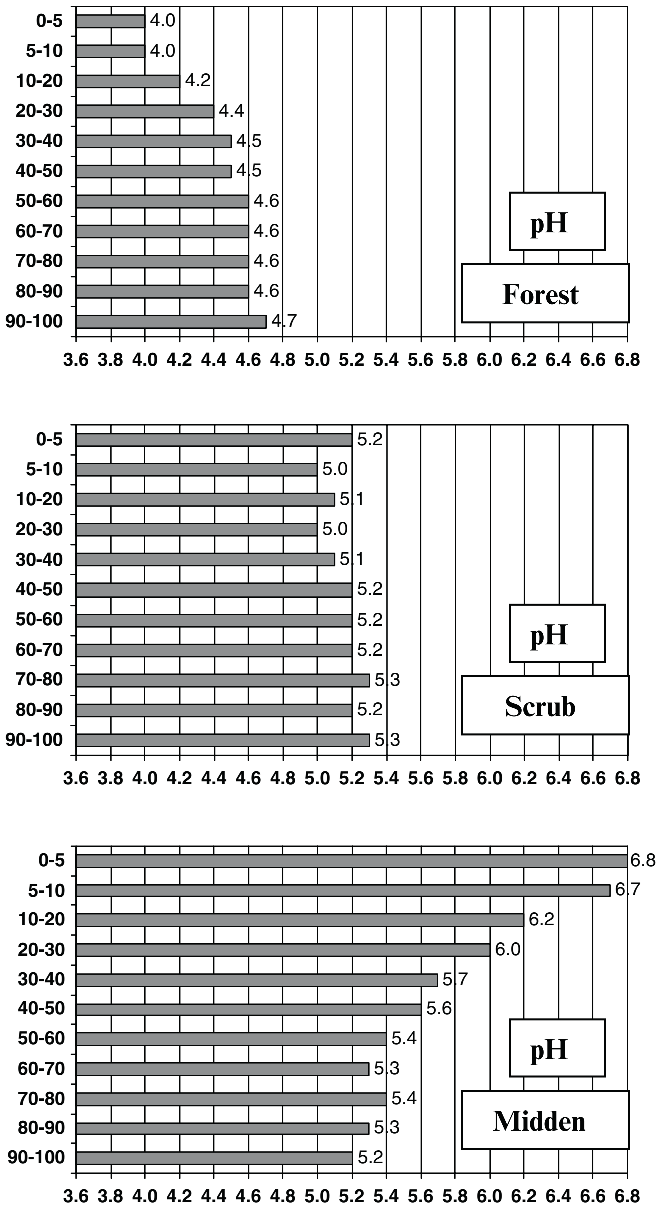
The coefficient of variation (CV) serves as a measure of the dispersion of results and has a minimum value of zero. The CV is useful for comparing groups of data with different means. A small number of samples would have a tendency to elevate the CV and so this measurement should be used with care when dealing with small sample sizes. The results suggest that some soil properties have a greater variation in certain activity areas. For example, as expected, there is more variation in the pH in level 0–5 cm in domestic areas (CV = 0.17, n = 237) than in middens (CV = 0.09, n = 13) or forest (CV = 0.06, n = 26). Organic C also reflects this. The variation in OC in domestic areas (CV = 0.37, n = 237) is higher than middens (CV = 0.3, n = 17) and forest (CV = 0.3, n = 26).

8.5.1 Baseline Soil Properties – Forest Soils

Baseline levels of soil properties were approximated by sampling an area of forest distant from the village and archaeological sites. Averages for pH and OC are based on 26 samples from each level 0–5, 5–10 and 10–20 cm, collected along three transects, and a lesser number of samples that were collected from greater depths down to 2 m. The pH for all forest samples varies between a minimum of 3.6 and maximum of 5.0. The mean is 4.0 in the first 10 cm, increases to 4.4 at the 20–30 cm level and increases gradually to 4.7 at 1 m depth (Fig. 8.8). For depths from 1 to 2 m, mean pH varies between 4.6 and 4.8. OC is high in the forest in the upper 10 cm (35.0 g kg^{-1} at 0–5 cm and 23.7 g kg^{-1} at 5–10 cm) due to the organic material accumulated on the surface. OC decreases gradually from 14.4 g kg^{-1} at level 10–20 cm to 3.1 g kg^{-1} at 1 m depth and varies between 1.8 and 2.6 g kg^{-1} at depths greater than 1 m.

In general, the available nutrients in forest soil present relatively low levels in comparison to activity areas. Nutrient levels generally diminish with depth. Mean phosphorous for 12 samples, 8.9 mg kg^{-1} in the 0–5 cm surface level, diminishes gradually, reaching the limit of detection at around 60 cm depth. Similarly, sodium starts at 3.2 mg kg^{-1} at 0–5 cm and is close to 0 at about 50 cm and potassium starts at 17.9 mg kg^{-1} in the surface level and diminishes to zero by 80 cm depth. Other nutrients also diminish from the surface (Ca = 8.9, Mg = 3.6, Cu = 0.3, Mn = 12.5,

Fig. 8.8 Mean soil pH by level to 100 cm depth



and Zn = 2.2 mg kg^{-1}) down to 1 m depth (Ca = 0.2, Mg = 0.4, Cu = 0.0, Mn = 2.3, and Zn = 0.7 mg kg^{-1}).

The exceptions are exchangeable iron and aluminum. The forest soil contains high levels of iron, especially in the upper levels. Average Fe is above 1,000 mg kg^{-1} from the surface level to level 20–30 cm and then diminishes to 305 mg kg^{-1} at 1 m depth.

Aluminum has a maximum average of 58.2 mg kg^{-1} in level 0–5 cm and a minimum average of 11.3 mg kg^{-1} in level 90–100 cm but the level of aluminum varies significantly. For example, in 12 samples from the surface level 0–5 cm, there was a minimum of 12.2 mg kg^{-1} and a maximum of 154.3 mg kg^{-1}.

8.5.2 Middens

Middens typically lie on the edge of the backyard and stretch along trails leading out from the village. Household, food processing, and craft production refuse along with yard and plaza cleanings are added to the middens. This material largely consists of ash and charcoal, manioc peelings and fiber, fish and animal remains, fruit remains, wood chips, grass and leaves, palm fiber, and broken ceramics. Decomposition of all of this organic material gives middens the aspect of a compost pile leaving a distinct anthropic soil that is obvious by its dark color to a depth (or height above original soil surface) of up to approximately 30–40 cm (Fig. 8.10). Households in the Kuikuro community typically plant nutrient demanding crops (annuals and perennials including fruit trees) in the trash middens behind their homes. The residents were also observed improving the soil in manioc gardens adjacent to the village by adding organic refuse. Another practice that was observed is the spreading of household organic refuse adjacent to (behind) middens, in effect expanding them, with the reported objective of improving the soil for future cultivation of (homegarden) crops.

The preliminary results seem to support the hypothesis that middens are the areas of greatest anthropogenic impact on the soil and corroborate the observation that middens are formed from the disposal of organic refuse mounded to a height of up to approximately 40 cm above the original soil surface. Furthermore, preliminary results suggest a human impact on the soil below recent middens (<25 years) to a depth of at least 1 m (Table 8.4). The data come from 17 sample locations in five different middens in the current village. Four of the middens are ‘well developed’, up to 25 years old. The other midden is more recent, just a few years old or in the initial stages of development. Further results for pH and OC come from middens in two historically abandoned villages that display differences from the ones in the current village. As expected, the middens exhibit consistently high levels of the majority of chemical properties analyzed compared to the other activity areas and forest soils (Schmidt and Heckenberger 2006).

While the pH of forest soil begins low and rises with depth, the pH of midden soils begins high and diminishes with depth (Fig. 8.8). In the first 10 cm of middens, the mean pH from 17 samples is close to neutral (6.8 in 0–5 cm and 6.7 in 5–10 cm) and stays above 6.0 until approximately 30 cm depth. From 30 cm, the pH gradually diminishes to 5.2 at 1 m depth. It is less acid than the forest soil (pH = 4.7) at the same depth indicating that the midden has an influence on soil pH to at least 1 m depth. Between 1 and 2 m, the soil beneath the midden is, in fact, more acid (4.7 at 100–110 cm, 4.6 at 110–120 cm and 4.5 below 120 cm to 2 m) than the forest soil (4.6–4.8) but this observation is based on only three sample locations. There is a possibility that this difference could be due to natural variation and we await the results from additional samples. Results from the historic village middens indicate that the pH diminishes over time in surface levels and rises over time at greater depths (Fig. 8.9).

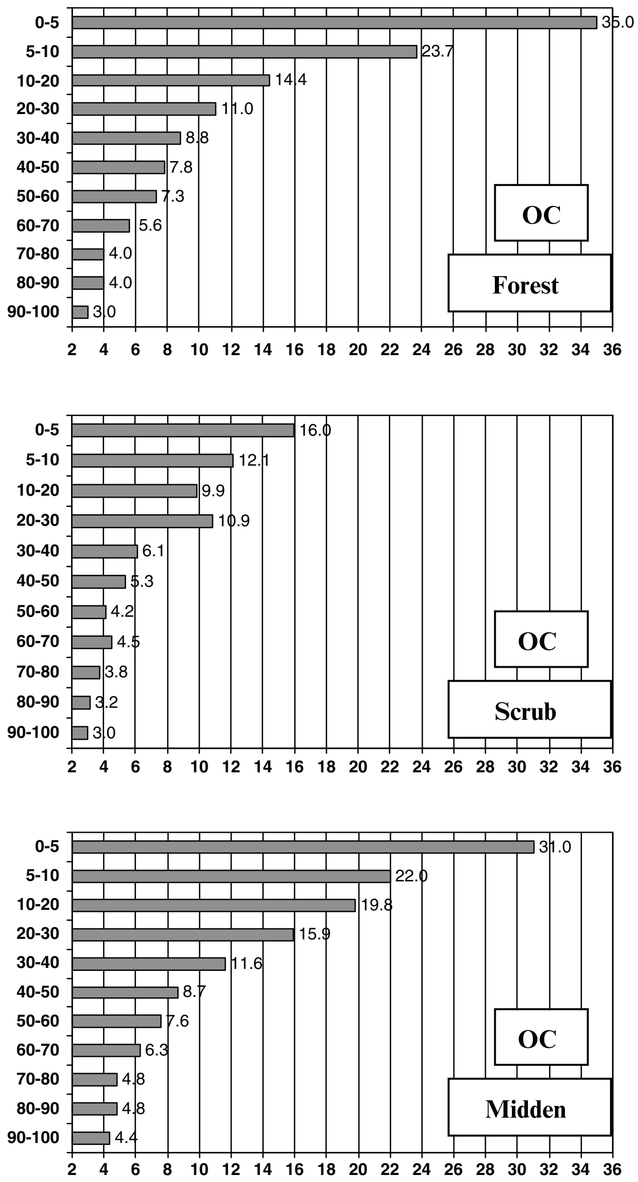


Fig. 8.9 Mean organic carbon (g kg^{-1}) by level to 100 cm depth

Fig. 8.10 Trash middens in current Kuikuro village. Refuse is piled up to a height of approximately 40 cm at the edge of the backyard and along trails leading out of the village

Average levels of OC in the upper 10 cm of middens (31.0 g kg^{-1} at 0–5 cm and 22.0 g kg^{-1} at 5–10 cm) are similar to forest soil. Below this, OC appears to maintain slightly higher levels than the forest soil to a depth of at least 1 m (Fig. 8.9). Average OC diminishes gradually from 19.8 g kg^{-1} at level 10–20 cm to 6.3 g kg^{-1} at 60–70 cm and 4.4 g kg^{-1} at 90–100 cm. Between 1 and 2 m, OC varies between 1.2 and 3.6 g kg^{-1}, similar to forest soil.

Samples from only seven locations have been analyzed so far for available nutrients. We can see, as expected, that there is a great horizontal variation in the results obtained both between middens and within middens that probably reflects the variable deposition and incomplete mixture of different types of organic refuse. The data suggest a tendency for nutrients to diminish with depth. The majority of elements in middens (P, Na, K, Ca, Mg, Mn, and Zn) are substantially elevated above the forest soils to at least 1 m depth (Tables 8.3 and 8.4). Copper appears to be slightly elevated to approximately 60 cm depth. Levels of aluminum and iron are lower than the forest soils (Table 8.5).

There is frequently an abrupt fall in nutrient levels at depths of about 30 or 40 cm. This makes sense as middens are formed from organic material piled to an approximate height of 30 to 40 cm but with significant spatial variation. They are highest bordering the back yard and along the trails leading away from the village. This sudden drop in nutrient levels can be seen in the majority of nutrients, especially P, Na,

Table 8.3 Mean averages for pH, organic carbon, and available nutrients in an area of forest (depth in cm below surface C in g kg^{-1}, Na and K in cmolc dm^{-3}, and the remainder in mg kg^{-1})

Depth	n	pH	C	n	P	Na	K	Al	Ca	Mg	Cu	Fe	Mn	Zn
0–5	26	4.0	35.0	12	8.9	3.2	17.9	58.2	8.9	3.6	0.3	1,020	12.5	2.2
5–10	26	4.0	23.7	12	5.8	2.4	8.6	35.0	2.0	1.8	0.2	1,129	9.3	1.7
10–20	26	4.2	14.4	12	4.3	1.2	3.4	22.8	0.8	0.5	0.2	1,022	4.2	1.1
20–30	8	4.4	11.0	4	2.8	0.1	4.1	45.7	2.6	1.1	0.4	1,165	5.7	1.3
30–40	8	4.5	8.8	4	3.2	1.6	2.8	13.2	0.1	0.3	0.2	971	5.3	1.1
40–50	8	4.5	7.8	4	1.2	1.0	1.2	28.9	0.6	0.8	0.3	726	4.5	1.1
50–60	5	4.6	7.3	2	0.8	0.0	1.3	29.8	0.6	0.7	0.3	664	4.1	0.9
60–70	4	4.6	5.6	2	0.0	0.2	0.1	28.2	0.7	0.5	0.1	480	2.9	0.7
70–80	4	4.6	4.4	2	0.0	0.0	0.4	25.4	0.6	0.3	0.2	377	2.7	0.8
80–90	4	4.6	4.0	2	0.0	0.0	0.0	26.7	0.6	0.4	0.1	373	2.7	0.7
90–100	4	4.7	3.1	2	0.0	0.0	0.0	11.3	0.2	0.4	0.0	305	2.3	0.7

Table 8.4 Mean averages for pH, organic carbon, and available nutrients in areas of midden (depth in cm below surface, C in g kg^{-1}, Na and K in cmolc dm^{-3}, and the remainder in mg kg^{-1})

Depth	n	pH	C	n	P	Na	K	Al	Ca	Mg	Cu	Fe	Mn	Zn
0–5	17	6.8	31.0	7	1,390	161	624	1.3	1,038	3.9	0.2	276	161	91.8
5–10	17	6.7	22.0	7	1,737	128	494	2.7	1,036	3.8	0.3	315	109	16.5
10–20	13	6.2	19.8	7	1,524	80	388	4.1	749	4.4	0.8	352	110	11.7
20–30	13	6.0	15.9	7	933	135	396	3.1	1,201	6.1	0.9	578	105	20.3
30–40	13	5.7	11.6	7	312	54	191	3.4	604	5.1	0.6	349	64	11.4
40–50	13	5.6	8.7	7	121	45	136	3.2	382	1.7	0.4	445	56	4.5
50–60	13	5.4	7.6	7	56	39	100	2.8	211	1.4	0.5	243	83	12.5
60–70	10	5.3	6.3	4	82	66	147	9.7	242	1.7	0.2	298	55	7.0
70–80	9	5.4	4.8	3	21	55	86	3.4	182	1.5	0.1	175	113	12.6
80–90	9	5.3	4.8	3	55	58	118	3.6	153	1.1	0.2	356	8	1.0
90–100	9	5.2	4.4	3	23	57	115	1.1	215	1.4	0.1	249	5	0.4

Table 8.5 Statistics (mean, minimum, maximum, coefficient of variation) of samples from areas of forest (C in g kg^{-1}, Na and K in cmolc dm^{-3}, and the remainder in mg kg^{-1}; levels 0–5, 5–10, 10–20 cm, n = 26 for pH and C, n = 12 for remainder; level 20–30 cm n = 8 for pH and C, n = 4 for remainder)

Depth (cm)	Statistic	pH	C	P	Na	K	Al	Ca	Mg	Cu	Fe	Mn	Zn
0–5	Mean	4.0	35.0	8.9	3.2	17.9	58.2	8.9	3.5	0.3	1,122	12.5	2.2
	Min	3.6	18.4	5.0	0	0	12.2	0	0	0	611	0	0.1
	Max	4.9	57.4	14.6	18.1	77.6	154.3	49.0	17.3	0.8	1,419	54.9	6.1
	CV	0.06	0.3	0.35	1.69	1.18	0.78	1.65	1.54	0.74	0.23	1.46	0.69
5–10	Mean	4.0	23.7	5.8	2.4	8.6	35.0	2.0	1.7	0.2	1,355	9.3	1.7
	Min	3.7	13.8	4.3	0	0	9.6	0	0	0	1,127	0	0
	Max	4.3	37.2	9.6	12.4	18.1	78.4	6.4	7.2	0.8	1,628	44.2	2.8
	CV	0.05	0.27	0.25	1.84	0.61	0.7	0.93	1.13	0.88	0.12	1.38	0.54
10–20	Mean	4.2	14.4	4.3	1.2	3.4	22.8	0.8	0.5	0.2	1,362	4.2	1.1
	Min	3.6	9.8	2.5	0	0	7.6	0	0	0	1,065	0	0
	Max	4.6	26.7	12.1	7.9	10.0	46.4	3.6	1.2	0.6	1,551	14.0	1.9
	CV	0.06	0.29	0.62	2.01	0.85	0.64	1.19	0.81	1.03	0.11	1.05	0.52
20–30	Mean	4.4	11.0	2.8	0.1	4.1	45.7	2.6	1.1	0.4	1,165	5.7	1.3
	Min	3.7	7.9	1.8	0	0.5	7.7	0	0.4	0.3	1,043	2.3	1.0
	Max	4.7	17.4	3.9	1.0	10.2	143.3	10.0	2.9	0.6	1,226	7.3	1.7
	CV	0.08	0.34	0.43	3.25	1.07	1.43	1.87	1.1	0.38	0.07	0.4	0.2

K, Ca, Mg, Mn, and Zn. For example, mean available P falls from 1,524 mg kg^{-1} at level 10–20 cm to 933 mg kg^{-1} at 20–30 cm, 312 mg kg^{-1} at 30–40 cm, and 121 mg kg^{-1} at 40–50 cm. This abrupt drop is masked when we observe averages because of the spatial variation in midden height. If we look at individual profiles the drop is even more apparent. One example is one of the 'well developed' middens where P drops from 1,434 mg kg^{-1} at level 20–30 cm to 37 mg kg^{-1} at 30–40 cm.

We can observe a possible abrupt change in extractable iron at the levels 20–30 cm or 30–40 cm. In some cases extractable Fe rises at these levels. Using the same previous example of a 'well-developed' midden, Fe rose from 377 mg kg^{-1} at level 20–30 cm to 1,044 mg kg^{-1} at 30–40 cm, similar to the high levels (above 1,000 mg kg^{-1}) in the upper levels of forest soil. This increase in iron below the midden is possibly due to reaching the original soil surface. There is also a possibility that available Fe is reduced in midden soils by fixation suggested by the low averages of this element in midden soils down to 1 m depth. The highest average Fe, 578 mg kg^{-1}, is found in level 20–30 cm in the midden, just about where we would expect (on average) the auger to reach the original soil that corresponds to the previous soil surface. This is only half of the value for the same level in forest soil (1,165 mg kg^{-1}), to be expected because of the variation in the height of the middens. There is also mixing of the original soil below with midden material through processes of bioturbation (Lima et al. 2002). Analysis of more samples for total Fe will help make this pattern clearer (Table 8.6).

As predicted, exchangeable aluminum in middens is low (Schmidt and Heckenberger 2006, in press). Average Al, which varies between 11.3 and 58.2 mg kg^{-1} in 1 m depth of forest soil, varies between just 1.1 and 9.7 mg kg^{-1} in midden soil down to 1 m. Low levels of exchangeable Al could occur because the upper levels of middens (made up of organic refused piled above the original soil surface) stay, in part, separate from the original soil which presents much higher levels of Al. It takes time for bioturbation to mix the upper levels of midden with the original soil beneath. Another explanation is that the available Al is reduced, with the increased pH, by the formation of Hydroxy Aluminum ions that are fixed with clay or organic matter colloids. This could explain why available Al is reduced to a depth of 1 m or more. Ongoing analysis for total Al may help elucidate this question.

Marked differences in nutrient levels between different depths probably reflects the age of the *lixeira* and the height of the mounded organic refuse. A look at the data from middens of different ages (four samples from a midden in the initial years of development and three samples from two 'well developed' middens (maximum 22 years old) suggest marked differences in the levels of some nutrients. The two nutrients that stand out most are available calcium and sodium. They are considerably higher in the older middens. Although only a small number of samples were tested so far, the difference between the older and younger middens for these two elements is marked and consistent. For example, in the upper 5 cm, average Na in the older middens is 332 mg kg^{-1} while it is only 34 mg kg^{-1} in the younger midden. In level 5–10 cm it is 259 and 30 mg kg^{-1} respectively and 135 and 38 mg kg^{-1} in level 10–20 cm. These conspicuous differences continue to at least 1 m depth. In the

Table 8.6 Statistics (mean, minimum, maximum, coefficient of variation) of samples from areas of midden (C in g kg^{-1}, Na and K in cmolc dm^{-3}, and the remainder in mg kg^{-1}; levels 0–5 and 5–10 cm, n = 17 for pH and C, n = 7 for remainder; level 10–20 and 20–30 cm, n = 13 for pH and C, n = 7 for remainder)

Depth (cm)	Statistic	pH	C	P	Na	K	Al	Ca	Mg	Cu	Fe	Mn	Zn
0–5	Mean	6.8	31.0	1,390	162	624	1.3	1,038	3.9	0.2	276	160.6	91.8
	Min	5.8	16.5	887	26	203	0	86	0	0	137	46.8	4.4
	Max	8.2	48.8	1,751	541	1,024	4.0	3,079	13.6	0.8	394	273.6	426.8
	CV	0.09	0.3	0.23	1.25	0.5	1.35	1.06	1.3	1.17	0.36	0.55	1.64
5–10	Mean	6.7	22.0	1,737	128	494	2.7	1,036	3.8	0.3	315	109.1	16.5
	Min	5.8	8.8	221	12	119	0	100	0	0	224	6.6	0.3
	Max	7.8	41.4	3,757	450	802	5.3	1,917	11.7	0.8	432	275.8	45.3
	CV	0.08	0.37	0.72	1.28	0.53	0.74	0.68	1.17	1.01	0.24	1.1	1.21
10–20	Mean	6.2	19.8	1,524	80	388	4.1	749	4.4	0.8	352	110.4	11.7
	Min	5.5	12.0	104	9	130	1.7	1	0	0.1	184	12.3	1.7
	Max	6.9	40.1	2,210	195	865	6.6	1,534	10.8	3.8	451	210.1	24.8
	CV	0.07	0.42	0.48	0.8	0.76	0.38	0.92	0.86	1.81	0.3	0.65	0.81
20–30	Mean	6.0	16.0	933	135	396	3.1	1,201	6.1	0.9	578	105.4	20.3
	Min	5.3	7.2	8	3	42	0	28	0	0.2	377	10.5	1.5
	Max	6.8	30.7	1,434	542	873	5.6	3,453	16.5	3.5	1,157	229.5	46.7
	CV	0.08	0.48	0.53	1.5	0.72	0.73	1.01	1.13	1.31	0.48	0.75	0.78

same way, average Ca is 2,070 mg kg^{-1} in the older middens and 264 mg kg^{-1} in the younger midden at 0–5 cm, 1,595 and 617 mg kg^{-1} at 5–10 cm and 1,424 and 243 mg kg^{-1} at 10–20 cm. This marked difference in Ca also continues to at least 1 m depth. The other nutrients are less conclusive but additional tests of many more samples from middens of different ages should help clarify questions about changes over time.

A comparison of pH between middens from the current village and historical villages reveals differences. Soil pH is approximately one factor lower in the historical middens in the upper levels with a mean of 5.8, minimum of 5.1 and maximum of 6.4 in the surface level and mean of 6.0, minimum of 5.2, and maximum of 6.4 at the 5–10 cm level. At level 40–50 cm pH is the same between the current and abandoned villages. At lower levels the situation turns the opposite. Historical middens have a pH one factor higher with an average of 6.3 at 90–100 cm compared to 5.2 from the current village. This suggests that in the older middens the soil pH has been gradually modified to greater depths over time.

If we look at the middens from the two historically abandoned villages of different ages we see that they do not follow this pattern, but rather the contrary. Soil pH in the older midden (>50 years) averaged slightly higher (6.1 at 0–5 cm) in the upper levels than the younger midden (22–32 years old) (5.7 at 0–5 cm). At level 50–60 cm the older midden has a lower pH than the younger one (5.4 versus 6.2). This suggests that the differences encountered here may not be simply a function of time but could be the result of differences in the quantity and/or type of organic material that was discarded. For example, they could have thrown more fire hearth cleanings (ash and charcoal) in one of the locations. Further research with additional analyses may be able to confirm patterns of changes over time and differences resulting from variations in discarded materials.

8.5.3 Houses

Samples were analyzed for pH and OC from 237 location inside four houses (Fig. 8.11). Houses show greater variation than other areas because of the diverse activities that take place inside them. In the upper 5 cm the pH varies from 3.8 to 8.6 with a mean of 5.7. At the 5–10 cm level it varies from 3.8 to 8.3 with a mean of 5.0. A lesser number of samples were tested from the 10–20 cm level in one house and returned a minimum of 3.8, maximum of 8.3, and a mean of 4.8. Like pH, OC also has a large variation in the house floor. OC in the surface level varied from 1.6 to 25.5 g kg^{-1} with a mean of 10.6 g kg^{-1}. In level 5–10 cm, OC varied between 2.4 and 21.0 g kg^{-1} with a mean of 9.3 g kg^{-1}. Samples tested from level 10–20 cm contain from 2.6 and 14.6 g kg^{-1} of OC with a mean of 8.3 g kg^{-1}.

The variation inside the houses makes more sense when each sample is placed in the context of its particular domestic activity area. Samples with a pH above 7 are all located either in fire hearths or in the manioc processing area. We can see in Fig. 8.6 that there are four distinct areas where pH is elevated including the

Fig. 8.11 Two soil sample transects inside a Kuikuro house (back half of the house is shown with cooking hearth in the center and a sleeping area with hammocks visible at top of photo)

area around the main cooking hearth (upper center in Fig. 8.6) and in the two sleeping areas (on the left and right ends in Fig. 8.6). The elevated pH is more pronounced in the 0–5 cm surface level. In other areas of the house including traffic areas, work areas, and eating areas pH is somewhat elevated above background levels. Soil pH values of less than 4.0 (more acid than forest soils) are located around the edge of the house. OC levels are lowest in hearths (2–5 g kg^{-1}). The heat generated oxidizes organic material and leaves the soil a brighter red color. Locations that have a concentration of higher levels of OC are the manioc processing areas (9–18 g kg^{-1}). The other three houses show similar patterns in pH and organic carbon.

8.5.4 Manioc Processing Areas

The soil surface in manioc processing areas forms a sort of cement pavement, almost always covered with a white crust. The soil is so compact in the upper few centimeters that the soil auger could only perforate the surface with much difficulty. Soil pH is also relatively high (6.0) in these areas, at least in the upper 5 cm. It is interesting to observe the results for aluminum elevated above levels from forest soil. One possible source comes to mind as the relatively recent introduction of aluminum pots for processing manioc. However, a more likely possibility is that the prussic acid from the manioc, liberates fixed Al in the soil, transforming it into extractable Al. Analysis of total Al may help to resolve this question.

The results so far suggest that the soil nutrients in manioc processing areas contain a distinct pattern or signature. In comparing manioc processing areas with other areas (Table 8.7), two elements, sodium (264 mg kg^{-1} at 0–5 cm) and magnesium (38.5 mg kg^{-1} at 5–10 cm) stand out by their levels above the forest soil (Na = 3.2 mg kg^{-1} at 0–5 cm, Mg = 1.7 mg kg^{-1} at 5–10 cm) and are even much higher than middens (Na = 162 mg kg^{-1} no 0–5 cm, Mg = 3.8 mg kg^{-1} no 5–10 cm). Some elements increase with depth as in the case of P, Na, Mg, Mn, and Zn. This could be the result of accelerated leaching from abundant water mixed with prussic acid in manioc juice that seeps into the ground during processing. Further samples are being tested at greater depths to determine the intensity of human influence on the soil from manioc processing.

8.5.5 The Plaza

Samples from the plaza have so far only been tested for pH and OC, but the results fit previous expectations (Schmidt and Heckenberger 2006, in press). The space in the plaza between the center and the edge (mid-plaza) has the lowest average soil pH in the village ranging from 4.3 to 5.1 with a mean of 4.6 in the surface level and from 4.1 to 4.8 with a mean of 4.4 at the 5–10 cm level. The slightly elevated pH above the level of the forest could be due to the absence of litter (litter has the effect of increasing acidity) and the practice of removing vegetation, piling it up, and burning it, a practice that introduces ash into the soil. The test for OC ranged from 4.0 to 18.1 with a mean 8.5 g kg^{-1} in the surface level and from 4.4 to 12.9 and a mean of 8.6 at the 5–10 cm level. Like pH, OC is also the lowest of all the activity areas in the village, except for isolated spots where it is elevated possibly due to the practices of burning weeds and digging holes to deposit and bury vegetation that may or may not also be burned.

The center and margin of the plaza had higher pH and OC values with more variation than the mid-plaza because of the activities such as food consumption, ephemeral fires, urination, and burials (plaza center). In the center of the plaza, soil pH ranged from 4.0 to 6.9 with a mean of 4.9 at the surface level and from 3.9 to 6.1 with a mean of 4.6 at the 5–10 cm level. On the margin of the plaza soil pH ranged from 3.7 to 6.6 with a mean of 5.1 at level 0–5 cm and from 3.9 to 5.0 with a mean of 4.3 at 5–10 cm. In the center of the plaza, OC varied between 3.6 and 16.1 g kg^{-1} with a mean of 9.4 g kg^{-1} at 0–5 cm and between 4.2 and 15.8 with a mean of 9.3 g kg^{-1} at level 5–10 cm. On the margin of the plaza OC ranged from 5.3 to 20.1 with a mean of 10.2 at level 0–5 cm and from 5.7 to 15.2 with a mean of 9.3 at 5–10 cm. Both the center and the margin of the plaza had variation in pH and OC similar to samples from inside houses.

Table 8.7 Statistics (mean, minimum, maximum, coefficient of variation) of samples from manioc processing areas (C in g kg^{-1}, Na and K in cmolc dm^{-3}, and the remainder in mg kg^{-1}; level 0–5 and 5–10 cm, n = 31; level 10–20 and 20–30 cm, n = 28)

Depth (cm)	Statistic	pH	C	P	Na	K	Al	Ca	Mg	Cu	Fe	Mn	Zn
0–5	Mean	6.0	12.0	35	264	430	11.7	68	1.2	0.1	416	7.4	1.0
	Min	5.9	4.1	1	42	15	0	0	0	0	189	0.4	0
	Max	7.4	19.4	188	1,017	1,955	44.2	520	9.0	0.6	625	40.5	6.2
	CV	0.13	0.35	1.47	1.07	1.22	0.94	1.98	1.74	0.94	0.3	1.32	1.68
5–10	Mean	4.9	9.8	21	100	194	57.3	96	38.5	0.1	363	6.4	0.5
	Min	4.2	4.7	0	3	6	1.4	1	0	0	116	0.9	0
	Max	6.4	19.4	157	561	1,054	137.9	466	271.5	0.9	527	36.7	2.9
	CV	0.12	0.39	1.77	1.37	1.42	0.76	1.15	1.73	1.2	0.31	1.17	1.34
		n = 28											
10–20	Mean	4.4	8.4	32	33	84	75.6	38	15.3	0.3	438	5.8	0.9
	Min	3.9	5.0	0	0	15	10.5	0	0	0	256	0.2	0.1
	Max	5.2	16.7	144	218	488	136.5	183	72.5	0.6	679	28.0	3.7
	CV	0.09	0.29	1.13	1.39	1.15	0.54	1.2	1.3	0.52	0.28	1.03	0.9
		n = 28											
20–30	Mean	4.4	6.9	108	5	85	75.1	28	9.8	0.4	608	25.9	3.2
	Min	3.9	3.5	1	0	6	6.0	0	0	0.1	313	0.3	0.3
	Max	5.2	16.7	389	36	286	134.2	137	48.3	0.9	828	75.3	14.0
	CV	0.09	0.35	0.96	1.81	0.87	0.56	1.25	1.17	0.6	0.22	0.87	0.98

8.5.6 Village Surroundings

An area of scrub (fallow field or regenerating forest consisting of grass and bushes that usually burns in the dry season) located approximately 300 m from the current village has a higher pH than the forest soil to a depth of 2 m. Soil pH is almost uniform through the profile, varying between 5.0 and 5.4 in the first 120 cm and increasing to 5.5 until 2 m. The elevated pH to a depth of at least 2 m may be the result of ash and charcoal additions to the soil from clearing and burning for cultivation, continued additions from the practice of coivara to burn timber and stumps not consumed in the first fire and to dispose of crop residue and weeds, and also from repeated seasonal burning of the scrub vegetation after field abandonment. Ash and charcoal are mixed into the upper horizon of the soil over a portion of the area from hoeing during planting. The grass scrub soil in the first 10 cm has half the OC (16.0 g kg^{-1} at 0–5 cm and 12.1 g kg^{-1} at 5–10 cm) of the forest soil presumably due to the absence of litter. OC levels below 10 cm down to 1 m continue similar to or slightly lower than forest soils.

A "latrine area" located outside the village at approximately the same distance as the above scrub area is located in a former field with scattered trees, bushes, grass, and bare ground that is beside a well-used trail and occasionally used to relieve oneself. All signs of any act of defecation are gone by the next day, carried away by ants and other insects. This area presented a somewhat elevated pH (ranging from 4.2 to 5.3 with mean of 4.6 at 0–5 cm and ranging from 4.7 to 5.2 with a mean of 4.9 at 5–10 cm) and an unexpectedly high OC level (ranging from 12.7 to 39.6 g kg^{-1} with a mean of 22.1 g kg^{-1} at 0–5 cm and from 12 to 40 g kg^{-1} and a mean of 19.1 g kg^{-1} at 5–10 cm). The elevated pH and OC could be attributed to previous use of the area as an agricultural field as well as seasonal burning and defecation.

8.6 Discussion

The preliminary results suggest that all of the soil properties analyzed are possible indicators of anthropic modifications to the upland soils in the Upper Xingu. Results show that elevated pH is a strong indicator of changes to the soil provoked by human activities. Averages of soil pH were higher in village activity areas than the forest soils in all cases, even in areas with relatively less human impact such as the mid-plaza and fields surrounding the village. Soil pH, by itself or in conjunction with other soil properties, could serve as a simple and inexpensive indicator of human soil modification for the purposes of survey or mapping of archaeological sites and outlying activity and agricultural areas.

The elements in activity areas that stand out as especially high or low in comparison to other activity areas will be fundamental in the establishment of 'soil signatures' for the various activity areas. These marked differences in soil properties will be used in the continuation of the research attempting to separate activity areas and define soil signatures or predictable patterns for each area using multivariate data analysis (Linderholm and Lundberg 1994). For example, the initial data seem to agree with the expected results that middens will display the highest levels of the greatest range of soil properties and that exchangeable Al is absent or very low in the upper levels of middens due to incomplete mixing with the underlying soil or fixation. Also, initial results suggest that certain nutrients, Na and Fe in particular, are elevated for manioc processing areas possibly making them distinguishable from other activity areas by having a unique soil signature. Fire hearths will display characteristically high pH, low OC, and elevated levels of certain other nutrients. These signatures will then be useful in interpreting data from archaeological excavations. For example, the signature will be compared with soil data from suspected hearths in excavations to provide further evidence for their interpretation in the archaeological record. In another example, data from systematic sampling may reveal certain areas deemed likely manioc processing locations because of a chemical makeup of the soil similar to the characteristic signature.

Activity areas in the current village are constantly shifting. Outdoor activities such as hearths and manioc processing may shift location at intervals of 1–2 years in many cases. The location of some activities may be relatively long-lived such as manioc processing under a preferred shade tree in the backyard. This area, however, may have begun as midden where fruit trees are often planted to take advantage of the rich, black soil. Homes typically last 5–10 years before they must be rebuilt and homes are sometimes burned in accidental fires. A new home is often built in front of or behind the old home or it may be overlapping but with a shifted position. Each activity area must be evaluated for its time in use and location possibly over a former activity area or midden. In some cases an activity area is overlapping a previous activity area. This was recorded in several cases. The house in Figs. 8.6 and 8.7, for example, is overlapping the footprint of the previous house. The back half of the current house lies over the front half of the previous house and the front half lies over the front yard of the previous house. In another example, the chief's manioc processing area is located under a large mango tree in an area that was previously midden. Activity areas such as manioc processing on top of a former midden could result in compaction, leaching, and cementing together of the soil, creating an extremely hard, compact soil over time, similar to soil that is sometimes encountered in archaeological excavations in various parts of the Amazon. In short, *terra preta* sites are made up of a shifting mosaic of activities having varying impacts on the soil over timescales of decades, centuries, or millennia. This observation is in conformance with the *terra preta* formation scenario presented earlier by Woods (1995).

It must be considered that at least several cycles of planting and abandonment may have occurred in the sampled areas (including the current village) in the centuries before or after 1500. There are at least four known historically abandoned villages close to the site of the current village (<2 km). Also the current village lies between two prehistoric sites, Nokugu (occupied at least since AD 800), just 2 km away, and Hialugihiti, 4 km away. The implication is that the soil may have undergone changes from relatively intensive agriculture and/or numerous cycles of planting and fallow along with the possible effects of seasonal burning. Those activities could result in residual anthropogenic impacts on the soil in the sampled area from prehistoric or historic agriculture. Further research is necessary to understand the impacts of prehistoric and contemporary agriculture on soils in the region.

Observations of Kuikuro cultivation practices on the edge of the village seem to offer a model for the development of so-called TM observed surrounding TP at archaeological sites. In fields close to the village, the Kuikuro were observed enriching the soil with mulch and organic waste, along with the usual burning of piles of crop residue and dry vegetation (*coivara*). Soils in these areas were observed to be darker (also apparent in photos) than the typical red soils. Similarly, middens are expanded by spreading organic refuse with the intention of improving the soil for later cultivation. Additions of kitchen wastes, ash, charcoal, and weeds over time would have the effect of raising pH and OC along with some nutrients but would not become black *terra preta* as in the mounded trash middens. It would become darker than natural soils eventually resulting in brown soils or TM. It seems, from observations and interviews in the Kuikuro village, that potsherds are most often thrown in parts of the middens closer to the house and therefore become more frequent in parts of the blackest soil while remaining sparse in the cultivation areas.

8.7 Conclusion

Results suggest that the Kuikuro Amerindian community modifies the soil over the entire village area and surroundings as a result of ritual, domestic, and economic activities as well as refuse disposal and cultivation. Village zones including the plaza center, plaza margins, house floors, backyards, middens, food processing and consumption areas, craft production areas, and surrounding fields, display soil parameters that are distinct from forest soils and one another. The current and historical villages offer a model for the processes of archaeological site formation in the Upper Xingu that can be extended to other regions of South America. Ethnoarchaeological data and observations can provide insights for the interpretation of the archaeological record. These results from an ethnoarchaeological context have implications for the interpretation of soil data from archaeological sites in Amazonia and beyond.

Learning the processes of ADE formation and the economic systems involved can provide insights into new ways to manage tropical soils. Some writers have argued that improved soil management could allow farmers to support themselves on less land using more intensive and sustainable methods thereby reducing pressure on forested land (Woods and McCann 1999). In short, if we can determine how agriculture supported past populations in Amazonia and some of the specific soil management and production techniques used, we could use this information to increase productivity, efficiency, and sustainability by today's farmers. One could argue that activities by Amerindians in the upper Xingu result in modifications that have the overall effect of improving the soil over a broad area within and around settlements that can benefit crop production both during and after occupation of the sites. It is possible that in prehistoric communities, similar settlement and economic systems (fishing and manioc agriculture and the creation of extensive fertile middens and areas of enriched soil) resulted in a positive feedback loop of soil improvement and crop production that led to agricultural intensification in the region.

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Chapter 9
Indigenous Knowledge About *Terra Preta* Formation

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9.1 Introduction

Throughout the world intensive agricultural land use often has resulted in soil physical and chemical degradation, due to erosion and higher output than input rates of nutrients and OM. In contrast, the intentional and unintentional deposition of nutrient-rich materials within human habitation sites and field areas has in many cases produced conditions of heightened fertility status (Woods 2003). An anthropogenic enriched dark soil found throughout the lowland portion of the Amazon Basin and termed Amazonian Dark Earths (ADE) or *terra preta de índio* (TP) is one such example. Its fertility is the secondary result of the transport of natural and produced foods, building materials, and fuel to prehistoric dwelling places (Woods 1995). These materials and their byproducts were then transformed and differentially distributed within the zone of habitation and associated garden areas. The resulting soil contains high concentrations of black carbon (C) as charcoal (Glaser et al. 2001a); significantly more C, nitrogen (N), calcium (Ca), potassium (K), and up to 13.9 g kg^{-1} P_2O (almost 4 g kg^{-1} available P) (Lima et al. 2002); and significantly higher cation exchange capacity (CEC), base saturation (BS), and pH values than in the surrounding Oxisols (Glaser et al. 2000; Zech et al. 1990). ADE is found at pre-Columbian settlements throughout Amazonia in patches ranging in size from less than a hectare to many square kilometres (Woods and McCann 1999). Today these soils are and presumably in the past were intensively cultivated by the rural population. The enormous total area encompassed by these soils suggests a large sedentary pre-Columbian population (Erickson 2000; Heckenberger et al. 2003). The existence of ADE proves that infertile Ferralsols and Acrisols can be transformed into permanently fertile and refractory TP in spite of rates of weathering 100 times greater than those found in the mid-latitudes. Such a transformation cannot be achieved solely by replenishing the mineral nutrient supply, however; the soil organic matter (SOM) is also of prime importance for insuring the retention of soil nutrients (Zech et al. 1990).

To overcome those limitations of poor soil and low nutrient retention capacity, the majority of farmers today clear and burn (slash-and-burn) new fields after two or three cropping cycles (shifting cultivation). Secondary forest is growing on the abandoned areas and accumulates nutrients and SOM for 5 to 20 years until the

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

next slashing and burning occurs. Slash-and-burn agriculture is the prevalent agricultural practice in the tropics affecting almost one third of the planet's arable land (Giardina et al. 2000; Goldammer 1993).

Changes in land use, particularly by clearing forests, reduce organic carbon by 20% to 50% in the upper soil layers (Sombroek et al. 1993). This reduction of SOM is responsible for soil degradation. A slash-and-burn site investigated by Tiessen et al. (1994) had lost 81% of its litter layer and 29% of its soil C to 15 cm depth over 3 years. Tiessen et al. (1994) concludes that the accelerated SOM decay under agriculture will lead to a mineralization of over half the nutrients in 2 years. Thus agriculture is not sustainable without nutrient inputs beyond 3 years of cultivation, although the release of remaining nutrients can provide for the re-establishment of secondary successions (Tiessen et al. 1994).

Prehistoric land-use was most likely quite different than that practiced today. Only the introduction of steel axes and modern tools for deforestation made it relatively easy to clear forests. Therefore, more effort would have been put into maintaining soil fertility on those areas that had been opened, rather than clearing lands for new fields (Denevan 1996). Inputs of organic char from low temperature burning of weeds and invasive plants would have provided the necessary soil fertility improvement on permanently or semi-permanently cultivated fields. These additions could also have been augmented by the residues of the organics that had accumulated at the habitation areas (Heckenberger et al. 2001, 2003). This is in contrast to today's urban wastes in the region which are deposited as contaminated toxic material far away from settlements or into the rivers.

Sustainable soil fertility management is a major constraint in the humid tropics. In order to gather more information about the creation of TP we addressed the following objectives: (1) to observe and describe indigenous soil fertility management; (2) to analyze managed and unmanaged soil and compare soil chemical and microbiological parameters with those of prehistoric TP (TPp); and, (3) to discuss the formation of TP under indigenous soil fertility management.

9.2 Materials and Methods

9.2.1 Study Site and Inhabitants

An indigenous family group was visited several times over a time period of 1 year. Information about their soil fertility management was collected by informal interviews and observation. Soil samples were taken on April 25, 2004. According to Bacu, at 50 years of age the oldest women in the settlement, they belong to the tribe Sateré-Mawé. The origin of the community is Vila Ponta Alegre on the Andirá River. The settlement consists of 22 adults (not all permanently living on the site) and 9 children. For 9 years they have been settled at the Ariaú River about 40 km southwest from the city Manaus, between the Negro and Solimões rivers (Fig. 9.1). The village location is close to the river and the forested part of it is influenced by seasonal flooding.

Fig. 9.1 Study site location

9.2.2 Interviews

Informal interviews provided information about soil management, agriculture, settlement habits, and the knowledge about ADE. Questioning about existing ADE sites and their properties was done during the last visit and included photographs of ADE sites and the ceramic sherds associated with them. The questioning was done in Portuguese.

9.2.3 Soil Sampling and Analyses

Soil samples were taken at seven different locations (0–0.2 m depth) with a small shovel and placed in plastic bags. The locations were chosen according to the soil management (Table 9.1). The various forms included burned soil termed *terra queimada* (TQ), *terra queimada* with burned organic amendments (TQ + bOM), soil called *terra preta* or *terra preta nova* (TPn), newly burned soil termed *terra cheirosa* (TC), and unmanaged background soil was taken in proximity of the football ground (BS) (Fig. 9.2).

The samples were analyzed for plant available P, K, iron (Fe), zinc (Zn), manganese (Mn), copper (Cu) (in Mehlich 1 extracts), and magnesium (Mg), Ca, and aluminium (Al) (in KCl extracts), pH, potential and effective CEC, BS, Al saturation, and acidity was determined. The micro-nutrients, Ca and Mg were determined by atomic absorption spectrometry (GBL Avanta Σ Analitica, Australia). Al was determined by titration and P was measured using a photometer (Heλios ß, Thermo Spectronic, Cambridge, UK) with the molybdene blue method (Olsen and Sommers 1982). Potassium was analyzed with a flame photometer (Micronal B 262, São Paulo, Brazil). The pH was determined in water using an electronic pH meter with a glass electrode (WTW pH 330, WTW, Weilheim, Germany) in a 1:2.5 solution. The N content was measured by the Kjeldahl technique and total C and N were analyzed by dry combustion with an automatic C/N Analyzer (Elementar, Hanau, Germany).

Before the total elemental determination large inclusions (organics, stones, ceramics, etc.) were removed from each sample by hand picking. The samples were then ground with a blender and materials larger than 2.0 mm screened out. The extraction was with concentrated HNO_3 and 6.0 *M* HCl. The elements in the resulting aliquot were determined by ICP (IAP Solid State Spectrograph, Thermo Electron Corporation).

Table 9.1 Description of soil- and organic matter samples

Sample	Designation	Description
BS	Football ground (proximity)	Control, unmanaged soil, background soil
TQ	*Terra Queimada*	Burned soil from the manioc field
TC	*Terra Cheirosa*	Smelling soil, 3 days after burning
TQ + bOM	TQ + burned OM	Burned soil amended with burned OM, from the medicinal garden
TPn	*Terra Preta Nova*	Relatively new created *Terra Preta* in the abandoned area of the medicinal garden. Needs new organic inputs according to Pacu
PAÚ	*Paú*	Rotten tree trunk, frequently used soil amendment
PAÚ b	Burned *Paú*	Burned *paú* in a wooden pot mixed with burned soil

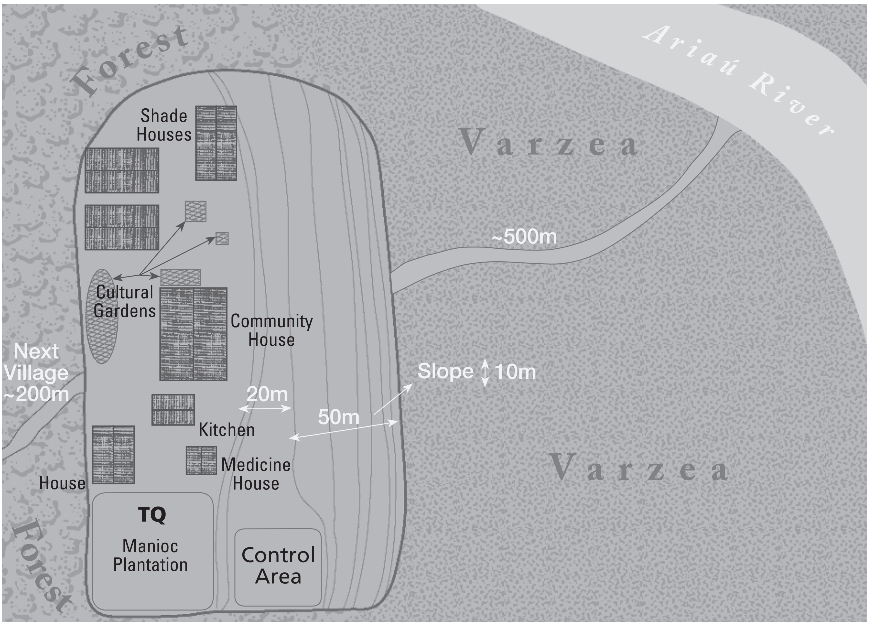

Fig. 9.2 Sketch map of ariaupacu settlement. Note that in reality the houses are not as closely spaced as indicated. The village of ariaupacu is about 500 m from the river. It is reached by boat through flooded forest during high water levels and by a way of a trail at lower water levels. Between the houses are some trees and on the slope are more trees with some fireplaces (small fires) for *Terra Queimada* production. The trees in the village are mainly Açaí and other palm trees. All of the houses are built with natural materials and the roofs are palm fronds. The special culture gardens are scattered throughout the area between the houses and the larger manioc plantation is immediately to the south. The football ground is in between the houses and the flooded forest on the slope on a flat area. The settlement is surrounded by forest and an adjacent village is quite close (ca. 200 m southwest to the next houses)

9.2.4 Microbial Activity

The microbial biomass can serve as an indicator for the effect of different management practices (Steiner et al. 2004; Stenström et al. 1998). Substrate induced respiration (SIR) also serves to assess the potential performance of microorganisms and this provides hints for nutrient supply potential, availability of organic compounds or inhibiting agents like toxic materials (Beck and Bengel 1992).

The microbial respiration was assessed using the IRGA-based (infra-red gas analysis) ECT-Soil Respiration Device (ECT Oekotoxikologie GmbH, Germany). The procedure is described in more detail by Förster and Farias (2000) and Steiner et al. (2004). The respiration was determined by measuring the carbon dioxide (CO_2) production over 11 h in a continuous flow-system at a constant flow rate of 300 mL fresh air per minute. Each sample (40 g DW) was measured once within 1 h. The SIR method is a physiological method for the measurement of the soil microbial biomass.

Microbial biomass was calculated according to Anderson and Domsch (1978). The specific respiration increment was quantified as the slope of the exponential respiration increase after substrate addition when the respiration rate is plotted on a scale against time. The exponential reproduction rate of microorganisms can serve as an indicator for the availability of nutrients (Ilstedt et al. 2003). The following parameters served as indicators of soil quality, OM turnover and nutrient availability: basal respiration (BR, OM turn over), substrate induced respiration (SIR), velocity of population increase (k) after substrate addition (nutrient availability and soil quality), activation quotient (QR = BR/SIR, microbial efficiency, metabolic quotient (CO_2-C h^{-1} C_{mic}^{-1}).

9.3 Results and Discussion

9.3.1 Soil Fertility Management

According to Bacu the knowledge about soil management was passed from one generation to the next and all indigenous groups are working this way. Fire and OM are the main components of their soil fertility management. The first level of soil fertility enhancement is the burned soil (*terra queimada*). Producing a TQ they pile up woody biomass and let it dry for about a week. Burning the biomass on the soil they pay attention that the fire is strong and hot. Three days after the burn the soil is called *terra cheirosa* (smelling soil). The soil had a very strong scent of the condensates from smoke (pyroligneous acid, PA). The *terra cheirosa* (TC) is left unplanted for 3 weeks, otherwise according to Bacu nothing will grow or the plants die. This soil remains fertile for 3 years. Only undemanding crops like manioc, pineapple, and trees (although the main food crops) are planted directly on TQ. For special plantings like vegetables and medicinal plants further soil management is necessary. These are abundant between their houses and mainly done in elevated or isolated gardens (Fig. 9.1). For further soil fertility improvements all abundant types of OM at the settlement are used (bones, wood, leaves, chicken manure), as are materials collected in the forest (*Paú*). *Paú* are rotten tree trunks and they are selected with certain preferences. Unexpectedly, the OM is burned too before it gets mixed with the TQ.

An advantage for burning was given that it is easier to work on burned soil mixed with burned OM. Soil fertility management is necessary and according to Bacu nobody knows how to plant on untreated soil. Woods and McCann (1999) explain the creation of pre-Columbian TP by elevating the organic content through long-term soil management practices (especially mulching and burning) under intensive agriculture. Also, Pabst (1993) reported the use of charcoal for soil amelioration from the Munducuru.

Bacu is not aware that her own soil management could create TP. The indigenous groups studied by Pabst (1993) do not associate TP creation with human activities. Bacu knows TP as a soil which does not need burning or fertilization and is good to cultivate. In the settlement she demonstrated a soil what she called an almost TPn. Intriguingly this TPn was found on the abandoned site of an herb and vegetable garden. According to Bacu this soil is tired and needs new organic or burned organic inputs. Lehmann et al. (2003) report an often occurring low N and K availability in TP and there are also some indications that permanent horticultural crops on TP may begin to suffer from a shortage of K and micro-nutrients such as boron (Sombroek et al. 2002). Therefore, addition of OM as manure or compost might be important for the maintenance of the productivity of ADE soils under long-term cultivation (Madari et al. 2003). Presently, chicken manure is frequently used to maintain soil fertility on TP (C Steine 2002, personal observation, Manus). The abandonment and revitalization due to additions of incompletely burned materials might explain the formation of TP and why horizons of more than 1 m depth were created. The soil fertility management for special plantings (vegetables and medicinal plants) between the houses likely creates a TP. TPp is often accompanied by dark brown bands of *terra mulata* (TM) with the same high amount of SOM. According to Sombroek et al. (2002) and Woods and McCann (1999) TM are pre-Columbian agricultural fields around the former Indian major villages. Therefore, we suppose that this might be the product of long term creation of TQ (for the main food crops).

This group chose sites for settlements on the basis of the soil fertility of the surrounding soils. The preference is given to dark and wet soils. Loamy and sandy soils were both avoided. The loamy soil materials were exploited just for the production of ceramics.

9.3.2 Soil Fertility and Nutrient Contents

Seven different soil types depending on the management intensity could be distinguished in the settlement area (Table 9.1). A comparison of the total nutrient contents (Table 9.3) with TP (TPp, $n = 8$) shows that most nutrient contents in TC and TQ + bOM are higher than the mean TP contents. P is well below the TPp mean but within the range of TPp soils (422–9,821 mg kg^{-1}). High ash content in TC can be assumed from the high Ca and K contents. Elevated sulphur (S) contents were found in those samples too. Boron (B) is quite abundant in the settlement and was found in higher concentrations than the TPp mean. The maximum value of B was found in the settlement's TP (TPn) (Table 9.2). Although most total nutrient contents in TPn are below the mean TPp contents most (Ca, K, Mg, Zn, Mn) are within the range. P and S levels are similar to those found in TM soils.

The fertility of TP varies greatly among sites. Not all soils classified as TP have higher soil fertility. Most TP soils (42 out of 56) discussed by Madari et al. (2003), had extractable P contents not higher than 180 mg kg^{-1}. According to Kämpf et al. (2003) total P contents of more than 200 mg kg^{-1} soil may give support to ancient anthropic activity if parent material contains low total P. Further they suggest the presence of charcoal and artifacts, a minimum organic C content of 10 g kg^{-1} and

Table 9.2 Available nutrient contents of the soil- and organic matter samples

Parameter	BS	TQ	TC	TQ + bOM	TPn	PAU	PAUb
N [g kg^{-1}]	1.47	3.41	10.70	16.34	4.40	15.42	8.16
P [mg dm^{-3}]	10.44	60.41	162.73	30.00	22.35	45.61	15.86
K [mg dm^{-3}]	18	84	470	163	43	38	45
Na [mg dm^{-3}]	1	6	23	28	3	6	40
Ca [mg dm^{-3}]	64.1	529.2	4,077.2	839.9	210.5	304.7	914.1
Mg [mg dm^{-3}]	12.2	59.5	399.7	746.0	21.9	35.2	325.6
Al [mg dm^{-3}]	21.13	6.12	0.00	3.24	52.29	8.17	14.99
Al + H [cmolc dm^{-3}]	7.55	10.31	7.26	13.82	27.06	11.81	18.26
SB [cmolc dm^{-3}]	0.47	3.37	21.64	10.87	1.35	1.93	7.53
CEC_{eff}	2.6	4.0	23.0	11.3	6.6	2.8	9.0
CEC_{pot}	8.0	13.7	28.9	24.7	28.4	13.7	29.2
BS [%]	5.9	24.6	74.9	44.0	4.8	14.1	29.2
AS [%]	81.8	15.4	6.0	3.9	79.5	29.7	16.6
Fe [mg dm^{-3}]	284	117	182	34	167	76	20
Zn [mg dm^{-3}]	1.63	3.84	13.92	17.8	2.58	9.74	6.14
Mn [mg dm^{-3}]	1.31	4.66	46.51	69.52	2.43	2.05	22.29
Cu [mg dm^{-3}]	2.86	0.47	1.89	0.69	0.39	1.46	0.08

SB = sum of bases, BS = base saturation, AS = aluminum saturation. BS = background soil (unmanaged soil), TQ = Terra Queimada (burned soil), TC = Terra Cheirosa (smelling soil), TPn = new *Terra Preta*, PAU = rotten wood, PAUb = burned rotten wood,TPp = prehistoric *Terra Preta*.

minimum thickness of 0.2 m and the presence of artifacts as TP classification criteria.

Knicker et al. (1996) found that a major portion of N is in forms that may survive most natural fires and that their stability towards further microbial degradation is increased by the heating. The increased recalcitrance is probably due to increased C–C and C–N bonds generated during thermal cycles or condensation and the formation of large amount of heterocyclic nitrogen compounds. These amide functional groups are difficult to identify by standard analytical procedures due to their insolubility and heat resistance and may therefore contribute substantially to the "unknown nitrogen" in soil organic mater (Knicker et al. 1996).

9.3.3 Microbial Activity

The managed soil shows clearly elevated microbial activity (Table 9.4). Especially the fresh burned soil (TC) and older burned soil with added OM (TQ + bOM) show very high soil respiration and microbial biomass. A list of substances found in smoke was given by Fischer and Bienkowski (1999). All these compounds can be consumed by strains of prototrophic bacteria occurring in the soil (Focht 1999). Typically the condensate PA is high in low molecular weight acids (formic and acetic), alcohols (methanol), and aldehydes (formaldehyde and acetaldehyde) (Diebold 1999; Focht 1999). If the concentration of PA applied is significant, then

Table 9.3 Total elemental extraction with HNO_3/hcl of the soil- and organic matter samples. TP $n = 8$, TM = *Terra Mulata* $n = 1$, C and N analyzed by combustion, TP $n = 13$, ph $n = 29$

Sample	BS	TQ	TC	TQ + bOM	TPn	PAU	PAUb	*Terra Preta* TPp			TM
Parameter								Mean	Min	Max	
N_{tot} [g kg^{-1}]	2.13	5.46	14.13	16.86	5.90	13.42	15.50	3.81[a]	2.49[a]	5.65[a]	–
C_{tot} [g kg^{-1}]	21.84	65.37	208.47	219.41	89.01	361.46	27.17	57.92[a]	36.19[a]	94.47[a]	–
C/N	10.23	11.97	14.75	13.01	15.08	26.93	1.75	15.13[a]	13.31[a]	17.47[a]	–
pH (H_2O)	4.06	4.61	5.83	4.15	3.20	3.72	4.02	5.4[b]	4.3[b]	7.9[b]	–
Ca [ppm]	431.1	605.5	11,610	1,852	348.4	1,554	1,734	3,220.5	68	17,280	94
P [ppm]	76.3	145.2	675.7	1,049	261.7	211.8	191.5	2,097.3	422	9,821	205
K [ppm]	275.7	207.6	2,182	364.3	114.4	337.4	102.3	269.4	63	1,104	62
Mg [ppm]	470.6	214.6	2,088	1,798	169	313.2	538.8	254.4	37	1,185	89
S [ppm]	127.9	123.4	1,507	1,331	354.2	820.2	355.5	160.2	84	268	350
Na [ppm]	76.4	55.4	154.1	93.3	51.1	91.6	161.7	135.7	69	224	265
Zn [ppm]	10.7	8.8	50.6	45.9	13.3	63.1	22.87	43.3	7	201	9
Mn [ppm]	24.8	23.9	121.1	201.1	26.4	16.1	65.9	192.6	7	789	27
Cu [ppm]	9.4	3.3	35.2	13.4	3.4	13.2	5.6	12.3	5	43	4
Fe [ppm]	7,472	11,870	10,370	13,650	27,910	2,574	8,078	10,025.0	3,540	21,780	23,100
Al [ppm]	22,760	22,430	32,790	7,464	32,660	2,103	7,199	27,163.3	6,910	64,700	71,800
B [ppm]	16.2	23.9	27.1	27.2	54.2	10.3	26.9	13.2	3	45	16

BS = background soil (unmanaged soil), TQ = Terra Queimada (burned soil), TC = Terra Cheirosa (smelling soil), TPn = new *Terra Preta*, PAU = rotten wood, PAUb = burned rotten wood, TPp = prehistoric *Terra Preta*.

[a]C Steiner et al. (2004), $n = 13$, tp sites near the study area.

[b]Smith (1980), $n = 29$, tp sites in the Brazilian Amazon.

Table 9.4 Microbiological parameters of managed soil, organic amendment and *Terra Preta* (TPp). The values for TPp are means from nine different TP sites (n = 41)

Parameter	BS	TQ	TC	TQ + bOM	TPn	PAU	PAUb	TPp
BR [$\mu L\ h^{-1}\ g^{-1}$]	0.55	1.09	8.33	33.08	1.35	34.17	0.46	0.91
SIR [$\mu L\ h^{-1}\ g^{-1}$]	3.96	5.46	22.50	108.69	7.02	111.72	0.20	6.82
Biomass [$\mu g\ C\ g^{-1}$]	158.9	219.1	901.1	4,352.2	281.4	4,473.6	8.45	273.4
C_{mic}/C_{org} ($\times 10^{-3}$)	7.3	3.4	4.3	19.8	3.2	12.4	0.3	4.5
k	–0.162	–0.019	–0.013	0.073	–0.054	0.070		0.135
QR (BR/SIR)	0.14	0.20	0.37	0.30	0.19	0.31	2.30	0.133
$\mu g\ C\ h^{-1} g^{-1}$ soil	0.27	0.53	4.05	16.09	0.66	16.62	0.23	0.44
BR CO_2-C $h^{-1}\ C_{mic}^{-1}$ ($\times 10^{-3}$)	1.7	2.4	4.5	3.7	2.3	3.7	26.7	1.6

BR = basal respiration, SIR = substrate induced respiration, k = microbial reproduction after glucose addition, BS = background soil (unmanaged soil), TQ = Terra Queimada (burned soil), TC = Terra Cheirosa (smelling soil), TPn = new *Terra Preta*, PAU = rotten wood, PAUb = burned rotten wood, TPp = prehistoric *Terra Preta*.

formaldehyde and the acids can serve as biocides (Doran 1932). However, at low concentrations these alcohols, acids, and aldehydes serve as carbon and energy substrates for soil microorganisms. Steiner et al. demonstrated a microbial mediated decay of PA. They found an increase in soil respiration from 0.8 to 1.8 $\mu L\ h^{-1}\ g^{-1}$ soil after charcoal application (50 g kg^{-1} soil) and an increase to 7.3 $\mu L\ h^{-1}\ g^{-1}$ soil after the application of PA (12.5 mL kg^{-1} soil). The increase in microbial biomass was from 45.8 to 76.4 and 418.3 μg C g^{-1} soil respectively. Similar soil respiration and microbial biomass were found in TC (Table 9.4). The charcoal and ash also increased soil pH, suppressing Al activity (Table 9.2) toxic to soil biota (Woods and McCann 1999).

The population increase after substrate addition as indicator for soil fertility was found positive only in TQ + OM but not as high as this was found in prehistoric TP (although the measurement was not long enough to find the respiration peak). "*Paú*" is an organic soil amendment and therefore cannot be seen as soil. One of the adjectives of TP is a relatively low soil respiration, but fast exponential population increase after the addition of easily degradable substrate. The newly created TPn had a slightly higher soil respiration (BR) than TPp and does not show an exponential population growth. The low pH might be responsible for the limited population growth. The microbial biomass is very similar to that found in TPp (281.4 and 273.4 μg C g^{-1} soil, respectively). Low mineralization due to recalcitrance of TP SOM was also found by Lehmann et al. (2003) and Pabst (1993). Incompletely burned residues from plant materials form stable high molecular weight and fused aromatic ring structures in TP rather than the more easily degraded polysaccharides that result from normal decomposition of plant matter (Glaser et al. 2001b).

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Chapter 10
Sweep and Char and the Creation of Amazonian Dark Earths in Homegardens

AMGA Winklerprins

10.1 Introduction

As described elsewhere in this volume and in previous publications (Woods and McCann 1999; Lehmann et al. 2003; Glaser and Woods 2004), Amazonian Dark Earths (ADEs) are a continuum of organically rich soils found in patches throughout the Amazon basin. The growing literature on these soils is convincingly demonstrating the importance of ADEs to smallholders of today as well as helping to reconceptualize the prehistory of the region. We know what the soils are, what they look like today from a pedologic, chemical, and microbial perspective, and we know how productive they can be. What is still poorly understood is how they were created in the first place. Research on this is beginning, particularly by considering modern analogs such as 'sweep and char' behaviors in *caboclo* (Amazonian mestizo) homegardens. What this chapter sets out to do is to discuss sweeping and charring in present-day homegardens and to explore descriptions of such behaviors in domestic spaces in the literature (past and present) in order to contextualize the behavior as observed today.

10.2 Sweeping and Charring in Homegardens

From studies to date we know that ADE were created through some combination of incidental refuse accumulation and long-term farming (Denevan 2004). But the details of these processes are not well understood yet are key to Wim Sombroek's dream of *Terra Preta Nova* – or the ability for ADEs to be generated wherever they are needed to improve soil quality and crop yields. There are two issues that need to be considered:

1. What type of behavior, specifically, creates ADE over time?
2. How intentional is the behavior that creates ADE?

From research with present-day mestizos in the Amazon region of Brazil we know about a technique called '*terra queimada*' (TQ) – 'burned earth,' a soil management

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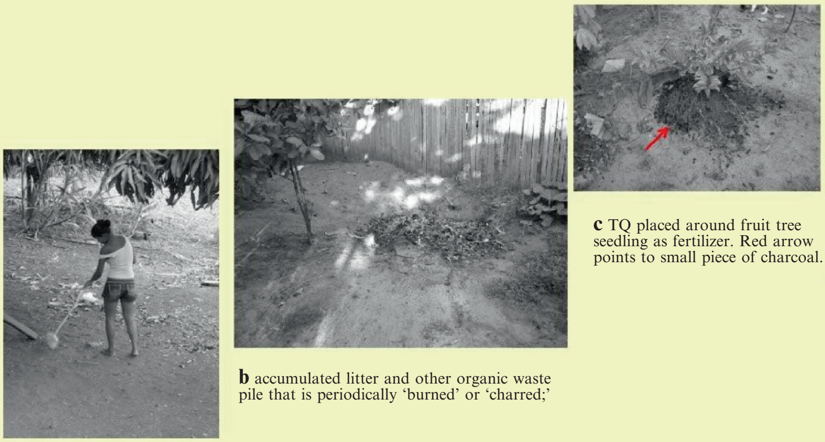
process that appears to be ubiquitous in present-day peasant homegardens (Smith 1996; Madaleno 2000; Hiraoka et al. 2003; WinklerPrins and de Souza 2005; Steiner et al. Chapter 9, this volume). Tree and other organic debris are The TQ creation process is as follows – (1) garden debris is swept, usually on a daily basis, from where it falls to an out-of-the-way place in the yard where it is accumulated. This accumulated litter and waste is periodically 'burned' or better said, 'charred'. Piles are often left to smolder for periods of time. The resultant material, with charcoal usually quite visible, is known as TQ (Fig. 10.1). It is used as a soil conditioner and placed directly around fruit tree seedlings; and sometimes young trees or shrubs are planted directly in an abandoned char piles.

Is this a modern-day analog of what Amerindians may have done in the past to make ADE? To put this observed behavior into context, I have begun to explore the ethnographic literature on indigenous and *caboclos* to look for references to sweeping, burning/charring, refuse accumulation, fertilization, soil management, and other such activities that may lead to the creation of TQ and the possibility that TQ eventually forms ADE. I have used these as key terms to start to search the wide ranging literature on Amazonian ethnography. This is difficult, however, as descriptions of activities that I am looking for were not actively observed or noted by many authors, and certainly not indexed in their books. It is quite possible that sweeping and burning/charring is so ubiquitous a part of daily life that scientists have not 'seen' or recorded the activity. Therefore is has made reviewing the literature a daunting task, but there are a few direct and a variety of tangential references, and I will elaborate on those below. But this is a mere beginning of a much longer task, and I welcome any further suggestions.



c TQ placed around fruit tree seedling as fertilizer. Red arrow points to small piece of charcoal.

b accumulated litter and other organic waste pile that is periodically 'burned' or 'charred;'

a sweeping of garden debris

Fig. 10.1 Sweeping and charring in homegardens in Santarém, Pará, Brazil (Photos by-AMBA Winklerprins 2002, 2003)

10.3 The Importance of Sweeping, Domesticating Space, and the Plaza

It has long been recognized that Amazonian societies organized their living space into domesticated and less domesticated spaces. In particular we know that plazas are very important symbolic spaces, places of ritual performance, and often the central component of a village or community. This symbolic importance of the plaza is maintained through use, and by the fact that it is kept meticulously clear:

> The plaza is cleaned on a daily basis by sweeping with a broom … debris resulting from daily activities are cleared centrifugally away from the household and accumulate immediately beyond the perimeter of the clearing … over time this results in a doughnut shaped midden. (DeBoer and Lathrap 1979:128)

DeBoer and Lathrap were describing the Shipibo in the Upper Amazon region, but similar spaces and their cleaning through sweeping, have been described by Verswijzer (1996), Hecht and Posey (1989) for the Mekrãnoti (Kayapó) in south-eastern Amazonia and by Heckenberger for the Xinguano (2005). Symbolic plaza spaces are pan-Amazonian phenomena.

Typically these open, symbolic spaces, are kept clear of any debris and considered to be domesticated spaces. This contrasts with the more disorderly and less domesticated spaces away from the plaza where refuse is discarded, and where TQ and therefore likely ADE were made.

From an ADE perspective what is most interesting about these plazas is not the plaza itself, but what lies behind it in the less domesticated space. For example, the Xinguano situate their homes around the plaza in a circular fashion. Behind these homes and away from the clean swept plaza, they establish ‘trash yards’ in which household refuse is deposited regularly (Heckenberger 2005). These dumping grounds are periodically charred, and smolder. Although they still contain ceramics today, in the past these trash yards contained much more ceramic material. Over time these trash yard likely become semi-circular ADE deposits (Erickson 2003).

But what do open plazas and trash yards have to with homegarden spaces in peasant communities today? Homegardens today are the sites of cultural reproduction in *caboclo* communities. After the arrival of the Europeans and the imposition of the nuclear family norm, Amazonian families no longer live communally as they did (and continue to in some Amerindian communities) in pre-Columbian times. Homegardens contain their own open spaces, miniature plazas as it were, the central space of domestic life with domesticated nature, sites of cultural transmittal. Homegardens have less kept ‘edges’ as well that are more peripheral (and less domesticated) and where refuse is discarded. TQ is typically made in the periphery of a homegarden. It is true that plaza in the indigenous villages of Amazonia are public spaces, whereas the peasant homegardens I have observed are private spaces. Given cultural change as a result of the colonial experience and the imposition of ‘western’ notions of the family unit and private property, this is not surprising.

As knowledge systems are transferred they are subject to the broad changes societies undergo, and this has certainly been the case in Amazonia. Sweep and char in homegardens today likely is the expression of strands and vestiges of indigenous knowledge and praxis systems that radically changed as a result of rapid depopulation. But fragments of past lifeways have persisted and fused with other knowledge systems and lifeways.

One of the things that has happened in this cultural morphing is that the important symbolic space has changed from the swept plaza imbued as men's space where significant cultural reproduction took place, to the swept homegardens that are the domain of women. This gender shift may be significant in explaining why the literature is quite silent of the everyday praxis of sweeping and charring around the homesite.

10.4 Sweep and Char as Soft Technology

Denevan introduced the concept of 'soft technology' (Denevan 2001) and I feel it is an appropriate term for the actions that might lead to ADE formation such as sweep and char. Sweep and char and the creation of TQ is a type of 'soft technology' developed by Amerindians as a way of making their environment a more productive one.

Charcoal that is the result of a slow, cool burn, is the type that is found in ADE. This seems to be formed as a result of 'charring' and not burning. The question is then, how ubiquitous is charring? Erickson notes "Amazonian people use regular low intensity burns to dispose of household garbage, weeds, and crop debris" (Erickson 2003:479) based on his own research in the Bolivian Amazon. I have already mentioned Heckenberger's reports on Xinguano 'trash yard' smoldering of refuse piles behind the houses that encircle the plaza. German (2004) documents creation of a soil conditioner by the burning of piles weeds and other organic debris by *caboclos* in the Rio Negro region of Brazil as a way of countering low soil fertility.

But the most significant body of evidence comes from the (Mekrãnoti) Kayapó who use this soft technology in an elaborate fashion to maintain fields in long-term production. As Susanna Hecht has put it, "to live among the Kayapó is to live in a place where parts of the landscape smolder" (Hecht 2003:364). In her collaboration with Darrell Posey they documented in-field burning, the term given for careful and very deliberate use of fire to manage fertility gradients in agricultural fields (Hecht and Posey 1989).

But overall the literature is actually quite silent about behaviors such a sweeping, charring, slashing and charring, or even in-field-burning. Is this because it is not done? Or is it that perhaps it is so obvious and pervasive that researchers have not commented on it? Perhaps it was not 'seen' as anything that was special. Another reason could be that it was lost and buried in the long held and repeated trope about slash and burn agriculture – it is difficult to see cool burning when the conjured up image is of a much hotter burn. Many of the classic ethnographies of Amazonians describe the activities in a predictable way. For example,

> The gardener sets fire to the plot, leaving a residue of charred stumps and larger tree trunks, but reducing the rest of the vegetation completely and covering the soil with fine, nitrogen-rich ash. (Murphy and Murphy 1985:86)

A description of burn to ash is now common to the region and has long been thought to have been a technique to have come from the Amerindians. When commenting on the agriculture of *caboclos* in the Lower Amazon Wagley noted: "The agricultural techniques used in Amazonia are mainly those inherited from the native Indians, 'fire' or 'slash-and-burn' agriculture" (Wagley 1953:4). This is now classic narrative, and often perpetuated without a second thought that perhaps it was not 'slash and burn' but something more nuanced. This makes me wonder – do scientists record what they see or do they record what they think they should see?

Another possible reason why action such as sweep and char has gone underreported is that it is typically practiced by women. Ethnographies have often paid lesser attention to the details of the domestic sphere, and so discarding and sweeping and charring were not or barely discussed and truly not seen by masculinist ethnographers.

Lastly, soft technology knowledge systems are often 'invisible' as they are embedded in everyday praxis. "To have to ask about practical knowledge is to miss the point of practical knowledge" (Thrift 1985:373); and "soil knowledge is as much a skill as knowledge… it is the heritage of practical everyday life" (Sillitoe 1998:189). This latter in combination with any or all of the above-mentioned reasons as to why sweep or char or similar behavior is not well noted in the literature.

10.5 Conclusion

To pursue Wim Sombroek's dream of developing *terra preta nova* we need to continue to look for analogs and for knowledge bridges to the past (e.g. Madari et al. 2004). This chapter demonstrates the importance of sweeping and charring as components of everyday praxis. Further queries of the literature will likely continue to support this position. Amazonians, through the ages, have swept debris away from symbolic spaces into area less domesticated. This behavior likely lead to incipient ADE, whether done deliberately or incidentally. This leads to a bigger question, which is, does this behavior, over time, result in ADE formation? In other words, is the creation of TQ in homegardens in Amazonia today a modern analog of what happened in the past? We are still a long way from knowing this, but future research will certainly endeavor to try to uncover the story. Knowledge systems in place today are fragments of past systems and amalgams of that fragmented knowledge with other infusions. As scientists we need to observe and record everyday praxis and be querying the obvious as we proceed with further research in how ADEs were formed in the past.

I do not have direct evidence for sweep and char in homegardens, but there is evidence of sweeping, of charring, and certainly of the importance of homegardens. There remains much more literature to trawl through to find more references to sweeping and charring (and, hopefully together); and to 'read' this information between the literature that on the surface is silent on the matter.

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Chapter 11
Pedology, Fertility, and Biology of Central Amazonian Dark Earths

NPS Falcão, CR Clement, SM Tsai, and NB Comerford

11.1 Introduction

A great challenge for the world's scientific community has been to find alternatives for the best use, management and conservation of the Amazonian tropical rainforest. The unbalance between increasing populations and the demand for food shows the urgency for looking for new alternatives that region, avoiding excessive degradation of natural ecosystems. In this respect, scientists in all countries in the tropics are working to understand the functioning of the rainforest and come up with alternatives to use and manage this natural resource, applying the best technology not only from an economic perspective, but principally from social and ecological perspectives. The replacement of the nutrients exported by crops is normally solved by inputs of chemical and organic fertilizers, in proportions that can vary with natural soil fertility and the nature and volume of the crops. Hence, problems like erosion, leaching, and compactation can only be solved by conservation practices utilized by farmers that change as function of land topography, precipitation, crop type, cover crop, or farming land use system, depending on the technology level of the community.

Small farmers living in Manacapuru, Iranduba, Presidente Figueiredo, and Rio Preto da Eva, in Amazonas, Brazil, work on Amazonian Dark Earth (ADE) sites, cultivating vegetables and perennial crops like oranges, coconuts, cupuaçu, and others. Their land use systems include monocultures, two species mixes, and agroforestry systems. In general, the small farmers report that ADE is very fertile and they never need to apply chemical and organic fertilizers to get high productivity. On the other hand, studies have shown that ADE presents some nutrient limitations to plant production. Some small farmers are using large amounts of chemical and organic fertilizers and even liming unnecessarily. This intensive exploitation and the excessive use of nutrients is causing chemical degradation (Falcão et al. 2003) and even physical degradation of ADE (Teixeira and Martins 2003).

This chapter focuses on the results of scientific investigations of some chemical, physical, and biological properties of ADE and their interactions, evaluating how these properties and characteristics can affect and stimulate crop growth and productivity in ADE environments Furthermore, we discuss the interaction and application

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

of pedology and soil fertility, plant and soil biodiversity, and land use system characterization and diagnosis in ADE and surrounding soils.

11.2 Pedology and Soil Fertility: Interaction and Application to Amazonian Dark Earth Soil Management

Approximately 75% of the Amazon region soils are classified as Oxisol and Ultisol (46% and 29%, respectively). Both of these soil orders are defined by their low concentration of exchangeable base cations, clay mineral with low activity like kaolinite and iron and aluminum oxides and hydroxides, low extractable phosphorus, high acidity and therefore high concentration of exchangeable aluminum and, sometimes, manganese. Both of these later elements can be toxic to crops (Sanchez 1976).

In contrast to the natural soil condition, ADE sites are found throughout Amazon. They are anthropogenic soils that are characterized by very thick, black or brown surface layers. They have high amounts of total CaO (1,810 mg kg^{-1}) and P_2O_5 (4,900 mg kg^{-1}). The high organic matter and biological activity, compared with surrounding soils, probably results from the animal and human residues found in these soils. Soil pH ranges from 5.2 to 6.4; extractable P is generally above 250 mg kg^{-1}; and Zn and Mn are above 200 and 450 mg kg^{-1}, respectively (Falcão et al. 2001). These characteristics often include massive amounts of pottery sherds with the dark soil matrix (Lehmann et al. 2003a; Glaser and Woods 2004).

Soil fertility is best managed based on concepts central to field of soil fertility but also in concert with concepts derived from soil pedology. This is reinforced when one realized that dark earth soils (*terra preta*) and *terra mulata* (anthropogenic soils without high concentrations of pottery remnants) can be found from the Andes Mountain to Marajó Island; existing on a wide range of soils and landscapes, varying in size from less than 1 ha to several square kilometer (Woods and McCann 1999; Sombroek et al. 2003; Kern et al. 2003).

While one talks about ADE soils, one must also realize that there is a great deal of variability in what is classified as an ADE soil. ADE soils studied in the municipalities of Manaus, Rio Preto da Eva, Manacapuru, Iranduba and Presidente Figueiredo are quite different in their physical and chemical properties. These differences highlight the necessity of integrated investigations encompassing both soil fertility and pedology perspectives with the aim to establish cause and effect relationships between soil fertility, soil forming factors and plant growing, and crop productivity.

The proper use of fertilizers and liming is based on soil chemical properties. Yet, the amount of nutrient uptake by plants is also dependent on soil physical properties. ADE soils change the chemical and physical properties to the benefit of crop production. For example, sandy soils are well known for their low soil organic matter content under good drainage; affiliated low cation exchange capacity; and low water retention capacity. Comparing the results of the chemical and physical analyses for three soil profiles, one studied on Rio Preto da Eva (Fazenda Jiquitaia) and two others studied on Manacapuru (Atadeu famer and Edmilson farmer in Costa do Laranjal), soils on Fazenda Jiquitaia were indeed sandy with sand content by weight ranging from 75% to 81%, soil organic matter from 1.3% to 4.7%, and effective cation exchange capacity from 3.44 to 2.11 cmol (+) kg^{-1}. Field observation on these sandy *terra preta* and *terra mulata* sites has shown that even during excessive dry seasons, crops not only survive the dry season, while crops on non ADE soils do not, but also do not suffer severe damage g through this dry season in terms of crop productivity.

11.2.1 Soil Reaction ($pH_{(H_2O)}$, $pH_{(Kcl)}$, ΔpH) and Exchangeable Acidity

In Amazonian soils, crop production is limited by soil acidity. This occurs indirectly by promoting poor availability of macro and micronutrients and directly through the accompanying high levels of Al and Mn that are toxic to plants. Soil samples collected from surface layers from ten different ADE soils near Manaus, showed $pH_{(H_2O)}$ ranged from 4.3 to 6.6 (average = 5.6). The $pH_{(KCl,\ 1.0N)}$ values ranged from 3.7 to 6.0 (average = 4.9). In the subsurface layer the pH ranged from 4.1 to 6.7 (average = 5.7 and the $pH_{(KCl,\ 1.0N)}$ values ranged from 3.7 to 6.2 (average = 4.9). Falcão et al. (2003) observed the for ADE soils $pH_{(H_2O)} > pH_{(CaCl2\ 0.01\,mol\ L^{-1})} > pH_{(KCl\ 1.0\,mol\ L^{-1})}$. In the ADE surrounding soil (*terra mulata*) the $pH_{(H_2O)}$ was still higher than that determined with $CaCl_{2\ (0.01\,mol\ L^{-1})}$ and $KCl_{(1.0\,mol\ L^{-1})}$. Oxisols under native vegetation are characteristically extremely acidic with $pH_{(H_2O)}$ between 4.0 and 5.0 (Sombroek 1966). For example, soil from an Oxisol collected Itacoatiara, AM, was 4.2 in the surface layer and 4.2 in the subsurface (Falcão and Silva 2004), while soil samples from an Ultisol had a $pH_{(H_2O)}$ of 4.5 (Falcão et al. 2001).

The ΔpH ($KCl–H_20$) allows one to interpret the degree of weathering and the soil electrical charge balance. If the delta pH value is negative it means the soil is dominated by silicate clay. The interpretation of a positive delta pH is that iron and aluminium oxides dominate (Kiehl 1979). If the difference between the values of pH in KCl and H_2O is large, the delta pH is more negative and this is often linked to a high content of exchangeable aluminum (Kiehl 1979; Fassbender 1982). This condition was observed on ADE soil samples collected at the Jiquitaia Farm (Rio Preto da Eva Municipality) in which the delta pH was more negative (−1.5) and the average level of aluminium was higher (0.96 cmolc kg^{-1}) then other ADE sites studied. In the Costa do Laranjal sites (Manacapuru Municipality) on the banks of the Solimões River the delta pH was also negative (−0.3) and the average level of aluminium was lower (0.69 cmolc kg^{-1}) showing the direct relation between the negative values of delta pH and exchangeable aluminium content.

It is important to note that if the soil's ΔpH is positive or zero the predominance of variable charge minerals is indicated as well as low exchangeable aluminum

(Kiehl 1979; Fassbender and Bornemisza 1994). The Δ pH on ADE soils ranged from −1.5 to −0.3 in the surface horizons and −1.4 e 0.0 in subsurface horizons. Based on regression analysis between $pH_{(H_2O)}$, ΔpH and exchangeable for 100 ADE soil samples, there is a direct relation between $pH_{(H_2O)}$ and ΔpH, and a inverse relation between $pH_{(H_2O)}$ and exchangeable aluminum (Figs. 11.1 and 11.2). Furthermore the influence the exchangeable Al^{+++} on ΔpH the changes observed on ADE sites are also due to total soil organic matter content, that present significative and positive correlation with the zero point charge (PCZ).

The inverse relation between exchangeable aluminum and $pH_{(H_2O)}$ on ADE soil is clear (Fig. 11.2). The high value of Al^{+++} found for the samples from 0–20 cm was from 1.60 cmolc kg^{-1}, with an average of 0.20 cmolc kg^{-1} and a minimum value of 0.01 cmolc kg^{-1}. In the 20–40 cm depth layer the maximum value of Al^{+++} was 1.90 cmolc kg^{-1}, with an average of 1.15 cmolc kg^{-1} and minimum value of 0.01 cmolc kg^{-1}. These results suggest that ADE soils are not expected to have Al toxicity problems and this must be one reason for their high productivity.

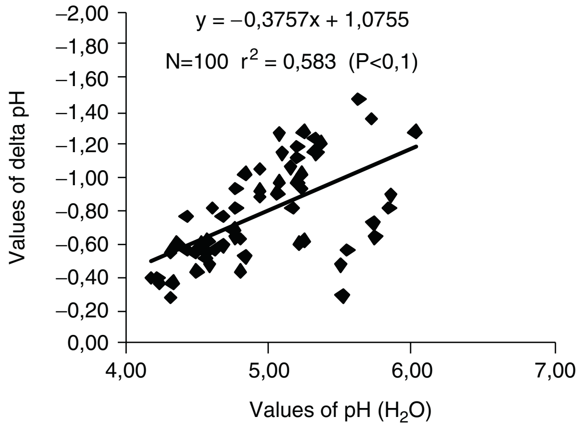

Fig. 11.1 Relation between $pH_{(H_2O)}$ and ΔpH values for 100 ADE soil samples

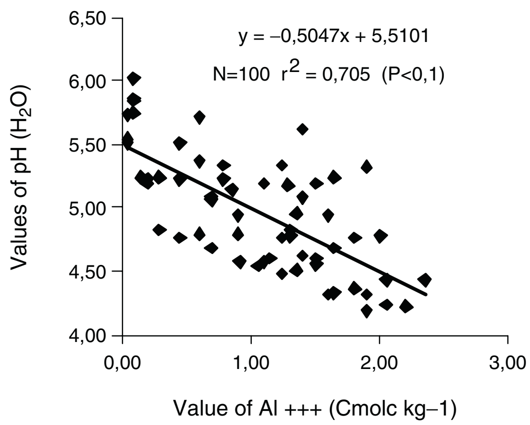

Fig. 11.2 Relation between exchangeable Al^{+++} and $pH_{(H_2O)}$ on 100 ADE soil samples

11.2.2 Total Base Cations (SB), Effective Cation Exchangeable Capacity (CEC), Percent Base Saturation (V%) and Percent Aluminum Saturation (M%)

Parameters like effective cation exchangeable capacity (CEC), total base cations (SB), and base saturation (%V) were higher in ADE soils than in surrounding soils (Table 11.1). The higher values of CEC are not only result of the high soil organic matter content in ADE soils, but also the presence of a high charge density accompanying carbon (Sombroek et al. 1993; Liang et al. 2006). This organic carbon property is specific to those soils with high pyrogenic charcoal content as found in ADE soils (Glaser et al. 2001). The reasons for this higher efficiency of nutrient retention by pyrogenic charcoal are: (1) the pyrogenic charcoal has higher specific surface area than does charcoal formed from wood burned made under high oxygen conditions; and (2) the resulting biochar has a higher negative charge density, consequently, more charge density (Liang et al. 2006). The high charge density can lead to more oxidation of its own biocharcoal or to adsorption of the non-pyrogenic charcoal (Lehmann et al. 2003b). Both process can be found in ADE soils (Liang et al. 2006).

Vieira (1988) studied an Amazonian Yellow Oxisol distrofic e and found nutrient levels in the range of 0.40 to 0.35 cmolc kg^{-1} of calcium and 0.33 to 0.20 cmolc kg^{-1} of exchangeable magnesium at 63 cm depth, extractable with 1.0 M KC_1. In the anthropic horizon of the ADE soil exchangeable calcium content was greater than 10.0 cmolc kg^{-1} and exchangeable magnesium was more than 3.0 cmolc kg^{-1} (Sombroek 1966, Sombroek et al. 2003; Falesi 1972; Kern et al. 2003; Falcão et al. 2003). Calcium and magnesium are the nutrients that contribute most to the high values to effective cation exchangeable capacity (CEC) and total bases (SB) on ADE soils. Amazonian Dark Earth soil samples analyzed has been shown to exhibit a large variation of these properties between different sites. On the other hand, solubility and bioavailability of P, Ca^{++}, and Mg^{++}, as well as Mn; K^+ and, possibly zinc, are expected to become immobilized and limit plant growing and production on ADE soils with time. Exchangeable K^+ (Table 11.2) is at a very low level (0.16 a 0.30 cmolc kg^{-1}) and should be expected to be one of the first nutrients for which the plant will exhibit

Table 11.1 Chemical characteristics of ADE samples (0–20 cm), collected from ten sites in Amazonas, Brazil (N = 100)

Values	K^+	Ca^{++}	Mg^{++}	Al^{+++}	CEC	SB	V	m
	(cmolc kg^{-1})						(%)	
Average	0.17	7.07	1.31	0.20	8.75	8.55	95.20	4.80
Maximum	0.40	15.46	3.25	1.60	17.52	17.50	100.00	48.71
Minimum	0.05	0.85	0.00	0.00	2.64	1.68	51.29	0.00
Deviation	0.07	3.89	0.68	0.37	3.95	4.14	11.60	11.60
CV	42.32	55.07	52.02	189.52	45.11	48.38	12.19	241.67

CEC – cations exchangeable capacity, SB – sum of bases, %V – percent base saturation, %m – percent aluminum saturation.

Table 11.2 Total phosphorus in different ADE sites of the Brazilian Amazon

	Values mg P_2O_5 100 g^{-1}						
Sites sampled	Min	Max	Mean	Soil texture	Layer (cm)	Methods used	References
Belterra – PA	120	1,350	950	Very clayey	Surface	Ataque sulfuric (H_2SO_4), d = 1.47	Sombroek (1966)
Belterra – PA	80	300	150	Very clayey	Subsurface	Ataque sulfuric (H_2SO_4), d = 1.47	Sombroek (1966)
Belterra – PA	60	370	150	Sandy loam	Surface	Ataque sulfuric (H_2SO_4), d = 1.47	Sombroek (1966)
Belterra – PA	70	140	100	Sandy loam	Subsurface	Ataque sulfuric (H_2SO_4), d = 1.47	Sombroek (1966)

deficiency symptoms (Alcarde et al. 1991). The low concentration of exchangeable K^+, combined with high Ca^{++} and Mg^{++} are expected to promote unbalanced nutritional status to plant growing on ADE soils. This may happen by competitive inhibition between the (2+) and (1+) cations (Marschner 1995; Malavolta 2006).

11.2.3 Total and Extractable Phosphorus

In the human body P is the second most abundant mineral nutrient, 80% of the P is sequestered in bone and teeth. In the plant P is necessary to photosynthesis, respiration, cell function, gene transfer and reproduction (Stauffer and Sulewski 2004). Phosphorus in the terrestrial crust is 0.12% and, in soil, varies from 0.02% to 0.5%, with an average of about of 0.05%.

Sombroek (1966) studied ADE profiles in Belterra, Pará and found high total P_2O_5 in the surface and subsurface layers, with the highest values of total $P_2O_{5,}$ in ADE soils with clayey textures. The lowest values were found (100 mg kg^{-1} de P_2O_5) in those ADE soils with a higher portion of sand (Table 11.2). Sombroek (1966) also observed that total P was related to CEC; which was an indication that high productivity, due to excellent P fertility, as enhancing the P and C cycles.

Soil P is often considered to be present in soils: (1) as an in the soil solution; (2) adsorbed to the surface of the soil; (3) as crystalline and amorphous mineral phosphorus; and (4) as a component of soil organic matter (Barber 1995). Phosphoric acid, H_3PO_4, has three different ionic species: $H_2PO_4^-$, HPO_4^{-2}, and PO_4^{-3} that dominate the form of solution P. HwPO4 is the dominate ionic form in most soils (Sanchez and Cochrane 1980; Fassbender and Bornemisza 1994).

In most acid soils, the Fe and Al ions concentrations are in higher than H_2PO_4 and, consequently, the ions $H_2PO^-_4$ react chemically with soluble Al and Fe ions, forming insoluble phosphates, giving very low amounts of ions $H_2PO_4^-$ immediately available by plants (Fassbender 1982; Brady and Weil 1999). Considering the pedogenesis of most Amazonian soils that are not in flood plains, P in solution should be very low. Conversely, P desorption should be low resulting in generally low soil P bioavailability. This, however, can be a function of crop being considered.

Comerford (1998) described two forms of bioavailable inorganic P present in soils. The first, desorbable by equilibrium exchange would be low in most Brazilian soils with clay a part of their fine earth fraction. The second pool, ligand desorbable P is described as a function of root exudates that can desorb P from inner sphere complexes. Cupuaçu is one species that appears to accumulate P in its tissue at higher than normal concentrations and is expected of being able to use a ligand desorbable pool of soil P. The relative contribution to inorganic desorbable P in ADE soils is unstudied, but other extractions has clearly indicated that desorbable P is high. In the Brazilian Amazon the P content in the surface soil layer is very low, on the other hand, in ADE soils the extractable phosphorus can be higher than 600 mg kg^{-1} in comparison to non-ADE soils where these values may be 1 to several mg kg^{-1}. Table 11.3 lists extractable P contents for several ADE sites of varying horizon depth and texture classes.

Table 11.3 Available phosphorus in ADE soils samples of different sites of the Brazilian Amazon

Sites sampled	Values			Texture classes	Layer (cm)	Methods used	References
	Min	Max	Mean				
Belterra – PA	6.5	66.0	40	Very clayey	Surface	Bray (HCl, 0.1N + NH_4F, 0.5 mol L^{-1})	Sombroek (1966)
Belterra – PA	3.8	65.1	35	Very clayey	Subsurface	Bray (HCl, 0.1N + NH_4F, 0.5 mol L^{-1})	Sombroek (1966)
Belterra – PA	3.2	98.8	40	Sandy	Surface	Truog (H_2SO_4, 0.01–0.001N + $(NH_4)_2SO_4$,0.05molL^{-1})	Sombroek (1966)
Belterra – PA	6.7	31.2	20	Sandy	Subsurface	Truog (H_2SO_4, 0.01–0.001N + $(NH_4)_2SO_4$, 0.05 mol L^{-1})	Sombroek (1966)
Cachoeira Porteira – PA	139	321		Clayey	Surface	Mehlich-1 (HCl 0.05N + H_2SO_4 0.025N)	Kern and Kampt (1989)
Cachoeira Porteira – PA	70	193		Clayey	Surface	Mehlich-1 (HCl 0.05N + H_2SO_4 0.025N)	Kern and Kampt (1989)
Costa do Laranjal	66.86	96.12	81.81	Clayey	Surface	Mehlich-1 (HCl 0.05N + H_2SO_4 0.025N)	Souza and Falcão (2003)
Costa do Laranjal	27.52	35.33	30.64	Clayey	Surface	Mehlich-3 (HCl 0.05N + H_2SO_4 0.025N)	Souza and Falcão (2003)
Costa do Laranjal	63.95	90.24	77.44	Clayey	Surface	Bray (HCl, 0.1N + NH_4F, 0.5 mol L^{-1})	Souza and Falcão (2003)
Costa do Laranjal	40.53	50.93	44.79	Clayey	Surface	Olsen Modificado	Souza and Falcão (2003)
Costa do Laranjal	174.14	187.15	181.13	Clayey	Subsurface	Mehlich-1 (HCl 0.05N + H_2SO_4 0.025N)	Souza and Falcão (2003)
Costa do Laranjal	70.44	76.29	73.65	Clayey	Subsurface	Mehlich-3 (HCl 0.05N + H_2SO_4 0.025N)	Souza and Falcão (2003)
Costa do Laranjal	108.17	126.57	119.07	Clayey	Subsurface	Bray (HCl, 0.1N + NH_4F, 0.5 mol L^{-1})	Souza and Falcão (2003)
Costa do Laranjal	101.32	111.72	106.29	Clayey	Subsurface	Olsen Modificado	Souza and Falcão (2003)

11.2.4 Total and Extractable Potassium

The average potassium content in the earth's crust is 2.6%, being the seventh most abundant. In soils, the K content ranges from 0.1% and 3.0% with a mean of 1.0% (Ribeiro et al. 2005). Lopes (2005) revising several paper concerning the potassium contents in Brazilian soils, reported that total potassium content in the most Brazilian soils ranged from 0.05% to 2.5%. The total potassium content (% of K_2O), in the surface layer of an Oxisol is roughly 0.14%. In more humid regions of Brazil, the extractable potassium content is generally lower than 200 mg kg^{-1} and rarely higher than 600 mg kg^{-1}.

The soil exchangeable potassium characteristic of the State of São Paulo, Brazil ranged from 0.16 to 0.30 cmolc kg^{-1}. For the State of Minas Gerais this value ranges from 0.18 to 0.31 cmolc kg^{-1} (Ribeiro et al. 2005). Potassium soil solution concentrations ranged from 2.0 to 6.0 mg kg^{-1} (Malavolta 2006). All ADE soils showed low available potassium contents (Table 11.4).

The limited work on ADE soils indicates that extractable and exchangeable K^+ have not accumulated as much as have P, Ca and Mg. Sombroek (1966) reported that K^+ and Na^+ together presents less than 2% of the potential CEC. Vieira (1988) describing profiles of an Oxisol and Ultisol with an anthropogenic A horizon in the Manacapuru Municipality found a Ca^{++}, Mg^{++}, and K levels of 9.39:1.91:0.07 cmolc kg^{-1}, respectively.

The same author found an average value of exchangeable K^+, to 63 cm depth, of 0.046 cmolc kg $^{-1}$. In contrast, exchangeable K for 100 ADE samples from the surface horizon was very close to the low limits considered sustainable in the

Table 11.4 Available K content analyzed on different ADE and surrounding sites. Mehlich 1 and Mehlich 3 extractor

Sites	Author	Mehlich 1 (mg kg^{-1})	Mehlich 3 (mg kg^{-1})
Iranduba – AM[a]	Lehmann et al. (2003)	–	17.3
Oriximina – PA	Kern and Kampt (1989)	25.5	–
S.Gabriel Cachoeira – AM	Smith (1980)	23.5	–
Novo Aripuanã – AM	Smith (1980)	19.6	–
Marabá – PA	Smith (1980)	90.2	–
Manacapuru – AM	Falcão (dnp[c])	14.0	12.0
Itaituba – PA	Smith (1980)	15.7	–
Iranduba – AM[b]	Grosch (2005)	–	183.0
Parintins – AM	Moreira (dnp[c])	24.0	22.0
Rio Preto da Eva – AM	Falcão (dnp[c])	66.0	40.0
Latossolo Amarelo	Moreira (dnp[c])	27.0	21.0
Neossolo	Moreira (dnp[c])	36.3	25.0
Argilossolo	Moreira (dnp[c])	8.0	13.0
Teor adequado	Álvarez Venegas et al. (1999)	71–120	–

[a] ADE from Caldeirão site.
[b] ADE from Hatarara site.
[c] Unpublished data.

São Paulo and Minas Gerais studies cited above (average = 0.17 cmolc kg^{-1}). Clearly, intensive agriculture in ADE soils will stress the K supply and future K deficiencies should be expected. In fact, Falcão and Borges (2006) evaluating the nutritional status and fruit production of papaya (*Carica papaya L.*) on ADE soils, found the lowest soil exchangeable potassium content (0.09 mg kg^{-1}) in the ADE not fertilized and the highest value of exchangeable potassium (0.19 mg kg^{-1}) in the unfertilized *terra mulata*.

11.2.5 Micronutrients (Ferro, Zinco, Manganês)

ADE soils exhibit low levels of extractable B, Cu, and Fe, with relatively high values of Mn, and Zn (Tables 11.5 and 11.6). Lima (2001) found high amounts of extractable Mn and Zn in the clay fraction of an anthropogenic A horizon, compared to the B horizon of the same soil, and compared to the A and B horizon of surrounding soils (Table 11.6). High concentrations of Mn and Zn were also found by Kern and Kampt (1989) in Para. Despite high soil organic matter, ADE soils

Table 11.5 Available B, Cu, Fe, Mn, Mo, and Zn in samples of Oxisol, Ultisol, Neossolo and ADE soils of Central Amazonia

	B	Cu	Fe	Mn	Mo	Zn
Soils				(mg kg^{-1})		
Oxisol	0.70	0.30	455.0	0.65	0.472	0.36
Ultisol	0.64	0.13	182.0	0.11	0.319	0.11
Neossolo	0.13	3.91	631.6	248.64	0.786	8.90
ADE	0.15 ± 0.10	1.23 ± 0.57	73.1 ± 68.9	73.12 ± 68.86	0.237 ± 0.014	18.85 ± 21.82
Suitable[a]	0.61–0.90	1.3–1.8	31–45	9–12	0.09–0.10[b]	1.6–2.2

Available B – hot water extractor; available Cu, Fe, Mn, and Zn – Mehlich 1 extractor; Mo – EDTA.
[a]Alvarez Venegas et al. (1999).
[b]Mean of contents found in high fertility soils of São Paulo State.

Table 11.6 Total Fe, Mn, Cu, Zn, Cd, Ni e Cr in the clay fraction of ADE soils (Lima 2001)

	Fe	Mn	Cu	Zn	Cd	Ni	Cr
Horizon			(mg kg^{-1})				
Yellow Ultisol with a anthropogenic horizon							
A	79.4	627	104	150	21	78	172
Bt	90.2	71	62	45	22	84	146
Yellow Oxisol with a anthropogenic horizon							
A	57.4	387	90	245	20	97	17
Bw	68.5	84	42	97	19	94	1
Cambissolo with a anthropogenic horizon							
A	59.3	289	69	248	18	88	3
Bi2	54.2	97	49	73	21	97	0

under rainforest appear to be low in extractable B, having similar concentrations as those under flood plain conditions. B, Cu, Fe, and possibly Zn should be expected to exhibit supply limitations to plant growth in the future. In the case of B, problems should be most evident during drier years.

11.3 Plant and Soil Biodiversity in *Terra Preta* and *Terra Mulata* Sites

Numerous classes of useful plants (roots, cereals, fruits, vegetables, medicinals) in different categories of domestication [incidentally coevolved (weeds), incipient, semi-domesticated, domesticated – see Clement (1999) for full definitions] appear to be better adapted on Amazonian Dark Earths than on adjacent soils (Clement et al. 2003; Major et al. 2005a). This is visible in comparisons of classes and categories of the most common plants in rural home gardens and swidden-fallows on ADE vs background soils. The sequences of plants that invade ADE during its management and then disappear in fallows provide information about the dynamics of succession (Major et al. 2005b) and a possible reservoir effect of ADE (Clement et al. 2003). The seed bank is an especially important factor in succession, both in terms of its dynamics and in terms of the reservoir effect.

The students and researchers involved in the study of plant diversity on ADE are looking at several topics that are important for ADE research. Are ADE home gardens richer in crop diversity than home gardens on other soils? Is it possible to verify a reservoir effect for Amazonian crop genetic resources? Are ADE home gardens active laboratories for *caboclo* and colonist farmers? What are the effects of markets on ADE management? The following paragraphs are a short summary of recent (reported more extensively in Clement et al. 2008) and on-going work in the INPA ADE project.

Major et al. (2005a) examined 16 home gardens on ADE to the north of Manaus and found 79 food crops, with individual gardens varying enormously in number of species: minimum of 7 and maximum of 44 species. The number of native species (defined as being present at the time of European conquest – see Clement 1999) was smaller (35) than the number of exotics (44), showing the importance of these gardens for experimentation and of ADE for the adaptation of exotic species. Distance to market had only a very minor effect on plant diversity in these home gardens.

Klüppel (2006) examined 12 home gardens on ADE in the *Comunidade do Santana*, Manacapuru, southwest of Manaus, and identified both food and medicinal species. There were 51 food species there, of which 20 were exotic. The majority of the food species were fruits (36), of which 14 were exotic. Klüppel also identified 79 medicinal plant species, with enormous variation among gardens: minimum of 1 and maximum of 34 species. As with the food crops, many medicinal plants were exotic (37%). In a comparison with a garden on a Yellow Oxisol, whose owner is considered to be the community specialist on medicinal plants, Klüppel found that certain species are restricted to ADE and all were exotic, again affirming the importance of ADE for adaptation of exotic species.

Major et al. (2005b) studied the spontaneous vegetation in four sites in which ADE was paired with background soils. Weeds covered the soil 45 times more rapidly on ADE than on adjacent soils and there were 11 times more weed species. The weed communities on ADE were more similar to each other than they were to adjacent non-ADE soils. The historical ecology of these sites showed a greater level of perturbation (more frequent fires, shorter fallows, etc.) on the ADE patches than on the adjacent non-ADE soils, and even so the ADE patches had many more species, strongly suggesting a reservoir effect.

Major et al. (2005b) also studied the seed banks in ADE and adjacent soils, both under mature second growth forest, and found that more plantlets emerged from ADE than from adjacent soils (1,365 plantlets m^2 vs. 330, respectively), and that a greater number of species occur in the ADE soils bank than in adjacent soils (2.1 species per experimental tray vs. 1.2). Interestingly, neither the ADE nor the adjacent soils had been used recently; so much of this seed bank may be due to seed rain from forests on adjacent soils. The implications of these differences require further investigation. Curiously, none of the species emerging from the seed bank are considered weeds in the active swiddens nearby, which suggests that the seed bank's duration is limited.

James Fraser is currently involved in expanding his observations on plant diversity on ADE in the municipality of Manicoré, on the Madeira River (see Fraser et al., this volume). Preliminary observations showed that manioc is much more important on ADE than the literature suggests. Hence, future work will examine manioc management, both in terms of the ADE seed banks contributing old and new combinations of manioc genetic resources to existing landraces, and in terms of how ADE farmers manage these seedlings. We hope to expand this work with genetic analysis of the manioc in collaboration with Nivaldo Peroni, of the Universidade Federal de Santa Catarina, and a new masters student.

André Junqueira is currently examining the reservoir effect in second growth on ADE vs on adjacent background soils in Manicoré, as well as mapping the occurrence of *terra mulata* and its association with anthropogenic forests. Several new indicator species are becoming apparent, as well as the presence of numerous indicators already identified (Clement et al. 2003). Nickolas Kawa is examining the effect of markets on ADE home garden diversity in Borba, also on the Madeira River. Borba has much more efficient river transport to the Manaus market than did the home gardens studied by Major et al. (2005a) and market orientation appears to be stronger.

At present, there is a need to understand the relation between biodiversity and conservation in ADE soils, as well as its role as a functional model to study soil management for small holders seeking to develop agricultural sustainability in tropical rain forests ecosystems, without serious disturbance to the relevant ecosystem. Studying microbial communities and their contribution to crop productivity in monocultural systems, such as cereals and legumes, has demonstrated that they are beneficial, but to determine the role of the microbial organisms for the functionality of a more complex ecosystem, such as the Amazonian Dark Earth (*terra preta de índio*), is a task that imposes strategic and multidisciplinary efforts.

With the rapid development of molecular tools in recent years, new insights can be obtained on microbial ecology and conservation studies, mainly generated from diversity data, with abundant uncultivated microbial groups, and from novel microbial functions (Prosser et al. 2007). On the other hand, the complexity and heterogeneity of soil microbial communities demonstrated by molecular techniques raises several new challenges that may influence the microbial communities and the co-existence and distribution of complete communities, including plants and animals, in one specific ecosystem. The influence of soil physicochemical characteristics and the existing plants on microbial diversity has been demonstrated via the heterogeneity of the soil physicochemical properties (Fierer and Jackson 2006) and the plant communities (Kowalchuk et al. 2002), which may influence the microbial communities and vice-versa. The rhizosphere can be a strong determinant for the existence of a variety of microbes active in the breakdown of plant exudates and other products present in the rhizosphere soil, which may also be strongly influenced by the soil physicochemical characteristics and agricultural management. Only recently have these issues been discussed in order to achieve a better understanding of the functionality of a complete ecosystem (Nannipieri et al. 2003; Prosser et al. 2007). By using molecular techniques, the structure of microbial communities has been examined as a function of the relative composition of specific microbial groups and related these to land-use history. The structure of bacterial communities from two undisturbed ADE soils, as well as nearby fields that (1) had never been cultivated (pristine forest soil) from the Caxiuanã National Park – Mina, Eastern Amazonia, and (2) had not been cultivated for at least four decades from the Balbina Lake, Central Amazonia, were assessed by molecular techniques using 16S rRNA-targeted oligonucleotide probes and clone libraries to quantify the composition and richness of bacterial species. In both undisturbed ADE soils, a higher richness of uncultivated/unknown bacterial species was observed when compared to a pristine forest soil (Mina) and those having a very short-term history of cultivation (Balbina Lake), confirming data obtained by Kim et al. (2007) studying a *terra preta* and a pristine forest soil from Western Amazonia – Rondônia, Brazil. It has also been found that microbial structure was more similar among ADE soils than from their adjacent background soils, which were also similarly grouped, independently of their geographical locations. In agricultural ecology studies in Michigan (USA), Buckley and Schmidt (2001) found that microbial community structure was remarkably similar among plots that shared a long-term history of agricultural management despite differences in plant community composition and land management that have been maintained on the plots in recent years. In contrast, microbial communities differed significantly between fields that had never been cultivated and those having a long-term history of cultivation. On the other hand, Kowalchuk et al. (2002) indicate the importance of coupling above-ground plant species composition and diversity and the diversity and functionality of soil microbial communities, as more refined and adequate molecular methods and tools are now more available to the microbial and molecular ecologists.

11.4 Conclusions

Considering the sites studied, we can conclude that ADE soils present great variability of chemical and physical properties, affecting directly soil biology, plant growth and crop productivity. These differences highlight the necessity of integrated investigations encompassing both soil fertility and pedology perspectives with the aim to establish cause and effect relationships between soil fertility, soil forming factors, plant growth and crop productivity. Field observation of perennial crops in these *terra preta* and *terra mulata* sites have shown that even during very dry seasons crops not only survive the dry season, while crops on non ADE soils do not, but also do not suffer severe damage in terms of growth and productivity. Clearly, intensive agriculture on ADE soils is going to demand K supply and future K deficiencies should be expected. Despite the fact that ADE soils exhibit large amounts of available Mg and Zn, perennial crops like orange usually present nutritional deficiencies of these nutrients; papaya (*Carica papaya* L.) is one of the perennial crops that normally shows nutritional deficiency of K and B. The work done and underway are providing answers and new questions about plant diversity on ADE. The answers to some of the questions will have implications for Native Amazonian plant and ecosystem management before European conquest, others may help guide future management recommendations for ADE farmers. The next decade will be exciting.

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Chapter 12
Historical Ecology and Dark Earths in Whitewater and Blackwater Landscapes: Comparing the Middle Madeira and Lower Negro Rivers

J Fraser, T Cardoso, A Junqueira, NPS Falcão, and CR Clement

> *…there is no way of describing what human beings are independently of the manifold historical and environmental circumstances in which they become – in which they grow up and live out their lives.*
>
> (Ingold 2004:215, emphasis in original)

12.1 Introduction

This chapter explores how the recent historical ecology of two distinct riverine settings in Central Amazonia has shaped the contemporary use (and non-use) of Amazonian Dark Earths[1] (ADE). Drawing on ethnography and oral histories from ongoing fieldwork on the Middle Madeira and Lower Negro rivers it asserts that patterns of land use on ADE by the Amazonian peasantries and Indigenous groups resident in each region are conditioned by divergent agro-ecological histories. The correspondence of life histories and particular configurations of agro-extractivist activity amongst informants suggests wider trends in the relation of livelihood to ADE. The distinctive processes of kinship and sedentary or mobile settlement encountered in each region are shown to be contingent on different patterns of social and economic history within and between the two great rivers. Kinship ties, permanency of residence and social networks are identified as being critical factors in enabling the practice of agriculture. The chapter reconstructs the divergent agro-ecological trajectories that have engendered the widespread practice of agriculture on the Middle Madeira, and the prevalence of extractivism in livelihood trajectories on the Lower Negro, until recent (1950 and onwards) migrants from the more agricultural regions of the Solimões and Upper Negro Rivers have begun to forge a local agricultural tradition. It argues that these current patterns of land-use – rather than being 'adaptive' strategies in response to certain static environmental constraints

[1] 'Amazonian Dark Earth' is used here as a general category to refer to both *terra preta*and *terra mulata* (for definitions of these soils see Lehmann et al. 2003a, Woods and Glaser 2004). When categorising soils specifically to *terra preta or terra mulata* they are referred to as such.

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

(Moran 1993) – have emerged vis-à-vis landscapes shaped by the interaction of historical and environmental factors over time (Baleé and Erickson 2006).

The historical ecology of the Lower Negro is shown to have constrained agriculture. People successfully farming ADE there are those who have migrated from regions where agriculture is more prevalent. In contrast, the historical ecology of the Middle Madeira is shown to have enabled agriculture. This implies that the longer-term trajectory of agriculture on the Middle Madeira (and for those families on the Negro from agricultural backgrounds) should have allowed the evolution of a greater repertoire of local knowledge related to ADE. The cultivation of ADE and awareness of its anthropogenic origins are examples of how local knowledge and ethnobiological perceptions are contingent on historical ecology. The chapter demonstrates the utility of comparative historical ecology in understanding contemporary agriculture on ADE in different regions. It concludes that further comparative research is important in order to explore the significance of manioc (*Manihot esculenta*) agriculture on ADE and how local understandings of the cultivation, management and creation of ADE could be incorporated into the creation of *Terra Preta Nova*.

12.2 A Social and Agro-ecological History of the Middle Madeira

The Madeira is the second largest tributary of the Amazon River, with its mouth just below the confluence of the Solimões and Negro rivers. Its headwaters are located in the Andes making it a 'whitewater' river, known as such owing to the alluvium brought down from the mountains that give the turbulent waters their colour (Junk and Furch 1985). Whitewater rivers are characterised by fertile floodplains enriched by sediments in the yearly flood. The floodplains offer various ecotones suitable for cultivation along the low (flooding each year) and high (flooding only once every 5 to 10 years or so) levees. Together, the floodplain and extensive ADE sites on the adjacent *terra firme* provide fertile agricultural areas, and a combination of floodplain and *terra firme* agriculture based on manioc and maize (*Zea mays*) was likely to have supported large settled Amerindian populations (Lathrap 1970; Roosevelt 1980; Denevan 2001; Myers et al. 2003). The high productivity of whitewater fisheries provides the protein necessary for such large populations (Moran 1993).

The devastating effects of European contact on Amerindian peoples that inhabited major Amazonian waterways (see Crosby 1972; Sweet 1974; Mann 2005) have eliminated all but the most tenuous historical links between today's populations and the Amerindians who dwelt there before them. On the Middle Madeira perhaps the most significant connection between the present and the past is environmental rather than historical. Domesticated riverine landscapes characterised by abundant ADE and anthropogenic forests (with concentrations of palms and trees associated with human influence) are indicators of the agency of pre-Colombian populations.

These landscapes persist whilst the peoples who created them fled or perished long ago (Woods and Glaser 2004).

The older residents of two communities, Barreira do Capanã and Vista Alegre, do recall that long ago their villages were the sites of Indian settlements. The contemporary residents of Barreira do Capanã and Monte Sião are referred to as 'the Mura' (a famous tribe which once occupied the Madeira) by the inhabitants of neighbouring communities. Eighty-year-olds remember a time when there were more 'Indians', who in some cases were their own parents, grandparents or relatives. However, it is often difficult find material to connect the present with this distant or even relatively recent past, as oral histories do not stretch far enough and most people are unwilling to entertain the notion that they might be the descendants of Indians.[2] Despite this, it is possible that some agricultural practices, knowledge and manioc landraces that are evident today are in some ways analogous to those of Amerindian peoples of the past. This is in no small part due to the presence of ADE, an Amerindian legacy which makes more intensive cultivation possible (more on this later).

As with many regions of the lower Amazon, the Madeira was heavily re-populated during the Rubber Boom and current social relations and kinship are a legacy of the local manifestations of region-wide social and economic transformations occurring during this period. The 1865 report of the *Repartição dos Negócios de Agricultura* (cited in Tocantins 1982:106) claims that the *Seringais* (rubber-stands) of the lower Amazon River and Marajó Island were being over-exploited. The Madeira had by then become the new destination of migration, to the extent that possession of the *Seringais* there was being contested and the most recent migrants were moving on to settle the Purús River (Tocantins 1982).

The image of life often represented in the literature of the Amazon during the Rubber Boom usually centres on the *Barracão*.[3] The *Barracão* was a large wooden building owned by a *patrão*. He was the boss and held the *freguezia* (clients) in a state of semi-slavery. He achieved this through monopolising the supply of manufactured goods with which the *fregueses* were paid for the rubber they produced on the *estradas* [trails through the forest to the rubber (*Hevea brasiliensis*) trees] they worked in the *seringais* of the high-levee floodplain and *terra firme*. The *patrão* paid the *freguezia* in advance at very high mark ups, ensuring their continued indebtedness and his control over them. In extreme situations (normally more

[2] The politics of identity are at play here. Even if some people may recognise their own Indian ancestry; until recently they have been loath identify this publicly. This is because for the past 500 years to be Indian has meant persecution; and marginalisation in wider society. Only recently, with the creation of Indian reserves has it become desirable to some to identify as Indian. This, predictably in the context of endemic corruption in Amazônia has led to widespread abuse of the system of Indian reserves, this in turn leading to the perception on the part of many rural dwellers of Indians as lazy scroungers who don't work and reply on government handouts to live. There have also been various conflicts involving people claiming to be Indians (often falsely) trying to claim ownership of vast areas of land.

[3] See for example Ferrante (1972); one of the main sources for the Globo miniseries 'Amazonia' screened recently on Brazilian television.

remote regions), the *patrão* would even forbid the *freguezia* from planting manioc, thus increasing his hold over them. This system of exchange of manufactured goods for extractive products is known as *aviamento*. The *patrão* himself was linked to bigger *aviadores* who worked for the big rubber exporting houses of Manaus and Belém, and who supplied him with manufactured goods in exchange for rubber. This system of exchanging manufactured goods for forest products has its roots in the earliest European colonial forays into the Amazon where tools and other goods were exchanged for turtle oil, spices, hardwoods, vegetable oils, and cacao (*Theobroma cacao*) beans gathered by Indian groups (Sweet 1974; Aubertin 2000). The rubber boom then was but a new and intensified phase of this established Amazonian mode of production based on extractivism, which stands in sharp contrast to the plantation agriculture that characterised other regions in Brazil (Weinstein, 1983:10).

The purpose here is not to question the historical accuracy of this representation of the *Barracão*, but rather to point out that it only tells part of the story. There also existed a multiplicity of other social forms around the Patron-client and *aviamento* relationships, for the production of rubber and other products, such as Brazil nut (*Bertholletia excelsa*), rosewood (*Aniba roseiodora*), *sorva* (*Couma utilis*), jute (*Corchorus capsularis*), and balata (*Manilkara* spp.), which have experienced boom periods over the last one and a half centuries. No one arrangement could be seen as typical (Weinstein 1993:20). Alongside the big operations, such as those described above,[4] there existed many smaller family-oriented enterprises. Weinstein notes:

> Many tappers were actually small-scale seringalistas who legally owned four or five trails, along with enough land to feed themselves and their families on a diet of manioc, fish and game. The propertied tapper would still have informal patron-client ties with a small town merchant or a wealthier neighbour, but the relationship would be more flexible and less susceptible to coercion than that between the propertyless tapper and the *seringalista*. (1983:20)

As Susanna Hecht argues, the image of the lonely and marginalized tapper trapped in debt-peonage may have been accurate in more remote regions, but it tells us nothing of the 'thriving yeomen communities, with well tended orchards and prudent husbandry' who also tapped rubber, described by early regional scholars such as Euclides da Cunha (Hecht 2004). On the Middle Madeira the concentration of extractive resources in areas of relatively easy access to people settling in riparian areas contributed to the sedentism that has characterised the lifeways of these rural folk until the present day. This in turn has allowed for the development of kinship relations and the widespread practice of agriculture. The most important crop in terms of subsistence was manioc, as it is today. Smallholders also produced

[4] In one example with as many as 200 *fregueses* resident at the *Barracão* belonging to the infamous *Colonel Vencedor Lindoso*, opposite Parana de Urua, on the Middle Madiera. Fregueses who disobeyed him were reportedly tightly bound and dropped into the middle of the river! He got his just deserts however when a group of men from the Mataurà River got together in 1930 and killed him along with his two brothers and burnt the three *barracões* they had along the river.

farinha for sale to river borne traders who supplied the more remote regions where this staple foodstuff was produced. The production of *farinha* probably fluctuated along with extractive cycles (Pinton and Emperaire 2000). Additionally beans (*Phaseolus* spp.), squash (*Cucurbita* spp.), and watermelon (*Citrullus lanatus*) Tobacco (*Nicotiana tabacum*), Sugar cane (*Saccharum officinarum*) were planted on the floodplain and on DE for subsistence, sale, and barter. Homegardens and agroforests were also productive, featuring various citrus species, cacao, coffee (*Coffea* spp.), and rubber grown for subsistence and market. Such a pattern was also characteristic of other Amazonian regions at the time (Miller et al. 2006). Since then the market for agricultural produce has grown steadily. Manioc is still both the base of agricultural subsistence and the sale of farinha (and sometimes other products such as *tapioca* and *beju*) provides a significant percentage of household income.

Today banana (*Musa* spp.) and watermelon are the major floodplain crops. Demand for other produce, such as West Indian gherkin (*Cucumis anguria*), açaí (*Euterpe* spp.) and passion fruit (*Passiflora edulis*), previously of little value, has greatly increased in recent years, stimulating production. Another critical element in enabling agriculture in the region is the amount of river transport on the Madeira. Daily ferries make the trip north to Manaus and south to Porto Velho. Almost all of these transport agricultural produce, and make stops along the banks of the Madeira to collect from farmers. This provides locals with a relatively easy way to get their harvest to market. In order to examine how local history has shaped contemporary patterns of land-use and livelihood, case studies are presented from communities in two different localities in the region.

The Manicoré River and the Água Azul Coast

The Manicoré River is a blackwater affluent of the Madeira, with its mouth on the east bank of the Madeira just above the city of Manicoré. The Água Azul Coast is catchall term referring to the riverside stretch of floodplain and *terra firme* on the west bank of the Madeira above Manicoré. The major difference between the Água Azul Coast and the Manicoré River in terms of agricultural potential is the presence of the floodplain along the former and its absence along the latter.

On the Manicoré River, migrants flooded into the region from the mid-1800s onwards, building houses, engaging in agriculture and planting *sítios* on the *terra firme* of the east bank of the river, while working cutting rubber in the *Hevea*-rich high-levee floodplain forming the west bank of the river (Fig. 12.1). Many of the sites occupied were abandoned Amerindian settlements, with fertile ADE in domesticated landscapes (see Clement 1999a, for a discussion of landscape domestication). Seven of the ten communities of the Manicoré River are located on DE sites. This chapter discusses three of these: Estirão, Barro Alto, and Terra Preta. These communities are located on ADE sites split into family landholdings. During the boom, the rubber of these villages and the river in general was produced by a series of smaller, more family-oriented enterprises, each with between one and ten *estradas*. The *freguezia* of each *barracão* was formed from people who lived with their families on the river, and

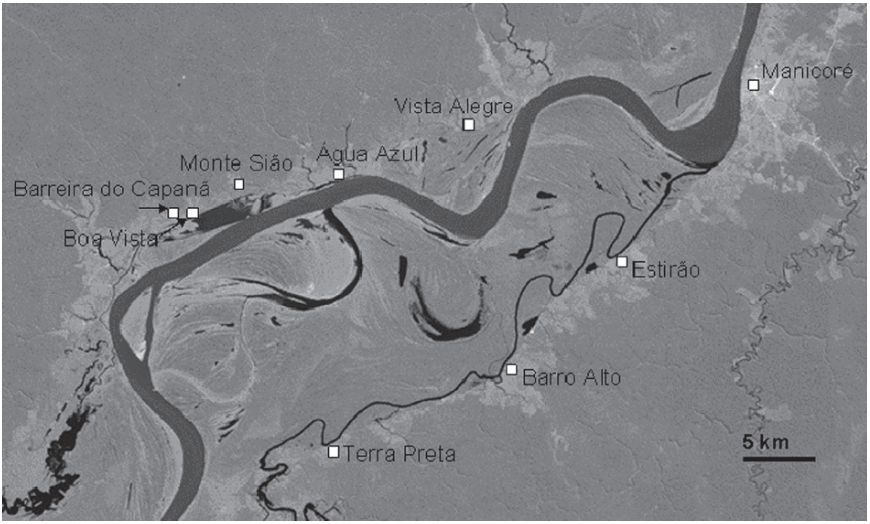

Fig. 12.1 Location of the communities of the Middle Madeira River that are discussed in this chapter

seasonal workers who lived at the *barracões* during the summer rubber season. This allowed the people working the *seringais, castanhais* (forests with abundant Brazil nut) and extracting other forest products greater autonomy than a typical *aviamento* relationship. The existence of many *patrões*, and even smallholders engaging in relationships of *aviamento* among themselves, meant that people had more choice in who they worked for, and the reality of their relationships was far more complex than the slave-like exploitation typified in the popular representation of the *barracão* outlined above. The river was inhabited by people who had their own plots of land (or had access to the land of others) and, while working seasonally gathering rubber and other extractive products, also engaged in subsistence agriculture. This appears to be a wider trend, as Dean (1987:41) notes:

By 1910, a more sedentary form of *Hevea* exploitation was beginning to appear…the *seringeiros* devoted part of their efforts to planting and tending their own farm plots, lessening their dependence on the stores of the patron. In these plots they were able to engage to some extent in raising crops for cash, even export crops like cacao, and they planted rubber as well.

After the Second World War the *patrões* abandoned their *barracões* (owing to the drastic reduction in the value of rubber), thus ending their reign as middlemen and allowing the long-term residents of the river to start to deal directly with the river traders. The communities along the river today can be characterised as extended families with collective landownership and agricultural trajectories with their roots in the Boom period and often earlier, especially when inter-marrying with local indigenous peoples occurred. During the early to mid-twentieth century DE was used for the cultivation of tobacco, beans, manioc, maize, sugar cane, squash and watermelon for the market and subsistence.

On the Água Azul Coast, the communities where research is taking place are Vista Alegre, Água Azul, Monte Sião, Boa Vista and Barreira do Capanã. All of these are situated at ADE sites. The major difference between this locality and the Manicoré River is that many farmers also plant in the high and low levee floodplain[5] (see below). Historically the extractivism along the coast from Vista Alegre to Barreira do Capanã was controlled by four *patrões*, Aristide Rosario (the resident *patrão* at Democracia, who also controlled trade at nearby Vista Alegre), Lucas Teixeira Pinto (owner of Água Azul), Joaquim Galdino (owner of the land from Monte Sião to Fazenda Jacaretinga) and Isaac Belelo, who was one of those responsible for the formation of the association *Nova Aliança*, created in 1924 from families who were the owners of landholdings which today form the communities Barreira do Capanã, Nazaré, São Francisco, Santa Ana, and Terra Preta. While the sphere of influence of each of these *patrões* was wider than on the Manicoré River, oral histories indicate that the people who worked for them were not subject to coercion and were relatively autonomous, even when they lived on land owned by the *patrão*.

Smallholders settled along the high-levee floodplain, which was rich in rubber. Others settled on the *terra firme*, some on ADE sites. People made a living from harvesting rubber and Brazil nut, along with other extractive products including *balata* and *sorva*. They also planted manioc in the floodplain and on the *terra firme*. There were various smaller *barracões* in the region, some with a small number of resident *fregueses*; as elsewhere, inhabitants obtained manufactured goods in exchange for their produce at the *barracões*. The various ADE sites situated along the coast were also cultivated. Manioc, maize, watermelon, tobacco and other crops were planted. Some of the sites have been under cultivation for a very long time. At Vista Alegre, Fazenda Boa Vista, and Barreira do Capanã, manioc and other crops have been planted for over a hundred years.

While it is difficult to gauge the chronology of cultivation and extractivism over the last hundred years, owing to the vagueness of many oral histories, what we can be sure of is that as rubber and other extractive products decreased in value agriculture increased in importance. Residents throughout the region agree that it was around 30 years ago that agriculture became the principal livelihood activity in the municipality. What emerges from oral histories then is that in the region of the Middle Madeira the relative autonomy of many families has enabled them to practice agriculture on high and low levee floodplain, and the ADE and other soils of the *terra firme* for generations. Many middle-aged informants state that it was their great-grandparents who first occupied (and often legally registered) the land where they now live. Seventy and eighty-year-olds recall the ships that arrived laden with Northeastern migrants from Ceará, Pernambuco, and Paraíba.

[5] Up until 30 years ago residents of the communities Água Azul and Monte Sião lived on the high levee floodplain, which formed part of an S bend in the river, locally renowned as forming the biggest curve in the course of the Madeira. People noticed that the river was to change its course as pressure on the middle of the bend was causing the land to erode away. In 1970, 18 local men cut a *furo* through the middle of the S bend. The high levee upon which people had built their homes began to be swept away and so residents were forced to relocate to the *terra firme*. A low-levee floodplain has emerged as the previous high levee was gradually swept away, and is now being cultivated by locals.

As an outcome of these historical processes the Middle Madeira is characterised by many small family-landholdings occupied by people with continuous agro-extractivist histories stretching back for up to 150 years. This time is enough to have allowed the development of a repertoire of manioc landraces, selected for different ecotones (floodplain, ADE, Oxisol, Ultisol) and different cropping systems (short-fallow, long-fallow), as well as the agro-ecological knowledge associated with manioc cultivation. Although oral histories do not stretch back far enough to recall settlers' preferences for where to live, the pattern of settlement today (i.e., many communities located on ADE sites) suggests that ADE and the wider domesticated landscapes within which they are embedded were particularly attractive to settlers because of the greater abundance of useful species and fertile soils. For instance, urucuri (*Attalea phalerata*, an ADE indicator species) must have attracted rubber tappers as its fruit (a woody endocarp) was thought to provide the most suitable material for smoking rubber (S. Hecht, 2007, personal communication). Existing concentrations of cacao and Brazil nut were augmented with the establishment of citrus and rubber groves. The age of the rubber, citrus, and mango (*Mangifera indica*) trees growing at many ADE sites testify to this. Both oral histories and old *sítios* (patches of agroforests situated near the households) reveal that many such sites have then been continuously inhabited and cultivated since the mid nineteenth century or earlier.

12.2.1 Kinship as History[6]

Kinship on the Middle Madeira has emerged through the social and economic trajectories outlined above. The contemporary pattern of rural settlement and agro-ecological practice can be traced to such historical processes. Communities in the region claim to be *tudo parente* (all kin), as most members are related through kinship. This history of residence and kinship means that people are strongly tied to one another and the land on which they were raised. Most private landholdings have ended up (at least *de facto*) in the hands of the community, even if they had one owner before, as after a hundred years of cohabitation residents are all related to each other. Many large landholdings (i.e., the site of large *barracões*) have also ended up in the hands of the community (usually the *freguezia* who worked there historically), although not always without a fight with the *patrões* or their descendents, which in some places is still going on (such as the Atininga River[7]). An important function of kinship in such a context is to mediate access to resources, principally land (Harris 2000).

When thinking about kinship and residence in rural Amazônia the idea of the 'cluster' is useful as a conceptual tool; this is defined as a 'dense network of multi-family houses, organised around a parental couple' (Harris 2000:84). The concept

[6] The work of Gow (1991), Leach (2003), and Ingold (2000) have been influential in the development of the ideas in this section.

[7] Which provides an interesting example of how history and kinship can constrain agriculture. In this case the *patrão* brought the *freguezia* from Maranhão. They worked mainly extracting Brazil-nuts. Their *patrão* was very exploitative, paying them badly for Brazil nuts and demanding 25% of the harvest of whatever they planted. There was a revolt in 1955, but the *patrão* succeeded in removing those who were against him with the help of the police. Owing to this up until very recently people planted very little there. Thankfully this situation is changing now owing largely to the efforts of a community leader.

was first presented by Lima (1992) in her doctoral thesis concerning rural dwellers of the Middle Solimões River. These clusters of households are closely related through kinship, and are the 'matrix of social organisation and reproduction … the primary units in which economic and social life are acted out' (Harris 2000:87). Clusters are often tied to one another through 're-linking marriages', creating a dense network of consanguineous and affinal ties. Harris highlights the developmental cycle of the cluster, which commences when an elementary cluster forms as a couple take up residence together in a nuclear family. It becomes a complex cluster as new generations of co-resident kinsfolk emerge. A complex cluster is formed from three to four vertically related generations and at least two sibling sets (Harris 2000:95). Communities then are usually formed from two or more intermarried complex clusters. With around 150 years or more of existence, many complex clusters have formed on the Middle Madeira, and these form the basis of most communities in the region.

The existence of such communities formed from complex clusters on long-term landholdings engenders their inhabitants with a collective agency. This locus of consanguinal and affinitive ties makes it relatively easy to organise the workgroups that are crucial for agricultural labour. It is through the cluster that access to land for residence and agriculture is mediated, and fishing rights in local waters distributed. There is an intensive sharing and co-dependency in the affective space within and between clusters, ranging from the daily exchange of objects such as food (fish and bush meat in particular), manioc cuttings and other plant seeds, labouring for one another and bringing up (*criando*) each other's plants, animals and children. Additionally, and most important for our discussion, the cluster is the nexus for the creation and transmission of agro-ecological knowledge and technique. It is in the social and ecological context of the cluster and its activities that children are brought into the world. Relatives are those who provide an 'education of attention' for young children during the activities of life in the houses, *sítios*, *roças*, rivers, and forests of the landscape (cf. Ingold 2000). In this way, the way children come to perceive and engage with their environment is mediated by their situatedness in the agro-ecological trajectory of the cluster and it is through them that its *habitus* is reproduced through time (cf., Robertson 1996). Through this process, the *habitus* of the cluster is in constant (re-) creation as well as transmission; the 'lived world' of each new generation emerging as a reinvention of the previous one (cf. Gow 2001; Harris 2007). Kinship and the corporeality (or embodied knowledge) through which it is made manifest represent a kind of 'cultural memory' (cf. Toren 1999).

12.2.2 Livelihood[8] and Land Use on the Middle Madeira

The staple diet of most families in the interior of Manicoré is fish and *farinha*, as it is in most parts of riverine Amazônia (see Murrieta and Dufour 2004). Manioc is a principal focus of regional agriculture. Production is both for subsistence and market, with a substantial portion of the income of many households coming from the

[8] The livelihoods of concern here are those of people who are subjects of research; that is rural farmers. Therefore the descriptions here are necessarily partial; there are other forms of livelihood in the interior of Manicore. Commercial fishing is widespread, both by people living in the interior and fishing boats from town.

Table 12.1 Basic information on the communities studied in the Middle Madeira

Community	Households	Population[a]	ADE (ha)	Main DE crops
Estirão	12	80	40	Manioc (mainly non-ADE)
Barro Alto	110[b]	588	35	Manioc (ADE, non-ADE)
Terra Preta	24	80	40	Manioc (ADE, non-ADE)
Vista Alegre	55	294	50	Banana, Melanica (várzea) Melancia (ADE). Manioc (non-ADE, ADE)
Água Azul	42	207	14	Banana, Melancia (Várzea). Manioc (non-ADE, ADE)
Monte Sião	8	35	30	Manioc (ADE, non-ADE) Watermelon (Várzea)
Boa Vista	4	16	20	Citrus (ADE), Manioc (ADE)
Barreira do Capanã	38	190	50	Manioc (ADE, non-ADE, Várzea)

[a] Increased number of households relative to overall population can be taken as an index of a younger population, as when a couple have a serious relationship they move out of their parents house and construct their own house, normally for their own (often quickly growing) family to reside. Thus while estirao and terra preta have the same population, there are many more young couples with children at the latter rather than the former, which has an aging population. The number of households can be taken as a crude indicator of this.
[b] Barro Alto is expanding, with 30 new homes being built, and 30 more planned.

sale of *farinha*. Cash cropping on more fertile soils (DE or floodplain) is also a major livelihood activity for some, with banana, watermelon, west Indian gherkin, beans, passion fruit, and other crops grown for sale (Table 12.1). Residents also regularly hunt game, such as *paca* (*Agouti paca*), *cutia* (*Dasyprocta* spp.) and *capybara* (*Hydrochaeris hydrochaeris*), for subsistence consumption; high social value is placed on the consumption of bush meat. Inhabitants also engage in seasonal extraction for sale of Brazil nuts and *açaí* in the rainy season. Most farming activities are done collectively in a workgroup known as the *mutirão*. These groups work efficiently, as members are usually kin and often co-residents in clusters. Extractivism and hunting is done in small groups or individually. Some people extract wood for sale, but this is relatively minor compared to other activities.

The Manicoré River: Terra Preta, Barro Alto and Estirão

The houses of the residents of Terra Preta, Barro Alto, and Estirão are located on ADE sites along the *terra firme* bluffs of the east bank of the Manicoré River. The opposite bank is a high levee floodplain, rich in *Hevea* and the site of most of the rubber *estradas*. This floodplain has not been cultivated in living memory.

At Terra Preta there is 20 ha of *terra preta* upon which houses are located close to the riverside with small kitchen gardens and orchards surrounding them (these are known as *sítios*), with recently planted fruit trees intermingled with elements of the historic anthropogenic forest. The land is divided into two landholdings on which the entire population resides. Behind this strip are fields and fallows also on *terra preta*. The average *roça* size planted per year is around 0.5 ha per household. *Roças* may be cultivated (and increasingly are) up to three times a year and may remain in production for up to 2 years (or six harvests) before fallowing for 2 or 3 years. Watermelon is planted in March, so that it may be harvested in May/June and fetch higher prices owing to scarcity before the main floodplain harvest in September. Black-eye beans (*Vigna unguiculata*) are planted in June, as the summer months are considered best because in the rainy season it is hard to dry beans. Beans are produced both for subsistence and market. After that maize is planted in October.[9] This is seen as a good season to plant as it catches the beginning of the rainy season. Sometimes squash and West Indian gherkin are also planted. Bitter manioc is also planted sometimes in *terra preta*. Behind the *terra preta* (about 200 m inland) is a mosaic of newly planted and mature bitter manioc fields and *capoeiras* (areas of secondary succession) in various stages of regrowth on *terra mulata* and Oxisols and Ultisols. Around 20 ha of bitter manioc are at various stages of cultivation by the community at any one time. In contrast, only an average of 6 ha of other crops are in production at any one time.

At Barro Alto the 35 ha of ADE on which the community is located has been the site of increasingly intensive cultivation as the population expanded over the last 50 years. The population is seven times that of Terra Preta and Estirão, hence there is much less space for *sítios* and houses are more closer together. Farmers cultivate ADE (with *roças* on both *terra preta* and *terra mulata*) with a short cropping – short-fallow system. The most frequently planted crop is bitter manioc. Beans, watermelon, and maize are also planted on ADE, but on a much more restricted scale.[10] Fallow periods are short, from 1 to 4 years. In the clayey Oxisols behind the ADE, manioc is planted in a long-fallow, longer-cropping system. Slow maturing varieties of manioc are planted and harvested 1–2 years after planting. Fields are fallowed for 10 or more years, and a rapidly growing population is causing agriculture to push into the primary forest further inland. While landownership is ostensibly collective, in reality once a *roça* is cut, burnt and planted it becomes property of the family. All *capoeiras* therefore have owners.

At Estirão the ADE is split between six landholdings. There are large *sítios* on *terra preta* close to the river with coffee and cacao planted. Behind these are small fields of 0.5 ha, where sweet manioc, maize, watermelon, and some tomato (*Lycopersicon esculentum*) and papaya (*Carica papaya*) are grown. The majority of the bitter manioc is planted on Ultisols behind the ADE itself. In recent history manioc was also planted on ADE, but the invasion of *limorana* (*Gynerium sagittatum*) has made this unfeasible. *Limorana* is an invasive, weedy, woody perennial that is very difficult to eliminate once established. Even when a *roça* is cut and burnt in an infested area, the roots of the plant regrow quickly, which interferes with

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[9] Some maize is eaten while still green, but most is kept to feed poultry; each family has around 30 ducks and chickens. This provides fresh eggs, meat for occasional consumption, but also chickens and ducks are sold in Manicoré providing a significant source of income.

[10] In May 2007 there were two 0.5 ha fields of watermelon, and three 0.5 ha fields of beans on ADE, compared to 20 ha of manioc in 0.5 ha and 1 ha fields on ADE.

development of manioc tubers. Today manioc is restricted to those areas of ADE where *limorana* has not taken over.

A major factor conditioning the intensity of land-use on ADE on the Manicoré River is demographic change. The site of major population growth, Barro Alto, is also the location where ADE was farmed most intensively. Were it not for the short cropping, short fallow system on ADE the community would undoubtedly have a greater impact on primary forest behind it. At Estirão and Terra Preta, land use was more intensive in the early to mid twentieth century, but ow more land has been turned over to fallow as population has declined.

12.2.3 The Água Azul Coast: Vista Alegre, Boa Vista, Água Azul, Monte Sião, and Barreira Do Capanã

The inhabitants of the Água Azul coast live in close proximity to high and low levee floodplain and many of them farm there. In the floodplain, crops such as banana (high levee), watermelon and beans (low levee) are grown for the market, along with maize and manioc for both subsistence and the market. Almost all families, irrespective of whether they plant in the floodplain or not, also plant manioc in the Oxisols and Ultisols on the *terra firme*. Along the coast there are large areas of ADE that are sparsely inhabited compared to those on the Manicoré River, leaving more space available for cultivation (as there are more spaces without houses, *sítios* or orchards are common on some of the ADE sites). Farmers plant mainly manioc and watermelon on ADE, with some maize, West Indian gherkin, and other crops. Perennials such as citrus, *açaí* and coffee are also planted on ADE.

The ADE site at Vista Alegre is large, over 50 ha. Farmers at Vista Alegre have planted watermelon, beans, maize, and manioc for more than 50 years. Cultivation of watermelon became increasingly intensive from the early 1980s, with the community producing 40,000 fruits per year on ADE. In 1997, ADE cultivation was largely abandoned owing to invasion of *limorana*. Short-cycled crops such as watermelon are still viable, as they can be harvested before the *limorana* takes over. Farmers began to plant watermelon again in 2005. As the cropping cycle is short (3 months) and plant growth is on the surface this is seen as viable, as produce can be harvested before the *limorana* takes hold again. Before *limorana* invasion manioc cultivation was widespread in ADE, but today it is restricted to areas of ADE not taken over by *limorana*. Many people now plant manioc in the clayey Oxisols behind the ADE. A major new livelihood practice is cultivating banana (*pacovão*) in the floodplain on the opposite bank of the Madeira.

The ADE site at Água Azul is small, only around 4 ha of *terra preta* and 10 ha of *terra mulata*. For many of the families, a major source of income is provided by banana cultivation in the high-levee floodplain on the opposite side of the Madeira. Owing to the restricted size of the ADE, its cultivation is limited to a handful of families, some of which have *açaí*, *cupuaçu* (*Theobroma grandiflorum*) and coffee plantations on *terra mulata* owing to a project by Prodex (The Programme to Support Vegetative Extractivism, a now defunct agroforestry initiative of the Banco do Brasil). Many other people are involved in the cultivation of banana in the high levee floodplain on the east bank of the Madeira, opposite the community. Manioc is mainly planted in clayey Oxisols, although some families also plant manioc in *terra mulata*.

Farmers of the community Monte Sião plant manioc, banana, watermelon, and maize on two ADE sites (each around 10 ha), which form part of the single landholding on which the community is situated. These sites are away from the houses of most of the community. As with Água Azul, people used to live on the floodplain, and moved to the *terra firme* around 30 years ago when the floodplain began to be washed away. In recent history the ADE site were *sítios*, but were abandoned by the families residing there owing to a land dispute. Two families from the community have recently reoccupied them. Land-use has been less intensive for these reasons and because the population of the community is small. At Fazenda Boa Vista there is a citrus orchard on *terra preta* with 700 orange (*Citrus sinensis*), tangerine (*C. reticulata*), and lime (*C. aurantifolia*) trees. Farmers there also plant manioc on ADE, with a little maize and watermelon.

At Barreira do Capanã many people plant manioc on *terra preta*. Some farmers also plant small amounts of watermelon, banana, maize, beans, and squash on ADE. Most families with ADE also have citrus orchards producing fruit for subsistence and market. Locals have begun to plant watermelon, maize, beans, squash, banana, and manioc on the newly emerged floodplain, principally in June and July. The proximity of low-levee floodplain and *terra preta* allow farmers to cultivate year round. These families were found to have the most agricultural livelihoods, being able to make use of two fertile ecotones (floodplain and ADE) in order to cultivate throughout the year. Those families that are most involved in farming the floodplain plant manioc on the *terra firme* only for subsistence.

These examples from the Manicoré River and the Água Azul coast show the prominence of agriculture in local livelihoods and the importance of ADE to local farmers. Over the last 30 years agriculture has been stimulated throughout the region by the rapid growth in demand for banana and watermelon.[11] Cropping systems range along a continuum from almost continuous cropping on the more fertile soils of the floodplain and ADE, to long fallow cultivation in the more infertile Oxisols and Ultisols. Demography is directly related to this. The most heavily populated communities, Barro Alto and Vista Alegre exhibit the most intensive land-use on ADE, oral histories indicating almost continuous cultivation for long periods of time. Vista Alegre has suffered from the invasion of *limorana* as a result of this.

This first section of the article has shown how the historical ecology of the Middle Madeira River has created a situation that is enabling of ADE agriculture. Long-term and relatively sedentary habitation has endowed people with close kinship-ties and a

[11] Watermelon has a particular significance, as the region has become the biggest producer in the North of Brazil, and the city has a festival for the fruit.

local knowledge of agriculture on ADE. Now let us turn to examine another region, the Lower Negro River, in order to show how its divergent historical ecology has shaped a contemporary situation that is strikingly different from that of the Madeira River.

12.3 A Social and Agro-ecological History of the Lower Negro

The Negro River flows from the Guiana Shield, one of the world's oldest geological formations. It is characterised as a blackwater river owing to the high concentration of humic acids coming from decomposing organic matter (Junk and Furch 1985), giving the water an appearance similar to that of black tea. The nutrient poor landscapes through which blackwater rivers generally flow are characterised by more oligotrophic environments. The soils, in general, are some of the poorest in Amazonia (Jordan 1985), the floodplain is not usually suitable for cultivation and ADE sites are of a much smaller size than those on the Middle Madeira. Hence, the contemporary landscape presents more environmental constraints (in terms of the absence of floodplain and much less ADE) on agriculture than in whitewater regions. Blackwater regions are less populous than whitewater regions, both today and in pre-Columbian times (Denevan 2001; Moran 1993).

A fundamental difference between the recent history of the Negro and that of the Madeira is that the Negro was subject to far less migration and re-settlement during the Rubber Boom period. Northeastern migrants, after having colonised the Xingu and Tapajós Rivers by 1850, moved onto the Madeira, Purús and Juruá rivers successively. The most intensive penetration was of the rivers on the south bank of the Amazon/Solimões rivers (Oliveira 1983:140). On the Negro River, however, the production of rubber during the rubber boom was relatively small (Prang 2001:122; Leonardi 1999:125). One reason for this was the inferior quality of the rubber trees there; *Hevea brasiliensis*, which is widespread on the Madeira, Purús, and Juruá rivers, is absent on the Negro; in its place are *H. microphylla* and *H. benthamiana*, which are less productive and less abundant (Dean 1987). Indians rather than settlers were responsible for the production of rubber that did occur along the Negro (Ribeiro 1992). This was another important factor in explaining the lower production of the region. Because there was a lack of labour and because of the absence of Northeastern migrants *patrões* would go to the upper Negro, enforce debt-bondage on the Amerindians there and bring them down to work. As Prang puts it "Thus, unlike the rivers of the right [south] margin of the rivers Amazonas and Solimões [such as the Madeira], where many *Nordestinos* and *caboclos* composed the labour force, the patron of the Rio Negro depended on the Amerindians of the Upper Rio Negro" (2001:130).

A key difference, which has resulted in divergent patterns of settlement on the Middle and Lower Negro as opposed to the Madeira, is the dispersal of extractive resources along the former, and their relative concentration on the latter. On the Lower and Middle Negro this was inimical to the formation of long-term communities, as people were forever in motion as they moved between distant sites of extractive resources. A key difference in the extractivism along the Negro compared to that along the Madeira was that the *patrão*[12] would take his *freguezia* on long journeys up often isolated rivers (for example the Unini, Jaú, and Puduari rivers) for months on end, a long way away from where they resided. Alternatively, people themselves would travel long distances for seasonal work. These people were subject to a more 'classical' system of *aviamento*, where they were exploited by a few *patrões* who established monopolies on the supply of manufactured goods and the sale of forest products along various parts of the Negro. Sometimes the *patrão* would not even allow people to plant manioc, or other times people didn't plant as they were not intending to remain in the region. The Unini River, one of the great tributaries of the Middle Negro, for example, was dominated by only three *patrões* in the mid-twentieth century. All this resulted in much less autonomy for the *freguezia*. The wide dispersal of these extractive resources in the Rio Negro basin resulted in low population density over a wide area, another factor preventing the emergence of denser long-term populations that characterise the Madeira (Prang 2001:130). Leonardi writes that while all of the rivers of the Jaú basin were inhabited seasonally by rubber tappers from 1880–1914, when the boom ended this population did not return, as many left to seek new opportunities elsewhere, with hundreds even returning to the Northeast (1999:145).

Along the Middle and Upper Negro (the origin of many of the current residents of the Lower Negro today), economic activity revolved around extractive products. Emperaire (2000) identifies three stages of extractivism on the Middle Negro. The years 1930–1960 were characterised by long expeditions of several months to extract the latex of various species (*balata, massaranduba, rosadinha, ucuquirana*, different Sapotaceae). She notes that the *freguezia* were extremely dependent on their *patrões*, with very little agriculture being practiced. During a second period from 1950–1980 extractivism diversified and began to be practiced throughout the year rather than seasonally. The most exploited species were *sorva*, *piassaba*, Brazil nut, and rubber. People began to work closer to where they resided and practiced subsistence agriculture, hunting and fishing. The final phase begins in 1990 with an increase in agriculture, especially for the sale of *farinha*, as a response to the decline in value of extractive products. The only forest products that continue to be exploited commercially today are *piassaba* (*Leopoldinia piassaba*) and *cipós* (lianas of numerous families). Oral histories from both the east and west banks of the Lower Negro reveal that the mainstay of the regional economy over the last half-century or more has been timber.

In this context it is possible to trace four fundamental types of agro-ecological history among the indigenous and non-indigenous residents of the Lower Negro

[12] Sometimes he even migrated from another region of Amazonia. In one example a *patrão* went from the Middle Solimoes to Unini bringing his indebted *freguezia* with him, another a *patrão* came from Juruá (picking up *freguezia* on lower Negro through his son in law on the lower Negro community of Samauma (itself actually formed from migrants from the Upper Rio Negro). Yet another lived at Taupessasu and took his *freguezia* up to work in the Jaú.

River today, which affect contemporary patterns of livelihood activity and agricultural knowledge. The first is formed of indigenous and non-indigenous families who migrated permanently from the Upper Negro or other regions of Amazônia to work in extractivism on the Middle or Lower Negro. The second category refers to indigenous families who worked in extractivism but at the end of the cycle returned to their places of origin on the Upper Negro and engaged in their traditional activities of agriculture, fishing and hunting. The third refers to indigenous families dedicated to agriculture who have remained in their places of origin. They produced *farinha* that supplied the extractive areas and villages and cities of the region. They prefer to remain autonomous from exploitative relationships with *patrões*; some have migrated recently to and from Manaus and the Lower Negro River. The final group is formed of indigenous and non-indigenous families that have recently migrated from other regions of Amazônia and come from a historical trajectory with significant agricultural knowledge (including ADE farming) (see Leonardi 1999; Peres 2003).

These four distinctive types of agro-ecological trajectory have shaped the ethnobiological knowledge of the inhabitants of the Lower Negro River, which in turn conditions their choices of livelihood activity. Contemporary residents of the Lower Negro can be divided between those who primarily practice timber extraction (the most economically rewarding activity), and those who principally engage in agriculture. Ethnographic research by the authors shows how the agro-ecological and ethnic history of each family strongly influences current livelihood activities. On the Cuieiras River indigenous families from the Upper Negro, who come from an agricultural tradition, today work almost exclusively with agriculture. In contrast to this, indigenous and non-indigenous families who originate in areas whose history has been characterised by extractivism are today heavily engaged in the timber trade. Ethnic origins are clearly also an influence, as 70% of indigenous families resident on the Cuieiras engage in manioc agriculture, while amongst non-indigenous people this figure drops to 40%.

The re-settlement of the Lower Negro occurred later than that of the Madeira, with oral histories demonstrating that the majority of families currently living there have arrived since the mid-twentieth century. Some came from the Northeast, but the majority migrated from other locations within Amazônia, many from the Negro itself. A stimulus of migration was the brief surges in demand for extractive products at different times during the twentieth century, along with social factors such as education and health (Peres 2003). Another attraction was that the river was seen to be empty and therefore there would be less competition for extractive resources than on more populous rivers, such as the Madeira. The reoccupation of the Lower Negro over the last 50 years was also influenced by the fall in price of rubber (after the Second World War) and the beginning of the urbanization and industrial development of Manaus; the latter activity attracted people from all over Amazonia to work in the construction of the city and the creation of the Free Trade Zone of Manaus. The emptying of many extractive areas of the Negro was part of this process, leaving few inhabitants working in agriculture, extractivism and the timber trade. With the rise of unemployment in the Free Zone in the 1970s and 1980s many people returned to the Lower Negro, which they reoccupied and began to work in agriculture and the timber trade.

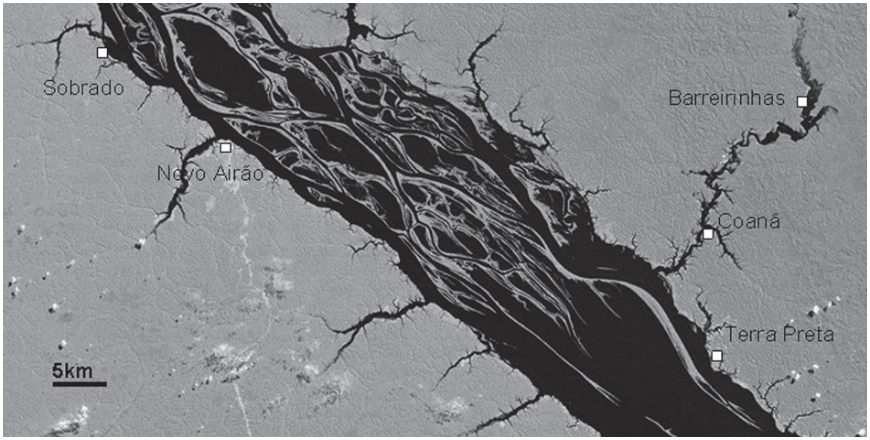

Fig. 12.2 Location of the communities of the Lower Negro River that are discussed in this chapter

The site of prolonged fieldwork on the lower Negro is *Comunidade Sobrado*, on the west bank of the Negro, and the communities of Cuieiras River (Fig. 12.2). The *Sobrado* locality is 1.5 h upstream from Novo Airão, a new town that has grown rapidly over the last 50 years (after having been chosen as the new site for the relocation of a town from the Middle Negro called Velho Airão), but positioned on the site of an old Indian *aldeia* known as Taupessasu. In the middle of the twentieth century, Taupessasu[13] was a small settlement of a few homesteads and eight families inhabited the locality of Sobrado. As with many parts of the Lower Negro, the main source of income was logging, with residents also engaging in the extraction of the aforementioned non-timber forest products. The demand for wood increased dramatically in the 1950s with the growth of boat building in Novo Airão. While some families cultivated manioc for subsistence, this was on a much smaller scale than the Middle Madeira. Members of a family arriving at Sobrado in 1960 from the relatively densely populated Upper Solimões River claim that no one grew manioc in the region when they arrived. They recall that people worked cutting wood and bought big sacks of *farinha* from Manaus. They even claim that people didn't even know how to plant manioc properly.[14] They had to go to the opposite bank of the Negro in order to find *maniva* (*maniva* refers to the branches of the manioc shrub, which are cut up to propagate the plant clonally) to plant. As one commented 'the people here were children of *seringa*, they didn't know how to cultivate.' While this is probably an exaggeration, it does suggest that there was little agriculture when they arrived.

[13] Also known also as 'vila' and 'freguezia' before being named Novo Airão.

[14] This family claims that people in the locality planted manioc in the same way as yams are planted; that is with the cutting being stuck in a mound of earth; and left half poking out. This was seen as a primitive and backward way of planting compared with the method of opening a hole in the ground with a hoe and burying two manioc cuttings as most people do in the interior today.

The Cuieiras River is 50 km upstream from Manaus, on the east bank of the Negro River. The area is today inhabited by many indigenous families who have migrated from the Upper Negro, principally from the Bare, Tukano, Karapano, and Pira-Tapuias ethnic groups, along with many families from the Unini River and the municipality of Novo Airão. Others come from other regions in Amazonia. The principal farmers of ADE on the Cuieiras River are the indigenous families that come from the Upper Negro where there is a long history of agriculture and, while having only recently arrived on the river, possess extensive social networks that connect them with other migrant families and their home regions. These indigenous peoples exchange knowledge with families from regions with a long history of ADE management. It is important to note that it is the women who are the primary loci of knowledge and practice of agriculture among the indigenous groups of the Negro River (Emperaire et al. 2001; Chernela 1987). In contrast to this, indigenous and non-indigenous groups from extractive histories (those from Unini and the municipality of Novo Airão) engage primarily in timber extraction.

12.3.1 Kinship as History

This social and agro-ecological history makes for a radically different process of kinship among non-indigenous people than that which is encountered on the Middle Madeira. The absence of long-term communities with close kinship ties, such as those found on the Middle Madeira, is a direct result of the more recent re-colonisation and agro-ecological trajectories of many families from Negro itself, which are characterised by peripatetic livelihoods owing to the mobility required of extractive activity. Also, in recent history the shifting of the population of Velho Airão to Novo Airão, the expulsion of inhabitants of the Jaú with the creation of the national park and the disintegration of communities along the Unini River caused significant migration to the Lower Negro (Table 2.2). Indigenous peoples of the Upper Negro have been migrating over the last 50 years to locations on the Lower Negro (including Manaus), in an attempt to improve living conditions (Peres 2003). The communities and kinship ties that existed or had been expanding in the source regions were disrupted in this process.

This mobility of families in recent history has disrupted the sedentary patterns of settlement required for the formation of the complex clusters that characterise

Table 12.2 Basic information on the communities studied in the Lower Negro

Community	Households	Population	ADE (ha)	Main crops
Sobrado	64	260	Various sites of 1–5 ha	Maize, beans, squash, papaya, watermelon (ADE) Manioc (mainly non-ADE)
Barreirinhas	14	43	5	Manioc (ADE, non-ADE)
Coanã	22	85	10	Manioc (ADE, non-ADE)
Terra Preta	21	105	10	Manioc (ADE, non-ADE)

the Middle Madeira. The families of *Comunidade Sobrado* live in dispersed homesteads or small clusters, rather than forming a community-wide cluster. Despite the recent construction of a centralised community (with houses, a school and an electric generator), most families have eschewed the possibility of residing there. Some families don't even see themselves as part of the community, a member of the aforementioned family from the Upper Solimões remarking that 'they are not my kin.' Others prefer to remain apart, as they see no reason to participate in the community. This situation constrains the inhabitants' abilities to engage in agriculture as, although there is a community *mutirão*, it functions poorly, with people refusing to work for those they do not like. The lack of kinship ties results in a lack of integration and cooperation in the locality. As one man complained of his neighbours 'they only come here when they want something.'

The kinship relations amongst Amerindian residents of the Cuieiras from the Upper Negro are entirely different, however. They have strong ethnic ties, evident both in kinship and *paraparenteseco* (formal friendships and partnerships related to affinity and alliance; see Eduardo Viveiro de Castro 1995). This type of kinship gives great importance to networks and alliances related to consanguinity and it is this institution that has allowed migrant indigenous people to reconstruct agriculture on the lower Negro and draw on traditional knowledge related to ADE. These indigenous families living on the Cuieiras have forged interethnic networks and also alliances with caboclo families, while maintaining and strengthening ethnic identity, realised through material exchange (including manioc varieties) and land tenure (reclaiming the land as an Indigenous Reserve through FUNAI). They are organised into small communities, with varying degrees of consanguinity. These families maintain a strong connection with their original territory (the Upper Negro), constantly relating themselves to the region where their 'kin' lives. There is a strong social network revolving around the exchange of *maniva* and agricultural knowledge (often in the context of the *mutirão*) between families engaging in this emerging local tradition.

12.3.2 Contemporary Livelihoods at Comunidade Sobrado and Cuieiras River

Comunidade Sobrado has approximately 40 families, 30 of which arrived in the past 50 years. It is possible to group them into three broad trajectories based on their origins: (1) long-term residents who have been present in the locality for a few generations (10 families); (2) recent arrivals from elsewhere on the Negro (20 families); and (3) recent arrivals from outside the Negro (10 families). There are strong similarities in livelihood between the families in each trajectory. All of those born on the Negro have had principally extractivist orientations until very recently. Various informants in this group recall their formative years working in the forests on the Middle or Lower Negro extracting *piassaba*, *sorva*, *balata*, rubber and timber, and hunting animals for their skins.

The long-term residents of the region (related by kinship but not as closely as along the Middle Madeira, and not co-resident) are those most involved in the illegal timber trade. Locals suggest that this is because they have been involved in timber for so long, and therefore have the connections and knowledge to avoid getting caught by IBAMA (the Brazilian Environmental Protection Agency). They attempt to dominate the extraction of timber, claiming that the timber resources of the locality are theirs and threatening to denounce others to IBAMA. Kinship here is again mediating access to resources. It is a sign of how ingrained timber production is in local livelihoods that many people continue such work despite its having been made illegal and the heavy penalties if caught.

The 20 families who were born in other regions of the Negro and arrived over the last 50 years live from varying combinations of manioc farming, commercial fishing, extracting *cipó* (the vines used for handicrafts) and *copaíba* (*Copaifera multijuga*, whose oil is sold and used for several purposes), timber and making charcoal and barbeque sticks. Those who fish commercially often go away on trips of up to a month. While nearly all families cultivate manioc, some don't even have enough to feed the family throughout the year. The only time when significant production occurs for the market is when loans are obtained from banks for the specific purpose of supporting manioc cultivation.

The livelihoods of the final group of families who have arrived from regions characterised by more widespread agriculture are remarkably different, however, and include all those families currently farming ADE. They show a strong tendency towards a more agricultural livelihood. This is demonstrated by the fact that some of these families chose to settle in the locality because they had secured ADE there to cultivate.

The first two farmers reside on Igarapé Sobrado, the most commercially successful of these is a recent migrant from Lago do Limão, an agricultural community in Iranduba, at the junction of the Solimões and Negro close to Manaus. He grows chilli pepper (*Capsicum* spp.), papaya, watermelon, West Indian gherkin, cucumber (*Cucumis sativus*), maize, beans, and squash, mostly oriented to the market. He uses a range of management techniques to maintain the fertility of his ADE, including mulching, chemical fertilisers, and crushed charcoal. Another farmer living close by, originally from Maranhão, cultivates maize, beans, manioc, and squash on his ADE, with more for subsistence and a little surplus sold in the market. He has been 'mining' his soil (not replacing lost nutrients through management or fallowing), however, and it is loosing its fertility. One of the reasons for his lack of fallowing is the lack of labour to clear another *roça* from mature forest.

The next two families cultivating ADE are from the Upper Solimões and live close to one another on the banks of the Negro. They plant maize, beans, squash, watermelon, cucumber, and West Indian Gherkin on ADE for subsistence and market. They have maintained fertility through fallowing.

The final ADE farmer is Henrique, who lives on Igarapé Curuçá. He is a recently arrived migrant from Acre, and has lived on the Solimões, Purus, Abacaxis (a tributary of the Madeira), and Unini rivers, and farmed ADE in all these regions. He plants watermelon and papaya for the market, maize, beans, and squash for subsistence and market, and sweet potato (*Ipomoea batatas*) and manioc for subsistence.

He manages nutrients on ADE through mulching and fallowing. His experiences living in various different regions lead him to be critical of the livelihoods of people from the Negro. 'The people here live from nature, they just fish a little to eat, plant a tiny *roça*, collect a little *cipó*.' He contrasts this with his livelihood, which is principally agricultural and which he sees as living from "the land" rather than from nature. Henrique later explained that he thinks that most people from the Negro live from nature; conversely, those in other agricultural regions (such as the Solimões and the Madeira) live more from the land. Another farmer from the Solimões living on Igarapé Sobrado said of people from the Negro 'they were born into that rhythm [extractivism], they don't know any other way.' Many families native to the Negro continue to ignore ADE despite the opportunities to cultivate it.[15] A new track has been opened to the 20 ha ADE site on Igarapé Sobrado, but only Henrique cultivates there. Other people use the track to clandestinely cut timber.

The Cuieiras River is a tributary on the east bank of the lower Negro. There are two communities there located on ADE sites: Barreirinhas and Coanã. In both communities *sítios* are located on ADE and manioc is planted on ADE. Coanã has 22 families, half of which are indigenous people from the Middle and Upper Negro and only two of which have been in the region for more than 30 years. Barreirinhas has 14 families, most of which are indigenous people from the Upper Negro. Many of the non-indigenous residents are from the Lower and Middle Negro, some of them from the Unini, and others are from the Solimões. Non-indigenous residents are more involved in the timber trade, while indigenous people engage in agriculture alone, or both agriculture and extractivism. For indigenous people, principally women, agriculture is symbolically linked to social status. They continue to engage in agriculture and many say that 'this is what I learnt to do on the Upper Negro, it's enough to keep me going on the Cuieiras.' They say that 'the people that work with timber want to get money quickly and don't want to dirty themselves in the *roça*.'

At Coanã two indigenous families from the Upper Negro cultivate manioc on ADE. One family is Cubeo (from the Tukano language family); the head of the family has lived in the region for 40 years. The other family is Karapano-tapuia (also from the Tukano language family) from the Colombian border. The first family learnt about ADE farming on the Lower Negro from contact with farmers migrating from the Solimões, while the second learnt how to farm ADE on the Upper Negro. They say that they met a *nordestino* (from the north-east of Brazil) in Santa Isabel, who taught them how to farm ADE. One of the older indigenous farmers, Sr. Aldenor, cultivates manioc on ADE, which he learned to do in the Upper Negro; he also plants watermelon, yam (*Dioscorea trifida*), and beans. A non-indigenous family that arrived in Coanã 2 years ago from the Solimões, reports that they planted a lot of manioc on ADE where they came from. This family does not currently have access to ADE but uses ADE from their neighbours to fertilize fruit trees and watermelon.

[15] German (2001) found a similar situation on the Middle Negro, with ADE little used for agriculture by local people who had grown up in the region.

At Barreirinhas two young families, one Baré and the other Tukano, plant manioc, other root crops, and fruit trees on ADE. The first family learned to cultivate ADE from their older kin, who live in the community, and have a wide repertoire of agroecological knowledge. The second family has lived for 40 years in the region and learned to farm ADE on the Lower Negro.

Many of the old indigenous people that live in the region say that there is ADE on the Upper Negro, but they used to be ignorant of its agricultural potential. They associate the presence of ADE on the Upper Negro and in Coanã and Barreirinhas with the *malocas* (communal houses) of the 'old ones' (ancestors). They say that after learning about ADE agriculture from peasant farmers, they started to plant manioc, chilli pepper, papaya, West Indian gherkin, sugar cane, beans, and squash for subsistence consumption. They also favoured ADE for planting fruit trees. In both communities, the most frequently planted crop in ADE today is bitter manioc, with some intercropping of pepper, yam, squash, sugar cane, banana, and beans. The Karapano family is renowned on the Cuieiras as true farmers and it is observed that they are responsible for a significant part of the manioc varieties under cultivation by other farmers, thereby contributing to regional agrobiodiversity. The family is linked through kinship to other rivers close by, and in wider networks that connect them to their indigenous 'kin' on the upper Negro.

Close to the Cuieiras is situated an indigenous community called Terra Preta, whose residents plant bitter manioc on ADE. Interestingly, non-indigenous inhabitants of Santa Maria, a neighbouring community, have arranged to use a part of the ADE to plant manioc owing to the greater soil fertility there.

This section has shown how most families resident on the Lower Negro today *come from somewhere else*. The trajectories of most families (whether extractivist or agricultural) are characterised by *mobility*. This diversity of origins strongly influences the perception of the environment and livelihood activities in relation to it. Those who are farming ADE come from an agricultural trajectory, whether migrant peasant farmers from the Solimões or indigenous people from the Upper Negro.

A person growing up in the context of a lifeway of mobility and extractivism will be more likely to continue to engage in extractive activity. Conversely, a person growing up in a more settled and principally agricultural community is more likely to engage in farming. A corollary of this is that regional historical ecology shapes people's ethnobiological knowledge. Differential repertoires of traditional knowledge are emergent from different agro-ecological trajectories (cf. Atran et al. 2004; Coley et al. 1999). This could explain why ADE sites on the Negro are cultivated by those people who have been endowed with appropriate skills by virtue of having grown up in areas where agriculture is widely practiced, while people from extractivist backgrounds with little experience in agriculture ignore them. People's perceptions of nature are mediated by their history of engagement with it; knowledge of nature inheres in the pathways of movement and growth in the landscapes in which people become (Ingold 2006; Gibson 1979). Growing up in a certain landscape and engaging with it in specific ways (i.e. extractivist, mobile) will engender a perception of the environment different from that of a person who grew up in another landscape (i.e. agriculturalist, sedentary).

12.3.3 Manioc Agriculture and Dark Earths

This chapter has shown how the particular history of the Middle Madeira – with its long-term landholdings, kinship ties, and sedentary populations – provided the conditions for a situated trajectory of agricultural practice, experimentation, and knowledge well over a hundred years. In other areas, such as the Lower Negro, with the vast majority having arrived in the last few decades, such knowledge is limited to individual families with agro-ecological trajectories that have endowed them with the relevant experience (in particular those migrating from regions where there is a long tradition of agriculture).

On the Middle Madeira generally and with some families studied on the Lower Negro the most frequently encountered crop in *roças* on ADE was bitter manioc.[16] This was surprising for two main reasons. First, this runs counter to the current consensus in the ADE literature, which holds that most farmers do not plant bitter manioc on ADE. Previous studies have reported that this is because the crop does not perform well on these soils: the shrub grows vigorously but yields small tubers (German 2003; Hiraoka et al. 2003). Second, as a prominent manioc scholar recently remarked 'why would anyone want to plant manioc on *terra preta*, when it does perfectly well in other soils and *terra preta* can be used to plant crops which do not grow in other soils [of the *terra firme*], it doesn't make sense'?

The reality encountered on the Middle Madeira and amongst some farmers of the Lower Negro confounds these points of view however. The claim that ADE is not suitable for manioc agriculture is paradoxical. The large and settled Amerindian populations located on *terra firme* bluffs along major rivers (Denevan 1992a, 2001) prior to contact and thought to be responsible for the creation of ADE were manioc farmers (Lathrap 1970; Oliver 2001; Denevan 2001). If manioc agriculture was integral to the (intentional or unintentional) creation of ADE then surely these anthropogenic soils should be superior for manioc cultivation. This point is supported by the fact that many farmers of the Middle Madeira claim advantages of planting on ADE as opposed to the clayey Oxisols and Ultisols that are the predominant soil types of the *terra firme* in the region.

Manioc farmers of the Middle Madeira have developed a repertoire of over 50 manioc landraces that are planted in the various ecotones of the *terra firme* (in Oxisols, Ultisols, and ADE) and in the floodplain. Cropping systems range along a continuum from almost continuous cropping in more fertile soils of the floodplain and ADE, to long fallow cultivation in the more infertile Oxisols and Ultisols. One of the most common statements among long-term ADE farmers of the region is that manioc grows *mais ligeiro* (faster) in ADE. They attribute this to the higher fertility and to the texture of the soil, which they see as being sandier and more *fofa* (fluffy) than the surrounding clay soils, thus facilitating tuber development. According to

[16] In some of the communities discussed (Barreira do Capanã; Monte Sião; Barro Alto; Terra Preta) the most frequently planted crop in DE roças by far was manioc. In Estirão and Vista Alegre, manioc was extensively cultivated historically, but today limited to areas not infested with *limorana*.

farmers the average *farinha* yield per hectare on ADE seems to be between 100–120 sacks which compares favourably to 60–80 sacks on Oxisols and 70–90 on Ultisols.

Manioc farming on ADE is frequently more intensive than on other soils of the *terra firme*. People for whom the production of *farinha* for the market is a major livelihood activity undertake the most intensive farming on ADE. For these people, manioc is often cultivated on a short-fallow (1–4 years) shorter cropping (5–10 months) cycle. Three fast-maturing landraces are among the most preferred on ADE: Pirarucu Branco, Pirarucu Amarelo, and Tartaruga (also known as Cosha Branca and 'Six Months'). Roxinha is slower maturing, also a favourite but not in the most intensive systems; however, farmers claim that it only does well in ADE when planted in a field cleared from capoeira over 5 years old. Farmers, therefore, have various landraces of manioc that perform particularly well in ADE, and logically plant more of these varieties on ADE. This leads to different selective pressures on manioc landraces, as new genetic material incorporated from volunteer seedlings favors traits (such as faster maturation and early seedling) already prevalent in varieties selected for cultivation on ADE by local farmers (e.g. Fraser and Clement n.d.).

Fast-maturing varieties are universally categorised as *fraca* by farmers, and are planted in all kinds of *terra firme* soils as well as in the floodplain. *Mandioca fraca* matures quickly, with tubers reaching harvestable size in 6 months. This is why they are planted in and possibly originate from the floodplain. There are drawbacks with *mandioca fraca*, however; farmers recognise that after being in the ground for more than a year these types of manioc are susceptible to rotting, and some of them will not soak properly after a year, meaning that they have to be dry-processed. Some landraces are also said to be very watery, so that they *quebrar*[17] (lose about a third of their mass) on being processed into *farinha*.

Mandioca fraca is almost universally recognised as performing better in ADE and other soils of the *terra firme*, reaching maturity after 10 months, while taking over a year to mature on Oxisols and Ultisols. Some farmers also claim that the tendency for *mandioca fraca* to rot after being in the ground for over a year is diminished on ADE, with *mandioca fraca* lasting 2 years or more if kept free from weeds. Conversely, many farmers state that *mandioca forte*, the slow maturing kinds that last up to 3 or 4 years in the land without rotting, are better planted in non-DE soils. These varieties are dryer and therefore do not '*quebrar na torragem*' (break during roasting).

Many of these *fraca* varieties originate in the floodplain; indeed, some farmers explicitly state that '*mandioca fraca vem da várzea*' and research shows farmers continually experimenting with floodplain varieties in the *terra firme* (the popular varieties Glai and Piraiba have only recently been transferred from the floodplain to *terra firme*). It is difficult however to establish direct origins of many popular fraca landraces (such as Tartaruga), as they have been present at some communities

[17] While *quebrar* means to brake, what farmers actually mean is that the *massa* (the manioc pulp after being soaked in water and trained in the *tipiti*) diminishes onces *farinha* is toasted. One and a half tins of massa then become one tin of farinha. This problem does not occur with the dry forte landraces such as Jabuti and Arroz.

for so long that people have forgotten where they came from. It is likely that varieties adapted to the fertile floodplains do particularly well in ADE as they are able to take advantage of the greater fertility of these soils.

The River Manicoré: Terra Preta and Barro Alto

Farmers at Terra Preta plant manioc in *terra mulata*, which they describe as either *terra preta* (black earth), *areião* (big sand), *areia preta* (black sand), or *areia misturado com barro* (sand mixed with clay). ADE is so associated with sand that sometimes the words are used together or interchangeably, as in '*é areia, é terra preta*' (it's sand, it's dark earth). As well as planting in this large extension of *terra mulata*, farmers plant in other Oxisols and Ultisols adjacent to the *terra mulata*, and these soils have also undergone anthropogenic transformation as a result of long-term shifting cultivation [see Topoliantz et al. (2006) for discussion on possible reasons for darkening].

Farmers assert that *terra mulata* is good for planting manioc, as they perceive the texture of the soil to be *mais fofa* (fluffy) and *macia* (soft/smooth). This gives various advantages: firstly it is much easier to dig holes to plant *manivas*; secondly manioc grows faster; and thirdly it is much easier to pull the roots from the ground when harvesting. Also, the soils are seen as better drained. This gives real advantages when compared to planting in the clayey Oxisols that predominate in the region. Farmers say that manioc roots which mature in 1 year on *terra mulata* take 1.5 years to achieve the same size when planted in clayey soils. Also the planting and harvesting are around a third quicker on *terra mulata* than clay owing to the sandy texture of the soils. Observations suggest that manioc harvests are one third quicker on *terra mulata* and labour requirements are around a third less than on clayey Oxisols.

Those planting on the *terra mulata* employ a short-fallow (4–8 years) shorter cropping system. In the first cropping a mixture of landraces, some more *fraca* (mainly Tartaruga, with some Pacú, Pirarucu Amarelo, and Manaus) and other more *forte* landraces (mainly Aruari and Roxinha) are planted. The fast maturing varieties are planted first, and harvested first 6–10 months after planting. The harvest of more *forte* varieties does not begin until a year after being planted. The replant (sometimes done twice) is almost exclusively done with Tartaruga. This contrasts with the system of long-fallow (10–30 years) shifting cultivation practiced by other villagers on the Oxisols and Ultisols further behind and beside the village, with the more *forte* varieties Roxinha, Arroz, and Aruari predominating over the *fraca*.

At Barro Alto, the system of short-cropping short fallowing on ADE is more intensive and much more pronounced than at Terra Preta. Tartaruga is almost the only landrace planted in ADE. It is mostly planted in small (0.5 ha or less) *roças* and harvested 5–10 months after planting, upon which it is replanted once or twice before a short (1–2 years) fallow. Most roças, rather than being populated by manioc plants of the same age, are mosaics of three or more age groups, owing to almost continual harvesting and re-planting. This can be understood as an outcome of population pressure leading to increasingly intensive agriculture with the almost exclusive cultivation of the highest and quickest yielding landrace, Tartaruga, which is also seen as being most suitable for planting in land which has had little or no fallow.

This contrasts strongly with the long-fallow, longer-cropping system on the clayey Oxisols further behind the community. Here, larger (from 1 to 2 ha) *roças* are planted with slower maturing varieties such as Roxinha, Aruari, and Arroz. Harvesting begins only after a year, with manioc left in the ground for up to 2 years. *Roças* are located in older *capoeira* (10–30 years) and mature forest. Owing to intensive, almost continuous cultivation, yields on ADE have decreased. One farmer noted that he produced 80 sacks of *farinha* from a 0.5 ha manioc field 40 years ago (Tartaruga, harvested 10 months after planting). Today, the same field (same variety, same cropping period) produces only 50 sacks. This is still greater than the 30–40 sacks per half hectare produced on adjacent soils.

Farmers at Barro Alto consider ADE to be sandier than other soils, just as do the farmers at Terra Preta. Why would farmers perceive ADE as sandier than other soils? What could make ADE sandier, or appear sandier than other soils? Firstly the literature suggests that ADE is more frequently sandy than clayey (e.g. Teixeira and Martins 2003:279; Lehmann et al. 2003:111). The sandy nature of much of the ADE on the Middle Madeira may be because they have formed on Ultisols rather than Oxisols. Ultisols are characterised by an argic horizon, which is 'a subsurface horizon with distinctly higher clay content than the overlying horizon'.[18] The overlying horizon is therefore relatively sandy compared with the subsurface horizon and other clayey soils. This overlying horizon (including the anthropic-A Horizon) is superior for manioc cultivation than that of clayey Oxisols (W. Teixeira, 2007, personal communication) as roots develop more easily in the looser soil structure afforded by sand, and the soils are much easier to work than clayey ones. It is also probable that anthropogenic processes cause soils to become sandier and/or appear sandier. The practice of manioc cultivation, followed by fallowing, and including deposits of organic waste (e.g. slash and weeds) all burning at various temperatures results in the incorporation of large quantities of fresh, partially carbonised, and fully carbonised organic matter. This organic matter, especially the different sized pieces of charcoal, causes changes in the physical structure of the soil, modifying especially the macro-porosity of the soil. The accumulation of charcoal fragments and increased macro-porosity make the soil 'sandier'. It is also possible that the fine charcoal and clay fractions interact, and may affect micro-porosity also, but this requires more study to confirm. How traditional agricultural practices modify soil structure will require further research.

The Água Azul Coast: Barreira do Capanã, Boa Vista, Monte Sião, and Água Azul

Farmers at all of these communities reported better yields on ADE compared to the Oxisols and Ultisols characteristic of the *terra firme*. Only six households occupy

[18] Quote taken from the ISRIC World Soil Information Website. Accessed 22/4/07 http://www.isric.org/UK/About±ISRIC/Projects/Current±Projects/World±Reference±Base/Acrisols.htm

the large ADE site at Barreira do Capanã. The most commonly planted manioc landrace on ADE is Pirarucu Branco. Many prefer this variety of bitter manioc with white tubers as it is seen to be very high yielding on ADE and because of the sweet tasting *farinha* that is produced from it. This is in spite of the *farinha* being cream coloured, while market demand is for yellow. This variety also defies classification as *fraca* or *forte*, being both fast maturing and durable in the soil. At Barreira do Capanã, owing to a smaller population and greater availability of land, the shorter-cropping short fallow system evident at Barro Alto and Água Azul is not necessary. For example, while in April and May 2007, Tartaruga of 6–8 months was being harvested at Barro Alto and Terra Preta, and Pirarucu Branco of 5–7 months at Água Azul, at the same time people were harvesting mature 18-month-old Pirarucu Branco grown on ADE at Barreira do Capanã.

At Boa Vista and Monte Sião, in areas with lower population pressure, farmers plant far greater quantities of Tartaruga and Pirarucu Branco in *roças* on ADE. They claim that these varieties perform much better in ADE whilst forte varieties, such as Jabuti, are better planted in clayey Oxisols. They claim that the varieties of manioc that perform better on ADE reach maturity quicker owing to the *fofa* texture of the soil. Owing to an abundance of ADE relative to the population, and some farmers also planting in the floodplain, the cultivation of manioc in ADE is less intensive.

At Água Azul, the site of the most intensive farming on ADE in the study area, a single plot of about 2 ha of *terra mulata* has been under nearly constant cultivation for over 30 years. In April and May 2007, 25 sacks of *farinha* were produced from 0.25 ha of 5 and 6 month old Pirarucu Amarelo. This is a high yield considering the amount of time the land has been under nearly constant cultivation. A similar sized plot of the same age on nearby Oxisols yielded only 15 sacks. This example shows that fast maturing manioc can be almost continuously planted in *terra mulata* with yields remaining higher than Oxisols and Ultisols. Farmers do report that yields were considerably higher when they began 30 years ago, however, which indicates that fertility is not unlimited (e.g. German 2003).

At Boa Vista and Água Azul smaller patches of bitter and sweet manioc were found to have been cultivated almost continuously for periods of up to 30 years or more in homegardens on *terra preta*. These appeared to have their fertility maintained (unintentionally) by virtue of being in the *sítio* and subject to fertilization from the burning of weeds and household waste, mulching from organic waste being swept into the manioc, and having chickens constantly scratching and defecating amongst the manioc bushes. This suggests that under certain conditions manioc can be cultivated almost continuously in ADE without reductions in yield. Even in the *roças* on ADE, which are receiving much less in the way of nutrient inputs, manioc may be replanted up to four times with little or no reduction in yield before fallow (with the fallow encouraged more because of weed pressure than fertility loss).

In the region of the Middle Madeira there is clearly local knowledge of manioc cultivation on ADE that stretches back several generations. When asked about the origins of their intensive cultivation practices, people often state that they remember helping their parents or grandparents in the *roça* using similar techniques.

Some of these techniques are possibly analogous to used by Amerindian peoples today and historically and are evident in the incorporation of seedlings (locally known as *maniva de viado, capitão, maniva do índio, maniva nativa*) into existing and new manioc landraces (see Elias et al. 2000). In various communities some of the old people claim the seedlings come from the roças of the 'old ones' or Indians, others see seedlings being planted by nature. Another possibly indigenous technique is the planting of different varieties all mixed together rather than separately (known as *intermediado*). Manioc landraces are then said 'cross' and produce new varieties. People also break the stems of seedlings, which is known to make them develop tubers in a manner similar to clonally reproduced plants.

Many people (usually those whose livelihoods are most dependent on manioc) constantly experiment with new varieties. The short-cropping systems described above, with fast maturing *fraca* varieties, are the outcome of situated trajectories of agricultural knowledge, practice and experimentation on long term landholdings of the region. The modern repertoire of manioc varieties in the region is emergent from this trajectory, and their circulation between clusters and communities takes place through kinship relations. In recent history fewer varieties of manioc were planted on the Água Azul coast, where in all communities studied people stated that over 50 years ago all that was planted was Jabuti, a *forte* variety very popular in the region. Through these processes local farmers have *increased* the number of landraces at their disposal, and have developed knowledge about the attributes of each. Modern landraces then result from a situated tradition of experimentation by farmers themselves.

The market has often been depicted as impoverishing genetic diversity of crops (e.g. Soemarwoto 1987). This simplistic viewpoint excludes the possibility that the market is possibly driving farmer innovation, as various different varieties are 'mixed' to create the best *farinha*, and seedlings are managed in a constant drive to find higher yielding varieties with yellower roots. There has certainly been a shift towards *fraca* varieties as people seek to increase production for the market.

The Lower Negro

The cultivation of ADE is more limited on the lower Negro, as we have seen. However, four out of five ADE farmers at Sobrado reported improved manioc performance on ADE. The farmer who cultivates the most manioc in ADE at Sobrado is the aforementioned Henrique. He claims to produce from 150–200 sacks of *farinha* per hectare in ADE, whereas the sandy soils characteristic of the region only produce 50–70 sacks of *farinha* per hectare. Recently, he made a whole sack (50 kg) of *farinha* from the roots of only ten mature manioc shrubs growing in ADE.

Indigenous inhabitants of the Cuieiras River who farm ADE hold the view that these soils are better for manioc cultivation, as they observe more rapid tuber growth. The Karapano and Cubeo families prefer to plant fast maturing manioc in ADE. The Karapano family have two rare varieties, *Pretinha* (fast maturing) and *Amarelão*, which they say yield better in ADE than other soils. The *Amarelão* variety was lost, but the family managed to find it again by opening a new field in an ADE *capoeira* where they had previously planted this landrace. This example shows the role of manioc seed banks in ADE in conserving particular varieties, selected previously for certain traits favourable to cultivation on ADE (cf. Peroni 2001). Another variety of manioc which is popular with these families as it does well on ADE is called *Aladim*. Families cultivating other soils do not favour this landrace, suggesting it is adapted to more fertile soils such as ADE, and is being selected for this trait. The fast maturing *Pretinha* comes from the floodplain of the Solimões. The origin of the other two varieties of manioc is not clear, but it appears that they come from the Lower Negro or the Solimões. These people do not have manioc varieties from the Upper Negro; they affirm this by saying 'here all of the *manivas* are different from the *alto* [Upper Negro]'. At these sites manioc is cultivated in ADE for 1–3 years, and is left in the ground for up to 4 years. Land is fallowed for 2–5 years. This contrasts with other types of soil where manioc is cultivated for 1–2 years and fallow periods range from 4 to 12 years.

The main difference between the Lower Negro and the Middle Madeira is that, in the former, only those farmers with agro-ecological trajectories from *other places* within a situated agricultural tradition have knowledge and skills to plant manioc on ADE. There is no widely shared tradition of ADE agriculture on the Lower Negro as there is on the Middle Madeira. On the Middle Madeira, the long-term tradition of agriculture and the kinship links between different communities has facilitated widespread cultivation of manioc on ADE, and a repertoire of local knowledge related to it.

Despite all this evidence that contradicts earlier literature, it is worth noting that some farmers do experience the restricted tuber size with vigorous growth of foliage as reported by German (2001, 2003) and Hiraoka et al. (2003). One of the Lower Negro farmers reported this happening on his ADE. Also, at Aracari, the next community upstream from Sobrado, farmers report that manioc grows *mais ligeiro* in their *terra preta* but claim that nearby clayey soils give better yields. Similarly, at Santa Helena, a community just inside the mouth of the Rio Mataurá on the Madeira, farmers report that unless a certain variety is planted, manioc produces only small roots. One informant also said that he thought the clayey background soils superior for manioc.

The majority of the farmers interviewed in the present study claim that ADE is better for manioc cultivation. This suggests that those for whom manioc does not perform well could be a minority. The results of German and Hiraoka may reflect the experiences of only those relatively few farmers included in their studies and therefore their results should not be assumed to be universally applicable (e.g. Sillitoe 2006:131). This shows how important it is to situate people's ethnobiological knowledge and perceptions in the context of their agro-ecological trajectories and regional historical ecology. In these aforementioned studies, such an approach might have shown that the 'vigorous growth but small tubers,' which farmers reported, was simply due to the wrong varieties being planted owing to the lack of a situated tradition of ADE cultivation in the region, or inexperience owing to a extractivist lifeways.

12.3.3.1 Awareness of Anthropogenic Processes

In the same way that generations of residence and manioc agriculture has allowed the development of local knowledge of manioc agriculture on ADE on the Middle Madeira, it has provided the context in which people have become aware of the anthropogenic processes through which ADE are formed. Various farmers in the region are well aware that ADE was made by Indians and of the processes of burning involved in its formation. In one instance, an old man (now deceased) was remembered who had claimed to have first-hand experience of the Indians 'making terra preta' when he lived with them. This awareness, which emerges both from personal experience and social memory (as with the old man), is demonstrated in the following quotes from three farmers on being asked about the origins of ADE:

> The old people told us how *terra preta* forms where there was an Indian village. Millions of them burning, making pottery, cooking, *roçando*. In this way the land became *terra preta* from burning. It's the same way when we burn a *roça* and do *coivara*, it makes *terra preta*, the soil goes black, any plant will grow better. Manioc planted in the *coivara* always grows better…when you burn the *coivara* like this it changes the soil forever, we sometimes find these places in the forest which have been burnt, these places are better to plant *roça* than places which have never been burnt. (Manuel Galdino Cavalcante, Monte Sião)

> There was an old man who said terra preta was made by Indians. Burning, planting manioc and maize the Indians made terra preta. These are the things that grow best in terra preta, no? If you wanted to make terra preta you could; we just don't because we already have plenty. We'd just make a roça with lots of coivaras, burn and it forms 3 fingers of terra preta [holding up 3 fingers horizontally]. Its like women do in the sítio when they make terra queimada; its terra preta. Some parts of terra preta are darker because they were burnt more. I think in the terra preta where there are pottery fragments is where the Indians lived and where there are no fragments is where they planted. (Raimundo Suares, 'Pindu', Boa Vista)

> It was the Indians that made *terra preta*. We always find their ceramics in the *terra preta. Terra preta* was formed by the Indians' burning. There are different types of *terra preta*, here it is really dark, further behind it is less dark…When we make a *roça* and burn, the soil becomes dark. Every *capoeira* has a little *terra preta* underneath, because it was burnt. The [non-ADE] *capoeira* is always better to plant manioc, the replant in the *capoeira* is better than the first in [non-ADE] primary forest. All the vegetation burns, rots and becomes *estrumo* [fertiliser]. When the earth burns it stays like that forever, the more times it is burnt the better it will yield manioc. It's because we transform the earth, digging, mixing. The more times the earth is burnt, the deeper the *terra preta* goes. When I began to cultivate the *roça* behind my house [on Oxisol] it was hard clay. When the earth is burnt it becomes sandier. As it becomes *terra preta* the soil becomes looser and sandier. I have cut and burnt there 8 times, now there is 10–15 cm of *terra preta*. Where the earth is darker, manioc yields better. In the *coivara* manioc grows beautifully and yields well. Manioc yields better now in that *roça* than before. Only the top of the soil is *terra preta*, but the manioc is also planted at the top of the soil, it grows bigger and faster now. (Raimundo Ipês dos Santos, 'Dico', Água Azul)

We argue that this local knowledge of the superiority of ADE for manioc and awareness of anthropogenic processes of formation is an outcome of regional historical ecology. This is because such knowledge is immanent in the activities of burning and planting manioc on ADE and other soils and experiencing how they change over time (e.g. Ingold 2000; Bateson 1973; Gibson 1979). Remembering that such knowledge is not just socially constructed (as with the old people's stories) but also inheres in people's engagement in environmentally situated activities allows us to suggest that there may be analogues here to the processes through which Amerindian farmers figured out how to make ADE and used these improved soils to increase the yields of manioc and possibly also cultivate maize and other more nutrient demanding crops (Denevan 2001).

12.4 Conclusions

This chapter has shown the kinds of insights that historical ecology can provide in explaining people's knowledge and practice of agriculture on ADE. It has demonstrated how the Middle Madeira has emerged as a landscape enabling of agriculture through the interplay of historical (sedentary life-ways, complex clusters, long-term land-holdings, river-transport) and environmental factors (the presence of widespread fertile ecotones in the form of ADE and floodplains). Conversely, the Lower Negro has emerged as a landscape that has until recently constrained agriculture through the interplay of historical (mobile life-ways, working primarily in extractivism and corresponding reliance on *patrões*, paucity of long-term communities and resulting lack of kinship;) and environmental factors (limited fertile ecotones in the form of ADE, lower fertility of background soils). The agriculture being practiced today on the Lower Negro is by people who *have brought it from somewhere else*, using knowledge from their personal histories within situated agricultural trajectories, such as the Solimões and Upper Negro. The contemporary landscapes of the Middle Madeira and Lower Negro have therefore emerged through a diachronic interplay of environmental and historical factors, such as those listed above.

This chapter has shown that the importance of ADE as an agricultural resource is regionally variable. The greater repertoire of traditional knowledge about agriculture among people who have grown up in white water regions means that the techniques of cultivation and soil management with which they are endowed makes them more likely to farm ADE, and to develop practices to manage and even create these soils. In contrast to the conclusions of other studies (e.g. German 2001), many long-term farmers interviewed have shown themselves to be well aware the anthropogenic origins of ADE *and* sometimes of the charring processes leading to their formation. However, processes of ADE formation today are qualitatively and quantitatively different from those that would have led to their creation in Amerindian times. Shifting cultivation today tends to be *extensive* in its land-use, in contrast to the *intensive* practices thought to have created ADE in Amerindian times, in part owing to the replacement of stone axes with metal ones (Denevan 1992a, 2001). The ability to plant manioc in semi-continuous intensively managed gardens becomes far more attractive when one only has stone axes with which to clear forest (Denevan 1992a, 2004; Hecht 2003; Myers et al. 2003). Denevan (2004, 2006) has proposed a short-cropping, short-fallowing crop system on ADE in Amerindian times, but curiously he chooses not to explicitly propose Bitter Manioc as the principal cultivar, despite the consensus in the literature that this was the carbohydrate staple of Amerindian peoples (Lathrap 1970; Oliver 2001). This is probably due to the aforementioned gap in the literature on contemporary manioc farming in ADE, something this chapter rectifies.

ADE formation today is most obvious in the homegarden, as it is here where intensive management involving the mixture of charred garden waste (*terra queimada*) and rotting wood (*paú*) takes place to create fertile soil for the cultivation of vegetables and condiments (see Winklerprins, this volume). It is also likely that *terra-mulata*-like soils form today under long-term shifting cultivation (Topoliantz et al. 2006), but more slowly than in Pre-Contact times owing to the extensive as opposed to intensive land-use mentioned above.

Farmers often note the darkening in soils after long term shifting cultivation and the increased friability. 'The more you *mexer com* (mess with) a soil,' said one, 'the better it is to plant manioc, it becomes more *fofa*.' ADE farmers sometimes make the leap of associating changes in the structure of the topsoil under longer-term cultivation with the formation of ADE. These understandings of changes under cultivation, and the perception of improved structure of ADE for manioc cultivation, suggests that the creation of *terra mulata* by Amerindian peoples could have been intended to improve the texture and fertility of the soils in manioc gardens. The precise changes in soils physics, chemistry and biology that result for the management practices described here remain to be investigated.

This chapter has shown that contemporary agriculture on ADE cannot be considered apart from the regionally divergent historical ecologies in which it is embedded. It has argued that landscapes emerge from the complex interplay between historical and environmental factors that have shaped the current circumstances found in the two regions. The historical ecology of the Middle Madeira then has led to the emergence of circumstances that have allowed for the development of widespread local cultivation of ADE and the formation of a repertoire of local knowledge in relation to it.

The practice of choosing to plant certain varieties on ADE, and other varieties on Oxisols and Ultisols, along with the differences in soil fertility of ADE and non-ADE soils, impose different selective pressures on the sexual reproduction of manioc. Varieties selected on ADE display fast maturing, early seeding traits. This poses intriguing questions with regard to the divergences between the co-evolution (selection as an interplay of human and natural agencies) of manioc landraces on ADE as opposed to other ecotones, such as the Oxisols and Ultisols, of the *terra firme* and high and low levee floodplain. ADE, considered by Clement et al. (2003) as a reservoir of agrobiodiversity, may contain seed banks of manioc adapted to these soils, as observed by Begossi et al. (2001). Farmers notice a high incidence of seed bank 'volunteers' on ADE manioc fields newly cleared from fallow. Some of these are incorporated into existing landraces and provide new genetic material, thus contributing to *in situ* reserves of agrobiodiversity (Rival n.d.; Pujol et al. 2005, 2007). Manioc seed banks are of crucial importance in regaining genetic material lost in the aftermath of disasters; it would be interesting to speculate on their role during and after the catastrophic impact of European contact (Denevan 1992b; Clement 1999a).

Further research is underway in order to explore farmers' ethnobiological understandings and processes of categorisation of the soils, landraces, cropping systems and seedlings involved in manioc cultivation. More comparative research is needed in other regions of long-term ADE farming in Amazonia in order to better explore the potential benefits of manioc agriculture in ADE and how local understandings of the cultivation, management and creation of ADE could be incorporated into a project looking to create *Terra Preta Nova*.

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Chapter 13
Amazonian Dark Earths in Africa?

J Fairhead and M Leach

13.1 Introduction

During the last 20 years, research on Amazonian soils has been central to a complete reappraisal of the region's social and natural history. Patches of dark and highly fertile soils have been found to occur throughout Amazonia, known as Amazonian Dark Earths (ADE) and sometimes distinguished as *terra preta* (Black Earths) and *terra mulata* (Brown Earths). The former are usually described as the legacy of the former settlement sites (middens) of pre-Colombian farmers, and the latter as a legacy of their agricultural practices. The ability of these soils to support intensive agriculture has undermined environmentally-determinist views of Amazonian history which until recently asserted that the inherently infertile soils could not support populous settled farming.

The importance of ADE is not restricted to their historical significance. First, these soils are sought after by today's farmers (Woods and McCann 1999; German 2003; Fraser et al., this volume). Second, the development of new techniques to establish them rapidly could help intensify modern farming in Amazonia and beyond. Third, because the secret to these soils is at least partially due to the high proportion of charred carbon they contain, farming technologies based on ADE have the potential to sequester enormous quantities of carbon, suggesting a 'win-win' opportunity, improving sustainable agriculture whilst mitigating climate change.

Unfolding research concerning the qualities of ADE has, however, been confined to Amazonia, or at least the neotropics of South and Central America (e.g. Graham 2006). Sillitoe (2006) has argued that the new research on ADE might offer useful technology to import into Africa and some research has been initiated on biochar technologies in Kenya. Yet this paper considers whether soils similar to ADE already exist, but unappreciated, in Africa, just as they had been unappreciated in Amazonia for so many decades. Could ADE research and technology be interesting not because it offers a new technology for transfer to Africa, but for the insights it offers to help understand the nature of existing African agricultural practices? And could African practices relating to former settlements and anthropogenic soil enrichment help us understand dark earths in the Amazon?

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

To address these questions, this chapter offers preliminary evidence concerning the existence of dark earth analogues in one part of West Africa and uses this to probe the historical and ecological arguments that have to date been used to draw strong contrasts and distinctions between Amazonian and African agro-ecological practices – contrasts that have to date restricted interest in anthropogenic dark earths to the neotropics.

We begin by outlining why the soils and broader historical ecology of humid West Africa offer broad parallels to Amazonia, and then outline some of the hypotheses forwarded which differentiate the historical agro-ecology of Amazonia from Africa and which restrict the ADE phenomena to Amazonia. We then present preliminary evidence from West Africa of 'African Dark Earths', and show why the social and ecological conditions leading to their establishment should force us to question the strong distinctions being made between African and Amazonian conditions.

13.2 Amazonian Dark Earths

Amazonian black earths contrast strongly with the soils that they develop in. They have about three times the soil organic matter (SOM), and more importantly, the component of SOM consisting of charred residues from incomplete combustion (carbons and charcoal) is 70 times greater (Glaser et al. 2004). This is chemically stable and resistant to microbial degradation and can thus remain stable in the soil for centuries. Current research indicates that it is – at least in part – 'biochar' which gives the soil its black colour, and improves soils structure, aggregation, water infiltration and retention, and nutrient storage capacity (Lehmann et al. 2003a).

The formation of black earth is not well understood. It does not form simply through wild fires and normal shifting cultivation. Several other factors appear to be at play combining intensive nutrient deposition and charring, which together initiate a particular set of biological and chemical processes. First, Amazonian farming practices appear to have incorporated biochar into the soil from slow burning fire hearths, and from the regular burning of trash cleared from gardens, and then mixing with soil. Second, farming practices appear to transform the soil fauna, and in particular the balance between arthropods other than ants (caterpillars, millipedes, springtails, and mites) and a community dominated by ants and worms (annelids). The latter build up in more regularly farmed soils, and worm and ant communities together ingest, powder, and defecate forms of biochar, mix it with mineral soil and homogenise the soil profile in burrowing (e.g. Ponge et al. 2006). With more organic matter to feed worms, this process is accelerated, generating a positive-feedback loop. Third, black earths have higher nutrient levels, with higher levels of phosphorus derived from excrements and bone residues and reduced acidity, and nitrates building up within an increasingly productive ecosystem (again through positive feedback – with better vegetation growth producing more pyrogenic carbon when burnt, and delivering more soil nutrient storage, leading to even better growth). Whilst oxisols and ultisols need fallows of about 8–10 years, *terra preta* farming can be sustained with fallows as short as 6 months (German 2004; Lehmann et al. 2003a, b). Whilst appreciation of ADEs has led to research on the processes that form them (e.g. Hecht 2003), a full understanding of the farming practices that lead to ADE formation still remain an outstanding research agenda (Glaser et al. 2004).

Indigenous farming practices were massively disrupted following European contact and colonialism. With huge population loss, the earlier, relatively settled, and populous agricultural existence ceded to hunting, gathering, and small scale agriculture. Although Balée (1992) characterises this as ‘devolution’, Rival (2006) makes the point that such a stark contrast may mask more complex balance of mobility and stability even in pre-Columbian times. Nevertheless, whilst ADEs are found in Amazonia today, the practices that led to their establishment are (generally) not. It is likely that the majority of ADE were created within an Amerindian semi-permanent farming system in which fertility was sustained by frequent infield burning and fallow burning, composting, and mulching. Patches of various sizes were fairly permanent, inside which there was a rotation of cultivated fields with managed fallows and fruit orchards (Denevan 2006). Just how intentional the formation of ADEs was, in this period, has been the subject of some debate over the extent to which they were deliberate investments or unintentional outcomes (German 2004),

13.3 Amazonia and Africa

There are several important similarities between the lowland humid tropics of Central and West Africa and those of the Amazon with respect to factors relevant to the dark earth phenomenon. First, the soil context is similar. About 80% of the tropical soils of the Amazon basin are Oxisols, Ferralsols (including ‘laterites’), and Ultisols which are highly weathered and leached, with extremely low nutrient reserves, nutrient storage capacity (CEC), and phosphorus availability. Most nutrients in their ecosystems exist in the standing vegetation, which is released to crops during shifting cultivation, and builds up again in its long fallows. The soils of the lowland humid tropics of Africa are in these respects broadly similar to those in Amazonia. A map of the global distribution of Ferralsols (WRB and FAO/UNESCO soil map of the world) makes this clear, showing how Ferralsols are restricted to tropical regions mainly of South and Central America and Central and humid West Africa.[1]

Second, inhabitants of both Amazonia and West Africa have lived for several thousand years in nucleated villages (within a wide variety of wider polities) with subsistence focused on farming, the nurturing and collection of plant foods, hunting, fishing, and trade. Prior to 1492, farming in the West African humid forest zone was more focused on rice, yams, and oil palm, but this was subsequently transformed by the introduction of the staples of the neotropics (cassava, sweet potatoes, groundnuts, maize, and beans).

[1] http://www.fao.org/AG/agl/agll/wrb/wrbmaps/htm/ferralso.htm

Third, evidence is emerging that climatic changes during these periods contributed to shaping the nature and extent of forests in both West Africa and Amazonia, meaning that the impact of agro-ecological practices has interplayed with a continually transforming forest. This makes it difficult to speak of the legacy of agro-ecological practices alone, as their legacy plays into broader ecological dynamics, including periods of forest transgression into savanna and of savanna transgression into forest (Maley 2002; Salzmann and Hoelzmann 2005).

Fourth, large areas of the West African humid tropics have, as in Amazonia, seen population collapse with large tracts of forests covering formerly farmed lands. Thus, large regions of Liberian forest have regrown following depopulation between the seventeenth and twentieth centuries (Fairhead and Leach 1998). In 1951, for example, an American forester observing these forests, Karl Mayer, described the country as an 'over used, worn out country of great antiquity'. The same is true for large tracts of the Congolese forests of Central Africa, and of the humid forests of Nigeria, Ghana, Cote d'Ivoire, Sierra Leone, and Guinea-Conakry which were encountered and reserved during the colonial period. A key difference, however, is that there are many other regions in humid tropical Central and West Africa where the farming worlds have not been disrupted in this way.

Several arguments exist that make strong distinctions between African and Amazonian agro-ecological history. The first concerns the availability of iron and especially iron axes. Amazonian agriculturalists prior to the conquest used stone axes, which, it has been argued, could not sustain shifting cultivation with short cropping periods and long fallows. This form of extensive farming required the more efficient iron or steel axes that became available post-conquest, and which African farmers had long had access too, with their iron age dating from about 2400–2800 BP (Vansina 2006; Denevan 1992). Given that the farming and livelihood practices that led to the creation of Amazonian black earths were probably more focused and intensive gardening, and not extensive shifting cultivation; an argument can be made for Amazonian exceptionalism. Yet one can ask whether, despite the earlier iron age in Africa, was (and is) African farming everywhere characterised simply by extensive shifting cultivation? Or were there also agro-ecological systems (or even parts of agro-ecological systems) which were also more intensive, and less reliant on the efficiencies of iron technology? Iron was not universally available nor was it cheap. Whilst an earlier African iron age enabled African farmers to practice extensive shifting cultivation many centuries earlier than in Amazonia, whether they did (or do) or not is a rather different question. Even where extensive farming is a possibility, intensive practices can be attractive for a wide variety of reasons, not least the availability of soils of old middens that can sustain it, the existence of crops and cultigens for which it is suitable, and the everyday convenience it can offer, but extending to their suitability under wider conditions such as high population density, political centralisation, states of siege, gender relations, and shortages of male labour for fallow clearance.

A second contrast that is at times drawn between African and Amazonian agro-ecological conditions concerns the use of domestic animals, for which there is a long history in West Africa, but not in Amazonia. It might be argued that in Amazonia it was the riverine and lacustrine environments which were the major sources of protein, with fish, aquatic mammals, and turtles providing the bulk of the catch, whereas in West Africa, terrestrial protein was more significant. Yet one can overdraw this contrast. Fishing in small as well as large inland water bodies has long been highly important to subsistence in the humid zones of West and Central Africa, just as hunting terrestrial animals has been important for peoples of the neotropics. African trade in dried and smoked fish from the coast and major rivers enables fish to be a principle source of protein even when where local fishing activity is limited. Moreover, whilst cattle and ruminants have historically been numerous in African savanna regions, this is not the case in all places and at all times in its humid forest regions. So, whilst some analysts might consider the importance of aquatic resources to influence settlement locations, and to facilitate chemical additions to the soils (directly via bones, and indirectly through faeces) in the Amazonian (Neves et al. 2003), these are not Amazonian specific.

The particular combinations of land use and ecological ingredients that lead to the formation of ADE are not yet known with precision. As indicated above, it is quite probable that among them will be interactions between biochar and the microbial (bacterial) and soil fauna (e.g. worm, termite, ant) communities involved in nutrient cycling and organic matter turnover (e.g. Woods and McCann 1999). For example, O'Neill et al. (2006) found that the bacteria obtained from *terra preta* soils were more closely associated with each other than with bacterial isolates from adjacent soils within the same site, indicating their suspected role in ADE ecology. It is quite possible that such soil ecological ingredients to ADE formation are specific to Amazonia. It is more probable, however, that they are not, and that similar anthropogenic soil ecosystems around dark earths would have evolved elsewhere, or have travelled along with crops. Moreover, given that ADE is less a single thing and rather more a 'family' of diverse soil types (including *terra preta* and *terra mulata* of different origins), the association of African dark earths with different, perhaps analogous soil ecosystems ought not, perhaps, to ostracise them from 'the family'.

13.4 African Dark Earths?

13.4.1 Suggestive Evidence from Guinea

Our observations on anthropogenic soils took place within the context of anthropological fieldwork in West Africa, among Kuranko and Kissi speaking farmers in Kissidougou Prefecture of the Republic of Guinea (e.g. Leach and Fairhead 1995;

Fairhead and Leach 1996) and then in a wider review of West African forest history (Fairhead and Leach 1998). Our fieldwork covered 2 years (1991–1993) with subsequent visits in 1994, 1996, 1999, and 2003. Research focused on agro-ecological practices and vegetation history.

Kissidougou lies within a semi-humid zone with rainfall levels in excess of 1,600 mm per annum, but with a pronounced dry season. The prefecture has a largely savanna landscape, but around each of its 800 or so villages there is usually an island of high semi-deciduous forest covering some tens to hundreds of hectares. Walking through any village's landscape also takes one past the sites of long-abandoned villages, hamlets, or farm camps. The soils of these ruins (*tombon* in Kuranko) are known as *tombondu* (*du* = soil/land). They are particularly appreciated for farming, enriched as they have been over long years of habitation from the ash of wood fires; the excreta of people, domestic animals, and poultry; and the residues of processed harvests, fish and purchased dried fish (*bonga*), gathered products (palm, kola and *Carapa procera* nuts), and cooking. In the village where we lived, a balance had to be struck between the use of these lands for farming, and for the tree crops (especially Cola nuts) and their shade trees growing there. Thus, some of these ruins are protected, whether for the tree crops, the graves, or the memories and ancestral worship sites they house.

Existing villages have rather a distinctive layout. The houses are built in a central clearing, and behind each, in a concentric circle are small kitchen gardens (used for tobacco, vegetables, and other high value crops), with these gardens soon fading into forest gardens in which fruit, nut, and other trees are encouraged to grow. The belt of forest surrounding each village is usually anthropogenic, having been established by transplanting and nurturing seedlings or cuttings of forest species (e.g. *Ceiba pentandra*), controlling fire, and nurturing regeneration. As they develop, and through history, these peri-village forest islands have become useful for many and evolving reasons. In pre-Columbian times, they served as vegetation fortifications, and more recently have been more useful as fruit and nut plantations, as a source of privacy for men's and women's private social associations, and as a source of privacy for morning ablutions. In recently abandoned villages, these different areas can usually be discerned, but once they are farmed, the whole site becomes *tombondu*.

Most villagers explain clearly how habitation and associated intensive gardening near houses transforms their soils, making them more workable and productive. Whist 'new' savanna land (*du kura*) which has never been cultivated is said to be hard and impervious, the regular gardening and rubbish accumulation and tree crop agro-forestry behind houses transforms these soils.

The use of soil mounding and raised beds and the incorporation of burnt resides and unburnt residues (of weeds, crops and everyday wastes) year after year is said to 'open' the hard 'new' savanna land characteristic of a new settlement, to let water in, and to make the soil oily (*tulu*), 'mature', and 'ripe' (*mo)*. The soils become softer and easier to hoe and weed, have good infiltration, and because they enable deeper rooting and remain damp for longer, they allow crops to resist dry periods better. Farmers find that the soil of old habitation sites maintains these qualities long after the site is abandoned.

Soils of former village sites are clear analogues of Amazonian *terra preta*. Pottery is found in the soils (though not in all), and the soils are much darker than those surrounding them. There are, however, also clear analogues of Amazonian t*erra mulata*. Farmers suggest that land farmed regularly in ways that mimics kitchen gardening 'will become like an abandoned site' (*a di ke tombondu di*), using the concept of a ruined village as a powerful metaphor for the result of soil change. For example planting crops such as cassava, groundnuts, fonio, maize, and okra in rotation in 'new' savanna, and using mounding techniques can begin to ripen the soil after 3 or 4 years, if the mounding is well done.

Soil ripening is not just a transformation in the soil, but also a categorical change in people's relationship with that place. In effect, through this work – including the sweat that farmers drain off their faces with a powerful gesture during preparation of land, the blood spilt from the cuts and grazes of farming, and through the defecation in the areas at the back of the house – new land is 'initiated' into a mature and productively fertile status, of which its oiliness is a physical embodiment. This transformation parallels that of a girl's initiation and excision, when she is considered to become more purely female and to acquire fertility as a mature woman, with oiliness again being the physical embodiment of this transformed state and accentuated in the festivities as initiated women are oiled. Moreover, land that is transformed from new land to ripened garden acquires an explicit association with female reproductive roles; a garden is *nako* 'mother's business'. People claim enduring rights to land of their ancestral villages, and to land that they improve through intensive rotational mounding. *tombondu*, whether 'real' (the land of an old settlement) or metaphorical (actively ripened to be like such land), is thus distinct not only as a land type, but also tenurially. It can be claimed by the patrilineal descent group whose members lived or worked there. This contrasts with unimproved land which is tenured at the village level.

Farms which become 'like *tombondu*' need to be fallowed after 4–6 years of cultivation, but the fallow vegetation will be a succession to forest, not savanna. After about a decade, farmers return to cultivate these improved places and cycle from one such improved area to another, leaving most of the rest of the land unfarmed. There are several reasons why these soils acquire a forest, not grassy vegetation. First, tree seeds germinate and establish well on these soils which are less prone to drought. Second, for the same reasons, dry season fires are less intense. And, third, the grasses that do germinate are more palatable to wild herbivores, which reduce fuel for the wild fires that pass. These improved soils are thus more than simply improved soils, as the vegetation associated with them recursively transforms the soils beneath them.

When discussing these soils with villagers, one informant likened their farming activity to that of termites, which also transform the soils and whose mounds (settlements, villages), once ruined, are prized for their fertility and support forest vegetation. Inhabitants also distinguished the land of a spirit 'village' that they entered only with extreme caution. Spirits live in more or less the same ways as people, and their villages and farming are understood to have similar effects on soil and vegetation as people. Thus a pervasive assumption in this region is that it is settlement itself (of people, animals, spirits) which transforms initially infertile soils and brings them into fertility.

At a second fieldwork site, about 40 km further south and further towards the more humid forest zone, the vegetation was not one of forest-savanna transition, but currently of forest and forest fallow land. Farmers speak Kissia, a very different language, and organise their farming in very different ways. Yet here, again, people appreciated the same important legacy of former inhabitation sites on their soils. The village we resided in had at least 12 ruined village sites in its territory. The sought-after soil of these former villages is called '*pulo ce pomdo*' (*pulo* = soil/earth; *ce pomdo* = village-old). Not all of these were intensively farmed. Descendants of those who lived in at least five of them retained tree crop (cola, coffee) plantations on them, along with shade trees, although used parts of them also for some gardens. The other ruined sites – some much older and others having been inhabited by other peoples – had since been reconverted to farm land. In this village, however, all families practice shifting cultivation on contiguous land, shifting each year on a 10 year cycle that covers the whole village territory. The old village sites are recognised by all for their quality, and each 10 years, when they are cultivated again, specific families have rights to return to them.

This is a region where statues are made from soft stone and these are at times dug up when farming in these old village sites. The statues are also called *pomdo*, after the ruined villages in which they are found. When they are dug up, they are themselves considered a portent of agricultural fertility.

We conducted short comparative studies in five other villages in other parts of Kissidougou prefecture, and combined the use of comparative air photography and oral history to ascertain how the balance had changed between the more intensive forms of cultivation focused on use of these soils (for 5–10 years, before fallowing), and other forms of shifting cultivation (principally of rice, but with maize and other intercrops). We reported on the findings elsewhere (Fairhead and Leach, 1996), but to summarise, the use of more intensive soil-ripening practices has increased since the mid-twentieth century, as has the use of former village sites for intensive farming, and this is largely because of changing patterns of gendered resource use. In the less densely populated areas, intensively cultivated *tombondu*-like sites used to be more limited to the proximity of settlements, but have now come to occupy larger areas of the landscape. Farming used to be more dominated by rice-focused shifting cultivation, involving large extended family and work-party organisation. Yet, with male out-migration combined with wider social changes that reduced 'household' size, there has been a shift to crops cultivated more independently by women who lack the male labour required for field clearance. They focus more on intensive gardening practices and on crops that they can exert greater control over (groundnut, cassava, fonio [*Digitaria exilis*], okra). The balance between garden-focused farming and shifting cultivation has also been influenced by general land availability. In some villages, there is insufficient land for continued shifting cultivation, with some families being especially affected.

13.4.2 Wider Perspectives

The findings from these study villages can help us reflect on arguments that distinguish Amazonian and African agro-ecological legacies. Firstly, farming in all our study sites balances shifting cultivation with more intensive gardening practices focusing on anthropogenic soils. Arguments differentiating Amazonia and Africa at the scale of 'differential iron age' are too broad-brush to capture the everyday mix of activities, land and soil-scapes that characterise farming communities. Many factors play into the balance of intensivity in every place. Secondly, both study sites rely on fish as well as the meat of hunted and domestic animals. This was more the case in the Kissi village which bordered a river and managed an elaborate fish trap. Moreover, they no longer had cattle (and former grazing lands have ceded to forest fallows in the past 50 years). Fish is a more 'everyday' food, and is regulated and controlled by women. And women in both sites regularly purchased dried and smoked fish from local markets. Again, it would be incorrect to contrast strongly these livelihood and agro-ecological practices with those in Amazonia. Indeed, there is a great deal in common.

The extent to which the soils of ruined settlements are analogous to (or the same as) *terra preta* of Amazonia, and the extent to which the improved soils 'like *tombondu*' are also 'like' *terra mulata* is a research question that needs to be examined – with attention to the many dimensions of Amazonian soils.

There has been virtually no research on African anthropogenic soils and on the legacy of past inhabitation and soil investments in these regions. Many researchers have appreciated the huge variety of 'fertilizing' practices developed by African farmers. Yet, whilst they are appreciative of temporarily improved fertility, this is represented either as a transient improved state, or as requiring the continuous import of fertility (as in infields). There has been almost no attention to the durable transformations to the soil that current research on Amazonian Dark Earths (ADE) reveals can occur – transformations which take the soil to a qualitatively different state.

There are some exceptions. Mitja (1990) and Mitja and Puig (1991) describe how in humid savannas in Cote d'Ivoire, farmers improve savanna land on slopes. Sites initially covered with low woody savanna, come to acquire, after 7 years of farming and a long fallow of 10–40 years, vegetation with a more closed, denser tree cover, and fertile soils with favourable infiltration characteristics, and with more surface pores from worm and termite activity. Similarly, Mondjannagni (1969) shows the establishment of forest thicket in earlier baobab-rich savannas, achieved through weeding and burning practices. In Togo, Guelly and colleagues show how farmers deflect ecological successions to create a forest formation in grassland savannas – creating anthropogenic forest fallows (Guelly et al. 1993), but do not comment on the underlying soils.

Such research as there is in West Africa which focuses on the logic of farming practices does highlight how farming can effect durable transformations on the soil. We can see this in the metaphors which speak of such transformations. Thus, as we indicated earlier, Kuranko farmers speak of soils 'ripening', and the vocabulary indicating a shift from dry to oily soils parallels representations of women coming into fertility and the transformations of a girl into a woman. Brouwers (1993) describes how farmers in Benin speak of 'waking soils up'. As we encountered earlier, such metaphors of qualitative transformation can be important to tenurial claims (and linked ancestral reverence).

Importantly, these processes of fertility improvement should not be understood simply within a 'zero sum' calculus of nutrient balance in which some land is being sacrificed at the expense of others. First, there is more to fertility than nutrient balance. There are changes here in soil structure, edaphic qualities, organic matter status, and fauna and flora influence. More significantly, farming techniques appear to be 'ratcheting up' biomass and its turnover, and it is plausible that the higher biomass turnover and increase in the organic energy available to soil organisms in upgraded lands (and associated increase and transformation of soil fauna, flora, and pH) might actually improve soil nutrient status in durable ways. We can hypothesise, for example, the potential increased activity of nitrogen fixing termites (Lilburn et al. 2001; Gomathi et al. 2005) and partly linked this, of plant symbionts enabling to nutrient availability, such as enhanced P delivery via enhanced mycorrhiza Andrianjaka et al. 2007; Diaye et al. 2003), and of access to nutrient-rich subterranean water via tree roots, and termite hydrological effects (Faillat 1990; Laperre 1971; Lobry de Bruyn and Conacher 1990; Lal 1987). Whether through improved infiltration and termite and fungal activity, or through the links with deep rooting plants, the agro-ecosystem gains access to nutrients from a much larger volume of soil. Once lands have been 'woken up', the resultant agro-ecological processes are likely to have a positive influence on the wider landscape (whether in acting as a source of nutrients, soil organisms or seeds).

Whilst these remain hypotheses, we should note that farmers discern soil quality and transformation through phenomena directly linked to the activity of termites, fungi and hydrology. Thus, farmers throughout much of Africa deliberately select land with many and large termite mounds. This is the case in the most famous of African 'biochar' farming practices, the *chitemene* in Zambia (Mielke and Mielke 1982). It is also the case in Guinea (Fairhead and Leach 1996). In Benin, Iroko (citing Quénum 1980) notes how an abundance of termite mounds is taken to indicate good soils for cereal farming, and an abundance of large mounds is considered a prerequisite for high fertility-demanding yam cultivation (Iroko 1982). Citing Mercier, Iroko goes on to note that this does not only concern agricultural aspects of fertility, but also ritual ones. Many agro-pastoralist Fulbe of Benin choose their encampments in areas with many termite mounds, 'signalling the presence of the goddess of fertility, of fecundity and of abundance' (Iroko 1982:54). Among Kissi farmers we worked with, the fungi species that grow on termite mounds are considered to signify fertility and prosperity. *Hol yio* (literally, mushroom of winged termites) is almost always found in twinned pairs, adding to its portent of fertility.

Methods to influence termite activity have been observed throughout Africa (although rather obscurely), whether in Zai farming in Burkina Faso, (Mando et al. 1993), in Sudan (Tothill 1948), or in Sierra Leone. Such termite management is often indirect (through manipulating the ecological conditions in which certain termites thrive), but it can also be direct, as when Guinean farmers speak of certain trees and fruits which they consider 'seed' termite mounds (Fairhead and Leach 2000). Both Mondjannagni (1975) and Iroko (1982) indicate that specific termite species are introduced in West Africa, stressing that this is a specialist and generally secret endeavour.

13.5 Misrecognition

Attention to anthropogenic soils in Africa has been obscured in many ways. As in Amazonia prior to the 1980s, many 'upgraded' anthropogenic soils appear to have been misrecognised as natural. A most extreme example comes from Benin where soil scientists have attempted to identify 'natural fertility' by assessing the nutrient availability in sacred groves, assuming these to be exemplars of the most natural soils. Yet evidence is reasonably strong that these groves exist over anthropogenic soils (and, indeed, they may be anthropogenic groves). Researchers come out with an inflated understanding of natural, and thus an inflated understanding of degradation of neighbouring unimproved, soils (e.g. Djegui 1995; see Fairhead and Leach 1998).

A preliminary review of colonial and post-colonial agricultural and social research reveals exemplars of soils which appear to resemble ADE, but which have been understood as natural. To take one example, Morgan and Moss (1977) describe in Nigeria patches of dark earths associated with forest vegetation in the forest-savanna transition region. They observed that the soil substrate across the sharp border between forest and savanna transition did not change, although the character of the soil under forest was radically different from that under savanna. They understood the soil and vegetation as having 'co-developed', although without human agency.

Archaeologists have observed the durable nature of anthropogenic soil transformations, and the improved productivity of past settlement sites centuries after they were abandoned. To date, these observations have not emerged from the forest region, but relate more to savanna ecosystems where such transformations are more easily visible (Keay 1947; Walker and Noy-Meir 1982; Blackmore et al. 1990). Such observations have also not been linked with research into the logic of farming practices.

Zech et al. (1990) note in passing that the existence of 'humus rich soils similar to *terra preta* have been found … around former settlements in Liberia and Benin'. They are, however, unable to give greater detail. Yet this paper has indicated that there are indeed strong reasons to speak of 'African Dark Earths', given that African farming practices have long been shaped by soil transformations wrought by former settlements or by mimicking them in a way very similar to *terra preta* and *terra mulata*.

13.6 Conclusion

The cases presented here call into question the arguments which have been forwarded to differentiate strongly Amazonian and African dark earths. Once we overcome this obstacle, close observation of extant African farming practices, and an understanding of their logic may help to discern other processes (or at least to develop hypotheses about them) involved in the durable transformation of soils which may well be of interest to Amazonian researchers. As with ADE, the extent to which these soil transformations are purposeful investments will need to be considered. However intentional or not, here we have indicated that this kind of transformation is also more deeply encoded in cultural perspectives on the relation between people and land.

This chapter has to be seen as provisional, and as a call for research. Before ‘importing’ the findings and technologies emerging from research on Amazonian Dark Earths into Africa, there is an urgent need for soil scientists to consider whether there are already ‘African dark earths’ similar to those of the Amazon. ADE research in Amazonia is leading to new collaborations between agronomists, ecologists and archaeologists. A similar engagement has yet to be established in West Africa, and across the African/South American divide and is long overdue. We have developed this chapter on the assumption that African ‘black earths’ would be found. Of course, if they are not, that in itself would be interesting – and what that would this tell us about Amazonian Dark Earths?

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Chapter 14
Locating Amazonian Dark Earths (ADE) Using Satellite Remote Sensing – A Possible Approach

J Thayn, KP Price, and WI Woods

14.1 Introduction

Amazonian Dark Earths (ADE) are the result of pre- Columbian humans' occupation of the Amazon Basin and are related to the need for fertile soils for growing crops (e.g. Glaser and Woods 2004). ADE soils contain highly elevated levels of organic matter, mostly in the form of very slowly decomposing charcoal, which retains water and nutrients, and makes ADE some of the most fertile soils in the world (Kern et al. 2003; Lehmann et al. 2003). When productivity of plants grown on ADE soil was contrasted with typical Amazonian soils, Major et al. (2005) found that maize yields were as much as 63 times greater, weed cover was 45 times greater, and plant species diversity was up to 11 times greater than for adjacent typical Amazonian soils. ADE soils contain up to 70 times more SOM than typical Amazonian soils (Mann 2002). Woods and McCann (1999) have shown that nutrient transfers from outside of ADE sites are necessary to explain current nutrient levels in ADE soils, suggesting that the formation of these soils ultimately became an intentional effort on the part of prehistoric Amerindian populations to improve the quality of their farmland. These nutrient sources may have been plant and animal food wastes, fish bones and other un-used fish matter, or human excrement, as well as a host plant materials used for fuel and construction. The presence of algae in ADE from *c.*1150 BP and later suggests that silt from riverbanks was incorporated into the ADE soils in at least one location (Mora et al. 1991).

In addition to opening a window to the past, ADE soils may hold a key to the future. The most readily observed characteristic of ADE soils is their high concentration of charcoal, which gives them the distinctive dark brown-to-black coloration. Glaser et al. (2001) found 64 times more charcoal in ADE soils than in the surrounding soils. To meet the challenges of possible global climate change caused by greenhouse gases, atmospheric carbon concentrations must be reduced. Vegetation actively withdraws carbon from the atmosphere and stores it as organic matter. Biochar is created when organic matter is heated without oxygen and it contains twice the carbon content of ordinary biomass (Lehmann 2007). Biochar is much more resistant to decay and can store carbon for centennial timescales (Lehmann et al. 2006). The addition of biochar to the soil was part of the creation

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

of ADE (Neves et al. 2003). This has lead some to speculate on the viability of a biochar carbon sequestration industry which would reduce atmospheric green house gases (Marris 2006; Sombroek et al. 2002) and improve soil fertility (Lehmann et al. 2003; Glaser and Woods 2004).

ADE range from 2,500 to 500 years old (Neves et al. 2003), so ADE soils offer a unique opportunity to study the long-term carbon storage capacity of biochar in soils. One factor that restricts this research is a lack of maps detailing the location of ADE sites. While some maps exist for relatively small subregions (Heckenberger et al. 1999), the geographic extent and location of ADE are unknown in the major portion of Amazoni (Woods 1995). However, Sombroek (2002) estimates that there is a patch of ADE soil for every 2 km^2 along certain Brazilian river corridors, and they extend into Colombia, Venezuela, Peru, Bolivia, and the Guianas.

Currently known ADE sites were found primarily by local *caboclo* residents who prefer ADE soils for agricultural settlement and subsistence farming (Sombroek et al. 2002). Woods and McCann (1999) report that local residents recognize ADE soils based on their lower vegetation canopy and more closed understorey, and unique species compositions including Brazil Nut (*Bertholletia excelsa*), cacao (*Theobroma cacoa*), cupuaçu (*Theobroma grandiflorum*), and the giant *Ceiba pentandra*. Unfortunately, traditional field methods are unsuited for locating ADE soils for two primary reasons: (1) the extreme difficulties associated with fieldwork in the dense tropical forest; and (2) the time that would be required to cover the enormous extent of the Amazon Basin. Therefore, most ADE soil sites have not been located. For these reasons, methods for predicting the geographic location and extent of these soils are required. Such information would greatly enhance researchers' ability to find new sites, could contribute to preserving tropical forests in this region, and would assist scientists' efforts to study and replicate ADE soils. Satellite remote sensing has tremendous potential for locating ADE soils using vegetation seasonal patterns and vigor as a surrogate for soil type.

14.2 Remote Sensing Overview

Before one can appreciate the advantages of using remotely sensed imagery for locating ADE sites, one needs at least a basic understanding of remote sensing system resolutions. The following overview will use the most commonly used remote sensing systems in existence at this time as examples. These systems include the U.S. Landsat Thematic Mapper (TM), the French SPOT, the private sector IKONIS, OrbView-3, and Quickbird, the Terra and Aqua systems that both carry the Moderate Resolution Imaging Spectrometer (MODIS), and the Polar Orbiting Meteorological Satellite that carries the Advanced Very High Resolution Radiometer (AVHRR). Some additional information about these systems will be presented throughout this chapter, but refer to Jensen (2005) or the Internet for a more complete overview.

14.2.1 Remote Sensing Resolutions

There are four types of resolution that needs to be considered when comparing remote sensing systems. These resolutions are: *spatial*, *spectral*, *radiometric*, and *temporal*. The following definitions are adapted from Jensen (2005).

Spatial resolution is a measure of the smallest angular or linear separation between two objects that can be resolved by the remote sensing system. From a remote sensing standpoint, the picture element (pixel) width is often used to describe the spatial resolution. For example, Landsat has a nominal spatial resolution of 30 m and the SPOT sensor has a nominal spatial resolution for the multispectral bands of 20 m. Spatial resolution of space-borne satellites varies from less than 1 m to 50 km, with most sensors in the 10 to 1,100 m range.

Spectral resolution is the number and dimension (size) of specific wavelength intervals (referred to as *bands* or *channels*) in the electromagnetic spectrum to which a remote sensing instrument is sensitive. Higher spectral resolution instruments have either more bands, or narrower bands, or both. Normal spectral resolution of space borne satellites is 3 to 36 bands. Hyperspectral sensors collect 126 to 256 bands.

Radiometric resolution is defined as the sensitivity of a remote sensing detector to differences in signal strength as it records the radiant flux reflected, emitted, or back-scattered from the terrain. It defines the number of just discriminable signal levels. The human eye can discriminate between 8 and 15 radiant intensity levels, or shades of gray ranging from white to black. The radiometric resolution of space borne satellites varies from 256 to 1,024 intensity levels.

Temporal resolution refers to how often the sensor records imagery over a particular area. For example, the temporal resolution of the Landsat TM is 16 days. SPOT has a repeat time of 26 days, but greater temporal resolution can be obtained if off-nadir views of the terrain can be obtained and used. The temporal resolution of the near 1 m resolution systems is 1–5 days, but this is only if one can use surfaces viewed from an oblique or off-nadir angle. Nadir views are obtained on an infrequent basis. The temporal resolution of the National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Meteorological Satellite that carries the AVHRR sensor is daily worldwide (except for 9° from the north and south poles).

Swath width, which is how wide of an area is imaged each time the satellite orbits the planet, is also a critical factor and obviously influences how often the sensor captures data over an area on the earth. The smaller the pixel or the greater the spatial resolution, the narrower the swath width. For example, the swath width of the meter to sub-meter measuring instruments is 8 to 11 km, compared to the 2,600 km width of the coarse resolution 1 km AVHRR data. Therefore, spatial resolution and temporal resolution share an inverse relationship. Anyone beginning a remote sensing based research project must determine which resolution, temporal or spatial, is most important for their application. Recent vegetation monitoring projects have shown that high temporal resolution is more useful for discriminating vegetation than high spatial resolution because a series of frequent images captures seasonal or phenologic trends (Bradley et al. 2007; Hill and Donald 2003; Jakubauskas et al. 2002; Wardlow et al. 2006; White et al. 2005).

14.2.2 Vegetation Indices

Converting satellite data into meaningful vegetation information involves calculating a vegetation index. Photosynthetically active vegetation, although it appears green to us, actually reflects more near-infrared light than any other wavelength. Healthy vegetation absorbs red light, which is used to power photosynthesis. There is an inverse relationship between red reflectance and chlorophyll content, and a direct relationship between leaf structure and near-infrared reflectance. Therefore, as vegetation density increases, more near-infrared light and less red-light are reflected. This inverse relationship is the foundation for most vegetation indices, which estimate the amount of photosynthetically active vegetation present in each pixel of satellite imagery. The most common of these indices is the normalized difference vegetation index (NDVI) (Rouse et al. 1973):

$$NDVI = \frac{NIR - R}{NIR + R} \tag{14.1}$$

Where *NIR* is near-infrared reflectance and *R* is red light reflectance. NDVI has been used successfully around the world (Dennison et al. 2005; Hill and Donald 2003; Oindo 2002; Shilong et al. 2004; Wang et al. 2004). The strong correlation between the NDVI and green photosynthetically active vegetation has caused some to refer to the NDVI as a plant "greenness" index. However, NDVI tends to saturate in locations with very dense vegetation, such as in the Amazon Basin. A modification of the NDVI, the enhanced vegetation index (EVI) has been developed specifically for the MODIS sensor:

$$EVI = G\frac{NIR - R}{NIR + C_1 RED - C_2 B + L}(1 + L) \tag{14.2}$$

Where *G* is green reflectance and *B* is blue reflectance. *L* is a soil adjustment factor and C_1 and C_2 are coefficients, which describe the use of the blue band in correcting red reflectance for atmospheric scattering. The coefficients *L*, C_1 and C_2 have been determined empirically to be 6.0, 7.5 and 1.0, respectively. EVI exhibits less saturation in tropical regions than many vegetation indices (Didian 2002), is related to forest stand biomass (carbon storage, Roberts et al. 2003), to tropical forest leaf litterfall (Saleska et al. 2003; Xiao et al. 2005), to leaf canopy processes (Xiao et al. 2005), and is more sensitive to seasonal dynamics than other vegetation indices (Ferreira et al. 2003). For research in the Amazon Basin, the EVI is suggested.

14.2.3 Maximum Value Composite Images

While satellite sensors frequently capture images of the earth's surface, cloud cover or other aerosol contaminants will obstruct many of these images. One major advantage of using satellite systems with high temporal resolution is the ability to construct maximum value composite (MVC) vegetation index images. Pixels with cloud contamination have depressed NDVI or EVI values and are not an accurate estimate of vegetation biomass. The MVC procedure groups a series of sequential satellite images and selects the maximum value of each pixel from the series (Hoblen 1986). The underlying theory is that, since cloud contamination lowers the NDVI or EVI value, a maximum value composite represents the most cloud-free pixel from the compositing period. Only the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) have sufficient temporal resolution to routinely compute MVC images. The imagery collected by the AVHRR is composited from 14-day periods and MODIS imagery is composited from 16-day periods. The ability to create MVC images is essential to any satellite-based remote sensing project undertaken in the Amazon Basin, where cloud cover frequently obscures surface vegetation.

While maximum value compositing reduces the effects of cloud cover, it also introduces temporal error. The MVC process selects the maximum value of the composite period and creates a single image, which is typically assigned the first date of the composite period. When using satellite vegetation indices to model vegetation seasonal patterns, knowing the Julian date of each index value is critical. Researchers attempting to calculate seasonal or phenologic variables from a time-series of sequential images were forced to make assumptions regarding the date of each value. Many researches, possibly for the sake of simplicity, have used the assigned first date of the period. This is the same as assuming that the maximum amount of photosynthetic activity during each composite period happens at the beginning of the period. This assumption is logical during the fall or senescence periods where vegetation vigor is steadily declining. However, during the spring or greening-up period, the more logical assumption is that the maximum value of the period occurs at the end of the period since photosynthetic activity is steadily increasing (e.g. Wardlow et al. 2006 for a further discussion). However, recent work at the Kansas Applied Remote Sensing (KARS) program at the University of Kansas has been unable to find a strong relationship between the actual Julian Date and its location within the composite period, indicating that methods based on these assumptions contain inherent error.

In order to determine the extent of the error introduced by using the end-of-the-period assumption, over 2,000 random points were selected within Douglas County, Kansas. The onset of green-up metric (Reed et al. 1994) was calculated using the Zhang method (Wardlow et al. 2006; Zhang et al. 2003) and MODIS NDVI imagery from 2001. The onset of green-up is the date at which vegetation begins to bloom at the beginning of spring. The Zhang method fits a monotonic function to an annual time-series of vegetation index values. The Julian date corresponding to the

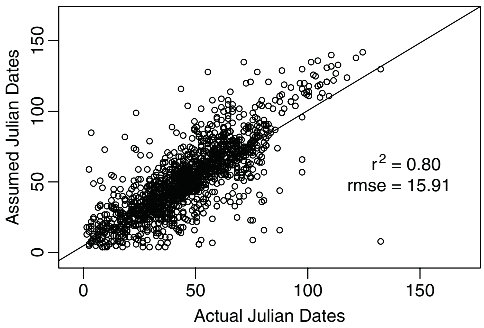

Fig. 14.1 Temporal error introduced by the Maximum Value Composite (MVC) process. Over 2,000 MODIS NDVI pixels from 2001 were selected from within Douglas County, Kansas. The onset of green-up (an approximation of the first day of spring) was calculated according to Zhang et al. (2003) using the actual Julian dates and the assumed dates from the MVC process. The root mean square error was high (15.91). This magnitude of error seriously hampers research projects attempting to study the seasonal pattern of vegetation

maximal point of the rate of curvature of the monotonic function is selected as the date of vegetation green-up (see below for more further explanation of the Zhang method). The onset metric was calculated twice, once using the last date of the composite period and once using the actual Julian date of each pixel. While the correlation between the two sets of onset dates was high ($r^2 = 0.80$), the root mean square error between the two was large, essentially equal to the interval of the composite period (rmse = 15.91) (Fig. 14.1). A potential error of half a month is a critical flaw in any project attempting to quantify seasonal patterns.

Beginning with version 5 of the MODIS data, the Julian date of each pixel selected in the MVC procedure is reported, eliminating the temporal error created by maximum value compositing. MODIS imagery is the only satellite data currently available with the Julian date information. At the time of this writing, the EROS Data Center offers 2007 satellite imagery as version 5 data and has started re-processing previous years. The anticipated completion date of this back-processing is mid-2008.

14.2.4 Remote Sensing System Requirements

As stated in the previous sections, the major purpose for using remotely sensed imagery is to locate Amazonian Dark Earth (ADE) sites that are currently hidden beneath the tropical forest canopy of the Amazon Basin. For this project, we determined that there are a least six requirements for a satellite system that must be met. These requirements are:

1. Conterminous spatial coverage of the Amazon Basin.
2. High temporal resolution in order to create maximum value composite images to minimize interference from cloud cover and to capture seasonal variation in vegetation.

3. Adequate spatial resolution to resolve patches of ADE soil.
4. Sufficient radiometric and spectral resolution to calculate NDVI or, preferably, EVI values.
5. The Julian date of each pixel selected during the maximum value composite process needs to be reported.
6. Low cost of image acquisition.

The only remote sensing system to meet all of these criteria is the MODIS sensor flown on NASA's *Terra* and *Aqua* satellite platforms. MODIS data are preprocessed as normalized difference vegetation index (NDVI) values and enhanced vegetation index (EVI) values. For reasons stated above, we suggest using the EVI. While most remote sensing systems collect imagery at a nadir viewing angle over an area once every 16 to 26 days, the MODIS sensor collects images over an area at least once daily, and because there is normally a morning and afternoon overpass by the Terra and Aqua orbiting platforms, MODIS imagery are often captured over an area twice daily. EROS Data Center computes maximum value composite (MVC) Enhanced Vegetation Index (EVI) images from 16-day periods resulting in an annual time-series of 23 images. The maximum EVI composites are created using the MODIS 250, 500, and 1 km resolution images. The images from each satellite are processed separately, creating two annual time-series of EVI data. In previous Amazonian work, we have merged the composites from the Terra and Aqua systems to create duel-system very near cloud-free EVI composites (Brown et al. 2007). These dual-system composites are more cloud-free than the original, single-system composites. These datasets have been produced for 2000 to the present. It is anticipated that these datasets will continue to be produced until the MODIS system becomes inoperable.

The spatial resolution of the imagery is 250-m (~15 acres per pixel) which is adequate for detecting ADE patches which range in size from 5 to 30 ha (Sombroek et al. 2002). MODIS scenes measure 1,200 km^2 and are distributed free of charge and are preprocessed to correct for atmospheric effects and to screen for clouds. Morton et al. (2006) further eliminated cloud contamination using a weighted cubic spline process. An example of a dual system maximum value composite, before and after cubic spline smoothing, is presented in Fig. 14.2. Another option is the 4253H-twice filter (Velleman 1980), which was found to be the most accurate of six smoothing filters tested by Klassen and McDermid (2007).

14.3 Past Remote Sensing Research in Amazonia

The use of satellite remotely sensed data for mapping tropical forests of the Amazon began in earnest with efforts to detect and monitor deforestation in the 1980s (Malingreau and Tucker 1988; Nelson et al. 1987; Skole and Tucker 1993). These projects focus primarily on differentiating between forest and cleared pasturelands rather than characterizing forest cover. More recently, the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) has examined the forest with

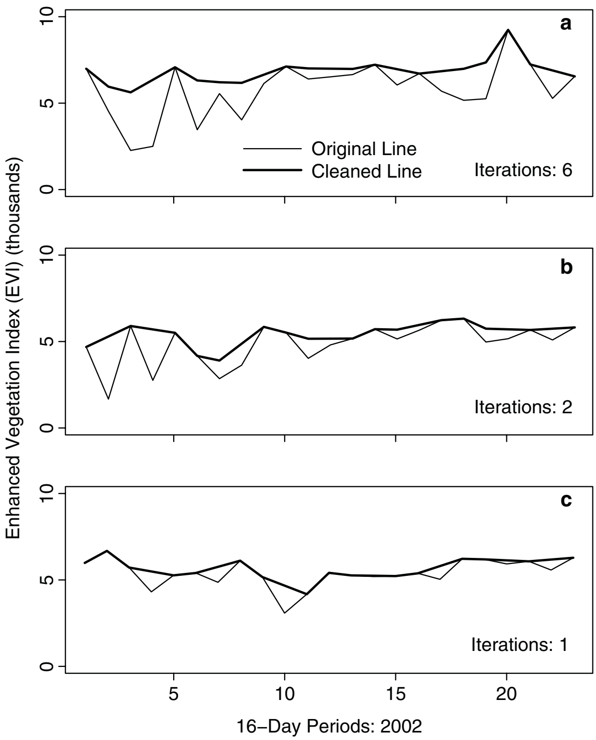

Fig. 14.2 Three examples of annual EVI signatures from Manaus, abrazil. The troughs in the annual signal are replaced with the mean of the two surrounding points; the process is repeated iteratively until a threshold is reached

greater detail by categorizing it into successional stages (Roberts et al. 2003). Most of these projects use a single date, or a few dates, of high spatial resolution imagery, such as Landsat TM, SPOT-4 and Ikonos imagery, and analysis methods such as linear spectral mixture modeling to estimate biomass. See Brown et al. (2007) for an excellent review of past remote sensing based studies of the Amazon Forest.

While most remote sensing projects in the Amazon Basin do not attempt to classify or characterize forest cover, there are a few exceptions. Lu et al. (2003) used Landsat Thematic Mapper (TM) imagery and linear mixture modeling to classify Amazonian forest from the Brazilian state of Rondônia. A linear mixture model calculates the percent cover, per pixel, of a pre-determined land cover type. Due to the mathematics involved, the number of pre-determined land cover types is limited. In this study, three pre-determined land cover types were used: shade, soil, and green vegetation. Lu and his colleagues were able distinguish Initial, Intermediate, and Advanced successional stages of forest growth with 78.2% accuracy. They conclude that the shade and green vegetation fractions are sensitive to change in vegetation stand structure and are therefore able to capture biophysical structure information. Although there is colloquial evidence that stand structure and forest biophysical parameters are possible ADE soil identifiers (Woods and McCann 1999), this method is limited in that it characterizes forest cover based on a single satellite image, or a single moment in the seasonal pattern of the vegetation. We hypothesize that locating ADE soils will require the analysis of a complete annual season.

Steininger (2000) used Landsat TM imagery to estimate above-ground biomass in the Amazon Basin. He discovered a strong correlation between mid-infrared reflectance and stand age, height, volume and biomass ($r > 0.80$, $p < 0.01$), although this relationship saturated at around 15 kg m^2 or at about 15 years of stand regrowth following deforestation. Vieira et al. (2003) was able to discern four successional stages in the forests of Pará, Brazil. They determined that the normalized difference vegetation index (NDVI) was insufficient for classifying forest cover. They, like Steininger (2000) found a strong relationship between mid-infrared reflectance and stand biophysical variables. The mid-infrared portion of the electromagnetic spectrum has been associated with water content in vegetation. Salovaara et al. (2005) used a ratio of the near-infrared band and the mid-infrared band from Landsat imagery to map inundated Amazonian forest with 85% accuracy.

14.4 Vegetation Vigor

The ability to distinguish forest cover growing on ADE soils from forest growing on typical Amazonian soils is more complicated than characterizing forest cover into successional or serial stages. The differences between forest parameters that are indicative of soil type are much more subtle, and therefore much more difficult to detect. We hypothesize that the most reliable differences in vegetation growing on ADE soils and that growing on typical Amazonian soils will be plant vigor. As early as 1885 (Hartt) it is reported that vegetation growing on ADE soils is more photosynthetically active during the dry season than vegetation growing on the surrounding Oxisols. Hartt attributes this difference to increased soil moisture associated with the ADE soils. Glazer et al. (2001) found ADE soils to contain 2.75 times more silt and 0.25 times more coarse sand than was found in the surrounding soils, making them more permeable and able to retain more soil moisture at greater depths (Lehmann et al. 2003). Tropical forest trees survive the six-month dry season by tapping into moisture reservoirs in the soil, and as the dry season progresses soil moisture reserves at increased depths become more important to survival, especially in severely dry years (Jipp et al. 1998; Nepstad et al. 1994). This means trees on ADE soils have a greater chance of survival during severe drought conditions and, to the extent that available soil moisture influences plant phenological processes (greening patterns), trees on ADE soils will exhibit different growth rates and timing of photosynthesis activities throughout the year. In a year with typical precipitation, Amazonian forests are not greatly affected by the dry season. In fact, photosynthesis and leaf production are limited during the wet season because of cloud cover and peak during the dry season (Huete et al. 2006; Saleska et al. 2003). A partial rain throughfall exclusion experiment indicates that water stress to vegetation is minimal during the drought year – stress occurs the year following drought, when soil moisture has been expended but not replenished (Nepstad et al. 2002). Record drought occurred in Brazil in 2005, so satellite imagery collected in 2006 offer a promising opportunity to locate ADE sites.

Current annual time-series research in the Amazon Basin indicates that remote sensing techniques would be sensitive to the differences between vegetation grown on ADE soils and that grown on typical Amazonian soils (Heckenberger et al. 2003; Huete et al. 2006; Nepstad et al. 1994, 2002; Saleska et al. 2003). In particular, Morton et al. (2006) used minimum, maximum, mean, median and harmonic variables (amplitude and phase of a sin/cosine curve fitted to the annual EVI pattern) calculated from annual EVI and NDVI time-series' to classify land-cover in Mato Grosso, Brazil as either cropland, cattle pastureland or regrowth forest. They were able to determine the conversion rates of forest to cropland from 2001 to 2004. This methodology is similar to that which we propose in this chapter. Harmonic analysis was used by Brown et al. (2007) to characterize the intensification of agricultural lands in Vilhena, Brazil. First- and second-order harmonic components were calculated from the annual time-series. A first-order harmonic is sin/cosine curve with a frequency of one that has been fit to the series. The second-order harmonic is the best-fit sin/cosine curve that has a frequency of two (Fig. 14.3). If the amplitude of the second harmonic was greater than or equal to the amplitude of the first harmonic, then the pixel was assigned to the double crop intensification class. The accuracy of this classification was approximately 80%.

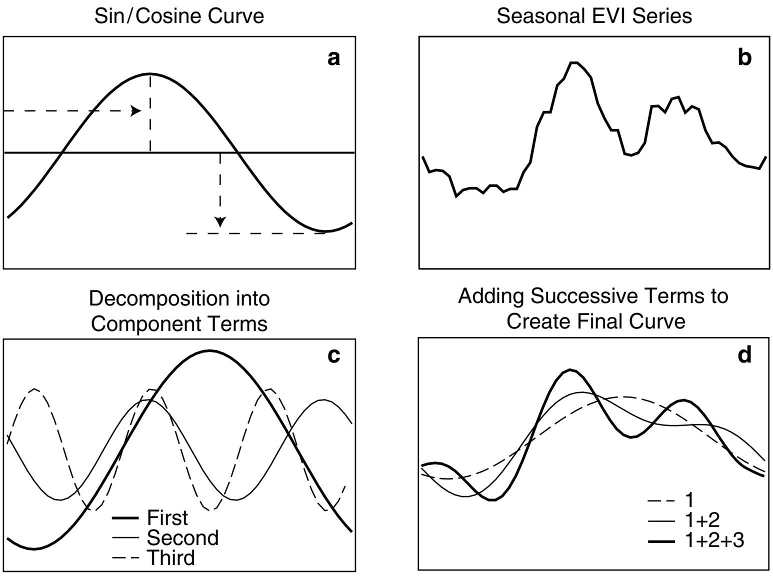

Fig. 14.3 Examples of Harmonic Wave Analysis properties: (**a**) each harmonic curve is defined by a phase and an amplitude, (**b**) an annual EVI signal of a double-cropped agricultural site, (**c**) the annual signal decomposed into its first three harmonic waves (the first harmonic completes 1 cycle, the second completes two, etc), and (**d**) the sum of the harmonic waves approximates the raw EVI signal. The sum of all possible harmonics equals the raw EVI signal. From a double-cropped field in Kansas

One (or even several) satellite image is unlikely to capture the subtle distinction in vegetation vigor that occurs between ADE and non-ADE forests during water stress conditions. A time-series of satellite images is required to visualize and quantify the differences in plant vigor that are symptomatic of ADE soils. Our preliminary work over known ADE sites has shown that the differences in phenological patterns are detectable using time-series analysis approaches. Therefore, the solution to identifying ADE sites appears to lie in the use of coarser spatial resolution imagery (250-m pixel width), which increases the frequency at which images over an area can be acquired. Increased temporal coverage by finer resolution satellite imaging systems, like Landsat, would be possible if multiple systems were placed in a proper earth-orbiting configuration, but such configurations do not exist at this time. Increased temporal resolution image datasets not only help resolve the differences in plant seasonal patterns, but it also greatly diminishes the problems of cloud cover contamination in the imagery; a problem that has plagued past studies conducted in the Amazon Basin.

14.5 Proposed Methods

A method for quantifying or characterizing the seasonal pattern captured in a time-series of remotely sensed images is required. Two likely candidate methods, Harmonic Wave Analysis and the Zhang method of determining phenologic variables, are discussed below.

14.5.1 Harmonic Wave (Fourier) Analysis

Harmonic wave analysis (HWA) permits a complex curve, such as an annual time-series vegetation index signal, to be expressed as the sum of a series of cosine waves. Each of these waves is defined by a unique phase and amplitude (Fig. 14.3a). The term of each wave designates the number of wavelengths completed over the chronological range of the data. Successive harmonic terms are added to produce a more complex curve, approximating the original signal (Fig. 14.3d). The lower order waves (1, 2, etc.) demonstrate trends in the data, while the higher order waves (n, n – 1, etc.) contain mostly noise (Jakubauskas et al. 2001). The sum of all of the component curves reproduces the original signal (Jakubauskas et al. 2001; Olsson and Eklundh 1994). A literature review discovers few Amazonian applications of harmonic analysis and, of those, most are precipitation pattern studies (de Angelis et al. 2004a, b).

The equations for calculating the amplitude and phase of a vegetation index signal are:

$$amplitude = \sqrt{C_f(x)^2 + S_f(x)^2} \qquad (14.3)$$

$$phase = \arctan\left(\frac{S_f(x)}{C_f(x)}\right) \tag{14.4}$$

The phase is multiplied by π if $C_f(x)$ is less than zero. The equations for $C_f(x)$ and $S_f(x)$ are:

$$C_f(x) = \sum_{j=1}^{n}\left(j * \cos\left(\frac{2\pi xf}{n}\right)\right) * \frac{2}{n} \tag{14.5}$$

$$S_f(x) = \sum_{j=1}^{n}\left(j * \sin\left(\frac{2\pi xf}{n}\right)\right) * \frac{2}{n} \tag{14.6}$$

where n is the number of points in the series, x is the temporal unit of each point, j is the VI value for each x, and f is the term of the harmonic being calculated.

When calculated from an annual time-series EVI signal, harmonic analysis summarizes patterns in vegetation dynamics in two terms, the amplitude and the phase. The amplitude of the first harmonic indicates the variability of productivity over the year as expressed in a single annual pulse of net primary production. The phase of the first harmonic summarizes the timing of vegetation green-up and senescence (i.e., the start and ending of the productive growing season) relative to seasonal climatic events. The second harmonic indicates the strength (amplitude) and timing (phase) of any biannual signal, such as secondary vegetation types like subcanopy grasses or secondary tree species. The 0th-order harmonic, or the mean value of the series, indicates overall productivity. The amplitude and phase of the lower-order harmonics have been used successfully in land cover/land use classification and works especially well in differentiating vegetation functional groups (Brown et al. 2007; Jakubauskas et al. 2001; Moody and Johnson 2001). When calculated for multiyear data sets, harmonic signals can be used to detect interannual patterns such as El Niño/Southern Oscillation events (Olsson and Eklundh 1994).

Harmonic analysis is particularly suited for application in neotropical forests like those of Amazonia. Harmonic waves extract primary vegetation phenology trends and reduce the effects of noise in the data (Jakubauskas et al. 2001). This is especially useful in tropical forest zones that experience frequent cloud cover and aerosol contamination from deforestation fires. Harmonic analysis has been used to reconstruct nearly noise-free data sets by computing the component waves and summing only the lower-order waves (Jakubauskas et al. 2002). This method has been used to reconstruct cloud-free time-series vegetation index data sets (Jun and Zhongbo 2004; Jung et al. 2004).

When calculated from an annual time-series vegetation signal, harmonic analysis summarizes patterns in vegetation dynamics in two terms, the amplitude and the phase. The amplitude of the first harmonic indicates the variability of productivity over the year as expressed in a single pulse of net primary production. The phase of the first harmonic summarizes the timing of vegetation green-up and senescence (i.e. the start and end of the growing season). The second harmonic indicates the strength (amplitude) and timing (phase) of any biannual signal. The additive term of the harmonic series, or the mean value of the data signal, indicates overall productivity. The amplitude and phase of the lower-order harmonics have been used successfully in land cover/land use classification and works especially well in differentiating vegetation functional groups (Jakubauskas et al. 2001; Moody and Johnson 2001). Examples of three vegetation signals from the study site, superimposed by their first harmonic wave, are displayed in Fig. 14.4.

Harmonic Wave Analysis will capture the seasonal differences of vegetation growing on ADE soils verses non-ADE soils. The increased vegetation greenness associated with ADE soils will be indicated by lower amplitude values (caused by decreased seasonal variation as vegetation retains greenness during the dry season) and by larger phase angles (caused by a longer growing season). Vegetation growing on ADE soils will also display a larger additive term associated with increased overall annual net primary production. An example of a first harmonic wave, calculated for ADE and non-ADE soils, is presented in Fig. 14.5. Notice that although the mean of the two signals are very similar, the amplitude and phase values are

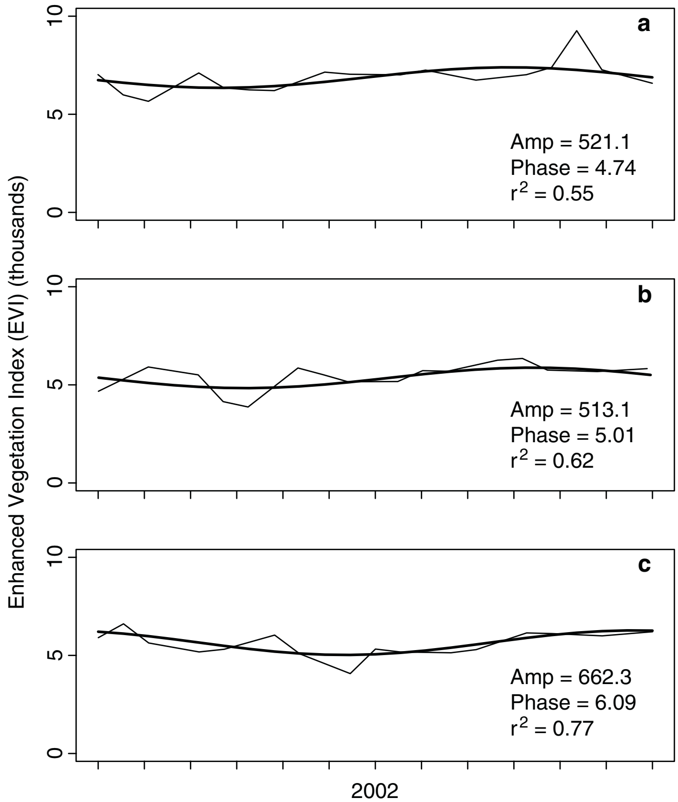

Fig. 14.4 Three examples of annual EVI signatures from Manaus, Brazil superimposed by their first harmonic curve. The amplitude and phase of each curve are provided, as well as the correlation between the annual signal and the harmonic curve

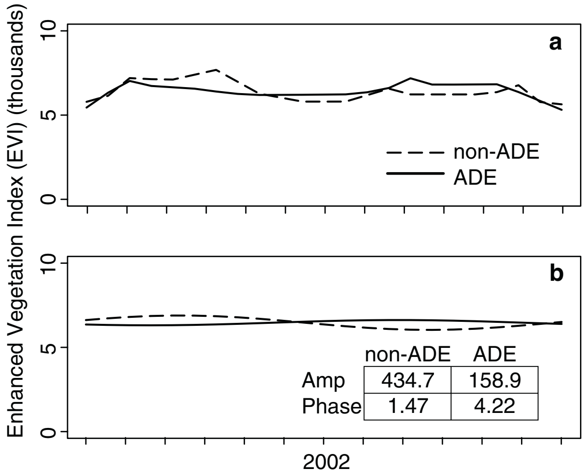

Fig. 14.5 An Amazonian Dark Earth (ADE) site compared to a non-ADE site; Santarém, Brazil. (**a**) shows the smoothed annual vegetation index signals; (**b**) shows the first harmonic of those signals. Notice that vegetation growing on ADE has a lower amplitude (less seasonal variation) and a higher phase angle (leaf exfoliation and plant domancy are delayed)

significantly different. A partial rain throughfall exclusion experiment conducted in the Tapajós National Forest in Brazil indicated that severe water stress occurs the year following drought when soil moisture has been expended but not replenished (Nepstad et al. 2002). Increased water stress will exaggerate the seasonal variation on non-ADE soils (causing amplitude values to increase and phase angles to be lower), making it easier to recognize ADE soils.

14.5.2 Vegetation Phenology Metrics

Phenology refers to the timing of changes in vegetation as a response to seasonal changes such as temperature and precipitation. The three key phenologic variables estimated using satellite remote sensing are onset of greenness (OG, the start of the growing season), the end of greenness (EG, the end of the growing season), and the length of the growing season (LG). When using satellite imagery to derive phenology characteristics, the object is not species or population phenology, but that of the general, pixel-wide plant community (Reed et al. 2003).

There are several methods for deriving phenology estimates using satellite imagery (Reed et al. 2003), but most are able to select phenologic variables from only the dates represented by the time series of imagery. Zhang et al. (2003) provide a method that can estimate phenologic variables for dates that fall between image dates. The methodology uses a piecewise logistic function that fits an s-curve to the temporal curve of the satellite imagery. The rate of change of the curvature of the logistic s-curve is calculated and the first peak or maximal value corresponds to the onset of greenness (Fig. 14.6). This is the point on the s-curve where the line first begins to climb – this estimates the date where vegetation first begins to photosynthesize beyond the background value.

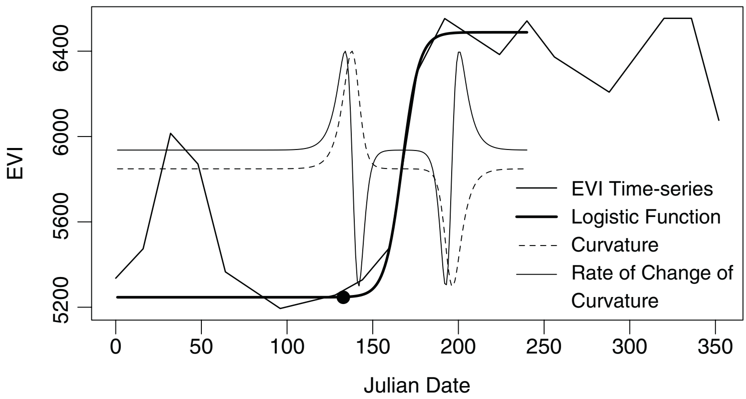

Fig. 14.6 The Zhang method for identifying onset of green-up (Zhang, 2003). A logistic curve is fit to a portion of the EVI time-series. The curvature of the logistic function, and then the rate of change of the curvature are calculated. The onset date is the Julian date of the first peak in the rate of change of the curvature. The EVI time-series in this example is the mean of several pixels located in the forest near Manaus, Brazil. The time-series has been smoothed

The s-curve is derived using the equation:

$$y(t)=\frac{c}{1+e^{a+bt}}+d \tag{14.7}$$

where t is time in days, $y(t)$ is the VI value at time t, a and b are fitting parameters, $c + d$ is the maximum VI values, and d is the initial background VI value. Zhang et al. (2003) optimized a and b and treating c and d and constants. However, Wardlow et al. (2006) were able to generate a better fit, and a more intuitive result, by optimizing c and d as well. The optimization was seeded using the definitions above.

Once a, b, c, and d have been found, the s-curve can be reconstructed using divisi9ons of the original time-series composite period. For MODIS data, which has 16-day composite period, points could be generated along the s-curve at one-sixteenth increments of the composite time-series. This would create a daily NDVI or EVI value as modeled by the logistic function. The mathematics of this process are robust enough to allow for irregularly spaced input values, so the actual Julian date of each pixel from within the composite periods could be used. As discussed earlier, this greatly increases the accuracy of the results.

The rate of change in the curvature of the fitted logistic s-curve is used to estimate phonological transition dates. The equation for the curvature of the s-curve follows:

$$K=\frac{d\alpha}{ds}=-\frac{b^2cz(1-z)(1+z)^3}{\left[(1+z)^4+(bcz)^2\right]^{\frac{3}{2}}} \tag{14.8}$$

where $z = e^{a+bt}$, $\propto$ is the angle (in radians) of the unit tangent vector at time t along a differentiable curve, and s is the unit length of the curve. The rate of change of the curvature is:

$$K' = b^3 cz \left\{ \frac{3z(1-z)(1+z)^3\left[2(1+3)^3 + b^2c^2z\right]}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{5}{2}}} - \frac{(1+z)^2\left(1+2z-5z^2\right)}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{3}{2}}} \right\} \tag{14.9}$$

The end of greenness is found by repeating the process at the senescence portion of the EVI time series. The length of the growing season is found by subtracting the onset of greenness from the end of greenness. During water stress years in the Amazon Basin, vegetation growing on ADE soils will have a longer growing season than vegetation growing on the surrounding oxisols due to its greater permeability and soil moisture capacity.

Another potential means of applying this method to locating ADE sites is to calculate the onset of senescence. This is the date at which vegetation begins to loose vigor and "greenness" due to annual water stress near the end of the dry season. As mentioned earlier, the onset of senescence will be more apparent during drought years or the year following a drought year. Under these conditions, the onset of senescence will be significantly delayed for vegetation growing on ADE soils compared to vegetation growing on non-ADE soils.

14.6 Conclusion

Amazonian Dark Earths (ADE) are the incredibly fertile soils created by pre-Columbian inhabitants of the Amazon Basin (Neves et al. 2003; Woods 2003). Finding and studying these soils will help understand the size and cultural complexity of pre-Columbian inhabitants and will enrich the cultural heritage of those nations that contain part of the Amazon Basin. In addition to offering a window to the past, ADE soils have the potential of effecting our future. Reproducing ADE soils would sequester atmospheric carbon in a stable, long-term form that would reduce the effects of possible climate change (Lehmann 2007; Marris 2006) while also increasing agricultural production (Sombroek 1966; Sombroek et al. 2002). One of the greatest impediments to studying ADE soils is that many ADE sites remain hidden beneath the tropical forest. The extreme difficulties of performing ground surveys in so dense and so large a region make traditional methods ineffective at locating ADE sites. Satellite remote sensing is the most effective and economical way of locating ADE sites in the Amazon Basin.

While the methods proposed in this chapter have yet to be fully tested, early trials suggest that they will be effective at locating Amazonian Dark Earths by examining vegetation vigor as a surrogate for soil type. Based on literature review and preliminary studies conducted thus far, several conclusions can be drawn regarding locating currently unknown ADE sites:

1. Satellite remotely sensed imagery is the most efficient tool for locating Amazonian Dark Earths (ADE) in the Amazon Basin.
2. The most reliable distinction between vegetation growing on ADE soils and vegetation growing on non-ADE soils will be the higher vigor and robustness of vegetation growing on ADE soils during times of water stress.
3. An annual time-series of imagery is needed to detect the subtle increase in vegetation vigor of vegetation growing on ADE soils. Locating ADE soils in the Amazon Basin using satellite imagery will be accomplished by examining vegetation seasonal pattern as a surrogate for soil type.
4. The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard NASA's Terra and Aqua satellites is the most appropriate satellite sensor for locating ADE soils. MODIS data are collected twice daily for every part of the earth's surface, allowing for the creation of nearly cloud-free maximum value composite (MVC) images. An annual time-series of MODIS MVC images consists of 23 images spaced throughout the year.

Future research will examine these conclusions in greater detail and will apply the described methods to locating Amazonian Dark Earths.

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Chapter 15
The Microbial World of *Terra Preta*

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15.1 Introduction

ADE sites vary in their size and degree of engineering (Woods and McCann 1999), and their biochemistry may be influenced by the addition of any of the following: large amounts of pottery sherds, concentrated organic wastes, charred biomass, fish bones, shells, various household wastes. In many ADE these additions have resulted in notably high nutrient concentrations of calcium, phosphorus, and potassium, and also high levels of black carbon (BC). The latter is thought to play a key role in greater nutrient retention and stabilization of soil organic matter, as decomposing residue or within living cells (Glaser et al. 2003; Sombroek et al. 2003), in spite of intense weathering conditions which typically lead to highly leached soils in the humid tropics (Lehmann et al. 2003). Thus the central role of the soil microbial community is in this unique soil environment should be traced to soil amendments such as BC. Black C is not unique to ADE, but occurs throughout terrestrial and aquatic environments (Schmidt and Noack 2000) as residue from naturally-occurring and human-induced burning. Once created, BC persists over time-scales of millennia and is thought be highly recalcitrant to microbial degradation (Schmidt and Noack 2000). In soil, BC may enhance soil fertility by decreasing bulk density, improving moisture retention and increasing pH, and the surface charge properties of BC are thought to increase cation exchange capacity (CEC), thereby reducing nutrient leaching (Glaser et al. 2002). The anthropic addition of BC to ADE may help stabilize inorganic nutrients and thus maintain soil fertility (Glaser et al. 2003), however, it may also serve directly as a habitat or as a platform for nutrient exchange for microorganisms (Abu-Salah et al. 1996; Chitra et al. 1996). High BC additions to soil due to fire events in northern boreal forest, have been shown to alter soil microbiological community structure and above ground plant communities (Pietikainen et al. 2000; Zackrisson et al. 1996), but little other research exists on the impact of BC on below-ground biological communities. Due to its prevalence in ADE and its unique physical and chemical characteristics, BC is thought to be central to the biogeochemistry of these soils.

While BC may be central to nutrient cycling in ADE, organic matter fluxes in soil are a dynamic interaction of chemical and physical factors that affect biological

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

processes (Chapin et al. 2002). Soil organic matter (SOM), consisting of both living cells and dead, colloidal fractions such as humus (Brady and Weil 2002), undergoes increased turnover rates with high temperatures and moistures typical of the tropics (Austin and Vitousek 2000; Zhang and Zak 1998). Rapid turnover of SOM together with environmental extremes leads to the fragile nutrient status of unmodified soils found adjacent to ADE. While BC may buffer otherwise tenuous soil fertility, changes in SOM are largely mediated by microbial processes throughout the soil ecosystem.

Soils are the most complex biological system on Earth (Young and Crawford 2004), containing as many as a million taxa in a 10 g sample (Gans et al. 2005), including Bacteria, Fungi and Archaea. Traditionally soil microbiologists have relied on culturing methods to identify soil microorganisms, but only 0.1% of these may be culturable with known techniques (Torsvik et al. 1990). Culture-independent methods using direct extraction of DNA followed by genetic analysis has dramatically enhanced the understanding of soil microbial populations (Theron and Cloete 2000). With increasing speed of DNA sequencing and computer processing, as well as great interest in soils as genetic reservoirs, the field of soil microbiology is rapidly evolving (Curtis and Sloan 2005; Rondon et al. 2000). Although soil microbiological studies of ADE are in their infancy they will benefit from rapid methodological improvements in the field. Given that ADE sites vary greatly in their distribution, age and extent (Kern et al. 2003) and soil ecosystems are highly complex, a suite of microbiological methods is needed to explore these systems.

Highly evolutionarily-conserved gene sequences, such as the 16S rRNA gene in Bacteria can be used identify individual organisms or compare microbial population profiles across samples (Marsh et al. 2000; Ranjard et al. 2001; Vinuesa et al. 1998). Community DNA extracted directly from soil contains a multitude of diverse 16S rRNA genes which can be isolated and amplified using the polymerase chain reaction (PCR). Collections of 16S rRNA gene fragments can be separated based on numerous criteria. For example, denaturing gradient gel electrophoresis (DGGE) uses the variable concentration of guanine and cytosine base pairs in DNA to separate 16S rRNA gene fragments based on distinct melting properties (Theron and Cloete 2000) and terminal restriction fragment length polymorphism (T-RFLP) uses variable sites of discreet endo-nuclease activity along genes to cut fragments into pieces and separate them by molecular weight (Marsh et al. 2000). Alternatively, individual gene fragments, representing distinct taxa, can be cloned into genetic libraries and the DNA sequenced directly (Sambrook and Russell 2001) to reveal both taxonomic groups and functional genes. Comparing microbial population profiles across samples or as they relate to experimental variable requires multivariate statistical techniques. Other methods in soil microbial ecology include culture-based approaches and microscopy. Cloning and culturing techniques continue to improve methodologically (Leadbetter 2003) and have the advantage of being able to directly test physiology and gene expression.

15.2 Current Findings

15.2.1 Isolating and Identifying Organisms

I. For unique soils, such as ADE, culturing techniques offer an excellent opportunity to screen for and reveal novel organisms that can be maintained and studied *in vivo*. Most probable number (MPN) estimations only reflect a small portion of soil organisms, but are a traditional means by which to compare microbial population levels (Woomer et al. 1990). Bacterial populations have been shown to be high at four ADE sites, and to remain at high levels with increasing soil depth compared to adjacent nutrient-poor soils (Fig. 15.1).
II. A comparison of different soil bacterial communities was made based on growth on different selective media followed by direct screening of 16S rDNA amplicons subjected to hydrolysis with various restriction enzymes. A phylogeny of sequenced rDNA (Sambrook and Russell 2001) was used to compare isolates across soil types, depths and sites.

15.2.2 Microscopy

Direct counts of microorganisms using a microscope is a common method for determining abundance of cells in complex environmental samples (Zhou et al. 1996). Various methods for directly observing and enumerating organisms microscopically can be used to assess both the efficiency of cell lysis and the selectivity of cell lysis for different cell types (Liu et al. 2001; Miller et al. 1999).

Fluorescence microscopy is better-suited to direct counts in soil, because of the variety of staining techniques and imaging technology that can be used to facilitate cell counts (Liu et al. 2001). Improvements in methods for identifying bacteria, such as fluorescence *in situ* hybridization (FISH) (Pernthaler et al. 2002), allow

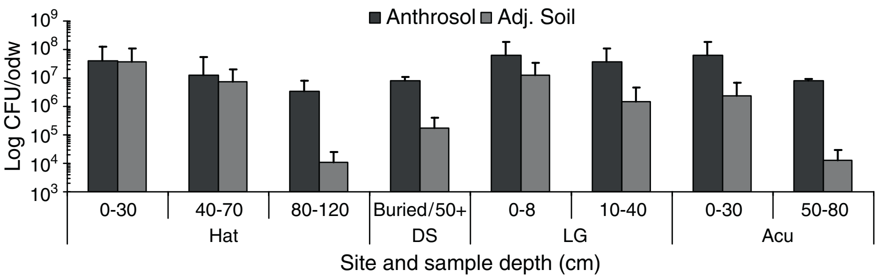

Fig. 15.1 Most probable number ($\log_{10}$) of bacteria colony forming units (CFU) g^{-1} ODW soil by depth, soil type (Anthrosol = black bar, adjacent soil = gray bar) at four sites. Mpns were calculated using MPNES software from (Woomer et al. 1990)

researchers to differentiate between organisms by creating and using fluorescent probes that hybridize with specific organisms. Finally, nonspecific fluorescent stains can be used to distinguish between living and dead cells (LIVE/DEAD, Molecular Probes).

15.2.3 Molecular Methods

To obtain robust information about the soil microbial community using molecular approaches, DNA extracted directly from soil must be representative of the whole community. The presence of BC in ADE may change the surface binding characteristics of soil particles and thus reduce the efficiency of nucleic acid extraction in ADE soils (Thies and Suzuki 2003). The mechanism behind reduced extraction efficiency has not been determined exactly, although it is suspected that the BC itself reduces total nucleic acid yield and thus DNA extracts from ADE may not be representative of the actual microbial community in either richness or dominance indices. Efforts from the group were made to develop T-RFLP, DGGE and clone libraries from ADE and adjacent soils to describe community level differences across ADE sites. We are also starting identification of microbial metabolites excreted by bacterial isolates from ADE, to determine the activity and biotechnological potential of natural compounds from these communities.

To study the microbial communities from ADE and adjacent soils, several expeditions to Amazon were made since 2003. The first reported the microbial structures in three ADE sites, with one showing soil features similar to ADE (Dona Stella site). Data from this study are shown on Figs. 15.1 and 15.2. Another expedition collected ADE soils from two regions: Balbina Lake (Figs. 15.3 and 15.4), at a site named

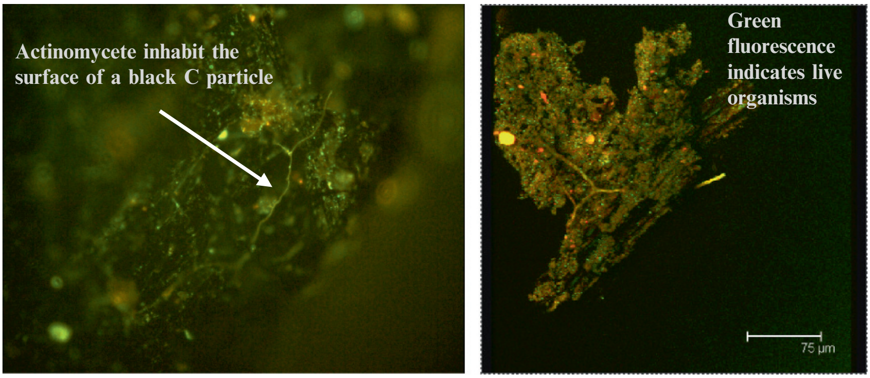

Fig. 15.2 Confocal microscopy of black carbon from ADE using fluorescent microscopy images demonstrated the presence of live (in green) microorganisms on BC surfaces, indicating that BC can serve as a habitat for microbes, despite its chemical recalcitrance, despite its chemical recalcitrance (*See Color Plates*)

Fig. 15.3 Global positioning system (GPS) for the ADE soil from Balbina Lake (Central Amazon) - 1°30'26,4';S and 60°05'34';W and for the adjacent soil - 1°30'27';S and 60°05'33';W. There is a typical high vegetation richness above the *terra preta* soils, as shown from Fig. 15.1. On the left, it is shown how the soil cores were collected at different depths (*See Color Plates*)

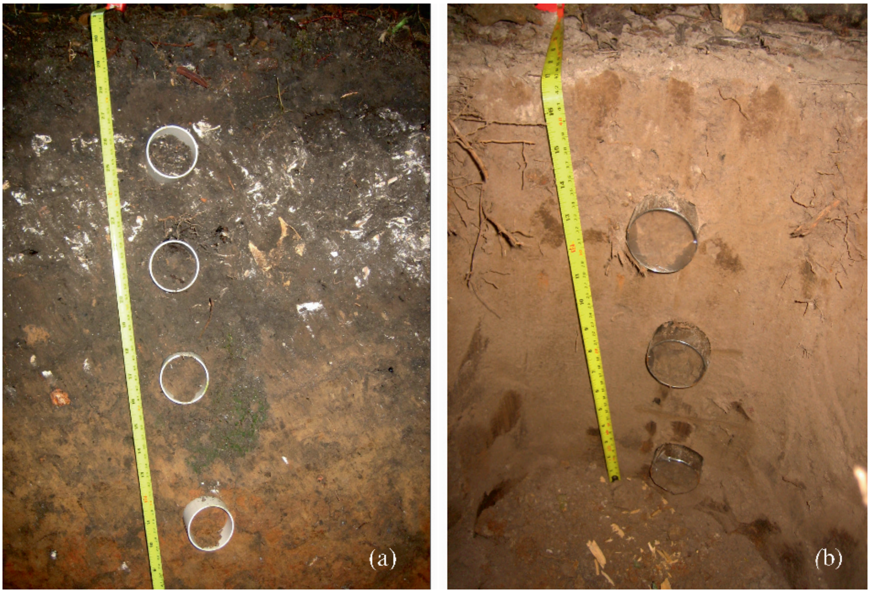

Fig. 15.4 Global positioning system (GPS) for the ADE soil from the National Forest of Caxiuanã (Eastern Amazon), with global positioning system (GPS) data for the ADE (Mina I) of 1°40'45,5';S and 51°20'71';W (*See Color Plates*)

Terra Preta (Central Amazonia-Amazonas State) and Caxiuanã National Forest, at the archaeological site Mina I (Oriental Amazonia – Pará State).

In ADE-Mina I, the prevalent phylla from the site ADE-Mina I were Proteobacteria (6.5%), *Acidobacteria* (4.7%), *Firmicutes* (1.4%), *Nitrospira* (1.1%), *Planctomycetes* (1.1%) and *Verrucomicrobia* (0.4%). In the ADJ-Mina I, the *phylla* found were *Acidobacteria* 27.2%, *Proteobacteria* 14.2%, *Firmicutes* 3.8%, *Verrucomicrobia* 3.8%, *Nitrospira* 1.3%, *Planctomycetes* 1.3%, *Actinobacteria* 0.4% e Gemmatimonadetes 0.4%. In this survey, the low soil pH may be one major aspect which may have directly influenced the bacterial diversity in those soils, as *Acidobacteria* were present in higher frequency when compared to other phylla (Fig. 15.7). In addition, the above-ground vegetation from the adjacent pristine forest in Caxiuanã-Pará may have also influenced the frequency of the prevalent *phylla*, which was not so clearly observed at the Balbina Lake. Four 16S rRNA clone libraries were obtained (Fig. 15.5), using genomic DNA extracted from the soil samples as templates in the PCR reactions. The PCR-products were cloned into the pGEM-T vector and 980 clones were selected and searched using the GenBank (NCBI-USA) and the RDP II program. Data analyses indicated predominance of unknown microorganisms, representing 41.6% among the sequences from ADE-Balbina, 68.3% from Adjacent-Balbina, 84.8% from ADE-Mina (Terra Preta) and 47.7% from Adjacent-Mina. In ADE-Balbina (Fig. 15.6), the predominant phylum was *Firmicutes*, representing 37.1% of the total sequences from that site, followed by *Proteobacteria* (9.6%), *Verrucomicrobia* (5.6%) *Acidobacteria* (2.5%), *Gemmatimonadetes* (2.5%), *Actinobacteria* (0.5%) and *Nitrospira* (0.5%). On the other hand, in the adjacent soil ADJ-Balbina, the predominant phylla were *Proteobacteria* (15.1%), *Acidobacteria* (12.5%), *Firmicutes* (2.3%), *Nitrospira* (1.1%) and *Verrucomicrobia* (0.8%).

The estimates of the Operational Taxonomic Units (OTUs) richness using Bootstrap directly corroborated the diversity values obtained from the Simpson and

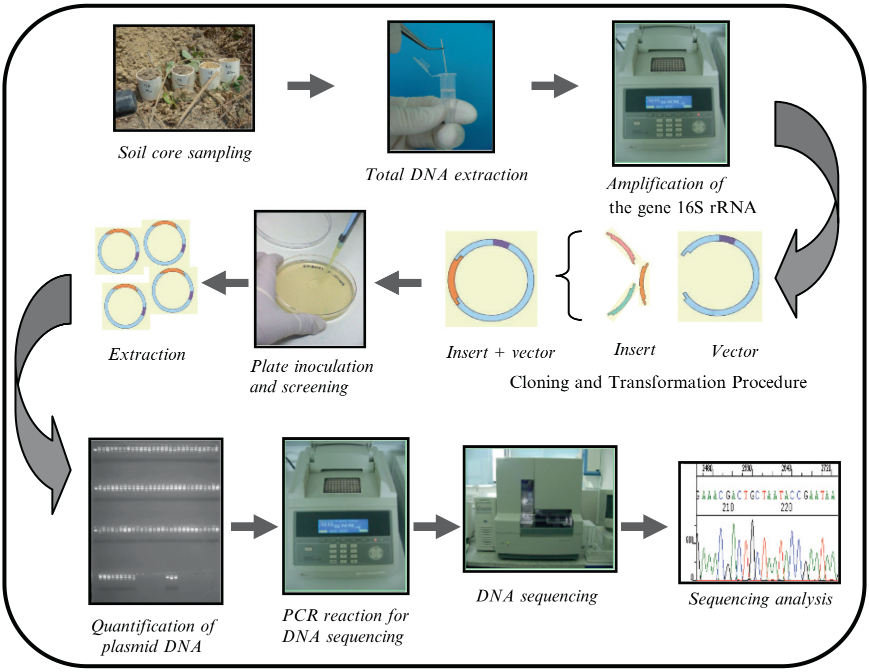

Fig. 15.5 Main steps for the bacterial 16S rRNA clone library construction (*See Color Plates*)

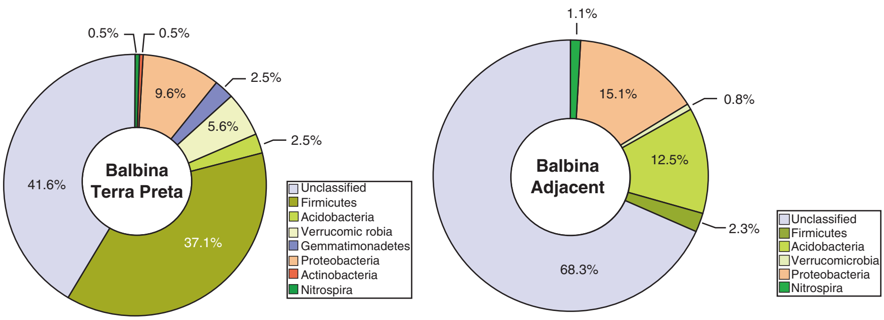

Fig. 15.6 Clone libraries from ADE (Terra Preta) soil and its adjacent soil from Balbina Lake (Central Amazon) (*See Color Plates*)

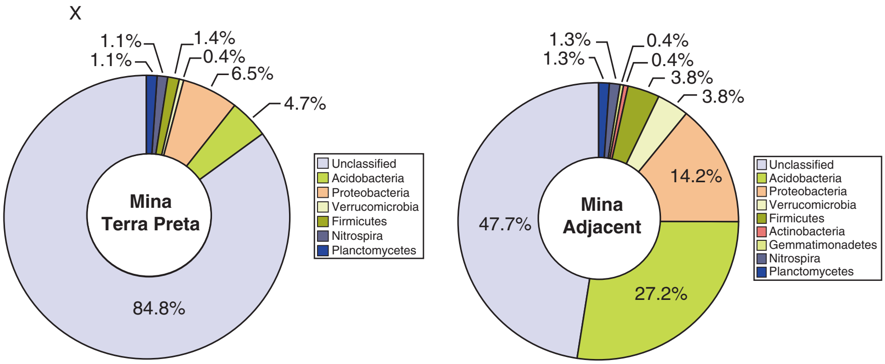

Fig. 15.7 Clone libraries from ADE (Terra Preta) soil and its adjacent soils from the Caxiuanã National Forest (Eastern Amazon) (*See Color Plates*)

Table 15.1 Estimates of OTU's richness and diversity index calculated from the four 16S rrna clone libraries, from ADE and adjacent soils of Balbina Lake – Central Amazon and the National Forest of Caxiuanã – Mina I, Eastern Amazon

	Estimates of OTUs richness						D index	
Libraries	SN	ON	ACE	Chao1	JK	Boot	Sp	Sh
ADE – Balbina	198	119	629.4	429.4	436.2	156.5	0.0259	4.286
Adjacent – Balbina	265	134	284.1	237.6	284.5	167.3	0.0102	4.608
ADE – Mina I	278	147	252.8	224.0	233.1	182.1	0.0070	4.783
Adjacent – Mina I	239	141	373.7	291.7	324.5	179.8	0.0082	4.705

OTUs = Operational Taxonomic Units D Index = Diversity Index
SN = Sequence Number ON = OTU Number
Sp = Simpson Index Sh = Shannon Index

Shannon indexes (Table 15.1), *Unique UTOs using* Jackknife *estimator were correlated with a higher percentage of the low frequencies of phylla in all the four clone libraries. The non-parametric* ACE *and* Chao1 *methods to estimate the OTUs richness also corroborated the* Jackknife *values.*

15.3 Conclusions and Future Research

Black C clearly has an impact on soil nutrient dynamics and ecological processes (Zackrisson et al. 1996), but it is unclear how such a variety of carbon species and their chemical characteristics impact microbial populations and to what extent soil microbes interact with BC. The degree to which BC alters the flow of organic matter in ADE, either through its effect on microbial biomass or on the chemistry of degrading C also needs to be explored. Pools of SOM can be subdivided based on decomposition rates as labile, slow and passive pools. Measuring these different C pools and relating them to microbial communities contributes information to models of organic matter decomposition, which can then be adapted for use in different ecosystems (Sohi et al. 2001).

Understanding the functional diversity associated with organic matter degradation in ADE, and soil in general, may pose as much of a challenge to understanding soil processes as trying to describe the actual taxonomic diversity. In an experiment varying C substrate quality, Degens et al. (2000) described both the richness and evenness of soil microbial populations in similar soils under different management practices, and responded to how these specific substrate additions in different combinations. By comparing respiratory response to added amino acids, simple sugars and carboxylic acids, significant differences were observed in catabolic activity between pasture and cropped soils.

The biochemical diversity and complexity of organic residues in the soil ecosystem is matched by species and metabolic diversity. Measuring the microbial communities associated with distinct C pools will illuminate how ADE has retained stable fertility for hundreds to thousands of years.

In many tropical forests, turnover of organic material occurs rapidly and near to the soil surface, leading to a rapid loss of soil organic matter when forests are burned and land is used for agriculture (Sanchez and Logan 1992). In ADE, the higher fertility at greater soil depth appears to be stabilized by the presence of BC and leads to large and diverse microbial populations. Understanding the biogeochemical processes involved in maintaining of fertility of ADE soils may lead to new technologies for soil management in the tropics (Glaser et al. 2002), and provide a novel strategy for mitigating atmospheric CO_2 by sequestering BC in soils, which may also serve as a nucleus for improved soil fertility.

From the first surveys, there is a clear idea that low soil pH may play an important role on microbial diversity in tropical soils, as Acidobacteria were present in higher frequency when compared to other phylla. In addition, the above-ground vegetation from the adjacent pristine forest in Caxiuanã-Pará may have also influenced the frequency of the prevalent phylla, which was not clearly found at the Balbina Lake.

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Chapter 16
Microbial Response to Charcoal Amendments and Fertilization of a Highly Weathered Tropical Soil

JJ Birk, C Steiner, WC Teixiera, W Zech, and B Glaser

16.1 Introduction

Charcoal is a major component of stable SOM in *terras pretas* alsocalled Amazonian Dark Earths (Glaser et al. 2001a, b; Glaser 2007). Apart from charcoal, special microbes could contribute to the formation of the highlystable SOM in *terra preta* (Woods and McCann 1999). However, this is stillmatter of speculation. There could be a link between the high amounts of charcoal in *terra preta* soils and soil microbial community composition (Glaser 2007). Although it is unlikely that charcoal is used by microorganisms as a direct carbon source, habitat properties are certainly different with the presence or absenceof charcoal (Saito and Marumoto 2002). Steiner et al. (2004) could demonstrate that charcoal addition to Ferralsols significantly increased microbial activity. Charcoal also promoted the colonization of agricultural plants with arbuscular mycorrhizal fungi (Nishio 1996; Saito and Marumoto 2002), it improved nodule weight (Nishio 1996) and nitrogen fixation (Tryon 1948; Nishio 1996; Rondon et al. 2007).

Most soil microorganisms cannot be characterized by conventional cultivation techniques (Zelles 1999). Amann et al. (1995) estimated that 80–99% of all microbial species have not yet been cultured. Therefore, biomarkers such as ribosomal nucleic acids (RNA) or phospholipid fatty acids (PLFA) are better analytical tools to provide an unbiased view on the structure of complex soil microbial communities (Zelles 1999). PLFA are exclusively found in the membranes of living organisms and comprise a relatively constant portion of living biomass within a microbial community (Zelles 1999). The analysis of PLFA allows the simultaneous quantification of microbial biomass and the characterization of the microbial community structure by specific biomarker PLFA (Tunlid and White 1992; Zelles 1999; Gattinger 2001).

Our objective was to assess the effects of charcoal application on the microbial biomass and community composition in an Amazonian Ferralsol in comparison with the effects of different management options such as slash and burn, mulching, compost application, and mineral fertilization.

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

16.2 Material and Methods

16.2.1 Experimental Set-Up and Sampling

The experimental site was situated in Amazonia, at the research station of the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA AMAZÔNIA OCIDENTAL), about 30 km north of Manaus. After clearing of secondary forest and removing the aboveground biomass the experiment was established on a highly weathered Xanthic Ferralsol following the soil classification of FAO (1990). Twelve treatments were applied on 4 m^2 – plots in five replicates and arranged in a randomized complete block design (Table 16.1). In February 2001 charcoal in small pieces (particle sizes smaller than 2 mm) and organic fertilizers (compost, litter, and burned litter) were applied to the soil surface and incorporated manually into the upper 10 cm soil depth. Some of the treatments received NPK (N as ammonium sulphate $(NH_4)_2SO_4$), P as simple super phosphate, and K as potassium chlorite (KCl)) partly enriched with micronutrients and lime (dolomite) in March 2001 and April 2002 shortly after seedling germination (Table 16.1).

Table 16.1 Details on individual treatments and abbreviations used in the text and figures. Amounts of applied charcoal, lime, and fertilizers are given in parentheses

Treatment	Organic fertilizer February 2001 ($Mg\ ha^{-1}$)	Mineral fertilizer and lime March 2001 ($kg\ ha^{-1}$)	Mineral fertilizer and Lime April 2002 ($kg\ ha^{-1}$)
Control	–	–	–
Mulch	Litter (13.0)	–	N (55), P (40), K (50), Lime (2,800), Zn (7), B (1.4), Cu (0.6), Fe (2.3)
Slash-and-burn	Burned Litter (13.0 before burning)	–	Mn (1.6), Mo (0.08) N (55), P (40), K (50), Lime (2,800)
Co	Compost (67.0)	–	–
F	–	N (30), P (35), K (50), Lime (2,100)	N (55), P (40), K (50), Lime (430)
F + Co	Compost (67.0)	N (30), P (35), K (50), Lime (2,100)	N (55), P (40), K (50), Lime (430)
Cc	Charcoal (11.0)	–	–
Cc + Co1/2	Charcoal (11.0) Compost (33.5)	–	–
Cc1/2 + Co1/2	Charcoal (5.5) Compost (33.5)	–	–
Cc + F	Charcoal (11.0)	N (30), P (35), K (50), Lime (2,100)	N (55), P (40), K (50), Lime (430)
Cc + F + Co1/2	Charcoal (11.0) Compost (33.5)	N (30), P (35), K (50), Lime (2,100)	N (55), P (40), K (50), Lime (430)
Cc1/2 + F + Co1/2	Charcoal (5.5) Compost (33.5)	N (30), P (35), K (50), Lime (2,100)	N (55), P (40), K (50), Lime (430)

Rice (*Oryza sativa* L.) was grown for the first vegetation period followed by three sorghum (*Sorghum bicolor* L. Moench) cropping cycles. Crop residues (stems and leaves) were left on the individual plots. For further details see Steiner et al. (2007). Soil samples were taken from 0–0.1 m soil depth after the third sorghum harvest in October 2002 and kept frozen until analysis. Table 16.2 informs about basic soil parameters determined according the following procedures: available nutrients were extracted using Mehlich–3 extraction (Mehlich 1984); pH was measured potentiometrically in water (1:2.5); acidity was determined by titration with NaOH; total C and N were analyzed by dry combustion with an automatic C/N-Analyzer (Elementar, Hanau, Germany).

16.2.2 Phospholipid Fatty Acids Analysis

Fatty acids were abbreviated using the commonly used omega notation (see e.g. Zelles, 1999). Lipids were extracted and fractionated into neutral lipids, glycolipids, and phospholipids using the modified method of Frostegard et al. (1991). Phospholipids were hydrolyzed and derivatized using borontrifluoride in methanol to form fatty acid methyl esters according to Knapp (1979). L-α-Phosphatidylcholin-1,2-Dinonadecanoyl and tridecanoic acid methyl ester were added as internal- and recovery standards.

Every sample was measured in four-fold replications using a gas chromatography – combustion – isotope ratio mass spectrometry (GC-C-IRMS) system consisting of a Trace GC 2000 gas chromatograph (Thermo Finnigan MAT, Bremen, Germany) coupled to a Delta^{plus} IRMS (Thermo Finnigan MAT, Bremen, Germany) because of a simultaneous determination of compound-specific $\delta^{13}C$ values of individual PLFA (Glaser et al. in preparation) For chromatographic separation, was used a BPX5 column (60 m × 0.250 mm × 0.25 μm film thickness, SGE, Melbourne, Australia).

Peak identification was based on comparison of retention times obtained from external standard compounds (Sigma-Aldrich, Seelze, Germany and Biotrend, Cologne, Germany). Total PLFA content is a measure for the total microbial biomass and was calculated as the sum of all identified PLFA.

16.2.3 Statistical Analysis

Statistical analyses were carried out with SPSS for Windows 10.0.1. (SPSS, USA). Correlation coefficients after Spearman were calculated and significance of correlation was tested two-tailed.

Principal component analysis was conduced using PLFA molar ratios (amount of individual indicator PLFA divided by the sum of all PLFA; data not shown). Principal components with an Eigenvalue greater than 1 were selected and Varimax rotation applied. Factor scores were computed using regression analysis.

Table 16.2 Total nitrogen (N), available phosphorus (P), available magnesium (Mg), available calcium (Ca), available potassium (K), ph (H_2O), and exchangeable acidity (Means and standard errors (in parentheses) of five field replicates (Steiner et al. 2007)

Treatment	N (%)		P (mg kg^{-1})		K (mg kg^{-1})		Ca (mg kg^{-1})		Mg (mg kg^{-1})		pH H_2O		Acidity (cmol$_{c+}$ kg^{-1})	
Control	0.16	(±0.01)	6.9	(±0.6)	19.6	(±0.7)	9.2	(±4.2)	7.0	(±0.5)	3.9	(±0.2)	1.7	(±0.1)
Slash-and-burn	0.15	(±0.01)	13.4	(±1.3)	27.4	(±2.5)	202.8	(±48.9)	62.7	(±17.2)	4.6	(±0.3)	0.7	(±0.2)
Mulch	0.17	(±0.01)	20.3	(±5.5)	28.8	(±2.9)	126.3	(±20.5)	33.4	(±2.7)	4.2	(±0.2)	1.1	(±0.2)
Co	0.17	(±0.01)	12.2	(±0.7)	33.4	(±1.1)	179.6	(±17.3)	26.5	(±0.7)	4.5	(±0.1)	0.9	(±0.1)
F	0.15	(±0.01)	19.5	(±2.0)	28.6	(±1.2)	224.4	(±44.2)	65.6	(±17.4)	4.6	(±0.3)	0.6	(±0.2)
F + Co	0.20	(±0.00)	34.0	(±6.3)	39.6	(±3.1)	520.2	(±87.5)	111.1	(±19.8)	4.9	(±0.3)	0.3	(±0.1)
Cc	0.17	(±0.01)	8.6	(±1.5)	24.5	(±6.5)	8.5	(±1.7)	7.6	(±1.3)	3.6	(±0.2)	1.8	(±0.2)
Cc + Co1/2	0.18	(±0.01)	10.5	(±0.6)	31.2	(±1.9)	111.0	(±21.1)	20.4	(±1.7)	4.1	(±0.2)	1.3	(±0.2)
Cc1/2 + Co1/2	0.20	(±0.01)	13.4	(±1.3)	36.0	(±6.2)	87.8	(±12.9)	19.0	(±1.7)	4.0	(±0.2)	1.5	(±0.1)
Cc + F	0.18	(±0.01)	20.3	(±1.7)	34.8	(±1.9)	317.0	(±59.8)	98.2	(±20.6)	4.9	(±0.2)	0.3	(±0.1)
Cc + F + Co1/2	0.20	(±0.01)	47.9	(±9.5)	39.9	(±1.6)	486.6	(±28.3)	129.8	(±4.2)	5.0	(±0.3)	0.4	(±0.2)
Cc1/2 + F + Co1/2	0.18	(±0.01)	41.4	(±12.9)	39.6	(±3.7)	412.4	(±70.8)	90.9	(±13.0)	4.7	(±0.3)	0.4	(±0.1)

Two-factorial analysis of variance was carried out using block and treatment as factors. The Least Significant Differences (LSD) test was used as a post-hoc test. Some variables were transformed to meet normality and/or equal variance assumptions.

We compared pairs of corresponding treatments which differs only in one kind of amendment (charcoal, mineral fertilization, compost) to select the different influences of the amendments. Mulched treatments (litter and mineral fertilizer) and slash-and-burn treatments (burned litter and mineral fertilizer) were compared with the control.

16.3 Results and Discussion

16.3.1 Microbial Biomass

Slash-and-burn, mulching, compost application, and mineral fertilization always raised PLFA contents and thus caused enhancement of soil microbial biomass. Charcoal application without further amendments resulted in higher microbial biomass compared to the control (Fig. 16.1). Also charcoal plus additional mineral fertilization application revealed higher microbial biomass than treatments receiving only mineral fertilizer (Fig. 16.1). These data show that charcoal addition caused an increase in microbial biomass apart from the treatments containing additionally compost (Fig. 16.1).

Looking at the basic soil parameters effected by the above-mentioned treatments, the sum of PLFA correlated positively with pH ($R_s = 0.378$; $P < 0.01$; $N = 59$). Such a positive correlation was also described by Baath and Anderson

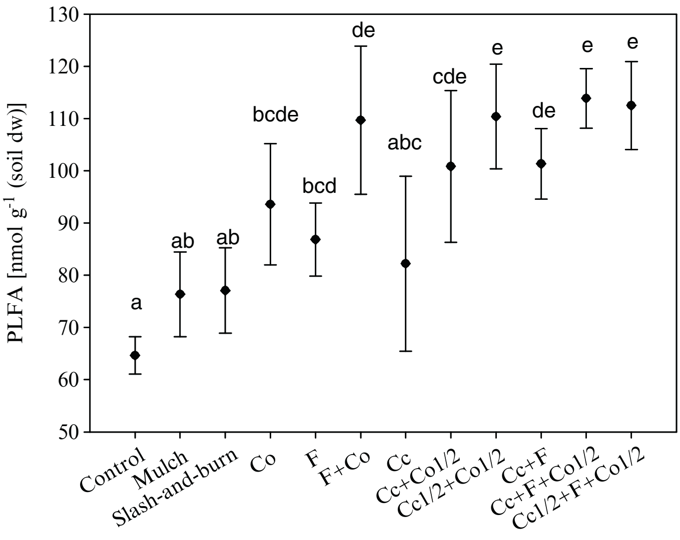


Fig. 16.1 Sum of all quantified PLFA representing a measure for the total soil microbialbiomass (means ± standard error, significant differences are indicated by different letters($P < 0.05$), $n = 5$)

(2003) in Northern Germany forests. In addition, we found positive coefficients of correlation between the sum of PLFA and available phosphorus ($R_s = 0.498$; $P < 0.01$; $N = 59$), available potassium ($R_s = 0.486$; $P < 0.01$; $N = 59$) and total nitrogen ($R_s = 0.635$; $P < 0.01$; $N = 59$).

16.4 Microbial Community Structure

16.4.1 Indicator Phospholipid Fatty Acids for Microbial Groups

After exclusion of common and widespread PLFA such as straight-chain PLFA (Zelles 1999), principal component analysis of known indicator PLFA molar ratios (data not shown) allowed a separation of PLFA representing different microbial units revealing four principal components, which could explain 86.6% of the total variance of PLFA molar ratios. On principal component 1 the PLFA 18:2ω6 and 18:1ω9c had high negative factor loadings and i15:0 and cy19:0 had high positive loadings (Table 16.3). Ruess et al. (2002) found the first two PLFA in high amounts in 16 different taxonomic groups of saprophytic soil fungi. Baath and Anderson (2003) and Frostegard and Baath (1996) found a high correlation between PLFA 18:2ω6 and ergosterol concentrations in soil, a compound which is characteristic for the cell membranes of fungi (Olsson 1999). Therefore, it is reasonable to assume that the PLFA 18:2ω6 and 18:1ω9c can be assigned to saprophytic soil fungi.

Iso- and anteiso- branched PLFA were found in gram-positive bacteria (Steinberger et al. 1999), but have been reported as well to occur in sulfate-reducing gram-negative bacteria and in the Genera *Cytophaga* and *Flavobacterium* (Zelles 1999). The contribution of PLFA cy19:0 generally increased with decreasing availability of oxygen and substrate (Burke et al. 2003). Thus, we assigned the PLFA i15:0 and cy19:0 as indicators for anaerobic bacteria.

Table 16.3 Identification of indicator PLFA by principal component analysis conduced with PLFA molar ratios

Principal component	Explained variance	Microbial unit	Indicator PLFA	Factor Loading
1	29.50%	Anaerobic bacteria	i15.0	0.87
			cy19:0	0.75
		Saprophytic fungi	18:1ω9	–0.92
			18:2ω6	–0.90
2	27.50%	Gram-positive bacteria	10Me18:0	0.92
			i17:0	0.85
			i14:0	0.80
			a17:0	0.73
3	20.60%	Gram-negative bacteria	18:1ω7c	0.85
			a15:0	0.80
			16:1ω7c	0.76
4	9.10%	Arbuscular mycorrhizal fungi	16:1ω5c	0.95

On principal component 2 methyl-branched PLFA (10Me18:0, i17:0, i14:0, and a17:0, Table 16.3) had high positive loadings. Phospholipid fatty acid 10Me18:0 was assigned to actinomycetes (Zelles 1999), and all other PLFA with high loadings on this principal component were assigned to other gram-positive bacteria (Steinberger et al. 1999; Zelles 1999).

High positive loadings on principal component 3 showed the PLFA 18:1ω7c, a15:0, and 16:1ω7c (Table 16.3). With a few exceptions, single unsaturated PLFA are generally assigned to gram-negative bacteria (Zelles 1999). Also PLFA a15:0 was found mostly in gram-negative bacteria such as *Cytophaga* and *Flavobacterium* among 29 taxonomically different microbial groups (Zelles 1997). Thus, we used the PLFA 18:1ω7c, a15:0, and 16:1ω7c as indicators for gram-negative bacteria.

On principal component 4 only the PLFA 16:1ω5c had a high loading (Table 16.3). The occurrence of this PLFA in soil was reported to correlate with the colonization of plant roots by arbuscular mycorrhizal fungi. Therefore, we assigned PLFA 16:1ω5c to this kind of fungi. On the other hand, high background concentrations in the absence of arbuscular mycorrhizal fungi have also been reported (Olsson et al. 1998; van Aarle and Olsson 2003) which have been assigned to membranes of bacteria and saprophytic fungi (Olsson 1999; Hedlund 2002). But the fact that on principal component 4 only PLFA 16:1ω5c had a high loading, but no PLFA characteristic for other microbial groups is a strong hint that PLFA 16:1ω5c was not extracted from membranes of other microorganisms and might be characteristic for arbuscular mycorrhizal fungi in our study.

16.4.2 Saprophytic Fungi and Anaerobic Bacteria

As measures for the absolute biomass of anaerobic bacteria the amounts of the PLFA i15:0 and cy19:0 were used and the amounts of the PLFA 18:2ω6 and 18:1ω9c represented measures for the absolute biomass of saprophytic fungi. The factor scores of principal component 1 were used to investigate relative effects. They were directly proportional to the proportions of anaerobic bacteria of the microbial biomass and inversely proportional to the proportions of fungi of the microbial biomass.

All management options tended to elevate the biomass of anaerobic bacteria (Fig. 16.2). The fungal biomass decreased due to compost application on treatments containing charcoal (Fig. 16.3). In contrast the treatments with single compost addition as well as the treatments with single charcoal addition, the treatments with single mineral fertilizer addition, the mulched treatments and the slash-and-burn treatments had an elevated fungal biomass compared to the control (Fig. 16.3).

The effects of charcoal addition on the proportion of anaerobic bacteria and fungi depended on additional mineral fertilization. On mineral fertilized treatments, application of charcoal enhanced the proportion of anaerobic bacteria and declined the proportion of saprophytic fungi (Fig. 16.4). Treatments which contained no mineral fertilizer showed a contrary effect due to charcoal addition (Fig. 16.4).

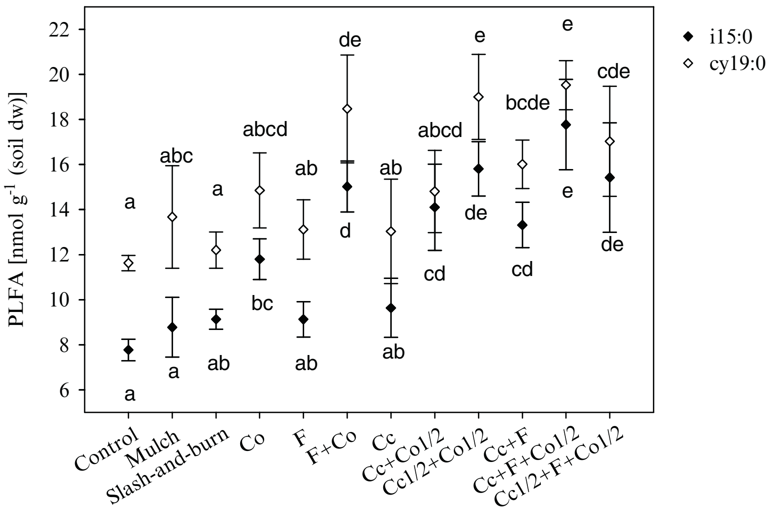


Fig. 16.2 Amounts of indicator PLFA for anaerobic bacteria representing a measure for the biomass of this microbial group (means ± standard error, significant differences are indicated by different letters ($P < 0.05$), $n = 5$)

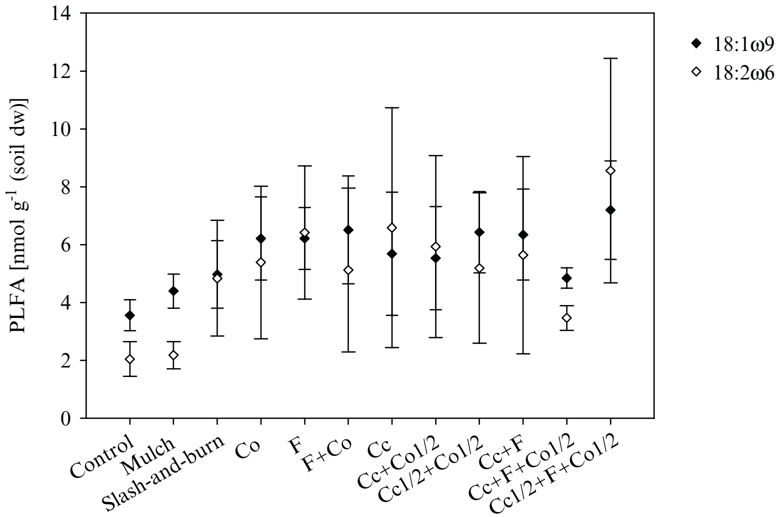
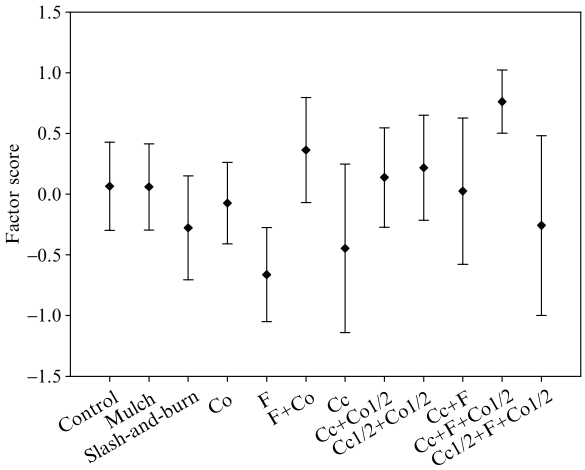


Fig. 16.3 Amounts of indicator PLFA for saprophytic fungi representing a measure for the biomass of this microbial group (means ± standard error, $n = 5$)

Single addition of compost, single addition of mineral fertilizer and slash-and-burn caused an elevated proportion of fungi and a reduced proportion of anaerobic bacteria in comparison to the control. Treatments where compost was applied in combination with charcoal, mineral fertilizer, and the combination thereof had a reduced proportion

Fig. 16.4 Factor scores of principal component 1 which were directly proportional to the proportions of anaerobic bacteria and inversely proportional to the proportions of fungi (means ± standard error, n = 5)



of fungi and an elevated proportion of anaerobic bacteria in comparison to treatments which differed only by the lack of compost addition (Fig. 16.4).

The factor scores of principal component 1 correlated negatively with the pH ($R_s = -0.398$; $P < 0.01$; N = 59). This implied that decreasing pH values caused a decreasing proportion of fungi and an increasing proportion of anaerobic bacteria. This result is in contrast to the general assumption that in soils with low pH fungi are relatively elevated in relation to bacteria (Wood 1995). But other studies found also no enhancement of PLFA characteristic for fungi with decreasing pH (Frostegard et al. 1993; Baath and Anderson 2003; Treonis et al. 2004). On the other hand an increase of the biomarkers indicating anaerobic bacteria (cy19:0 and i15:0) with decreasing pH was also observed by Frostegard et al. (1993) and Baath and Anderson (2003).

The proportion of fungi decreased while the proportion of anaerobic bacteria increased with increasing nitrogen contents (Rs = 0.430; $P < 0.01$; N = 59). Calderon et al. (2001) set the PLFA cy19:0 in relation with facultative anaerobic denitrifying bacteria. The PLFA cy19:0 and i15:0 could be extracted from membranes of facultative anaerobic denitrifying bacteria. In this case the positive correlation could be explained by substrate limitation.

16.4.3 Gram-Positive Bacteria

To examine the influences of charcoal addition and fertilization on gram-positive bacteria we used the PLFA 10Me18:0, i17:0, i14:0, and a17:0, as well as, the factor scores of principal component 2 which were directly proportional to the proportions of gram-positive bacteria of the microbial biomass.

The effect of charcoal addition on gram-positive bacterial biomass was strongly influenced by additional mineral fertilization. Minerally fertilized treatments receiving the whole quantity of charcoal had elevated amounts of biomarkers for gram-positive bacteria in comparison to corresponding treatments without charcoal or only the half quantity of charcoal (Fig. 16.5).

In contrast to the absolute biomass of gram-positive bacteria the effect of charcoal addition on the proportion of gram-positive bacteria was not influenced by additional mineral fertilization but by additional compost application. By the lack of compost addition, smaller proportions of gram-positive bacteria were found due to charcoal addition (Fig. 16.6).

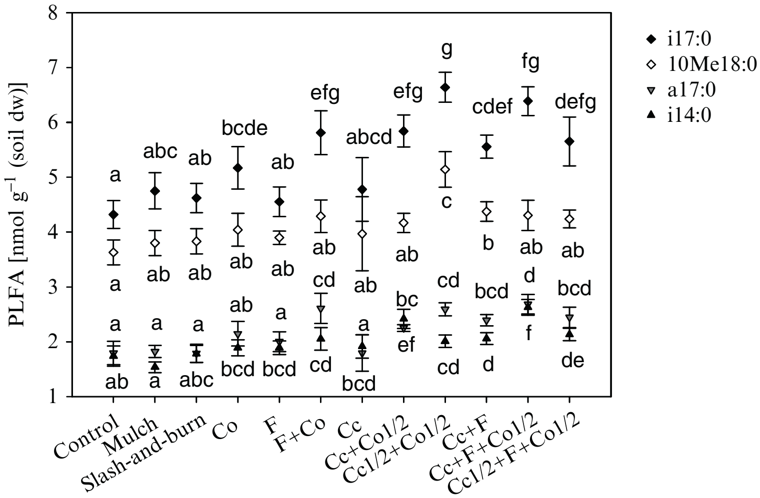


Fig. 16.5 Amounts of indicator PLFA for gram-positive bacteria representing a measure for the biomass of this microbial group (means ± standard error, significant differences are indicated by different letters (P < 0.05), n = 5)

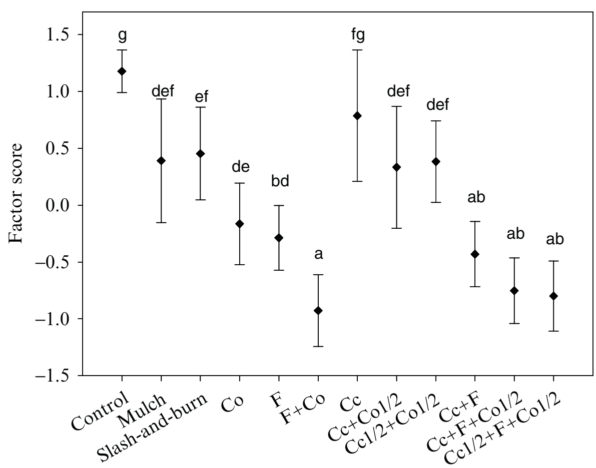


Fig. 16.6 Factor scores of principal component 2 which were directly proportional to the proportions of gram-positive bacteria (means ± standard error, significant differences are indicated by different letters (P < 0.05), n = 5)

In the majority of cases, an increased biomass of gram-positive bacteria were found due to mineral fertilization and application of compost (Fig. 16.5). All soil management practices apart from charcoal application decreased the proportion of gram-positive bacteria (Fig. 16.6).

The contrast between the influences of soil amendments on the absolute biomass of gram-positive bacteria and the influences of soil management practices on the proportion of gram-positive bacteria could be a result of soil nutrient contents. The proportion of gram-positive bacteria were negatively correlated with available phosphorus contents ($R_s = -0.564$; $P < 0.01$; $N = 59$), available potassium ($R_s = -0.526$; $P < 0.01$; $N = 59$), available magnesium ($R_s = -0.574$; $P < 0.01$; $N = 59$), available calcium ($R_s = -0.585$; $P < 0.01$; $N = 59$), and total nitrogen ($R_s = -0.594$; $P < 0.01$; $N = 59$). We also found a negative correlation between the proportion of gram-positive bacteria and pH ($R_s = -0.400$; $P < 0.01$; $N = 59$) although the correlation coefficient was smaller than the correlation coefficients of total nitrogen contents and available nutrients. Furthermore gram-positive bacteria have sometimes been considered to grow slowly (Waldrop et al. 2000). This assumption is corroborated by the negative correlation between the factor scores of principal component 2 and the microbial population growth rate ($Rs = -0.675$; $P < 0.01$; $N = 59$; data from Steiner et al. (2004). The correlations indicate that gram-positive bacteria are weak competitors for the nutrients in relation to other microorganisms with faster population growth capacity.

16.4.4 Gram-Negative Bacteria

The absolute biomass of gram-negative bacteria was quantified by the amounts of PLFA 18:1ω7c, a15:0, and 16:1ω7c and the factor scores of principal component 3 were directly associated to the proportions of gram-negative bacteria of the microbial biomass. With the exception of charcoal application and slash-and-burn all soil management practices caused both an absolute and a relative elevation of gram-negative bacteria. (Figs. 16.7 and 16.8). The effect of charcoal addition on the proportions of gram-negative bacteria is dependent on the presence of compost. In the absence of compost charcoal decreased the proportions of gram-negative bacteria (Fig.16.8). In contrast, treatments where charcoal in combination with compost was applied higher proportions of gram-negative bacteria occurred in relation to corresponding treatments which were fertilized with compost and received only the half quantity of charcoal (Fig.16.8).

The factor scores of principal component 3 correlated positively with pH ($R_s = 0.532$; $P < 0.01$; $N = 59$) and negatively with acidity ($R_s = -0.690$; $P < 0.01$; $N = 59$). These correlations showed that gram-negative bacteria are more favored by a pH increase and decrease of acidity than other groups of microorganisms. Higher amounts of the PLFA 18:1ω7 and 16:1ω7 were also found by Frostegard et al. (1993) and Baath and Anderson (2003) in soils with elevated pH.

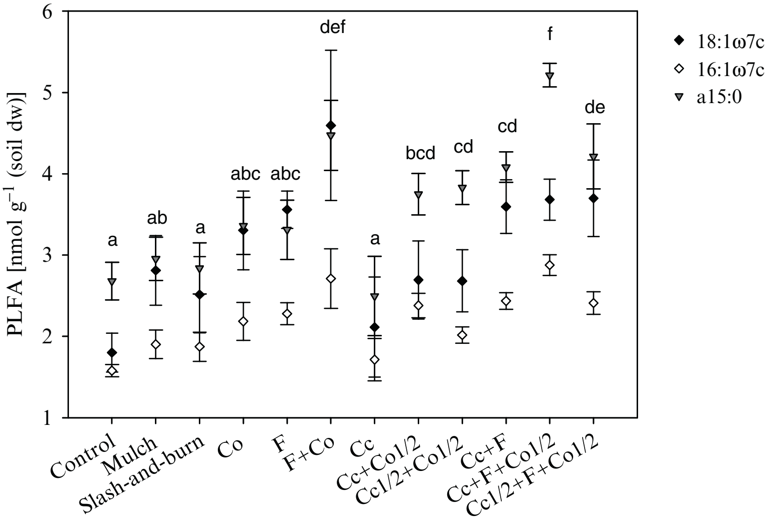
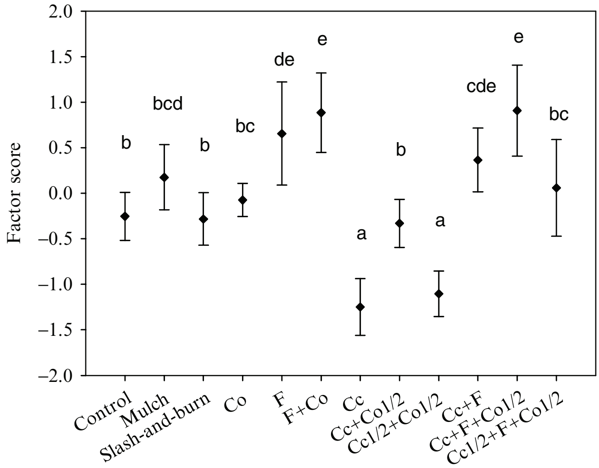


Fig. 16.7 Amounts of indicator PLFA for gram-negative bacteria representing a measure for the biomass of this microbial group (means ± standard error, for a 15:0 significant differences are indicated by different letters ($P < 0.05$), $n = 5$)

Fig. 16.8 Factor scores of principal component 3 which were directly proportional to the proportions of gram-negative bacteria (means ± standard error, significant differences are indicated bydifferent letters ($P < 0.05$), $n = 5$)



16.4.5 Arbuscular Mycorrhizal Fungi

We used the amounts of 16:1ω5c as measure of the absolute biomass of arbuscular mycorrhizal fungi and the factor scores of principal component 4 as measure for the proportion of arbuscular mycorrhizal fungi of the microbial biomass. The biomass of arbuscular mycorrhizal fungi was only minor influenced by charcoal additions

(Fig. 16.9). But the proportion of arbuscular mycorrhizal fungi was always reduced due to charcoal addition (Fig. 16.10). The opposite was found by Saito and Marumoto (2002). But Sakamoto et al. (2004) showed that the PLFA 16:1ω5c is not present in all species of fungi responsible for arbuscular mycorrhiza formation and Nishio (1996) showed that arbuscular mycorrhizal fungi are only enhanced due to charcoal addition if arbuscular mycorrhizal fungi exceeded a certain level in the soil.

Also compost addition and slash-and-burn caused smaller proportions of arbuscular mycorrhizal fungi (Fig. 16.10), whereas the total biomass of arbuscular mycorrhizal fungi was enhanced by these soil management practices (Fig. 16.9). Mineral fertilization and mulch addition tended to increase absolute biomass and relative amounts of arbuscular mycorrhizal fungi (Figs. 16.9 and 16.10).

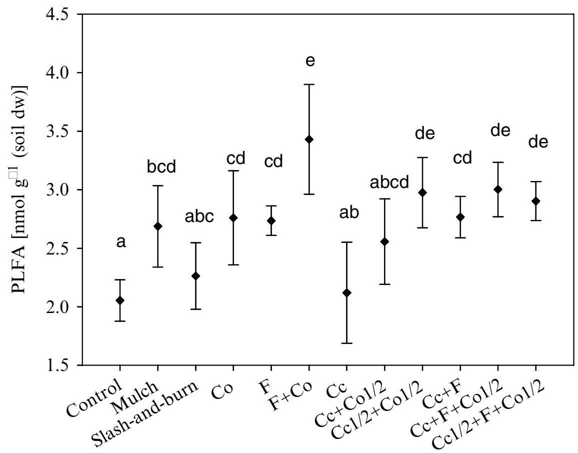


Fig. 16.9 Amounts of PLFA 16:1ω5c representing a measure for the biomass of arbuscular mycorrhizal fungi (means ± standard error, significant differences are indicated by different letters ($P < 0.05$), $n = 5$)

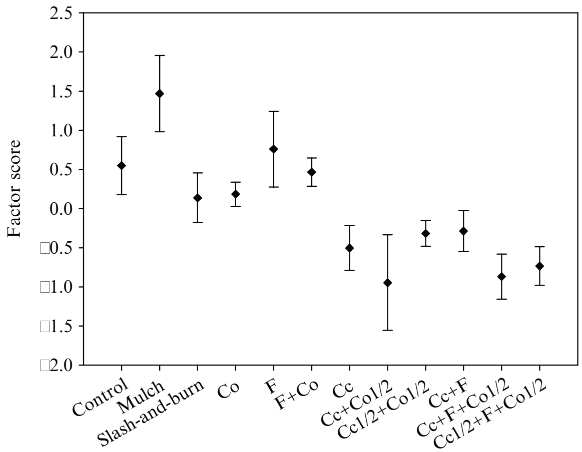


Fig. 16.10 Factor scores of principal component 4 which were directly proportional to the proportions of arbuscular mycorrhizal fungi (means ± standard error, $n = 5$)

16.5 Conclusion

Soil chemical parameters are related with soil microbial biomass and with microbial community structure. Soil nutrient contents correlate positively with the microbial biomass and negatively with the proportion of gram-positive bacteria. The proportion of gram-negative bacteria correlate positively with pH via a broad pH range (pH3–6).

Our results show that mineral and organic fertilization had more distinct effects on the soil microbial biomass and the microbial community structure than the addition of charcoal. Fertilization caused a greater microbial biomass and especially enforced gram-negative bacteria whereas the proportion of gram-positive bacteria declined.

The effect of charcoal strongly depends on additional fertilization. Only charcoal containing soils and soils with additional mineral fertilization had a greater microbial biomass but smaller proportions of gram-positive and gram-negative bacteria than soils treated with mineral fertilizer only and soils obtained no fertilization at all. Charcoal additions together with compost enhance the proportion of gram-negative bacteria. In minerally fertilized soils, charcoal addition increased the proportion of anaerobic bacteria and declined the proportion of saprophytic fungi, otherwise due to charcoal application the proportion of saprophytic fungi elevated and the proportion of anaerobic bacteria decreased. The total amount of arbuscular mycorrhizal fungi was not enhanced due to charcoal additions and its proportion on the microbial biomass even declined.

We conclude that by creating *Terra Preta Nova* in addition to charcoal the kind of fertilization is of major importance in order to feed possibly beneficial microorganisms.

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Chapter 17
Effects of Charcoal as Slow Release Nutrient Carrier on N-P-K Dynamics and Soil Microbial Population: Pot Experiments with Ferralsol Substrate

C Steiner, M Garcia, and W Zech

17.1 Introduction

Giardina et al. (2000) reported that 300 million people annually practice shifting agriculture, affecting 400 million hectares of the planet's 1,500 million ha of arable land. The sustainability of shifting cultivation and slash-and-burn continues to be a topic of discussion. Kleinman et al. (1995) characterized sound slash-and-burn agriculture as an ecologically sustainable agroecosystem because crop yields can be maintained without inputs of non-renewable fossil energy resources for fertilizers, pesticides, and irrigation. According to Woods and McCann (1999) shifting cultivation can be an environmentally friendly analogue to the natural processes of disturbance and regenerative succession in tropical forests. They suggest that the Amerindian population made long lasting improvements to notoriously infertile tropical soils by long-term mulching, frequent burning, and the application of charcoal and ash which increased soil pH and thereby suppressed Al activity favourable for specific microorganisms responsible for the darkening of these soils, called *terra preta de índio*. The theory that a correlation between shortened fallow periods and yield decline in shifting cultivation exists is questioned by (Mertz 2002), but in general most authors describe recent shifting cultivation above a certain population density or frequency of clearance (shortened fallow periods) as disastrous and leading to soil nutrient and soil organic matter (SOM) depletion (Goldammer 1993; Hölscher et al. 1997b; Silva-Forsberg and Fearnside 1997; Zech et al. 1990). The effectiveness of conventional fertilization on highly weathered and acidic Oxisols in the Amazon Basin is limited by high rainfall, low nutrient retention, and rapid water flow. Easily available and mobile nutrients, such as those supplied by mineral N or K fertilizers are rapidly leached into the subsoil (Giardina et al. 2000; Hölscher et al. 1997a; Renck and Lehmann 2004).

P is usually considered the primary limiting nutrient in plant production on highly weathered soils of the humid tropics because it is strongly bound to aluminium and iron oxides and, thus, not easily available for plants (Garcia-Montiel et al. 2000). Heterophobic phosphate solubilizing microorganisms make mineral bound P available by the excretion of chelating organic acids. (Kimura and Nishio 1989) showed that insoluble phosphates which are not crystallized can be solubilized by indigenous microorganisms when abundant carbon sources are supplied.

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

Under the high leaching conditions of the *terra firme* soils in the central Amazon, reduction of nutrient losses by leaching is important in order to improve sustainability. The properties of charcoal and its effectiveness to ameliorate adverse soil conditions are reviewed by Antal and Grønli (2003) and Glaser et al. (2002b). Charcoal might be suitable to combat constraints of soil infertility in the tropics (Ogawa 1994).

Charcoal has a large inner surface area due to its porous structure with both high reactivity and adsorptivity. Ionic adsorption of NO_3^-, NO_2^- and PO_4^{3-}, was shown by Fujita et al. (1991). Ammonium can also be adsorbed by charcoal (Lehmann et al. 2002). A further mechanism could be nutrient immobilization through stimulation of the microbial community. Microbial biomass can represent a large pool of nutrients, especially in less fertile soils (Giardina et al. 2000), and has a rapid turnover compared with soil organic matter (Baath and Anderson 2003). Bengtsson et al. (2003) conclude that leaching of nitrate from forest soils may be largely dependent on the density and activity of the microbial community.

In the USA a charcoal based slow-release fertilizer is in development (Day et al. 2005) and Radlein et al. (1996) have produced an organic slow-release N fertilizer by pyrolysing NH_3 or urea with organic wastes. Charcoal has widespread usage in agriculture (Antal and Grønli 2003) and can easily be produced out of woody biomass. If re-growing vegetation is used, such a practice of slash and char as alternative to slash and burn would sequester carbon dioxide (CO_2) from the atmosphere and would address some of the soil fertility constraints in the tropics. Residues of charcoal production are used to improve soil quality in the vicinity of Manaus and in other parts of Brazil. Farmers report higher fertility and increased resistance of plants against diseases and pests using charcoal amendments in planting holes (Steiner et al. 2004b).

Our objective was to find a practical way for Amazonian colonists to improve agricultural charcoal use by adding nutrients to charcoal powder. In detail this study addressed the following questions: (1) Are mineral N, P and K fertilizers absorbed by charcoal? (2) To what degree are the absorbed or chemically bound nutrients available to plants and/or microorganisms? and, (3) Does charcoal increase the retention of mineral N and K fertilizers?

17.2 Material and Methods

This study was conducted in the greenhouse facilities of the Embrapa-Amazônia Ocidental (Empresa Brasileira de Pesquisa Agropecuaria) station, 30 km north of Manaus (3°8'S, 59°52'W, 40–50 m a.s.l.), Brazil. Mean annual temperature is 25.8°C (1987–1997), with an average relative humidity of 85% (Correia and Lieberei 1998).

Two kinds of mineral fertilizers were prepared for the experiment. One treatment was based on charcoal powder as nutrient carrier and the other on kaolin. Kaolin was used as contrast to the charcoal; it is an abundant mineral in the region, and served to obtain the same dilutions of the corresponding treatments. Ammonium sulphate [$(NH_4)_2SO_4$], potassium chloride (KCl), and ordinary super phosphate (OSP) were either mixed with kaolin or with charcoal powder prior to fertilization. The fertilizers were dosed to apply 3.6 g elemental N, K and P kg^{-1} of charcoal or kaolin which corresponds to about 40 kg ha^{-1} of these elements at a charcoal application of 11 Mg ha^{-1}. The mineral fertilizers were dissolved in distilled water, charcoal or kaolin was stirred into the solution and left for drying at room temperature.

Topsoil (0–0.1 m) of a Xanthic Ferralsol (FAO 1990) was collected and sieved (<2 mm). The soil is fine textured with 70–80% kaolintic clay. It is strongly aggregated and has medium contents of organic carbon (C) (24 g kg^{-1}), low pH values of 4.7 (in H_20), low cation exchange capacity of 1.6 $cmol_c$ kg^{-1}, and low base saturation of 11.2%. After adding water (humidity of 30%) the soil was amended with dried and milled elephant grass (*Penissetum pupurium*) (1 kg DW 50 kg^{-1} of soil) and stored in a closed box for 2 months. Elephant grass was added to ensure a basic biodegradable C-stock for microbes. The soil was fertilized in a manner to create five treatments and divided into five different boxes. Treatment 1 contained unfertilized soil *Penissetum* mix (C); Treatment 2 (CI) was fertilized with charcoal based fertilizer (11 Mg ha^{-1}, N, P, K 40 kg ha^{-1}); in treatment 3 (KI) the same amount of NPK was applied but kaolin based (11 Mg ha^{-1}); and, treatments 4 and 5 were fertilized with twice the amount of either charcoal (CII) or kaolin based fertilizer (KII), respectively (Table 17.1).

Pots of 11.5 cm height and 12.5 cm diameter were filled with 840 g (DW) soil each. Twenty-five pots were filled to form five repetitions of each treatment. The pots were randomly distributed on a table in the centre of the greenhouse. In each pot five pre-germinated rice seedlings were planted (February 2, 2003). Insect control (caterpillars) was done manually and every day if encountered. The rice plants were watered with 25 ml per pot for the first 3 days. No water occurred at the bottom of the pot at that watering level. From 10th February to 6th May 100 ml of water was applied daily and the leachate was collected for analyses of N, P, K, and pH. After 4 months the pots were emptied, the rice biomass was dried at 65°C and weighed separately as roots and aboveground biomass. For the determination of foliar nutrient contents (N, P, K) a digestion with a mixture of H_2SO_4, salicylic acid, H_2O_2, and selenium was used according to Walinga (1995). For the extraction of exchangeable soil P and K the Mehlich-3 extraction was used (Mehlich 1984). Potassium was analyzed with a flame photometer (Micronal B 262, Sao Paulo, Brazil). Phosphorus was measured using a photometer (Heλios ß, Thermo Spectronic, Cambridge, UK) with the molybdene blue method (Olsen and Sommers

Table 17.1 Treatments and fertilization in grams kg^{-1} soil

Treatment	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Charcoal (g kg^{-1})	Kaolin (g kg^{-1})
C (control)	–	–	–	–	–
CI (charcoal I)	0.04	0.04	0.04	11	–
KI (kaolin I)	0.04	0.04	0.04	–	11
CII (charcoal II)	0.08	0.08	0.08	22	–
KII (kaolin II)	0.08	0.08	0.08	–	22

1982). Soil pH was determined (in H_2O and 1 N KCl 1:5 w/v) and in the leachate using an electronic pH meter with a glass electrode (WTW pH 330, WTW, Weilheim, Germany). Total C and N in soil and plant samples were analyzed by dry combustion with an automatic C/N- Analyzer (Elementar, Hanau, Germay). Leached N contents were measured by the Kjeldahl technique.

17.2.1 Microbial Population

Respiration kinetics can be used to gain information about soil fertility (Ilstedt et al. 2003; Steiner et al. 2004a). In a previous study the microbes' reproduction rate after addition of an easily degradable substrate (glucose) correlated significantly with soil fertility parameters like nutrient contents and biomass production (Steiner et al. 2004a). It was of interest if microbes are able to utilize nitrogen carried by charcoal to the same extent as carried with kaolin. The exponential reproduction rate of microorganisms can serve as an indicator for the availability of nutrients (Ilstedt et al. 2003). Substrate induced respiration (SIR) serves to assess the potential performance of microorganisms and this provides hints for nutrient supply potential and availability of organic compounds or inhibiting agents like toxic materials (Beck and Bengel 1992).

For respiration measurements the same soils (but different subsamples) were used as for the pot experiments. The microbial respiration was assessed in three repetitions using the IRGA-based (infra-red gas analysis) ECT-Soil Respiration Device (ECT Oekotoxikologie GmbH, Germany). The procedure is described in more detail by Förster and Farias (2000) and Steiner et al. (2004a). The respiration of sieved (<4 mm) soil samples (40 g dry weight) was determined by measuring the carbon dioxide (CO_2) production in a continuous flow-system at a constant flow rate of 300 ml fresh air per minute. A disadvantage of working with sieved soil samples is that their original structure is lost; but in regard to their lack of macrofauna and plant parts, plus the possibility of mixing these to give a high degree of homogeneity, they are well suited for studying the soil microbiota (Anderson 1982).

Each soil sample was measured once within 1 h over a period of 50 h. The SIR method is a physiological method for the measurement of the soil microbial biomass. When easily degradable substrates, such as glucose, are added to a soil, an immediate increase of the respiration rate is obtained, the size of which is assumed to be proportional to the size of the microbial biomass (Stenström et al. 1998). The basal respiration is measured before the addition of the substrate and the substrate induced respiration (SIR) shortly after the substrate (240 mg glucose) addition. Microbial respiration was calculated according to:

1. Respiration [nL CO_2 min^{-1} g^{-1} soil] = (C * F)/S
   where C = IRGA measured CO_2-value [ppm]
   F = Flow rate through cuvette [mL min^{-1}]
   S = soil dry weight [g]

Microbial biomass was calculated according to Anderson and Domsch (1978):

2. Microbial biomass (C_{mic}) [µg C_{mic} g^{-1} soil] = (R * 40.04) + 0.37
   where R = respiration [µL CO_2 g^{-1} h^{-1}]

The specific respiration increment was quantified as the slope of the exponential respiration increase after substrate addition when the respiration rate is plotted on a scale against time. This slope was described by:

3. $N = N_0e^{kt}$
   where N_0 = the initial concentration of microorganisms
   k = the specific growth rate
   t = time

The following parameters served as indicators of soil quality, organic matter turnover, and nutrient availability: basal respiration (BR, OM turn over), substrate induced respiration (SIR), velocity of microbial population increase (k) after substrate addition (nutrient availability and soil quality), activation quotient (QR = BR/SIR), microbial efficiency, and metabolic quotient (MQ, CO_2-C h^{-1} C_{mic}^{-1}).

17.2.2 Statistical Analyzes

Results were analyzed using the software SPSS (12.0) and completely randomized design. The treatments were compared using one way ANOVA and Fisher's LSD test (least significant difference). Homogenous subgroups were detected by the Student Newman Keuls post hoc test.

17.3 Results and Discussion

17.3.1 Leaching of N, P and K

Leaching of N was reduced if ammonium sulphate was applied with charcoal. The difference was significant ($P < 0.05$) between the double dosed treatments (CII and KII). The opposite was observed for K. More potassium was leached in pots with charcoal. Again the difference was significant ($P < 0.05$) only between treatments CII and KII. These findings corroborate those of (Lehmann et al. 2003). Glaser et al. (2002b) and Lehmann et al. (2003) assumed that higher nutrient retention and nutrient availability in charcoal treated soils are related to higher exchange capacity, surface area, and direct nutrient additions. Charcoal is rich in K (0.23 g K kg^{-1} charcoal). This explains the higher K leaching from charcoal containing pots.

Leaching of P remained low and was only influenced by the amount fertilized, not by the carrier applied (Fig. 17.1). This was expected as P is rather bound to aluminium and iron oxides (Garcia-Montiel et al. 2000) than leached in this type of

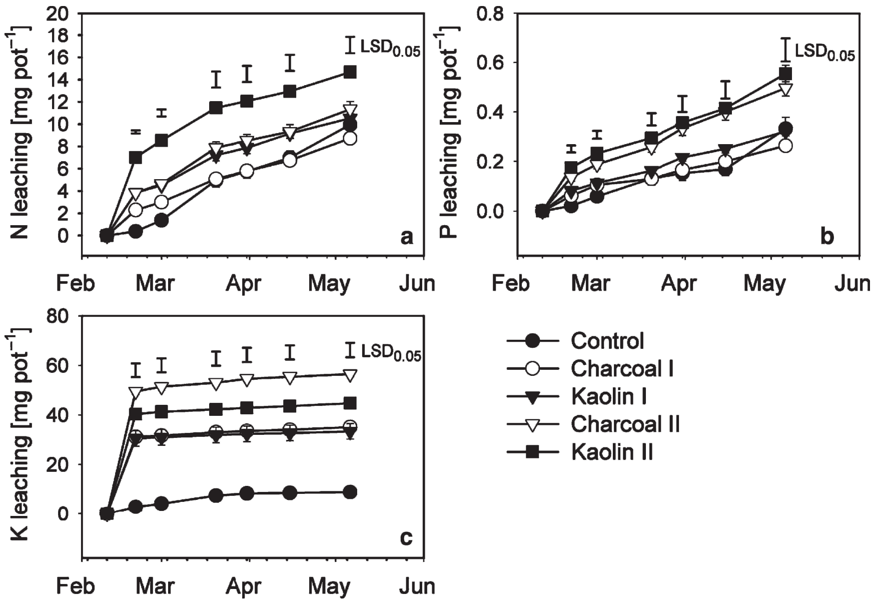

Fig. 17.1 Cumulative leaching of N (**a**), P (**b**) and K (**c**) (mg per pot) after mineral fertilization at two different levels (I and II), based on either charcoal as nutrient carrier or kaolin (means and standard errors; $n = 5$, LSD at $P < 0.05$). The symbols are mostly bigger than the standard errors

soil. Charcoal did not change the availability of P by stimulating phosphate solubilizing microorganisms (Kimura and Nishio 1989). In comparison to the control the cumulative N leaching was significantly ($P < 0.05$) higher in KII, P losses were significantly higher only in the higher fertilized treatments (KII and CII), and K leaching was significantly increased in all fertilized treatments in comparison to the control. The largest proportion of N and K was lost during the first sampling period (10 days, 1 l of applied water). The losses of N during the first sampling period were 4%, 26%, 37%, 34%, and 48% of the total leached N for the treatments C, CI, KI, CII, and KII, respectively. Potassium got lost to an even higher extent and quantified 30% for the control and 90% of the total leached K for the fertilized treatments.

At the first sample period both charcoal treatments retained significantly more N than the kaolin treatments. At the beginning of the experiment the amount of leachate was equal between the treatments, but increased and the colour turned yellowish in the control and kaolin pots during the course of the study. Higher water consumption by plants in charcoal pots might insufficiently explain the unequal surplus water generation (Table 17.2). The Amerindian population influenced the soil physical properties by addition of organic matter and charred organic matter, favouring the formation of aggregates, reducing the cohesion and plasticity, and providing favourable conditions for aeration and tilth (Kern et al. 2003). Agricultural scientists early recognized the importance of SOM in enhancing soil fertility, soil structure, and water-holding capacity (Kononova 1966). But Glaser et al. (2002b)

Table 17.2 Amounts of leachate collected between February 20, 2003 and May 6, 2003. Homogenous subgroups are indicated by the same letter, Student Newman Keuls post hoc test ($P < 0.05$, $n = 5$)

	Control		Charcoal 11g kg^{-1}		Kaolin 11g kg^{-1}		Charcoal 11g kg^{-1}		Kaolin 11g kg^{-1}	
Sampling date					ml					
20.02.03	438	a	407	a	439	a	435	a	432	a
01.03.03	453	b	307	a	308	a	370	a	436	b
20.03.03	1117	c	563	a	676	ab	690	ab	774	b
31.03.03	442	c	364	ab	388	bc	346	ab	310	a
15.04.03	446	a	392	a	432	a	370	a	368	a
06.05.03	812	b	676	a	694	a	658	a	694	a

reviewed that improvements of soil water retention by charcoal additions may only be expected in coarse-textured soils or soils with large amounts of macropores. Although Antal and Grønli (2003) reports that significant amounts of oxygen and moisture can be chemisorbed by charcoal and chemisorbed oxygen causes the charcoal to become hydrophilic.

This process and mineralization of N might explain the acceleration in N leaching in control pots (Fig. 17.1). At the last sample date the N concentration was significantly higher in leachate derived from charcoal pots (CI) in comparison to kaolin pots (KI) (Table 17.2). This might show the ability of charcoal to release N slowly. Leachate pH increased in all treatments significantly during the study and was highest in the control (from 3.6 to 6.8, Table 17.2). Water (pH ~ 7) was applied in access, thus H^+ ions were reduced due to leaching.

17.3.2 Soil N, P and K Contents

At the end of the experiment the charcoal treatments CI and CII contained significantly ($P < 0.05$) more soil N than the higher dosed kaolin treatment (KII). Highest total N concentrations were found in CII, whereas KII had the lowest ones (Fig. 17.2) due to higher leaching and plant uptake. The available soil P contents correspond clearly to the amount applied at the beginning of the experiment with: lowest contents in the control plots C, medium contents in CI and KI, and highest ones in CII and KII. There was no change in available P contents due to the charcoal amendment. Exchangeable K contents were significantly higher in the charcoal treatments in comparison to the kaolin treatments. The double K fertilization carried by kaolin (KII) resulted in significant lower exchangeable K content in comparison to a single K application carried by charcoal (CI). As with the soil leachate this might be explained by the charcoal's K richness. Certainly, K uptake by plants explains the significantly higher soil K contents in the control plots in comparison to the kaolin treatments (Fig. 17.2). Soil pH (in KCl) was decreased in the kaolin treatments due to fertilization (NH_4), it did not change pH in the charcoal pots CI

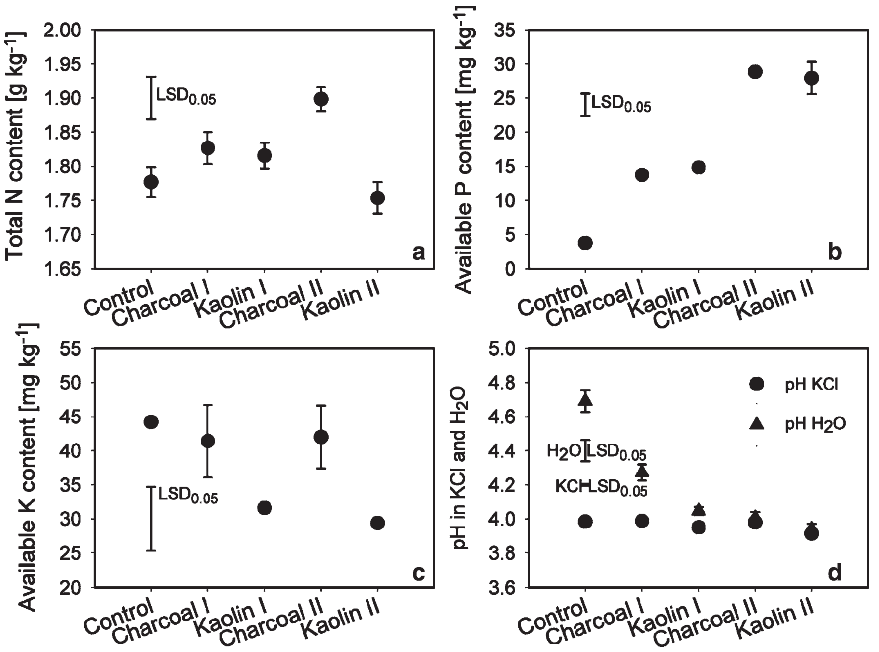

Fig. 17.2 Soil NPK contents and soil ph at the end of the experiment, after harvesting and leaching (means and standard errors; $n = 5$, LSD $P < 0.05$)

and CII. The significant decrease in pH due to fertilization is somewhat buffered by charcoal (Fig. 17.2d). Soil pH measured in water is the pH closest to the pH of the soil solution in the field, but in salt (KCl) it is less dependent on the recent fertilizer history (Hendershot and Lalande 1993). Unfertilized pots had significantly higher pH (H_20) than fertilized ones. Soil C contents as well as C/N ratios were significantly increased by charcoal application.

17.3.3 Plant Biomass Production and N, P and K Uptake

Root biomass as well as above ground biomass were significantly increased by fertilization, but charcoal did not significantly influence plant growth (Fig. 17.3). Means were slightly higher in the higher dosed treatments (CII and KII) in comparison to the lower dosed ones (CI and KI). Foliar N concentrations were significantly increased by treatments CII and KII in comparison to treatments C, CI and KI. Maximum foliar N levels were found in plants of treatment CII. Foliar P contents reflect the amount of P fertilizer applied, no charcoal or kaolin effects could be identified. Charcoal is supposed to provide a microhabitat for arbuscular mycorrhizal (AM) fungi and, thus, can increase the P availability for plants (Saito and

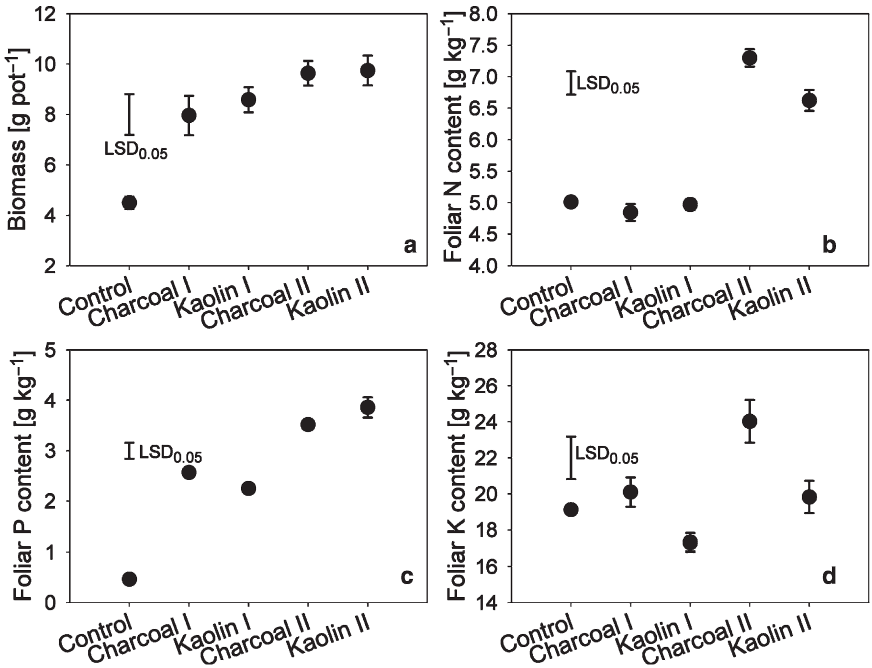

Fig. 17.3 Effects of charcoal and kaolin based NPK fertilization on total rice biomass production (g per pot) and on foliar NPK contents (g kg^{-1} dw) (means and standard errors; $n = 5$, LSD $P < 0.05$)

Marumoto 2002). As the pots were not inoculated with AM fungi a colonization of the soil might not have happened. The opposite was obtained for foliar K. Only charcoal increased K contents significantly ($P < 0.05$, Fig. 17.3).

For the region's agricultural practice and subsistence farming this is important as both manioc and sweet potatoes respond much better to K than to N fertilization (Hecht 2003). In this study no shortage of K was observed. Plant biomass production correlates significantly with available soil P (R = 0.801, $P < 0.001$), but not with total soil N. It even correlates negatively with available K (R = −0.589, $P < 0.01$) and pH in H_2O (R = −0.830, $P < 0.001$). As mineral fertilization is responsible for the lower pH a negative correlation with plant growth is not surprising. Foliar N and P contents correlate with plant biomass production (R = 0.532, $P < 0.01$ and R = 0.808, $P < 0.001$, respectively), but foliar K does not correlate.

17.3.4 Microbial Populations

Soil respiration curves (Fig. 17.4a) show that the NPK fertilizer was equally utilizable either if applied with charcoal or kaolin. The amount of N, P, and K applied did not show limitations in either microbial population (Fig. 17.4a) or plant growth

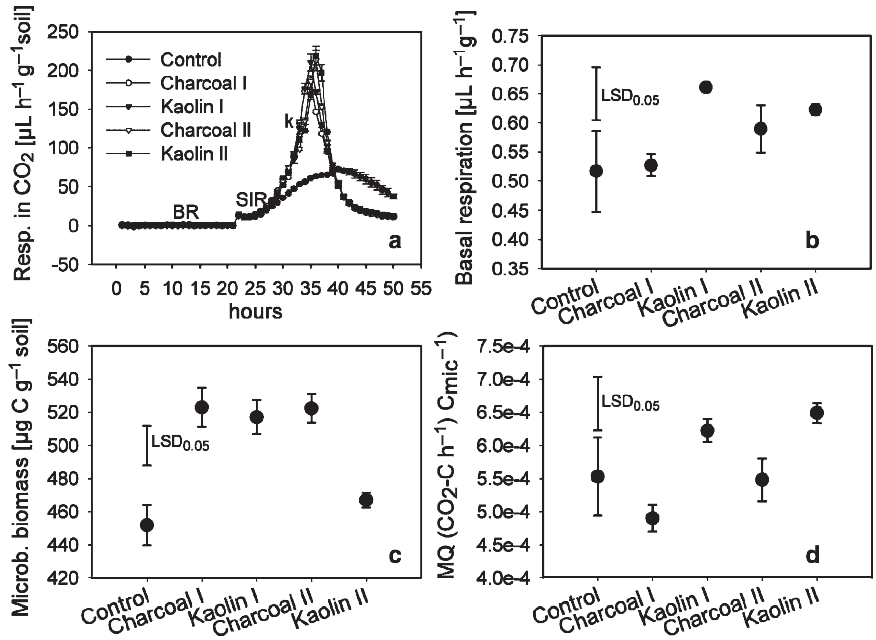

Fig. 17.4 (a) Respiration curves obtained by measuring soil respiration once within 1 h over a period of 50 h after NPK fertilization at two different levels (I and II) with either charcoal or kaolin as nutrient carrier (means and standard errors; $n = 5$); (**b**) Basal respiration (BR Fig. 17.4a); (**c**) Microbial biomass assessed by substrate induced respiration (SIR Fig. 17.4a); and, (**d**) Metabolic quotient express the microbial efficiency as carbon turn over (CO_2-C h^{-1}) per microorganism (C_{mic}) means and standard errors; $n = 3$, LSD $P < 0.05$)

(Fig. 17.3a). This might indicate that the lower NPK dose (CI and KI) was sufficient to prevent growth limitations. Basal respiration (BR) was lower in the treatments with charcoal, but microbial population size as measured by substrate induced respiration (SIR) was higher when nutrients were applied together with charcoal. This was manifested significantly ($P < 0.05$) between CI and KI for BR (Fig. 17.4b) and between CII and KII for SIR and microbial biomass (Fig. 17.4c). Microbial population growth rate after substrate (glucose) addition is significantly ($P < 0.001$) lower in the unfertilized soil. The reproduction rate of KI was significantly increased in comparison to CII. Mean reproduction rates tend to decrease due to charcoal (CI and CII in comparison to KI and KII, respectively) and double fertilizer application (CII and KII in comparison to CI and KI, respectively).

In this study we could not find a higher specific microbial growth rate in charcoal containing soil (Pietikainen et al. 2000; Steiner et al. 2004a) perhaps because NPK were applied in excess. A repetition of the soil respiration measurements after depletion of nutrients at the end of the experiment might have shown differentiated results like those obtained by Steiner et al. (2004a). They could show a linear dependency of microbial reproduction potential on availability of soil nutrients. The average turnover time of N in microbial biomass is estimated to 1–2 months

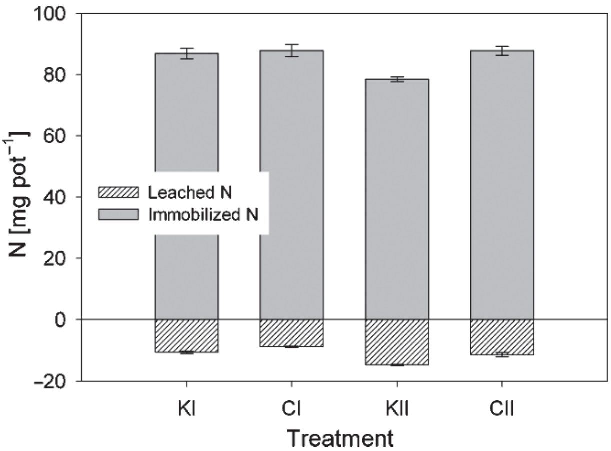

Fig. 17.5 N leaching and N immobilization (calculated from the microbial biomass, assuming a C:N ratio of 5:1) of charcoal containing soil (CI and CII) in comparison to soils without charcoal (KI and KII). KII and CII got twice the amount of N fertilizer based on kaolin (K) or charcoal (C) as nutrient carrier

(Bengtsson et al. 2003). Assuming a C:N ratio in the living microbial biomass of 5:1 (Tiessen and Shang 1998) immobilized N in the charcoal treatments exceeds approximately 1 mg in CI and 9 mg in CII of that amount of N immobilized in KI and KII, respectively (calculated from the differences in microbial C derived from SIR). Whereas CI lost less N due to leaching than estimated from the difference in microbial N between KI and CI, CII lost more N as the calculated difference in immobilized N between CII and KII (Fig. 17.5). The aromatic backbone makes charcoal more resistant to microbial degradation than SOM (Schmidt and Noack 2000); therefore, the microbial biomass might have been limited by pH, easily decomposable C source, or micronutrients to immobilize all fertilized N in the higher dosed treatment. Whether or not immobilization is the only mechanism, charcoal is reducing leaching indirectly by stimulating the microbial biomass or probably by direct mechanisms like sorption and chemical binding (Braida et al. 2003; Glaser et al. 2002a; Lehmann et al. 2003). These effects could not be distinguished in this study. However, Lehmann et al. (2002) found adsorption of ammonia to charcoal when microbial activity was suppressed by additions of azide. To which extent charcoal-C can be utilized by microbes and thus causing immobilization of N is uncertain.

The charcoal used for this study was not weathered and might contain easily decomposable substances like bio-oils, which are utilized by microbes (Steiner et al. 2007a). The equal microbial biomass in the charcoal treatments but significantly higher N leaching in CII do support the assumption that immobilization causes increased N retention. As microbial N immobilization is taking place simultaneously with inorganic N production (Burger and Jackson 2003), significant amounts of the organic N pool might have been mineralized. The microbial biomass correlates with the soil's C (R = 0.660, $P < 0.01$) and N (R = 0.611, $P < 0.05$) contents, but not with plant biomass production nor with soil K, P, or pH. Reproduction rate of the microorganisms after glucose addition correlates with plant biomass production (R = 0.719, $P < 0.01$) the soils' available P contents (R = 0.663, $P < 0.01$), and even to a greater extent with foliar P (R = 0.823, $P < 0.001$). A positive correlation of microbial biomass with soil pH was found by (Baath and Anderson 2003; Steiner et al. 2004a), but could not be found in this study. Neither pH in first leachate nor soil pH at the end of the study correlates with the estimated microbial biomass.

The activation quotient was significantly lower in the soil after charcoal application ($P < 0.05$ CI vs. KI, and $P = 0.056$ CII vs. KII), which means that the decomposition was smaller in relation to microbial population size (MQ, CO_2-C h^{-1} $C_{mic}{}^{-1}$, Fig. 17.4d). Bengtsson et al. (2003) suggest that differences in respiration rate and ATP content are more indicative of the magnitude of potential gross immobilization and mineralization than soil C/N ratios. The property of a forest soil as source of nitrogen for plants and of excess nitrogen ending up in ground water and surface water may thus be more variable with and dependent on its microbial biomass and activity than on its C/N ratio (Bengtsson et al. 2003). This may be especially true for very recalcitrant organic additions such as charcoal.

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Chapter 18
Terra Preta Nova: The Dream of Wim Sombroek

DC Kern, M de LP Ruivo, and FJL Frazão

18.1 Introduction

In the Amazon soils occur that were formed during pre-historical human occupations. These soils are highly fertile and stable and are most commonly referred to as *terra preta*, Amazonian Dark Earths (ADE) (Woods and McCann 1999), or Archaeological Black Earth or Indigenous Black Earth (Kern 1988, 1996; Kern and Kämpf 1989). It appears that ADE form proper micro-ecosystems where the soils do not exhaust themselves easily, even in the tropical conditions where are exposed for long periods of time. Several process-oriented designations have been suggested for the ADE formation processes, such as: “vegetable soils”, “plaggen epipedon” or “anthropic soils”. The latter one, the most accepted, proposes that the ADE were intentionally formed by the pre-historical inhabitants. Archaeological evidence indicates that ancient human activities in the Amazonian habitats transformed, significantly, the landscapes of the vicinity of their settlements (e.g. Kämpf and Kern 2005). In many areas, indigenous societies formed extensive deposits that altered the soil properties (Lehmann et al. 2003; Woods and McCann 1999). These archaeological sites’ dark soils were created by deposits of vegetal origin (charcoal, ash, leaves and diverse palm fronds, manioc residue, seeds, etc.) and residues of animal origin (bones, blood, fat, feces, chelonian carapaces, shells, etc.). These materials resulted in highly fertile soils with elevated levels of P (more than 1,000 mg/kg^{-1} of soil), Ca, Mg, Zn, Mn, and C (Kern 1996). The organic matter in ADE is on the order of six times more stable than in the soils of forest (Pabst 1992), owing to the stability of fertility in ADE. In locations where Black Earth is present a strip of soil with dark brown coloration is often also found, without ceramics artifacts, but with elevated levels of OM. These soils were called *terra mulata* (TM) by Sombroek (1966). According to Sombroek et al. 2002, the areas of TM are the resultant of the intentional application of charred plant materials sometimes associated with human or animal residues (fishing and hunting products, calcium from shells and mollusks from consumption) and from other residues of plant origin. The development of the terra mulata expanses associated with the habitation areas allowed for expansion of horticultural food production and most reliability of sustainable harvests.

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek’s Vision*,

Since 1966 Wim Sombroek, dreamt about the possibility to "produce" or "re-create" Black Earth and Brown Earth, calling this new soil *Terra Preta Nova* (TPN) (Sombroek et al. 2002; Madari et al. 2004). To do this, a variety of research would be necessary:

1. Ethno-archaeological research with isolated indigenous groups who still use pre-Columbian practices to help in the understanding of the fertility increases within the soil
2. Ample regional surveys of ADE with studies on their genesis and aspects connected to the ethno-(or agro) biodiversity
3. Ample archaeological studies within these sites
4. Laboratory research through physical-chemical and mineralogical analyses to understand OM stability
5. The durability of ADE after their abandonment by Amerindians and to what degree these areas are being degraded, due to reoccupation
6. To conduct greenhouse experiments
7. To conduct agronomical and agro-forestry experiments in areas of current production with the intent to recuperate Amazonian degraded areas and
8. Transference of knowledge about management practices of TPN soils toward priority areas of integrated environmental handling and promote awareness about the value of the indigenous patrimony stimulating collections of reference from ADE materials, locations of archaeological occurrences, etc.

Sombroek believed that the development of successful social and economic techniques could contribute, essentially, to the sequestration of atmospheric CO_2 in the handled soils and, at the same time, to leave the primary forest intact with its proper stock of CO_2, with its function of CO_2 sequestration, and with its rich biodiversity (Sombroek et al. 2002).

In the 2000 to 2003 period, Wim Sombroek was granted a scholarship from CNPq-LBA as visiting researcher to develop researches in the Coordination of Earth and Ecology Sciences of the Museu Goeldi in Belém. During 2000 and 2001 intense discussions regarding how to do a long-term field experiment were held, with the objective of implanting a *Terra Preta* Replication Experiment (*Terra Preta Nova* Project) in the Amazon. Key to forming ADE, seems to be the abundance of discarded organic matter from animal and vegetal origin. The abundance of material from vegetal origin could be obtained from locations where the lumbering activity is present, where sawmill waste production is very large, so to each m^3 of cut lumber are necessary 2 to 3 m^3 of wood in trunk. These sawmill wastes are currently incinerated, casting large quantities of CO_2 in the atmosphere, contributing to the increase of heat islands and the greenhouse effect, and directly affecting the population and urban environments with environmental discomfort. Another issues with sawmill waste is its deposition in inadequate locations, causing siltation in the local watershed.

Thus, to try to produce *Terra Preta Nova* the Municipality of Tailândia in Pará State was chosen. It is one of the biggest centers in the lumber industry in the State.

The sawmill wastes, along with slaughterhouse waste (with which there are also issues of waste management), are available. This practice seems to be ecologically correct, first because of the destiny gave to material, as vegetal as animal origin. Moreover, the research takes into consideration the sustained management of the soil and its natural recourses, being supported in three fundamental bases: the conservation of urban and rural ecosystems, development of sustainable system of the recourses from earth, and the diffusion of sustainable handling systems in ecological, social, and economic terms.

In this context, the project "Economic utilization of residues from lumber as alternative to minimize the socio-environmental problems in the Pará State," financed by Fundo Estadual de Ciência e Tecnologia-FUNTEC/Pará, was begun as part of the systematic studies of the *Terra Preta Nova* experiment. The Project intends to attain the following goals: to implement an experiment utilizing different types of organic residues; chemical, physical, mineralogical, and microbiological analyses of the organic compounds formed; to implant community vegetable gardens; making of an environmental education primer, directed to rational utilization of wood waste; and to disseminate viable practices to economic utilization of the lumber residues.

18.2 Characterization of the Study Area

The Municipality of Tailândia is situated to 200 km from Belém, along route PA 150, in the northeast of the State. Its area is 4,780,370 km^2 with a population of 38,453 inhabitants (Fig. 18.1).

The municipality is relatively flat with low terrains, hence, does not present much relief, with an average altitude of 35 m, with a maximum of 96 m in the south, and 45 m at its capital. The drainage is formed mainly by the Acará River. The predominant soils are Yellow Latosol with clayey texture and the Yellow Argisol, with a medium/clayey texture. In the floodplain areas (flooded soils), it is common to find Gleysols and Fluvic Neosols, eutrophic and dystrophic, with indiscriminate texture (Rodrigues 2001).

The climate of Tailândia region is tropical humid, type Afi, according to Köppen's classification. The rainy period is generally long, average annual precipitation is 2.837 mm, with a monthly average of 60 mm, and annual temperature amplitude around 5°C, with annual medium temperature of 26°C. The predominant vegetation is upland Equatorial Rain Forest, with Dense Forest of the low plateaus as subtype. In the lowest terrains, liable to inundations, there are occurrences of floodplain forest (seasonally flooded areas), mainly on the Acará River margin. There is pressure from agriculturists and cattle breeders to remove the mature forests to plant crops and pasture. This results in temporary abandonment causing an accelerated rising of secondary forests, the "*capoeiras*". But, the area still has mature forest cover which deserves to be preserved.

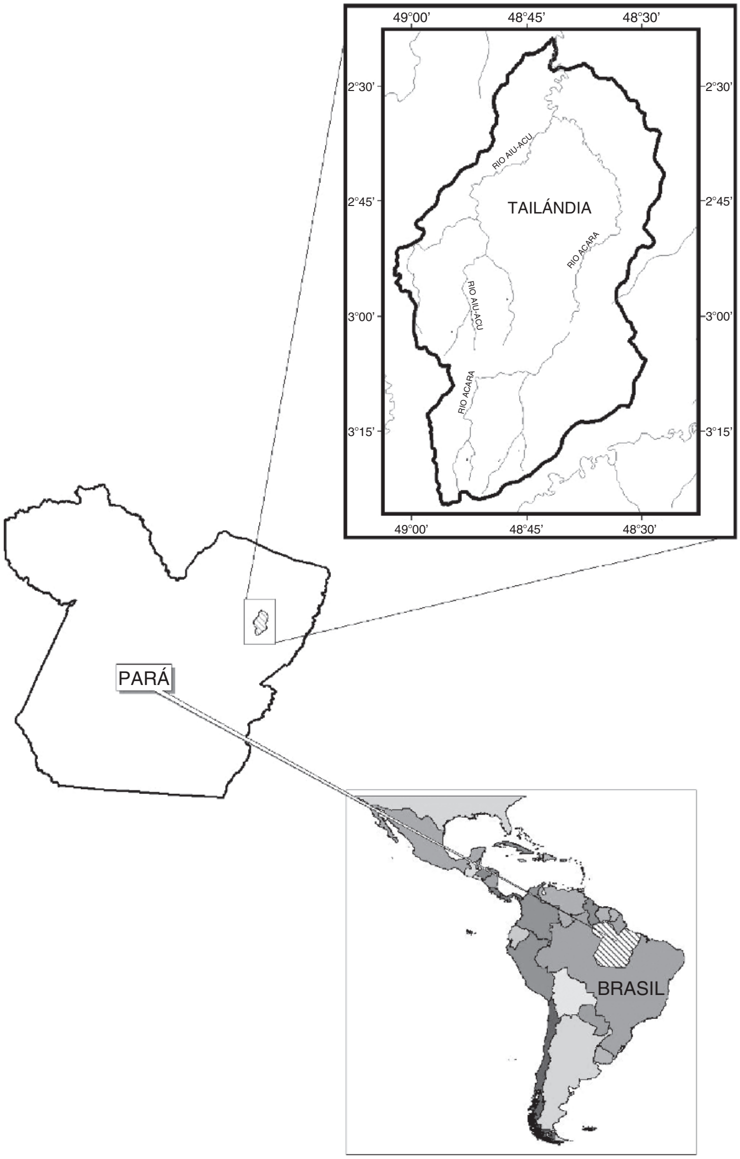

Fig. 18.1 Locator map of Tailândia

18.3 The *Terra Preta Nova* Experiment

The *Terra Preta Nova* (TPN) experiment was started in July 2003 along the area of servitude Tucurui/Albrás border, coordinates 02° 57' 021"S and 048° 57' 21"W., in the Municipality of Tailândia. The Tailâminas Plac business ceded 4 ha of this area for an estimated period of 25 years. This location was chosen because it is flat, presents a unique type of soil and it is situated along a transmission line, where it is forbidden to build and to plant big trees (Fig. 18.2). This area is ideal because the experiment intends to follow a form of soil management with incorporation of organic residues of organic and animal origin, with the monitoring of physical, chemical, mineralogical, and biological variations for decades, as in the formation of *terras pretas*. In the experiment, 17 treatments with 4 repetitions each were initially implemented, totaling 68 parcels measuring 3 × 3 m each. For the distribution of the parcels, we utilized a randomized blocks experimental design, a combination of charcoal, sawmill and butchery residues (Figs. 18.3 and 18.4). The soils of these parcels were collected in the dry and rainy periods of each year for chemical monitoring. For the microbiological studies, the samples of substrates were collected in the dry and rainy periods (2003 and 2005), at 0–5 cm depth, for the microbiological analyses at 0–5 and 5–15 cm of depth for analyses for levels of microbial carbon (Cmic) and microbial nitrogen (Nmic).

Fig. 18.2 Area views

Fig. 18.3 *Terra Preta Nova* Experiment in July, 2003

Fig. 18.4 *Terra Preta Nova* Experiment in July, 2006

18.3.1 Laboratory Analyses

In the laboratory analyses of total carbon by the Walkley & Black Method; K and Na, by flame photometry after extraction with HCl 0.05 mol L^{-1}; exchangeable Ca, Mg, and Al by atomic absorption spectrophotometry, after extraction with KCl mol L^{-1}; and micronutrients (Fe, Cu, Zn, and Mn) by Mehlich 1 method, in ratio soil: extractor 1:5, determined by atomic absorption spectrophotometry; identification of potential acidity (Al + H) by extraction with calcium acetate 0.5 mol L^{-1} at pH 4.5 and 7.0; determination of available P, by colorimetry in presence of ascorbic acid, after extraction with solution of Mehlich-1. The analyses are being realized in the laboratory of CCTE, according to methodology adopted by EMBRAPA (1979).

The microbiological analyses (count of fungi and bacteria) were determined using the "Pour Plate" technique of counting in Petri plates, utilizing the culture medium Standard Agar (for bacteria) and Potato Agar acidified (for fungi). The carbon (Cmic) and nitrogen (Nmic) levels from microbial biomass of the soil were determined by fumigation-extraction, following the methodologies proposed by De-Polli and Guerra (1999). The data referring to microbial population were submitted to variance analysis and comparison of mean, by LSD Student test ($P < 0.05$) (Muniz 2006).

18.3.2 Edaphic Aspects of the Terra Preta Nova Substrate

The initial soil profile of the *Terra Preta Nova* experiment, corresponds to time zero of the experiment and presents the following characteristics: it is a well drained and developed soil, with a depth of more than 260 m and with the following sequence of horizons Ap, BA, Bw_1, Bw_2, Bw_3 and Bw_4. The coloration varies among very dark grayish brown (10 YR 3/2.5) in the A horizon and brownish-yellow (10YR 6/6 to 7/6) in the subjacent B horizons. The texture varied from loamy sand in the Ap horizon to sandy clay loam in the B horizon; the consistence of the soil when humid is very crumbly and, when moist, it is no clammy and no plastic in the Ap horizon and firm, nimbly clammy and nimbly plastic in the rest of the horizons; the structure is firm small medium granular in the Ap horizon and weak that breaks into sub-angular small and medium blocks in the rest of the horizons.

The granulometric composition of the soils shows a predominance of sand fraction (gross sand + fine sand) in the horizon A (840 g/kg^{-1}), in the rest of the horizons the values of sand remains virtually constant, varying from 600 to 700 g/kg^{-1}. The values of silt are low and present little variation in all profile (varying from 40 to 80 g/kg^{-1}), while the clay fraction increases from A horizon (80 g/kg^{-1}) to BW2 (300 g/kg^{-1}), decreasing again to Bw_4 (260 g/kg^{-1}). The density of the soil varied from 1.32 to 1.60 g cm^{-3}, attaining this maximum value in the BA horizon (18–32 cm) and decreasing with depth. In the first horizons, the density was most elevated probably by action of the heavy machines, used for soil preparation before the start of the experiment, promoting its compactation. The total porosity includes macroporosity and microporosity. Normally, the total porosity of the soil will be as minor as more compacted if it were to be. The values encountered for total porosity varied from 42% to 49%. The lowest value was encountered in the BA horizon (18–32 cm), agreeing with the values of density of the soil.

Regarding the chemical characteristics, calcium, sodium and potassium presented elevated levels in the first horizons, until about 130 cm of profundity, where these levels decrease abruptly. Calcium levels are 1.9 cmolc dm^{-3} in the A horizon and 0.8 cmolc dm^{-3} in the Bw_4 horizon, while the Na and K present, respectively, 0.16 and 0.34 cmolc kg^{-1} in the A horizons A and 0.02 and 0.03 cmolc kg^{-1} in the Bw_4 horizon. The phosphorous values are very low in all horizons, varying from 3 cmolc kg^{-1} in the A horizon and 1 cmolc kg^{-1} in the rest of horizons. Hence, the soil presents more cation exchange capacity and saturation of bases in the upper horizons than in the B horizons. The levels of Al^{+3} are significantly lower in the A and BA horizons (0.1 cmolc dm^{-3} of soil), increasing until the BW2 horizon (2.64 cmolc dm^{-3} of soil) and decreasing again to Bw_4 (1.98 cmolc dm^{-3} of soil), behavior in the profile similar to the clay.

For the physical and chemical characteristics presented, the soil of the *Terra Preta Nova* experiment was classified as typical Yellow Argisol, Dystrophic, sandy/medium moderate texture, equatorial rain forest, and wavy suave relief.

18.3.3 First Results Referents to the Terra Preta Nova Experiment

The results of the 6 months (first collection), 12 (second collection), and 18 (third collection) show a large variation in the levels of the chemical elements as a result of the decomposition process of the material. This variation is more intense in the experiments that had a higher amount of organic matter mixture. Generally, the pH presented a variation very significant among treatments where the values increased in the elapsing of the time. However, the lowest value detected (1.9 to 18 months)

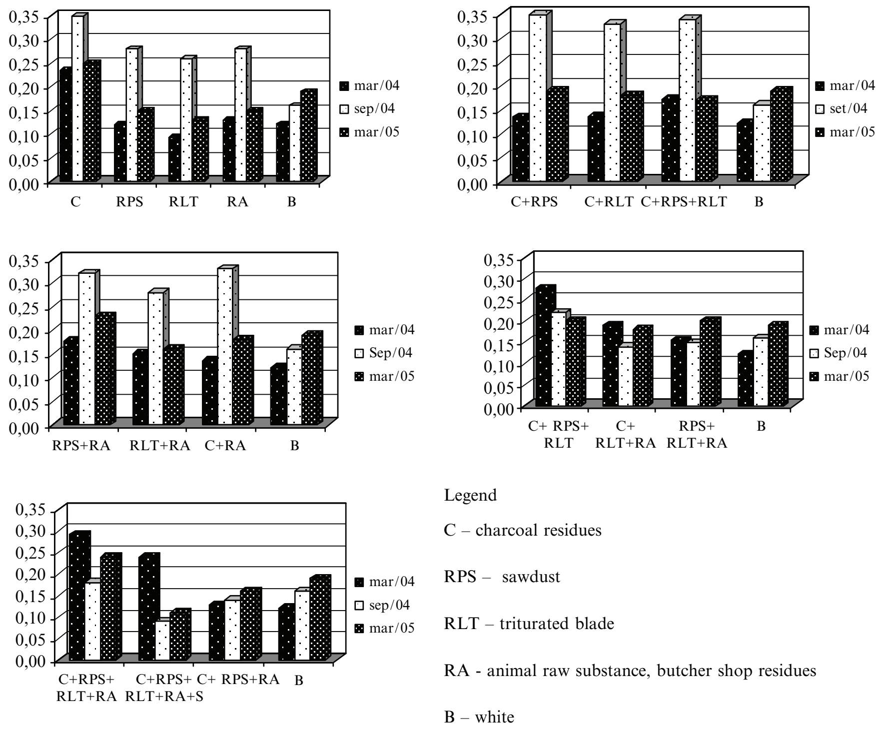

Fig. 18.5 Variation of the Ca (cmolc) in the different treatments, sample 1 (March 2004); sample 2 (September 2004), and sample 3 (March 2005)

was in the treatment with all mixtures, include blood, while the highest value was in the treatment only with charcoal (6. to 6 months). The calcium and magnesium presented similar behaviors, where the major values encountered were to 12 months, and 0.35 cmolc to Ca (charcoal and charcoal + saw powder) and 0.06 cmolc to the Mg (coal, triturated lamina + butchery residue and where had all mixtures) (Fig. 18.5). Regarding to the soil where did not occur addition of organic matter (blank), happened a significant increase in the levels, in these parcels the levels were 0.16 and 0.03 cmolc, to Ca and Mg, respectively. The Na presented large levels 6 months, mainly in the treatments that had triturated lamina, attaining to 0.24 cmolc, while the minor values presented were to 12 months (0.04 cmolc), in the parcel with saw powder, minor until that one encountered on the original soil (0.15 cmolc). The potassium presented a gradate diminution along the time, hence presenting more elevated tenor to 6 months (0.15 cmolc) in the treatment with triturated lamina. The P presents large variation, attaining the maximum 897 mg kg^{-1} to 12 months of the experiment, in parcels where butchery residues were present (Fig. 18.6). Despite large allocation of organic matter added to soil, the increase of C was little significant. In some treatments with addition only of RA and RLT, the values of C (1.5 g kg^{-1} in 6 months) stayed below the original values of the

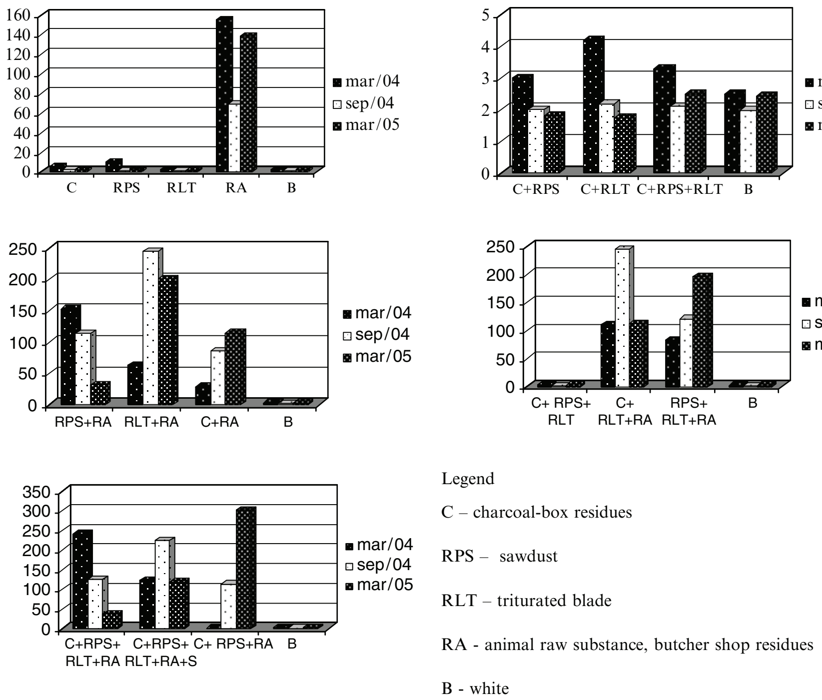

Fig. 18.6 Variation of the P (mg/kg) in the different treatments, sample 1 (March 2004); sample 2 (September 2004), and sample 3 (March 2005)

soil (5.2 g kg^{-1}), however those with addition of RPS obtained 18.1 g kg^{-1} in this period. These results represent still the initial phase of experiment, but it is pereived a straight relationship between the behavior and availability of the nutrients in the analyzed treatments. We perceive a clear increase in the concentration in the parcels where residues were incorporated, relative to the parcels of the original soil.

As for microbiology Muniz (2006), the parcels with highest diversity of residues showed major value to microbial carbon, while the parcels that present lowest diversity of residues showed inferior Cmic. As major the C of microbial biomass, major will be the C reserves in the soil, this express a minor potential of organic matter decomposition. The most quantities of microbial nitrogen in the parcels where had the application of major diversity of residues can indicate major capacity of nitrogen immobilization in this ecosystem. During the rainy period, a considerable increase in bacteria number as well as fungi occurred in the studied parcels, representing major microbial activity in the rainy season, but when a comparison was made between to bacteria and fungi quantities, it was observed that the bacteria number exceeded the fungi number in all collections. In the rainy season, the action of microorganisms is higher, increasing its biomass and participation in organic matter decomposition. The best results were obtained in the parcel which had a mixture of charcoal + sawdust + butchery residues, presenting 73.67 UFC/g of soil in the third collection while in the second collection was 45.67 UFC/g of soil, also in the parcels with a major variety of residues. Thus, with regard to microbial diversity, the results show that the effects of application of the studied residues were most significant in the bacteria population, being that under application coal + triturated lamina residue + butchery residue, the differences as for fungi population were more accentuated. The different types of residue and the diverse combinations that were utilized favored differently the increase in the carbon and nitrogen levels of microbial biomass of the soil.

18.4 Final Considerations

The results are still preliminary. A narrow relationship between the behavior and availability of the nutrients in the analyzed treatments was observed, particularly in the parcels where the residues had been incorporated, relative to the parcels of original soil.

The knowledge obtained in the project is being disseminated to community of Tailândia in the form of seminars, workshops, and short-duration courses. These activities are being developed together with businesses and students to reinforce the benefits of the practice of residue utilization in the soil, mainly in perennial cultures and community vegetable gardens, as well as to demonstrate the damages caused to environment with the burning practices of these residues or open-sky waste deposition, causing river siltation. For the better interaction between the experimental project and the community, multiplier agents that work with basic concepts of environment, solid residues, sustainable development and citizenship, are being implemented through seminaries, group dynamics, posters, and visits by locals to the experiments.

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Chapter 19
Microbial Population and Biodiversity in Amazonian Dark Earth Soils

M de LP Ruivo, CB do Amarante, M de LS Oliveira, ICM Muniz, and DAM dos Santos

19.1 Introduction

Many aspects of the origin of Amazonian Dark Earths (ADE) are still unclear. The analysis of Amazonian anthropogenic soils indicates that the alterations caused by human actions, such as the incorporation of organic residues and the effects of fire on the upper horizons influenced many of the chemical and physical characteristics of these soils (e.g. Woods 1995; Kern 1996; Glaser 1999; Woods and McCann 1999; Ruivo and Cunha 2003; Ruivo et al. 2004). Ruivo et al. (2004) show that the microbial biodiversity is higher in ADEs than in Yellow Latosols. ADE soils are more aggregated than Yellow Latosols, a factor that facilitates soil aeration, root distribution, water retention and movement.

Soil is an important habitat for microorganisms. The biology of ADE soils is important. Little is currently known about the abundance, activity, and diversity of organisms extant in ADE. So, we have much to learn (e.g. Thies and Suzuki 2003; Tsai et al. this volume, Chapter 15). The study of local knowledge of soil and land management in an ecological perspective in the Amazon Region is very important. The soil microbiological relationships are important for soil fertility management. Analysis of the past and present can help make recommendations on how ethnopedological studies can contribute to enhanced sustainable land use and management in the Amazon (Lehmann et al. 2003; WinklerPrins and Barrera-Bassols 2004; Silva and Rebellato 2004; Thies and Suzuki 2003).

Soil consists of a variety of surfaces that influence nutrients availability and affect interactions between different microorganisms. Pores of various sizes are available for exploitation and colonization. The organic matter occurs as freshly added plant, animal, and insect remains, which gradually transformed into stabilized nutrient-rich humus material. These varied components form heterogeneous aggregates of various sizes called *peds*, which contain a complex network of pores. Bacteria and fungi use different functional strategies to take advantage of these complex physical matrices. Most soil bacteria are located on the surface of soil particles and require water and nutrients that must be located in their immediate vicinity. Bacteria are found most frequently on surfaces within smaller soil

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

pores. Here, they are probably less liable to be eaten by protozoa, unlike bacteria that are located on the exposed outer surface of a sand grain or organic matter particle.

The filamentous fungi, in contrast, tend to be located on the outside of the aggregates. These organisms, with their filamentous growth will form bridge between separated regions where moisture is available. The filamentous fungi can move nutrients and water over greater distances in soil. Protozoa, soil insects, nematodes, and other soil animals contribute to the formation and maintenance of soils (Prescott et al. 1999).

In Amazon there are soils called Amazonian Dark Earths (ADE), Archeological Black Earth (ABE), or Indian Black Earth (IBE); all of which have higher fertility than those of their surroundings (e.g. Kern 1996; Woods and McCann 1999). This superior degree of fertility of ADE is, possibly, related to the great diversity and amount of the species, which constitute its micro flora.

Long-term research on ADE has resulted in the *Terra Preta Nova* Project – TPN (Sombroek et al. 2002; Madari et al. 2004). In this direction, the experience of the Company of Lamination Tailâminas Plac, in the Municipality of Tailândia, State of Pará, and of researchers from the Museu Goeldi, Belém, has shown that the addition of sawmill and other organic residues such as forest, urban, and animal, can lead to new soil management strategies. Also, at the same time that, they look for increasing the fertility of the soil and the sustainability of the planted forest, plus contributing to solving other environmental problems, such as the reutilization of industrial or urban wastes.

This study aims to evaluate the microbial community population and diversity of some ADE zones and NDE through colony counting of bacteria and fungi as well as their identification by genus. It is a small contribution to the study of the biodiversity in ADE soils.

19.2 Characterization and Localization of the Dark Earth Soils and Experiments with New Dark Earth (*Terra Preta Nova*)

A. The samples collected in the four ADE sites localized in:

1. The Ferreira Penna Scientific Station is located in the Caxiuanã National Forest, in Melgaço, 350 km west of Belém, Pará State. The upland forest, one of the most representative natural ecosystems in the Amazon region, covers the area. The sample ADE soils were collected from surface soils: in Caxiuanã, Ilha de Terra and Manduquinha sites (0–10 and 10–20 depth). They vary from well to very well drained and their texture varies from sandy to clay.
2. In area of the Amazon River, Pará State the areas in study are located near Santarém in the area of the Tapajós River, Pará State, under silviculture, site Embrapa-Cpatu, localized in the Municipality of Belterra. Santarém/Belterra

(0–20 depth), Juruti/Tabatinga (0–5; 5–10 and 10–20 depth). This soil has a clayed texture.

3. Area of the Amazon River near Manaus, Amazonas State under upland forest. Manaus (0–5; 5–10 and 10–20 depth). These soils have a predominantly sandy texture with a similar mineralogy (kaolin and quartz) in the soil matrix and high fertility. The complete soil characterization and description are found in Ruivo and Cunha (2003), Kern (1996), and Ruivo et al. (2004).

B. The New Dark Earth Experiment of the Company of Lamination Tailâminas Plac, in the Municipality of Tailândia, State of Pará (see Kern et al., this volume).

The adoption of adequate management systems for agriculture and forest sustainability also assist in the reduction of the harmful emissions of gases to the atmosphere and visual pollution and respiratory illness caused by the open-air storage of industrial residues. Besides, it makes use of environmental services associated with the presence of secondary vegetation, which includes improvement of the carbon balance, the water transport to the atmosphere and the leaching protection, by the presence of a true net of security represented by the roots.

The replication experiments of the ADE were set in Yellow Latosols using the following materials: charcoal (C), sawmill dust waste (RPS), grinded veneer waste (RLT), animal bone waste (RA), and animal blood and fat waste (S). Each experiment occupied an area of 3 × 3 m, with a distance of 2 m between each. There are 68 plots using combinations of 1, 2, 3, 4 and 5 kinds of materials listed above, using a randomized plot experimental outline with up to 4 repetitions each. The substrate samples were collected in both rainy and dry seasons (2003 to 2005), in the depths of 0 to 5 cm and 5 to 10 cm for microbiological analyses, arranged as described in the associations below:

1**st** (C), 2**nd** (RPS), 3**rd** (RLT), 4**th** (RA), 5**th** (C + RPS), 6**th** (C + RLT), 7**th** (C + RA), 8**th** (RPS + RLT), 9**th** (RPS + RA), 10**th** (RLT + RA), 11**th** (C + RPS + RLT), 12**th** (C + RLT + RA), 13**th** (RPS + RLT + RA), 14**th** (C + RPS + RLT + RA), 15**th** (C + RPS + RLT + RA + S), 16**th** (Control), 17**th** (C + RPS + RA).

19.3 Methods of Biological Analysis

The samples were analyzed for microbial population. The bacteria and fungi counting was carried out by the Pour-Plate method using the Plate Count Agar (PCA) and Acidified Potato Dextrose Agar (PDA) media, incubated at 35°C and 25°C for 24 h and 5 days, respectively. The number of bacteria and fungi was determined by the colony-forming unit technique with assistance of a Colonies Counter (CP-602).

The bacteria isolation was made by the use of the Brain Heart Infusion Agar media for the individual colony growth. The genus identification was achieved through microscopic examination of colony and cell morphology, by Gram staining and also by biochemical tests such as: VM-VP, Starch, Gelatin, NH_3, H_2S, Indole, Sugar Fermentation, Oxidase, Catalase, and Nitrate. For fungi isolation and identification the Sabouraud at 2% Agar media in wet chamber cultivation was used and after the colonies' growth were made microscope observations using the lacto phenol cotton blue in order to stain the cellular morphology, mycelia and reproductive structures. The predominant colonies were isolated and their morphological characters observed in optical microscopy and scanning electron microscopy.

19.4 Results

A. Microbial Population in the ADE soils

The count results of ADE sites samples from Caxiuanã (Portel County-PA), Santarém (PA) and outskirts of Manaus (AM) show remarkable predominance of bacteria population over fungal (Table 19.1). This higher bacteria number is likely due to factors such as greater metabolic versatility and fast growth.

In this work samples of black earth soil from the Ilha de Terra site located in Caxiuanã, Pará were analyzed. The results indicate that in these soils the fungi are higher in quantity than the bacteria (Tables 19.2 and 19.3). The predominant fungus species are *Aspergillus sp*., *Penicillium sp*., and *Sclerotium sp*. With regard to bacteria, those of type cocos Gram-negatives represent the major occurrence of the total bacterial population, up 80% of the occurrences. The evidence also indicates that these bacteria are probably aerobe types due to their decreasing tendency in the number of former units of colonies (UFC) when the soil's depth increased. In these conditions, resulting the reduction on the oxygen concentration results.

The identification tests showed the presence of Gram-negative bacteria of the *Achromobacter*, *Flavobacterium*, *Nitrobacter*, *Nitrosomonas*, *Pseudomonas*, *Escherichia*, *Enterobacter,* and *Celovibrio* genera; and Gram-positive bacteria of the *Arthrobacter*, *Bacillus*, *Micrococcus*, *Streptomyce,s* and *Sarcina* genera (Fig. 19.1). Among these genera we can find cellulolytic, humic acid producers, lignin decomposers, starch decomposers, and nitrogen producers.

Identity tests reveal that the fungal population is very homogeneous, finding the same genus of the fungi in all sites, except some peculiar cases. The following fungal genuses were identified in these soils: *Mixotrichum*, *Rhizopus*, *Rhizomucor*,

Table 19.1 Microbial population in an archaeological dark earth (ADE)

Substrate	Bacteria	Funguses Moulds	Yeasts	Actinomycetes
	CFU/g of soil			
ADE Manaus (0–20 cm)	1×10^6 to 10×10^7	1×10^{4t} to 53×10^4		–
ADE Santarém. (0–20 cm)	32×10^4	38×10^4	80×10^4	2×10^3
ADE Caxiuana/Manduquinha (0–10 cm)	54×10^4 to 213×10^4	6×10^4 to 42×10^4	63×10^4 to 108×10^4	2×10^3 to 3×10^3
ADE Caxiuanã/Manduquinha (10–20 cm)	120×10^4 to 258×10^4	12×10^4 to 18×10^4	185×10^4 to 25×10^5	–

Table 19.2 Fungi population counts from ADE soils, Ilha de Terra Site (IT), Caxiuanã – Amazon Region – Brazil

Depths	(10^3 UFC*/g Soil)	Fungi Diversity
	IT1	
0–10 cm	26	*Aspergilus, Penicilium, Sclerotium, Sporothrix, Trichoderma, Eurotium, Epicocum*
10–20 cm	70	*Penicilium, Emmonsia, Sclerotium*
20–30 cm	21	*Aspergilus, Penicilium*
30–40 cm	6	*Aspergilus, Eurotium, Plectomicete*
	IT2	
0–10 cm	16	*Sclerotium*
10–20 cm	30	**Helminthosporium, Sclerotium, Paecilomices**
20–30 cm	12	*Penicilium, Sclerotium*
30–40 cm	20	*Plectomicetes, Eurotium*
	IT3	
0–10 cm	43	*Aspergilus, Penicilium*
10–20 cm	29	*Geotrichum, Penicilium*
20–30 cm	45	*Aspergilus, Plectomicetes*
30–40 cm	3	*Aspergilus, Penicilium, Sclerotium*
	IT4	
0–10 cm	107	*Aspergilus*
10–20 cm	23	*Aspergilus*
20–30 cm	4	*Aspergilus, Penicilium, Sclerotium*
30–40 cm	18	*Penicilium*

Table 19.3 Bacteria population counts from ADE soils, Ilha de Terra Site (IT), Caxiuanã – Amazon Region – Brazil

Depths	(10^5UFC/g Soil)	Bacteria Diversity
	IT1	
0–10 cm	7	Cocos (Gram-negative)
10–20 cm	5	Cocos (Gram-negative)
20–30 cm	21	Cocos (Gram-negative)
30–40 cm	8	Cocos (Gram-negative)
	IT2	
0–10 cm	15	Vibrio (Gram-negative), Bacilos (Gram-positive)
10–20 cm	10	Cocos (Gram-negative)
20–30 cm	13	Cocos (Gram-positive)
30–40 cm	1	Cocos (Gram-negative)
	IT3	
0–10 cm	50	Cocos (Gram-negative)
10–20 cm	4	Cocos (Gram-negative)
20–30 cm	3	Cocos (Gram-negative)
30–40 cm	2	Cocos (Gram-negative)
	IT3	
0–10 cm	12	Cocos (Gram-negative)
10–20 cm	17	Cocos (Gram-negative)
20–30 cm	0	....
30–40 cm	3	Cocos (Gram-negative.), Estreptobacilos (Gram-positive.)

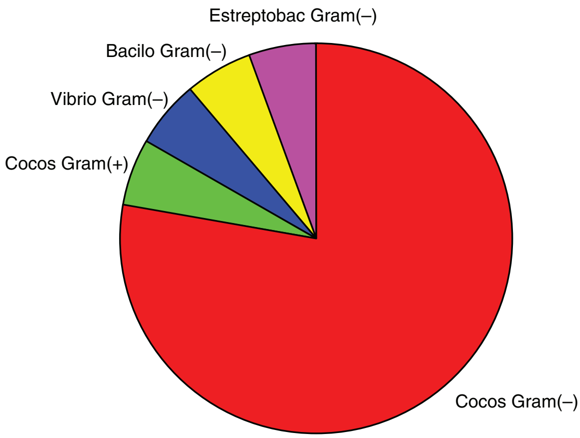

Fig. 19.1 Bacteria diversity in Amazonian Dark Earth (Ilha de Terra site)

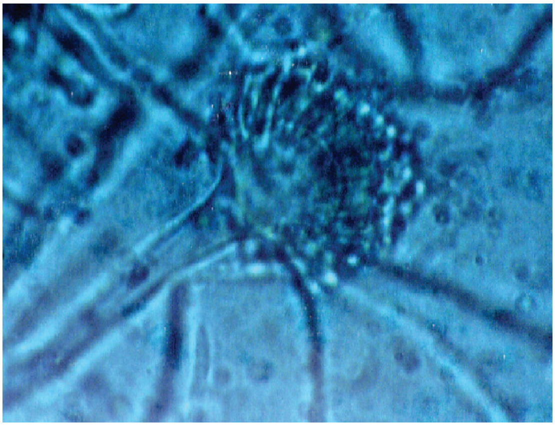

Fig. 19.2 Optical microscopy photo of morphologic structure of *Aspergillus* genus: conidia with vesicle (extreme apex inflated) and stipe (cylindrical section situated below vesicle)

Sporotrix, *Trichoderma*, *Cladosporium*, *Penicillium*, *Mucor*, *Aspergillus*, *Fusarium*, *Geotrichum*, *Paecilomices*, *Helminthosporium*, *Emmonsia*, *Epicocum*, *Chaetomium, Plectomicetes,* and *Ascomicetes*. The predominant fungi are: *Aspergillus* spp., *Penicillium* spp., and *Trichoderma* spp. (Figs. 19.2 and 19.3).

B. Population Microbial in the NDE Experiment

It was observed that in the first sampling, according to the Fig. 19.4, the amount of bacteria surpassed fungi's. In the 16th plot was verified the major difference. The average value of bacteria was 78 CFU/g of soil, whereas the fungi's average was 7.5 CFU/g of soil. This fact may be related to the fast growth and more efficient bacteria metabolism carried out in the beginning of the experiment.

It was observed in the second sampling (Fig. 19.5) that the bacteria quantity surpassed the fungal one in almost all the plots, however, in the 15th the difference was bigger. In that plot the bacteria average number was 75 CFU/g of soil and the

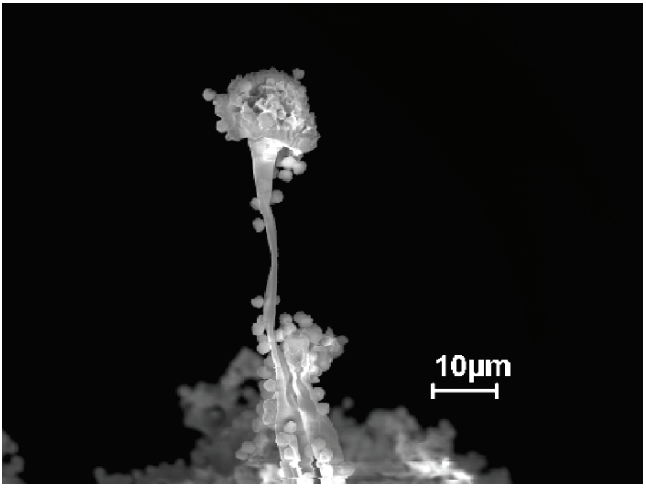

Fig. 19.3 Scanning electron micrograph of *Aspergillus* genus, allowing tridimensional visualization of the morphologic characters: stipe, vesicle and asexual spores

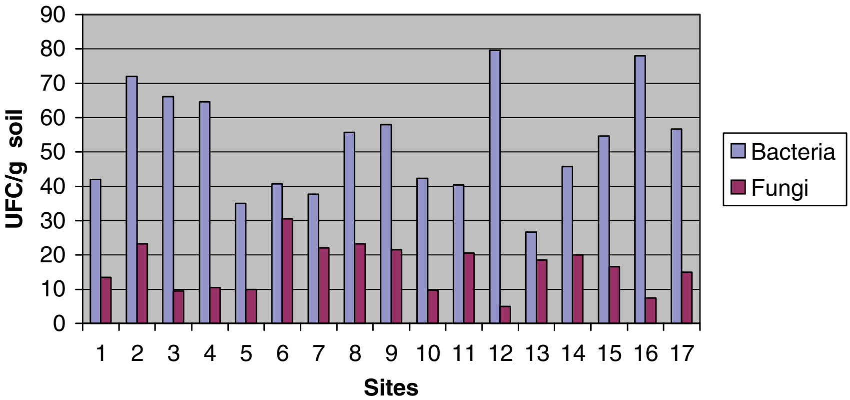

Fig. 19.4 Bacteria and fungi population in dry season (November, 2003)

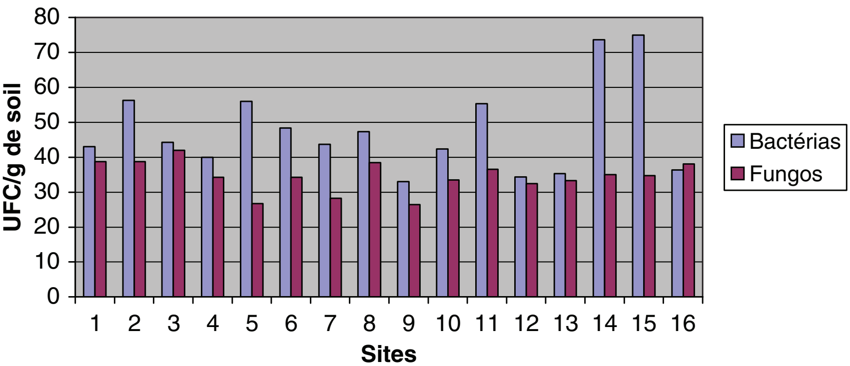

Fig. 19.5 Bacteria and fungi population in rainy season (March, 2004)

fungi average value 34.7 CFU/g of soil. We notice that the fungi's amount of CFU/g of soil in the third sampling (rainy season) was bigger, achieving numbers close to those obtained by bacteria CFU/g of soil, differently from what occurred in the previous sampling (dry season).

The amount of fungi in the third sampling was higher in almost all plots, compared to the second sampling (Fig. 19.6). In the 4th plot the difference was sharply bigger, presenting 35 CFU/g of soil in the third sampling and 20 CFU/g of soil in the second sampling, corresponding to rather half of the number showed in the third sampling. In the second sampling (dry season), the control plot corresponded to the smaller fungi amount presenting the number of 7.5 CFU/g of soil (Plot 16). In the third sampling in the same 16th plot though, the number attained was 38 CFU/g of soil, a considerably higher number than the counting noticed in the previous period. In nine plots the bacteria population showed a substantial increase in the third sampling compared to the numbers of the second.

In the fourth sampling (Fig. 19.7), the bacteria population results did not differ among themselves when compared to those obtained in the previous samplings, that is, 79.67 and 98 CFU/g of soil, [C + RPS + RLT + RA] and [C + RPS + RLT + RA + S] respectively, what was considered due to the bigger variety of additional materials in such treatments. In this sampling (4th) the fungi population was substantially higher in all treatments when compared to the fifth sampling, specifically in RLT and C + RPS + RLT, of 70 and 56 CFU/g of soil respectively, whereas in the fifth, during a period of lowest pluviometric rates, the numbers for the same treatments were 61.5 and 33.25 CFU/g of soil, respectively.

In the fifth sampling, in spite of having occurred in the period with the lowest pluviometric rates in the region, an increase in the bacteria population compared to previous studies was observed, stressing that the best results occurred in the plots containing grinded veneer waste (RLT). The preliminary results above fungi population in the TPN soils reveal higher diversity, that is, besides *Aspergillus spp.*, *Penicillium spp*. and *Trichoderma spp*. genus occurs too other *taxons* and need more investigation.

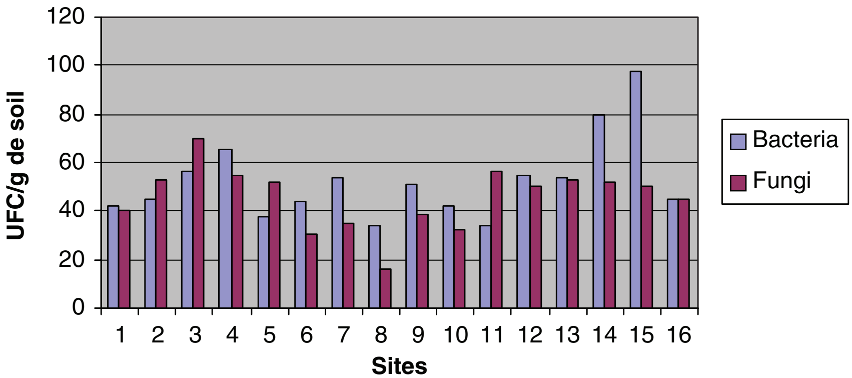

Fig. 19.6 Bacteria and fungi population in rainy season (March, 2005)

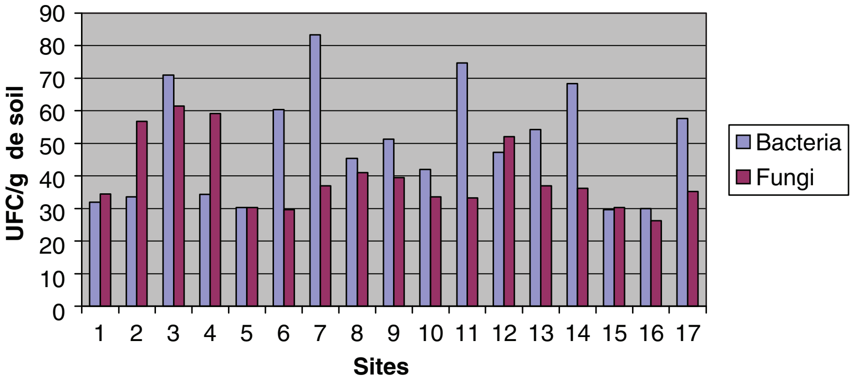

Fig. 19.7 Bacteria and fungi population in dry season (November, 2005)

19.5 Discussion

Studies of soil micromorphology, chemistry, and biology show that high fertility of anthropogenic soils results from a favorable combination of mineral and organic components, making these soils highly enriched in exchangeable forms. The organic-mineral stabilization of soil organic matter showed that is mainly stabilized by chemic-sorption to mineral surfaces, as well as physical stabilization by entrapment into interior of aggregates (Glaser et al. 2001; Lima 2001; Ruivo et al. 2004).

This chapter shows that the number and diversity microbial population is as diversified in the ADE soil as in the *Terra Preta Nova* (TPN) experiment. The preliminary results above show that the fungi population in the TPN soils reveal higher diversity, that is, besides *Aspergillus spp., Penicillium spp*. and *Trichoderma spp*. other *taxons occur* and need more investigation. The large variability probably results due the incorporating of different types and quantities of organic matter. Because of that, different species of microorganisms can be grown, since there is a large diversity of substrates. This fact can influence the plants growing to be more favorable to some species and prejudicial to others. The technology employed in each case depends of the types of microorganisms since distinct microorganisms degrade different types of compounds.

Fire, charcoal, and ash have an important effect on soil fertility and increase microbiological activity as they add colloidal-size organic components. This is verified in the ADE soils as well as in the TPN soils. The analysis of Amazonian anthropogenic soils indicate that the alterations by human actions, such as the incorporation of organic residues and the effects of fire in the superficial horizon influenced some of the chemical, physical, and biological characteristics (Woods and McCann 1999; Glaser 1999). We believe that more occurrence of the production of the organic substances and micelles distribution in the ABE soils contributed to the higher maintenance of biological activity and high nutrient retaining capacity.

In comparing the microbiota of the TPN with *terra preta*, there was a higher diversity, including more fungal and bacteria genus, occurrence of actinomycetes, more occurrences of the organic substances and micelles distribution. Experiments made in Aranjuéz (Madrid) also showed that soil treated with organic matter and microorganisms had intensive biological activity, contributing to quick humification of fresh organic matter. It was observed that treated soil samples had a significant increase in the production of polysaccharides and alkaline phosphatase and esterase enzymatic activities.

In the dry season sampling, in spite of it occurring in the period with the lowest pluviometric rates in the region, an increase in the bacterial population compared to previous studies was observed, stressing that the best results occurred in the plots containing grinded veneer waste (RLT). In this same sampling (5th) the bacteria population considerably surpassed the fungal in almost all plots. In the third sampling (rainy season) the fungi CFU/g of soil quantity was bigger, getting close to those CFU amounts of bacteria, but differently from what occurred in the previous sampling (dry season). In the fifth sampling, in spite of having occurred in the period with the lowest pluviometric rates in the region, was observed an increase in the bacteria population compared to previous studies, stressing that the best results occurred in the plots containing grinded veneer waste (RLT). For this reason we need to consider the microbial biomass of the ground that represents most of the active fraction of the organic substance and is important in the cycling of the nutrients, and should be a reservoir of nutrients supplying nutrients for the plants (Jenkinson and Ladd 1981). The carbon and the nitrogen used by the plants are derived from the decomposition of the organic substance, and this is entirely on the microbial biomass.

Soil microbiota are an ecological pointer in the cycle of nutrients, therefore, the microorganisms temporarily immobilize nutrients that could be availability its after death. The activity and the size of the microbial community determine the intensity that biochemical processes happen. The amount and quality of the organic residues in the productive systems provoke alterations in the composition of the microbial community, influencing in the decomposition rate.

In this form, the systems of handling of the soil directly influence the persistence of the residues in the ground, reflecting its physical, chemical and biological characteristics, the size of microbial biomass and, consequentially, in the sustainability of agro-ecosystems. Thus, the microbial biomass can be used to indicate the level of degradation of the ground, in function of the system of used management beyond organic carbon.

In ADEs most part of this genus possess lignin and cellulose decomposer species (Roitman 1991). This data is likely to contribute to the conclusion that the ADE soils are, presumably, more fertile than the average soils. Another aspect to point out is the differences found among bacteria counting from different ADE soil sites, which suggests that the sites' environmental heterogeneity play an important role in this result.

The counting techniques carried out in plates, as done in this study, attest the existence of only a minor portion of soil microorganisms, approximately 10%

(Prescott et al. 1999). Only this fraction proved to be able to grow "in vitro" under laboratory environmental conditions. For this reason, the counting does not reflect the total amount of microorganisms present in the analyzed ADE soils. Because of that it is more accurate to consider the obtained results only as an indicator of microbial density in those kinds of soils, which means that the total microorganism number could be 90% higher than the found amount portrayed in this experiment.

The addition or incorporation of organic residues in the soil constitute one of the most correctly process used to maintain the organic matter tenor in tropical soils with high taxes of lixiviation and, consequently, with larger damages of nutrients. For the enrichment of these soils and at the same time, to improve its physical chemical properties, the utilization of organic residue as cover have showed promising results trough traditional management practices of tropical soils.

19.6 Conclusion

This research indicates that ADE and TPN are soils with higher microbial populations and higher diversity than background soils. The predominance of *Aspergillus spp., Penicillium spp.,* and *Trichoderma spp*. genus in ADE soils indicate that their presence is a good reference parameter to evaluate the soil quality due their highly capacity to decompose the organic matter.

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Chapter 20
Spectroscopy Characterization of Humic Acids Isolated from Amazonian Dark Earth Soils *(Terra Preta De Índio)*

TJF Cunha, EH Novotny, BE Madari, L Martin-Neto, MO de O Rezende, LP Canelas, and V de M Benites

20.1 Introduction

Soils are one of the most important natural resources, and are essential for the development and continuation of any society that practices agriculture. Ancient civilizations in the Old World generally began in valley regions and floodplains along big rivers. As examples, one can cite Egypt in the Nile River valley, the Mesopotamia between the Tigris and Euphrates rivers, the Indian Subcontinent by the margins of the Indus and Ganges rivers, and China in the valleys of the Yellow and Blue rivers. In different areas of the world, many detailed comparisons have been accomplished between natural and human influenced soils, and the results of the latter have been documented (Cunha 2005)

In the last decades, agricultural activities have been modifying the original vegetation cover of a great part of the Brazilian territory. Ecosystems, such as the Amazon forest, are losing their original characteristics, being replaced by agricultural and extractive activities. The expansion of the agricultural borders has been causing great changes in forest areas in Brazil, with the introduction of rice, soybeans, and pastures, mainly in the southern part of the Amazon area. This has lead to degradation and a loss of biodiversity, a reduction in organic matter, and also the degradation of the pedologic covering, through the exhaustion and erosion.

However, in the Brazilian Amazonian area, there are soils with upper horizons of dark coloration that exhibit elevated levels of nutrients, called anthropic A horizons. These soils, even when used for agricultural purposes maintain their fertility characteristics and high contents of organic matter for many years. This epipedon has been found in several types of soils occurring in the Brazilian Amazon, such as Latossols, Argissols, Cambissols, Plintossols, and Nitossols, under forest or agricultural use such as the cultivation of corn, beans, and manioc, in addition to fruit cultivation, horticulture, and even the production of pasture on a wide scale.

The *terra preta* or Amazonian Dark Earths (ADE) are soils that can be distinguished from other soils by particular characteristics that are products of ancient anthropic activities. Most frequently, in the Amazon basin, their formation is attributed to ancient habitation agricultural activities (Woods and McCann 1999) by previous Amazonian civilizations.

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

Characteristic properties of these soils are the presence of artifacts (e.g. ceramics, lithics, etc.) at any amount, and/or Melich-1-extractable phosphorus (elemental P) in the fine earth fraction (at least 65 mg/kg^{-1}), charcoal in the fine earth fraction, fine earth organic carbon content (10 g kg^{-1} or more) as determined by the Walkley-Black method (Embrapa 1997), in the absence of any other evidence of ancient anthropic activity, the HA: FA ratio must be ≥2.0.

Both the organic C content and the HA:FA ratio should be higher from the soil surface down to the depth of 0.6 m or more in comparison to surrounding background soils. Indicators of anthropic origin can still be the presence of fragments of shells and other aquatic organisms, bone artifacts, or accumulation of organic compost or mud, or solid earth additions with or without cultural artifacts. Clear spatial association of soil with prior human activities can also be indicators of Archaeo-anthropogenic soils. These soils form a wide array of soil classes as indicated by the 4th level units of the proposed Archaeo-pedological Classification (Kämpf et al. 2003).

Today, these soils represent important islands of high soil fertility in the Amazon environment. The exact management practices responsible for the formation of ADE still remain unclear, but the relationships between its organic matter and their production potential have become evident (Cunha 2005).

Several studies were accomplished to understand the genesis of the soils with an antropic A horizon. However, very little was done in relation to the soil chemical characteristics, physical-chemical, and spectroscopic properties of its organic matter. The study of the humic acids (AH) of the anthropogenic soils, through its spectroscopic characteristic can contribute to the knowledge and the action of the organic matter of these soils, as well as the several aspects related to the structural characteristics, functionality, reactivity, effect of the agricultural use, and its productive potential. Thus, the objective of this work was to study the spectroscopic characteristics of the humic acid of soils with an anthropic A horizon, under agricultural use, compared to others in several areas of the Brazilian Amazon, for the best knowledge of the influence of the organic matter on its micro and macroscopic characteristics.

20.2 Material and Methods

20.2.1 Description and Morphologic Characterization

For this study 18 areas of occurrence of anthropogenic soils were selected in the areas of Humaitá, Lábrea, Apuí, New Aripuanã, Manicoré, and Manaus, in Amazonas State. In those soils, the anthropic A horizon was sampled (Horizon Au1), according to Lemos and Santos (1996). The samples were collected in the 0–20 cm layer, with several sub-samples collected that were mixed and prepared for future analyses. The study areas were selected in function of the different use systems found, embracing areas under forest and cultivated areas. Four soils were also selected adjacent to anthropogenic soils under forest. In the total 22 samples were analyzed and grouped in function of the current use and soil type, as followed: Anthropogenic Soil under Forest (ASF); Cultivated Anthropogenic Soil (CAS); and the control, Non-Anthropogenic Soil Under Forest (NASF).

20.2.1.1 Extraction, Chemical Fractionation and Purification of the Humic Material

The extraction and the division of the humic substances to obtain the humic acids, as well as their purification, were accomplished according to method suggested by the International Society of Humic Substances (IHSS), whose methodological protocol is described in Swift (1996). The humic acids extraction process involved air drying the soils, H + -exchanging (0.1 M HCl), and then extracting overnight with NaOH (0.1 M) under N_2. The supernatants were recovered by centrifugation and filtration, and the pH was immediately adjusted to 2 using 6 M HCl. The residues were re-extracted and the supernatants were mixed. The acidified suspension was centrifuged at 5,000 relative centrifugal forces (RCF) for 10 min and the sediment was re-dissolved in 0.1 M KOH in an atmosphere of N_2. Then this solution was made 0.3 M with respect to KCl and the flocculated colloidal particles were recovered by centrifugation at 40,000 RCF for 15 min. The supernatant was acidified to pH ~2 using 6 M HCl and the precipitated HAs were recovered by centrifugation. The HAs were treated twice with 0.5% HF + HCl for 24 h and centrifuged at 5,000 RCF. The treated samples were recovered by centrifugation (5,000 RCF), washed with 200 ml of 0.01 M HCl, centrifuged (5,000 RCF) again, and the precipitated material was dialysed and then freeze-dried.

20.2.1.2 UV-VIs Spectroscopy and E_4/E_6 Relationship

The spectra in the UV-VIs were obtained according to procedures described in Chen et al. (1977) in a 200 to 800 nm waive length, at25°C, with 1 cm optic way, in solution prepared with 20 mg of humic acid diluted in 1 L of $NaHCO_3$ 0.05 mol L^{-1}, with pH around 8.0. For the determination of the relationship coefficient E_4/E_6, the absorbency was divided in 465 nm by the obtained in 665 nm.

The Δlog K value was adopted in this study, aiming to analyze the optical properties of the humic acids, because it expresses the nature of the humic substances (Yonebayashi and Hattori 1988). The Log K is defined as the difference among the logarithms of the absorbance at 400 nm (log E_{400}) and at 600 nm (log E_{600}) (Kumada 1987).

20.2.1.3 Diffuse-Reflectance Infrared Fourier Transform (DRIFT) Spectroscopy

For the study of the DRIFT, the spectra were obtained in units of Kubelka-Munk, with a nominal resolution of 4 cm^{-1}, inside of the spectral strip between 4,000 and 400 cm^{-1}. The samples of humic acid were analyzed by a spectrophotometer adapted with an unit of diffuse reflectance, being used approximately 5 mg of AH and

250 mg of KBr, that were conditioned in a cell of 1.2 cm of diameter, being the spectra treated in a similar way to the spectra obtained by absorption spectroscopy.

20.2.1.4 Aromaticity, Hydrophobicity and Reactivity Index

The relationship among the absorbance of the absorption band in the 3.057–3.055 cm^{-1} and in 2.934–2.928 cm^{-1} region was called in this work of aromaticity index, once it expresses the relationship between the stretching of C-H of aromatic groups and asymmetric axial stretching of C-H aliphatic, respectively.

On the other hand, the relationship among the absorbancy of the absorption band in the 2.928 cm^{-1} and 1.050–1.080 cm^{-1} region, was called, in this work, of hydrophobicity index, once it expresses the relationship among apolar (CH_3) and polar (-OH, C-O) groups respectively. The reason among the absorption bands for 1.720–1.722/1.525, was called reactivity index, for expressing the relationship among stretchings C = O of COOH and ketones and the stretching of aromatic C = C.

20.2.1.5 Electron Paramagnetic Resonance (EPR)

The study of organic free radicals was accomplished by EPR, through the Bruker-EMX spectrometer with rectangular cavity, operating in band X (approximately 9.0 GHz) under room temperature conditions. The concentration of organic free radicals (spins g^{-1}) was obtained by the integration of the signal of the first derivate of the free radicals, compared to the pattern of strong pitch, supplied by Bruker, with concentration of well-known spins (3×10^{15} spins cm^{-1}), using the synthetic ruby as secondary pattern (Martin-Neto et al. 1994).

The amounts of free radicals were normalized by mass (or carbon content). The line width was estimated through pick by pick separation of the first derivate of the sign absorption (Senesi and Steelink 1989). The measurements of RPE were accomplished in a spherical resonant cavity, with magnetic field (Ho) of 340 mT, modulation frequency of 100 kHz, modulation amplitude of 0.05 mT and 0.2 mW microwave potency.

20.3 Results and Discussion

20.3.1 UV-Visible Spectroscopy Analysis

In all the spectra obtained in the UV-Vis region, a decrease on the absorption intensity with an increase of the wave length was observed. A discreet "shoulder" was observed around 270 nm (Fig. 20.1). This is possibly related to the fact of this material possesses chromophores that absorb in the whole analyzed region, as noted by

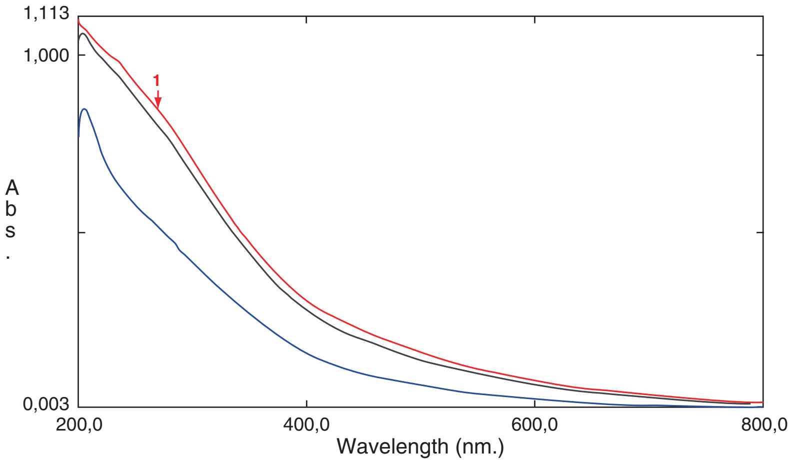

Fig. 20.1 Representative spectra of light absorption in the strip of the ultraviolet and of the visible light of the samples for groups of humic acids. In black, group ASF; in red, group CAS and in blue, group NASF

Stevenson and Schnitzer (1982). This "shoulder" can be attributed to the presence of aromatic structures. Analyzing samples of several origins, Ghosh and Schnitzer (1979) observed a "shoulder" in the region of 250 to 270 nm, and they attributed it to the structural conjugation of quinone and ketones, therefore indicative of aromatic systems (Canellas 1999).

The values of Δlog K differed significantly among the groups ASF and CAS and the group NASF, indicating that the humic acids of the groups ASF and CAS, that present low values for Δlog K (Fig. 20.1) in relation to the humic acid of the NASF group, possesses high humification degree, and are in agreement with results obtained by Ishiwatari (1985) and Yonebayashi and Hattori (1988).

Using the absorption characteristics in the UV-Vis region, the humic acids can be classified in 4 different types: A, B, Rp, and P (Kumada 1987). Humic acids of the A type do not present characteristic absorption bands and the values for Δlog K are smaller than 0.6. Humic acid of the B type presents a weak "shoulder" of absorption at 275 nm and the value of Δlog K among 0.6 to 0.8. Humic acids of the Rp type present the same spectrum of the B type, but with elevated values of Δlog K (between 0.8 and 1.1). The humic acids that present characteristic absorptions in the 615, 570, and 450 nm visible regions are considered as the P type. Analyzing the Δlog K data (Table 20.1), the humic acid of the groups ASF and CAS can be classified as the A type and the humic acid of the group NASF as being of the B type, suggesting that the humic acids of the groups ASF and CAS possess a larger evolution, that is reflected in its smallest relation E_4/E_6.

The weak radiation absorption in the region of the visible for humic substances is of uncertain cause (Bloom and Leenheer 1989), but it is useful for allowing the obtaining of the reason E_4/E_6, used as humification parameter. The relationship E_4/E_6 is related to the aromaticity and to the degree ofcondensation of the chain of

Table 20.1 Differences in the optical properties among the groups of humic acids

Groups	n°	Δlog K	E_4/E_6
ASF	6	0.5 b	4.2 b
CAS	12	0.5 b	4.2 b
NASF	4	0.7 a	6.0 a

Different letters in the same column differ significantly at 5%

aromatic carbons of the humic acids, and could be used as a humification index (Kononova 1966; Stevenson and Schnitzer 1982). The values obtained in the relationship E_4/E_6 (Fig. 19.1) were located around 4.0 for the humic acids of the groups ASF and CAS and around 6.0 for the humic acids of the group NASF. Kononova (1982) suggests values of the relationship E_4/E_6 for humic acid smaller than 5.0 and between 6.0 and 8.0 for fulvic acids. The humic acids of the group NASF, is inside the strip indicated for fulvic acids, suggesting these humic acids are less chemically evolved in relation to the CAS and ASF groups.

The cultivation did not alter the values of the relation E_4/E_6 among the humic acid of the groups ASF and CAS. In that way, based on Kononova (1966) and Stevenson and Schnitzer (1982), this behavior is indicative that the same did not affect the levels of condensation of the aromatic rings of these humic acids.

20.3.2 DRIFT Spectroscopy Analysis

The absorption spectra in the infrared region presented characteristic absorptions, but with relative variable intensities. In the region below 1,800 cm^{-1}, some important differences were observed. The similar characteristics (typical bands of humic acids), but with different relative intensities, are related to an intense and large absorption band centered among 3,470 and 3,300 cm^{-1} attributed to the stretching of O-H (contribution of OH aliphtic and amina); a pick of medium intensity, centered between 3,061 and 3,055 cm^{-1}, attributed to the stretching of aromatic C-H; a band of intense absorption among 2,934–2,928 cm^{-1} and a weaker absorption band between 2,857 and 2,853 cm^{-1}, attributed to asymmetric and symmetrical stretching of C-H aliphatic, respectively; an absorption band between 1,246 and 1,250 cm^{-1}, attributed to the bending of O-H and stretching of C-O of the carboxilic group and a weak absorption band in the region from 1,080 to 1,049 cm^{-1}, attributed to the stretching of C-O of polysaccharides and silicates sludges.

The different characteristics observed in the area below 1,800 cm^{-1} of the spectra of DRIFT were concentrated in the 1,720 to 1,709 cm^{-1} region, attributed to the stretching of C = O of carboxilic acids, aldehydes and ketones, whose relative intensities are strong for the humic acids of the group CAS, averages for the humic acids of the group ASF and weak (when existent) for the humic acids of the group NASF. In fact, the relation among the 1,720–1.722/1.525 absorption bands (denominated in this work of reactivity index) was of 1.15 and 1.17 for the humic acids of the groups SAF and CAS, respectively. The values above 1.0 indicate a larger relative concentration of stretchings C = O of the carboxilic groups compared to the stretching aromatic C = C. The calculation for the group NASF was not possible due to the absence or little definition of those bands.

An absorption band between 1,661 and 1,628 cm^{-1}, observed only for the humic acids of the group NASF, attributed to the stretching C = O of groups amide (band I of the amide), and also C = O of quinones and H tied to conjugated ketones; a fourth peak between 1,614 and 1,612 cm^{-1}, generally attributed to the stretching of aromatic C = C and symmetrical stretching of the anion COO^{-}, that are only present in the humic acids of the groups ASF and CAS; an absorption in 1,553 cm^{-1}, attributed to the N-H deformation of the amide (band II of the amide) and stretching of C = N just observed in the spectra of the humic acids of the NASF group; a band in the region from 1,354 to 1,327 cm^{-1}, attributed to the symmetric deformation of CH_3, just observed in the spectra of the NASF group; absorption in the region from 762 to 669 cm^{-1}, attributed to the angular deformation out of the plan of connections C-H of aromatic rings, observed in the spectra of the ASF and CAS groups.

In general, the data obtained through the DRIFT spectroscopy, suggest a mixture of aromatic/aliphatic characteristics, a great amount of carboxylic groups and a smaller number of N- containing groups for the humic acids of the ASF and CAS groups. The humic acids of the group NASF was characterized for presenting a larger content of of N- containing components, for example, polypeptide chains (Senesi et al. 2003), and a smaller content of carboxilic and fenolic groups, demonstrating that qualitatively the humic acids of the NASF group are less reactive than the ones of the ASF and CAS groups and that N is a important part of the structures of the humic acids of the NASF group. Among the ASF and CAS groups, the reactivity index was relatively larger for the CAS group (1.17), meaning the humic acids of this group are the more reactives.

20.3.3 Aromaticity (IA) and Hydrophobicity Index (IH)

In Table 20.2 it can be observed the medium values for the aromaticity and hydrophobicity index in the different groups of humic acid. The observed aromaticity index was larger in the anthropogenic soils. The humic acid from the soils under forest (ASF and NASF groups) came out more hydrophilic than the humic acid from cultivated soils (CAS).

Table 20.2 Aromaticity (IA) and hydrophobicity index (IH) obtained of the infra-red spectra

Groups	IA	IH
ASF	0.87 a	0.37 b
CAS	0.85 a	0.48 a
NASF	0.77 b	0.35 b

Different letters in the same column differ significantly at 5%

20.3.4 EPR Spectroscopic Analysis

The spectra were characterized by a unique line of fine and symmetrical absorption without any hyperfine interaction, with the value-g centered around 2.0033 (Fig. 20.2). Among the humic acid extracted from anthropogenic soils, the ones from the CAS group presented the smallest line width, together with the concentration values of organic free radicals (CRLO) indicate that these were more humified (Table 20.3).

The line width value is related with the time that the excited electron spends to return to the environment the absorbed energy (relaxation time) and also with the interaction of the organic free radical with the environment. The more condensed the molecules, the smaller the line width (Senesi and Steelink 1989). The largest value for line width was observed for the humic acids of the NASF group indicating smaller condensation and aromaticity of the humic acid belonging to this group.

The concentration of organic free radicals, in the humic acids of the CAS group, was three times higher than the concentration obtained for the humic acids of the NASF group. Significant differences were also observed in the concentration of organic free radicals of the ASF and CAS groups, suggesting the humic acids of the ASF group are less aromatic than the humic acids of the CAS group. The humic acids of the NASF group would be the less aromatics of all the humic acids studied.

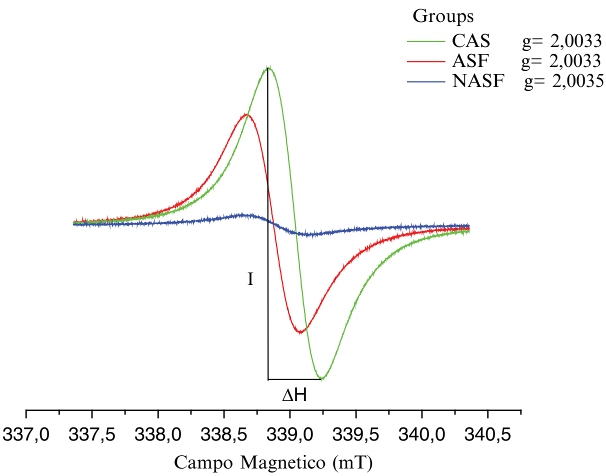

Fig. 20.2 Typical spectra of EPR of samples of humic acids belonging to the studied groups (I = intensity of the sign; ΔH = width of the line). Experimental Conditions: Ho = 3,400 G, ΔH = 100 G = 9.44 ghz, temperature sets, modulation Width = 0.5 G

Table 20.3 Data of EPR for groups of humic acids

	CRLO	Line width	
Groups	Spin $g^{-1} \times 10^{17}$	Gauss	Value-g
ASF	4.07 b	4.27 a	2.0033 a
CAS	6.59 a	3.73 b	2.0033 a
NASF	2.11 c	4.32 a	2.0034 a

Different letters in the same column differ significantly at 5%.

20.4 Conclusions

The HA of the anthropogenic soils are different from the HA of the non-anthropogenic soils. The main differences among the ASF and CAS groups, in relation to the NASF group were in the humification degree of HA. The HA belonging to the ASF and CAS groups were in a more advanced stage of humification than those of the NASF group. The largest humification degree of HA of the anthropogenic soils were due to the larger concentration of aromatic structures and of organic free radicals. Some results suggest that this fact is related to the pyrogenic origin of these HA.

The HA of the anthropogenic soils under forest and under cultivation are different. The main differences among HA of the ASF and CAS groups were related to the hydrophobicity. The HA of the CAS group were more hydrophobics.

Also, differences were detected in the stability characteristics of HA of the ASF and CAS groups. The HA of the CAS group had a larger concentration of more aromatic structures which could be due to the selective preservation of these structures in comparison to the HA of the ASF group.

In the anthropogenic soils that are rich in the humified organic matter, recalcitrant and, at the same time, of high reactivity, there is a favorable environment for ionic exchange, reactions with inorganic colloids of the soil, with organic molecules and of complexation with metallic cations, among others. Due to the fact of the anthropogenic soils possessing more humified and stable organic matter than the organic matter of non-anthropogenic soils, these soils probably processes that favor the carbon accumulation and the formation of stable structures.

The high fertility, sustainability, and consequently, the high agricultural potential use of the anthropogenic soils, at least partly can be attributed to the physical-chemical characteristics of the HA fraction of the organic matter of the soils with anthropic A horizon.

The spectroscopic technics of UV-Vis, DRIFT and RPE used in this study were complementary in the obtaining of information on the physical-chemical characteristics of HA, demonstrating the great potential of those tools in the studies of humics substances coming of soils of anthropogenic origin.

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Chapter 21
Solid-State ^{13}C Nuclear Magnetic Resonance Characterisation of Humic Acids Extracted from Amazonian Dark Earths (*Terra Preta De Índio*)

EH Novotny, TJ Bonagamba, ER de Azevedo, and MHB Hayes

21.1 Introduction

The environmental organic matter is the link between the biosphere, geosphere, hydrosphere and atmosphere and is fundamental for ecosystem sustainability. Estimates of the total mass of organic carbon in soils are in the range of 1.22×10^{18} g (Sombroek et al. 1993) to 2.456×10^{18} g (Batjes 1996). This reservoir is at least three times greater than all organic materials above the earth's surface, and the way the soil sequestered carbon is managed can have significant influences the levels of atmospheric CO_2. Estimates of the amounts of fossil organic carbon (gas, oil, coal etc.) are considerably greater, of the order of 4×10^{18} g (Falkowski et al. 2000; Janzen 2004). An increase of carbon improves the fertility of soil, especially in tropical conditions, and thus increases the vegetal biomass that this soil can support.

The soil carbon stock represents a continuous process of deposition (5.67×10^{16} g C year^{-1}), in the form of vegetal and animal residues, and decomposition (with emissions of 5.50×10^{16} g C year^{-1}). The deposition and decomposition fluxes are not equal because of the inputs of fossil fuel carbon (5×10^{15} g C year^{-1}). However, fossil fuel carbon emissions are one order of magnitude less than that due to the decomposition of natural soil organic matter (United States 1999).

It is evident, based on considerations of the magnitudes of the different stocks and fluxes, that soil organic matter has great importance in the global carbon cycle, and in the planning of strategies that seek anthropic emissions mitigations (Schnitzer 1991; Borin et al. 1997; Reicosky et al. 1997; Piccolo and Mbagwu 1994; Piccolo 1999; Swift 2001).

The quantity and the quality of the organic matter have an important influence on the chemical, physical and biological properties of soils. Among the most important properties influenced are the improvement of soil aggregate stability, a decrease of soil plasticity, an increase in soil water retention and in cation exchange capacity (CEC) and an essential participation in the microbial respiration (Schnitzer and Khan 1978; Stevenson 1994; Lovley et al. 1996; Preston 1996; Clapp et al. 2005). Additionally, soil organic matter is the principal sorption site of pesticides and trace metals in the soils, and is a reservoir for some micronutrients, and an

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

immobiliser as the toxic elements (Kabata-Pendias and Pendias 1985; Wang et al. 1990; Senesi et al. 1996). These effects are particularly important in tropical soils because such soils are naturally acidic and their mineral fraction is composed mainly of low activity clays (Benites et al. 2005).

Some very fertile anthropogenic soils are found in the Amazon basin and this fertility has been maintained through the centuries in spite of the unfavourable environmental conditions and intensive cultivation. This special characteristic, allied to an exceptionally high level of sequestered organic carbon, is attributed to a high level in the soils of pyrogenic carbon of anthropic origin. It is now being recognized that the production systems of former, native cultures may provide knowledge that could serve as a basis for the development of modern sustainable management systems in agriculture. The *terra preta de índio* of the Amazon basin is a remarkable example of sustainable ancient agricultural management systems in tropical ecosystems. Thus, by investigating the compositions of the components responsible for the sustainable fertility of *terra preta de índio* soils, it may be possible to reconstruct the conditions that gave rise to the phenomenon (Madari et al. 2004) and to gain an understanding of technologies that could generate improved fertility in other soil systems. Also, the knowledge gained from such investigations could have applications for considerations of carbon sequestration which is highly relevant at this time. Nuclear Magnetic Resonance is a powerful tool for such studies and, when carefully used and the data appropriately interpreted, it can provide valuable and unique information that is inaccessible by other experimental techniques.

21.2 *Terra Preta De Índio* (ADE)

Due to intense weathering, most tropical soils have mainly low activity clay (e.g. kaolinite) and oxides and hydroxide minerals (such as goethite and gibbsite). Because of their compositions, and as the result of leaching, these soils are frequently acid, have low CEC, low fertility, and a low production potential. As a result, the contribution of soil organic matter to the fertility is highly important. This is the dominant situation in the Amazon basis, where the dominant soil types are the Ferralsols, Acrisols, and Sesquisols that cover 70% of the region (Rodrigues 1996).

In such an environment, where soil fertility is a limiting factor for sustainable agricultural development, isolated patches of very fertile soils occur. Most of these patches do not exceed 2 ha, but larger sites, with areas up to 350 ha, have also been reported (Kern et al. 2003). According to geographer Willian I. Woods, soils modified by humans correspond at 10% of the Amazon tropical forest, an area equivalent to France (Mann 2002). The soils are characterised by darker colour (dark brown or black), higher P contents (200–400 mg kg^{-1}), higher CEC, pH, and base saturation values, and with higher stable organic matter contents than the surrounding soils (Sombroek 1966; Smith 1980; Kern and Kämpf 1989; Sombroek et al. 1993; Glaser et al. 2000, 2001; Lehmann et al. 2003).

The presence of an archeo-anthropedogenic horizon is another characteristic feature of these soils. This is a surface horizon of varying depth in the soil profile that features elevated organic matter contents and ceramic pieces or lithic artefacts (Kämpf et al. 2003) (WRB Anthrosols (FAO 1990).

It is now generally accepted that these soils are of pre-Columbian origin (Woods and McCann 2001), although there are several hypotheses with regard to the processes of their formation. It is not clear whether the soils resulted from soil improvement processes that were intentional, or arose from the agricultural and household activities of the settled indigenous populations that practiced agriculture as an important livelihood occupation, especially along the river banks (Smith 1980). Dwelling places in the pre-Columbian past gave rise to accumulations of plant and animal debris, and to large amounts of ashes and bonfire residues (charcoal) and chemical elements, such as: P, Mg, Zn, Cu, Ca, Sr, and Ba, that represent a geochemical signature of human occupation (Costa and Kern 1999). These accumulations are likely to be major contributors to the formation of these fertile soils.

Because of these characteristics the soils are called *terra preta de índio*, but are also known as Amazonian Dark Earths, Anthropogenic Dark Earths (ADE), Indian Black Earths, or Archaeological Dark Earths.

21.3 Pyrogenic Carbon in ADE

The most important agronomic characteristic of ADE soils is their high fertility, and the sustainability of this fertility. These characteristics are attributed to the high levels of organic matter and to its physical-chemical properties. *Terra preta de índio* soils have carbon contents up to 150 g C kg^{-1} soil compared to 20–30 g C kg^{-1} in the surrounding soils (Sombroek 1966; Smith 1980; Kern and Kämpf 1989; Sombroek et al. 1993; Woods and McCann 1999; Glaser et al. 2000). Additionally, the organic matter is about six times more stable than that in the adjacent soils (Pabst 1992; Glaser et al. 2001) and horizons that are enriched in organic matter may be as deep as 1–2 m (with average values ca. 40–50 cm) compared to depths of 10–20 cm for the surrounding soils. Therefore, the total carbon stored in these soils can be one order of magnitude higher than in adjacent soils.

The contribution of pyrogenic carbon (black carbon) in the soil organic matter of *terra Preta* soils is up to three times its contribution in organic matter from surrounding soils lacking an archeo-anthropedogenic horizon (Glaser et al. 1998, 2000). Pyrogenic carbon is derived from the partial carbonisation of ligno-cellulosic and others organic materials and is composed of polyaromatic units of different sizes and organisational levels (Kramer et al. 2004). It is highly resistant to thermal oxidation, and to chemical and photo-oxidation (Wolbach and Anders 1989; Skjemstad et al. 1996). Pyrogenic carbon has a high resistance to degradation in the soil, although it does undergo some natural degradation (Bird et al. 1999). Thus its incorporation in the soil is an important mechanism of carbon sequestration (Schmidt and Noack 2000; Glaser et al. 2001; Swift 2001; Masiello 2004; Lehmann 2007).

The genesis of the organic matter of high stability in ADE soils has been attributed to chemical and biochemical transformations of carbonised residues deposited by the Indians in pre-Columbian ages. Because of partial oxidation, peripheral aromatic units contain acidic (carboxyl) substituents (Kramer et al. 2004; Glaser et al. 2002) that give rise to high CEC values. This is very similar to the organic C in Mollisols of the mid-west USA thought to be formed by the burning of vegetation over prolonged periods (Clapp et al. 2005). The humic components derived from pyrogenic carbon also have high aromaticity and charge density and are characterised by heavily carboxylated, hydrogen-deficient, condensed aromatic structures (Kramer et al. 2004; Novotny et al. 2007).

Terra preta (TP) pyrogenic carbon provides big enhancements of stable soil organic carbon, and the high fertility levels that are characteristic of these soils. Besides this, the TP soils present more favourable physical properties (structure, water retention, etc.) and higher biological activity than the adjacent soils that are less enriched in organic matter and in pyrogenic carbon.

Pyrogenic-carbon derived substances are important compositional and functional components in tropical soils where there are historical records of vegetation burning, such as Brazilian Savanna soils (Roscoe et al. 2001), and in areas of rocky complexes at high altitude (Benites et al. 2005). The organic components in these soils have the common characteristics of high resistance to thermal degradation, and the charge characteristics to which the high soil CEC values are attributed. Because of its high stability and reactivity, pyrogenic carbon is of great importance for the conditioning of tropical soils subjected to climatic conditions that favour organic matter mineralisation, and where the clay fraction has low CEC values.

Pyrogenic carbon is not, of course, restricted to tropical soils. In general, pyrogenic carbon is thought to represent between 1% and 6% of the total soil organic carbon (González-Pérez et al. 2004a), and in general estimates are less than 10% of the soil organic matter (Druffel 2004). It can reach 18% in native prairie in the U.S. (Glaser and Amelung 2003), 35% in some U.S. agricultural soils (Skjemstad et al. 2002), up to 30% in Australian soils (Skjemstad et al. 1999), up to 45% in German Chernozems (Schmidt et al. 1999), up to 65% in Canadian Chernozems (Ponomarenko and Anderson 2001), and in some contaminated soils, anthropic pyrogenic carbon can be up to 80% of the total organic carbon (Schmidt et al. 1996). However, these values can be overestimates because of problems in obtaining accurate data (Derenne and Largeau 2001; Masiello 2004; Simpson and Hatcher 2004a, b).

21.4 Pyrogenic Carbon Measurement

Pyrogenic carbon is a continuum of combustion products, ranging from slightly charred biomass with significant amounts of recognisable plant tissues to highly transformed refractory soot dominated by highly condensed aromatic structures (Masiello 2004). According to Masiello, the techniques for measuring pyrogenic carbon fall into six general classes: microscopic, optical, thermal, chemical, spectroscopic, and molecular markers. Each of these methods has a pyrogenic continuum for which it is most accurate. However, despite the urgent need of a method to improve the accounting of global total carbon, and of its fluxes and cycles, we sill await a standardized, thoroughly tested, and established method of measuring pyrogenic carbon (Simpson and Hatcher 2004a).

Nuclear magnetic resonance could, in principle, detect the entire range of the combustion continuum (Masiello 2004). However, the signal overlap from other constituents found in organic matter, especially those arising from lignin, is one of the major challenges associated with applying nuclear magnetic resonance to the determination of pyrogenic carbon (Simpson and Hatcher 2004b). Several methods have been suggested to overcome this problem. Some of the methods are destructive, such as: oxidation of non pyrogenic carbon by chemical-oxidation (Simpson and Hatcher 2004b), thermal-oxidation (Gustafsson et al. 2001), and photo-oxidation (Skjemstad et al. 2002). Other methods are non-destructive, e.g. spectral editing based on different relaxation properties of the organic matter components (Smernik 2007), and mathematical treatment of data by multivariate methods, such as principal component analysis (Novotny et al. 2007).

21.5 Nuclear Magnetic Resonance

Nowadays, Nuclear Magnetic Resonance (NMR) provides fundamental contributions in several scientific areas (physics, chemistry, biology, medicine, agriculture, etc.). There is a large number of complex multiple pulse sequences that can involve the excitation of several nuclei at the same time, including the interactions between these through dipolar interactions, selective suppression and manipulation of spin interactions (e.g. homo- or hetero-nuclear decoupling, magic angle spinning, spin echo techniques, multiple quantum methods, etc.), and signal acquisitions in a multidimensional way. This allows information to be obtained about dynamical, structural and morphological properties of many classes of materials within several times (from ns to s) and length (from Å to mm) scales, in solid, liquid, or gaseous samples. There are now several spectrometers in the market which permit the use of NMR, not only in Soil Science, but also in: materials science, petroleum science, analytical chemistry, medicine, microscopy, and quantum information processing, which make NMR a powerful method for both fundamental and applied research.

Barton and Schnitzer (1963) and Neyroud and Schnitzer (1972) first suggested employing NMR experiments for the studies of humic substances. González-Vila et al. (1976) employed ^{13}C NMR for the structural characterisation of soil extracted humic substances and Wilson et al. (1981) reported ^{13}C CP MAS high-resolution solid-state NMR experiments of whole soils and since then solid state NMR is being employed for studying structural aspects of environmental organic matter (Newman et al. 1980; Newman and Tate 1984; Wilson 1987, 1990; Malcolm 1989; Preston 1996; Olk et al. 1995; Hu et al. 2000; Kingery et al. 2000; Mao et al. 2003; Mao and Schmidt-Rohr 2003; González-Pérez et al. 2004b; Novotny et al. 2006a, b; Simpson et al. 2007).

NMR is now one of the most important methods used in soil science. However, soil and NMR scientists have different expectations about the information that this experimental method can provide. Due to the structural complexities of environmental organic matter, soil scientists have especial interests in the semi-quantitative information that NMR can provide about the relative amounts of aromatic, aliphatic and carboxylic groups, but few NMR scientists tend now to be attracted by such information and are showing less interest in the study of these important materials. A better link needs to be established between soil and NMR scientists in order to obtain more meaningful information about the compositions and structures in soil organic matter. This connection is essential not only for improving the NMR data and its interpretation, but also for establishing a standardisation of some of the experimental parameters because much of the published procedures and data are controversial (Dudley and Fyfe 1982; Preston and Blackwell 1985; Fründ and Lüdemann 1989; Kinchesh et al. 1995; Conte et al. 1997; Hemminga and Buurman 1997; Smernik and Oades 2000).

In this chapter we summarize part of our efforts to obtain better NMR data and provide more consistent interpretation of these data for the characterisation of soil organic matter.

21.5.1 Interpretation of ^{13}C NMR Spectra of Humic Substances

^{13}C NMR spectroscopy can offer good information about structures and can be used in the characterisation of the soil organic matter and to follow its decomposition because several of its components present distinct mineralisation rates, and some of the products synthesised by the microorganisms can be easily detected.

Characterisation of humic substances in terms of aromaticity, defined as the proportion of aromatic functionalities (110–145 or 110–160 ppm) relative to the total area under the spectra, less the carboxyl and carbonyl groups (Hatcher et al. 1981), and correlating this value with the usual indexes of humification (Inbar et al. 1989; Barančíková et al. 1997), cannot be considered to be adequate since unhumified materials, such as lignin and tannins, will contain aromatic groups. Additionally, during the transformation processes the ratio of the areas between the oxygenated and non-oxygenated aromatic groups decreases (Guggenberger et al. 1994), and recalcitrant or microbial synthesized groups that accumulate during the organic matter transformations, such as alkyl, contribute to the aliphatic region of the ^{13}C NMR spectra. In this way it is possible that material that has been only slightly transformed but with high aromaticity (e.g. rich in lignin and tannins) or a highly humified material with a low aromaticity (rich in recalcitrant and/or new-synthesised alkyl groups) can lead to misinterpretations.

It is necessary therefore to be aware of the extents and the nature of the transformations of soil organic matter during the humification in the system under study before the interpreting the analytical results and making inferences about lability and recalcitrancy. Knowing which portions of the soil organic matter are more labile and which are more resistant and accumulate during humification, and being aware of the compositions of the original materials (ligno-cellulosic, cellulosic, waxes, resins etc.), makes interpretations of the ratios between these different regions of the ^{13}C NMR spectra results more comprehensive. In this text humification is considered to involve the degradation of labile and the accumulation of chemically recalcitrant materials Therefore, unaltered materials preserved in the soil by physical protection are not considered to be humified. A short bibliographic presentation follows dealing with applications of NMR spectroscopy to follow the alterations that occur in the soil organic matter during the humification process in natural oxic conditions.

During the oxidative degradation of the lignin, a decrease of signal intensities attributable to oxygenated aromatic (160–145 ppm) and methoxyl (62–50 ppm) groups is observed (Guggenberger et al. 1994). The degradation of lignin aromatic rings is accompanied by a decrease of oxygenated aromatic groups (aryl-O; 160–145 ppm) and of the signals attributed to aromatic groups (120–112 ppm), and the concomitant conversion of the several aromatic peaks and shoulders from the aromatic lignin structure to a single broad band at 132 ppm, attributed to substituted aryl C groups (Preston 1996). Kögel-Knabner et al. (1991) observed a decrease in the signal intensity of aryl-O groups with a concomitant retention or increase of aromatic signals, but did not suggest possible reaction pathways for this. However she suggested the importance of catalytic activity from minerals for these conversions, and Guggenberger et al. (1994) suggested that the increase of recalcitrant aromatic structures during the humification could have origins different from lignin.

A decrease in the intensities of resonances in ^{13}C NMR spectra in the oxygen- and nitrogen- containing aliphatic groups (110–50 ppm) during the humification is evident (Kögel-Knabner et al. 1991; Guggenberger et al. 1994; Preston 1996) since the signals in this region arise from compounds that are easily degradable by microorganisms, such as proteins and peptides (~53 ppm), methoxyl from lignin (~58 ppm) (Catroux and Schnitzer 1987) and carbohydrates from cellulose and hemicellulose (~64, 74, 85 and 105 ppm) (Guggenberger et al. 1994).

Microbiological degradation of soil organic matter leads to the accumulation of paraffinic structures (alkyl: 0–50 ppm), and substances from plants (waxes, resins, suberin, cutin, etc.) that have resistance to degradation (Baldock et al. 1992; Preston 1996), or from microbiological neo-synthesis (Baldock et al. 1990).

A loss of resolution due to increased structural complexity, and a broadening of the resonance peaks in the ^{13}C NMR spectra due to paramagnetic contaminations (iron, copper, manganese etc.), and increases in organic free radicals is observed as the result of humification (Preston et al. 1994). The peak, attributed to long chain alkyl C (30 ppm), from plants and microorganisms, decreases but broadens. The modifications of aromatic rings, mainly from lignin, are characterised by the decrease of O-aryl and specific aryl from lignin signals (120–112 ppm), with the result that all resonances attributed to aromatic groups become a single broad band at ~132 ppm (Preston 1996).

In general, the ^{13}C NMR spectra show that labile oxygen and nitrogen functionalities resonating in the aliphatic region (110–50 ppm) from carbohydrates (cellulose and hemicellulose; O-alkyl and di-O-alkyl: 112–62 ppm), proteinaceous materials and methoxyl and/or N-alkyl (62–50 ppm) make important contributions to the compositions of soil organic matter. In the aromatic region, the signals at 160–145 ppm (O-aryl) and 124–112 ppm (aryl) can be considered to be from lesser humified materials because both have important contribution from lignin, tannins, coumarins etc. On the other hand, the signals attributed to alkyl C (50–0 ppm) that are preserved or neo-synthesised, and the broad signal at 145–124 ppm, attributed to altered aromatic compounds, can be considered to be recalcitrant or humified materials.

The signal of pyrogenic carbon is characterised by a broad featureless aryl signal at 130 ppm, with a continuous broadening and diamagnetic shift (decreases of chemical shift values) attributable to increases in graphitisation due, for example, to the increase of carbonisation temperature (Freitas et al. 2001). Additionally, the conjugation of the aromatic rings through the carbonisation can be detected and quantified by the dipolar dephasing technique, where the signals of rigid protonated carbons are suppressed.

21.5.2 Adaptation of NMR Methodology to the Study of Samples Rich in Pyrogenic Carbon

The most generally used excitation methods for quantitative measurements of the organic matter composition are Direct Polarisation (DP) and Variable Amplitude Cross Polarisation (VACP), both carried out under high (>12 kHz) Magic Angle Spinning (MAS) frequencies (Cook 2004). Although DP is the most quantitative ^{13}C NMR technique (Cook 2004; Mao and Schmidt-Rohr 2004), cross polarisation, in spite of its limitations in quantitative analyses due to variations in the cross polarisation efficiencies among the different kinds of carbons (Preston 1996), is used routinely because it requires less instrument time (Cook 2004; Simpson and Hatcher 2004b; Knicker et al. 2005a). Several methodologies were proposed to minimise the problems encountered (Smernik et al. 2002a, 2002b; Smernik and Oades 2003).

Among the different Cross-Polarisation (CP) semi-quantitative methods used (Single-Amplitude with MAS – CP/MAS; CP with Total Suppression of Spinning Sidebands – CP/TOSS, and VACP with high MAS frequency – VACP/MAS), the VACP/MAS is preferred (Cook 2004). This is so because the radiofrequency ramp used during the Hartmann-Hahn contact provides a more uniform magnetisation between ^{1}H and ^{13}C nuclei. That makes the excitation profile similar in ^{1}H rich or poor and in mobile or rigid segments. Thus it gives the possibility of replacing the time consuming DP/MAS experiments with VACP/MAS without severe loss of quantification (Simpson and Hatcher 2004b; Knicker et al. 2005a; Novotny et al. 2006a) (Fig. 21.1). However, it should be mentioned that VACP is not truly quantitative, but can be used in comparative studies in samples with similar physical-chemical characteristics. Even in these cases it requires a careful tune-up (usually

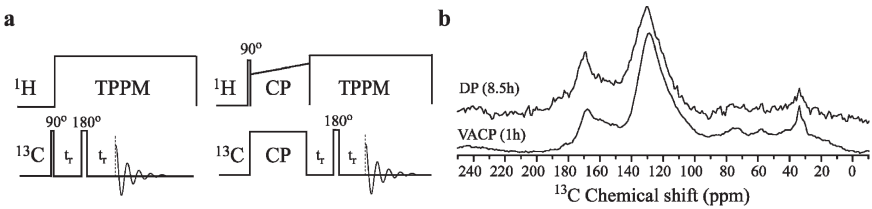

Fig. 21.1 (**a**) DP/MAS (left) and VACP/MAS (right) pulse sequences with Hahn echo acquisition; (**b**) DP/MAS (12 kHz; 1,024 scans) and VACP/MAS (12 kHz; 8,192 scans) spectra of a humic acid sample extracted from an area rich in black carbon

made in standard samples) of the radiofrequency ramp at the measuring spinning frequency and external magnetic field strength. If that is not done the technique can be as bad as the standard CP in terms of quantification.

The method proposed by Mao and Schmidt-Rohr (2004) for quantifying aromaticity by NMR combines the use of high MAS frequency DP experiments and low MAS frequency CSA filter experiments incorporating TOSS acquisition. However, based on experiments recently proposed (Novotny et al. 2006a) and reports in the literature (Cook 2004; Simpson and Hatcher 2004b; Knicker et al. 2005a), including the possibility of saturation effects in DP experiments due to very long ^{13}C T_1 (>300 s), like that observed for O-alkyl groups by Knicker et al. (2005a), it is possible to replace the DP experiment by the VACP in order to decrease the experimental time. Thus, even though the VACP data may not be truly quantitative, the technique is adequate for the comparisons made in this study.

The presence of graphitic-like structures can induce local magnetic susceptibility heterogeneities (Freitas et al. 1999) and lead to some RF pulses imperfections (Fernandes et al. 2003; Knicker et al. 2005a). This problem is enhanced when carrying out the CSA filter and TOSS experiments required for the quantification method of Mao and Schmidt-Rohr (2004) because these experiments involve the application of many cascaded π pulses that enhance the effect of the pulse imperfections. The CSA filter TOSS spectrum with conventional π pulse works well for the International Humic Substances Society (IHSS) standard peat humic acids sample, which does not have a pyrogenic characteristic (Fig. 21.2b). On the other hand, both spectra of pyrogenic carbon rich samples (char from paper, Fig. 21.2c, and the humic acids from the Amazonian anthropogenic soil, Fig. 21.2d) have both positive and negative intensities, and poor suppression of the signal with large CSA, which results from π pulse imperfections.

To overcome this problem all the ^{13}C π pulses of the CSA filter-TOSS were replaced by the composite π pulses, as suggested by Raleigh et al. (1990) and Hagemeyer et al. (1991), and recommended by Cook (2004). Details about this are in Novotny et al. (2006a). The results obtained for pyrogenic carbon rich samples using this approach are shown in Fig. 21.3. Notice also that the broad resonance around 105 ppm (attributed to the anomeric carbon of carbohydrates) in the humic

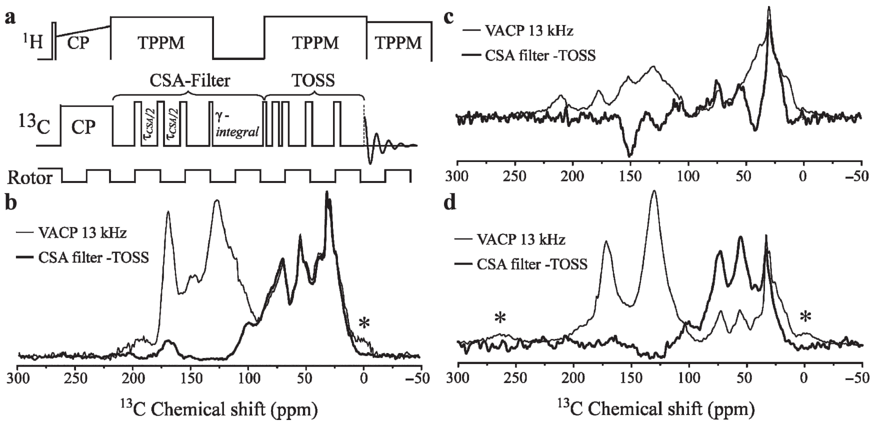

Fig. 21.2 (**a**) CSA filter TOSS pulse sequence with standard π pulses; (**b**) VACP/MAS (13 kHz; 4,096 scans) spectrum of a standard International Humic Substance Society peat humic acid sample (thin line) and corresponding VACP/TOSS spectrum (5 kHz; 4,096 scans) after 35 µs CSA filter (thick line) – using conventional π pulses; (**c**) VACP/MAS (13 kHz; 4,096 scans) spectrum of a char sample from paper (thin line) and the corresponding VACP/MAS TOSS spectrum (5 kHz; 4,096 scans) after 35 µs CSA filter (thick line) – using conventional π pulses; (**d**) VACP/MAS (13 kHz; 4,096 scans) spectrum of a humic acid sample extracted from an Amazonian anthropogenic soil (thin line) and the corresponding VACP/MAS TOSS spectrum (5 kHz; 4,096 scans) after 35 µs CSA filter (thick line) – using conventional π pulses. The symbols * indicate the spinning sidebands

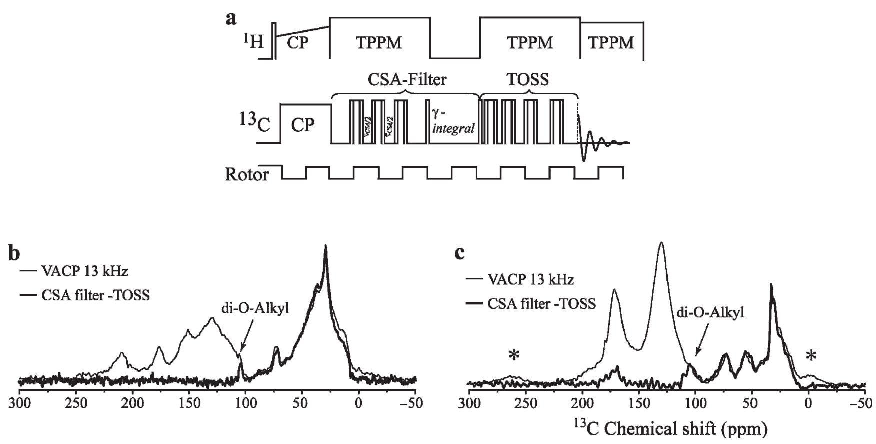

Fig. 21.3 (**a**) CSA filter TOSS pulse sequence (with π composite pulses; (**b**) VACP/MAS (13 kHz; 4,096 scans) of a char sample from paper (thin line) and the corresponding VACP/MAS TOSS spectrum (5 kHz; 4,096 scans) after 35 µs CSA-filter – using composite π pulses (thick line); (**c**) VACP/MAS (13 kHz; 4,096 scans) of a humic acid sample extracted from Amazonian anthropogenic soil (thin line) and the corresponding VACP/MAS TOSS spectrum (5 kHz; 4,096 scans) after 35 µs CSA filter – using composite π pulses (thick line). The symbols * indicate the spinning sidebands

acids from the Amazon anthropogenic soil, and the same resonance, but narrower, for the char from paper can be readily distinguished, despite the strong line overlap in the VACP/MAS spectrum.

21.6 Characterisation of Humic Acids Extracted from *Terra Preta de Índio* by ^{13}C Solid State Nuclear Magnetic Resonance

The compositions of humic acids isolated from cultivated and forest *terra preta de índio* (anthropogenic soils) was compared with those from adjacent non-anthropogenic soils (Control Soils) using elemental and thermogravimetric analyses, and a variety of solid state nuclear magnetic resonance techniques.

The thermogravimetric index, which indicates the molecular thermal resistance (Benites et al. 2005), is greater for the anthropogenic soils than for the control soils. That suggests the presence of polycyclic aromatic components in the former. The cultivated anthropogenic soils are more enriched in C and depleted in H than the anthropogenic soils under forest. That results from the selective degradation of aliphatic structures and the possible enrichment of H-deficient condensed aromatic structures.

The VACP spectra in Fig. 21.4 show typical features of humic acids extracted from tropical soils, differing in the relative contribution of each spectral region among the groups. The signals in the region of 0–46 ppm are from alkyl C groups of microbial (Baldock et al. 1990) or plant origins, and the persistence of signals at 21 and 30 ppm in the DD spectra (Fig. 21.4) indicate the presence of terminal CH_3 and of long-chain mobile CH_2, respectively (Hu et al. 2000; Petsch et al. 2001; Lorenz and Preston 2002; Knicker et al. 2005a). Examples of plant compounds, normally founded in soil organic matter that could generate this signals are cutin, suberin, waxes and dehydroxylated lignin side chains (Baldock et al. 1992; Preston 1996; Knicker et al. 2005b). The signal at 105 ppm, observed in the DD spectra, cannot be attributed exclusively to aryl-C in condensed tannin, as is cited in the literature (Lorenz and Preston 2002), but also to ketose anomeric carbon. However, the latter is preserved after application of the CSA filter while the former is suppressed (Fig. 21.4, right).

The humic acids from the control, non-anthropogenic soils present higher contents of lignin and lignin-like residues, as indicated by the methoxyl C signals at 56 ppm in the DD spectra (Malcolm 1989; Golchin et al. 1994; Novotny et al. 2006a, b). These compounds contribute to the clear signals and shoulders in the chemical shift region of aryl C between 109 and 143 ppm and to the O-aryl signal, while the humic acids of the anthropogenic soils present the typical aryl featureless signals of pyrogenic- carbon derived humic acids (Simpson and Hatcher 2004a; Knicker et al. 2005a; Novotny et al. 2007). Additionally, the aliphatic region (carbohydrates, methoxyl, N-alkyl and alkyl) is more prominent in the control than in the anthropogenic soils. In this way, O-aryl C signals (142–164 ppm) in the humic acids from the control soils have larger contributions from lignin- type compounds

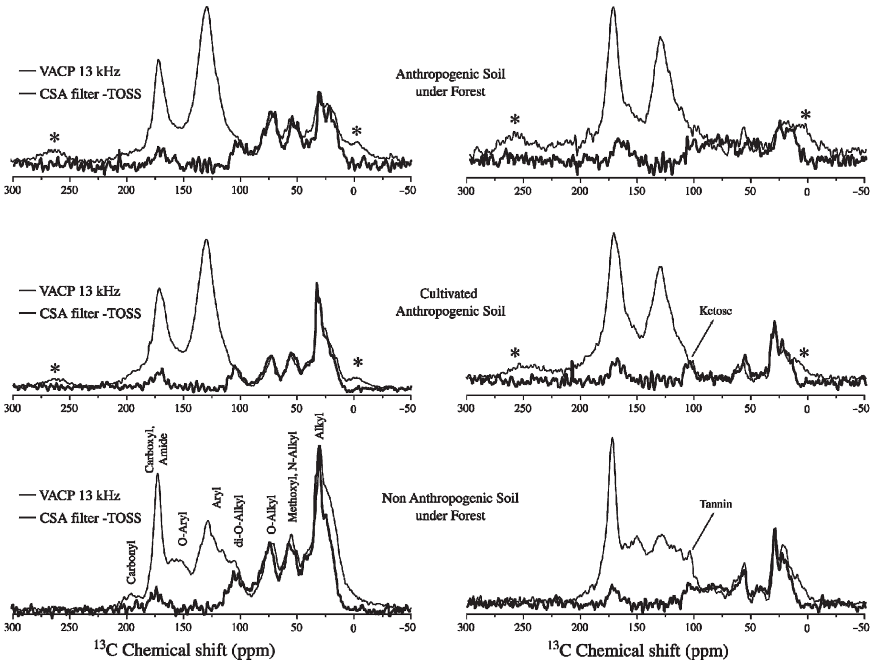

Fig. 21.4 Left: Full VACP (13 kHz MAS) spectra of a humic acid sample extracted from Amazonian soils (thin line) and the corresponding VACP/TOSS spectrum (5 kHz MAS) after 35 µs CSA filter (thick line). Right: Corresponding VACP (13 kHz MAS) spectra after dipolar dephasing with 67 µs of gated decoupling (thin line) and corresponding VACP/TOSS spectrum (5 kHz MAS) after 35 µs CSA filter and 40 µs of gated decoupling (thick line). The symbols * indicate the spinning sidebands

which would give rise to phenolic C, which would contribute to the total acidity (CEC) of humic acids (Novotny et al. 2007).

Despite the higher content of lignin residues in the control samples, the humic acids from anthropogenic soils presented higher aryl C contents, both total and substituted-C (Fig. 21.4). That is typical of pyrogenic- carbon derived humic acids (Simpson and Hatcher 2004a; Knicker et al. 2005a; Novotny et al. 2007).

A fraction of C- substituted aryl groups in anthropogenic samples could be undetectable by NMR because of, in the case of cross polarisation experiments, the remoteness of hydrogen to carbon in polycyclic aromatic structures. That results in inefficient polarisation transfer (Simpson and Hatcher 2004a), or to local anisotropic magnetic susceptibility that broadens the aryl signal. This broadening cannot be removed by MAS, making this signal undetectable, even by DP (Freitas et al. 2001). However, the significant correlation between aryl C and the thermogravimetric index (R = 0.82) and aryl C and the atomic H/C ratio (R = −0.89) indicate that NMR data are, at least, semi-quantitative. In addition, the thermogravimetric index presented negative correlations with labile groups, such as alkyl (−0.73), N-alkyl/methoxyl (−0.82), and carbohydrates (−0.86), are indicating that this index is a good tool to estimate the degree of humification.

The multivariate analysis, e.g. Principal Component Analysis (PCA), is a powerful technique to help in data interpretation. The first principal component (PC1) (Fig. 21.5), extracted by PCA, corresponds to 61% of the total variance and is characterised by positive loadings for the pyrogenic carbon aryl signal (broad featureless signal at 130 ppm) and negative loadings for the signals for carbohydrates, methoxyl, N-alkyl, alkyl (0–100 ppm) and O-aryl (151 ppm). In this way, the positive loadings at 169 ppm can be attributed to carboxyl groups attached to pyrogenic carbon aromatic rings, and the negative loadings at 174 ppm to amide from proteins/peptides (Fernandes et al. 2003). Thus, the larger the scores for this PC, the larger is the contribution of pyrogenic carbon structures to the compositions of the humic acids, and these structures are characterized by recalcitrant (aryl) and reactive groups (carboxyl). On the other hand, smaller scores indicate larger contributions of labile structures, and/or structures of lower degrees of humification such as carbohydrates, proteins and lignin. This PC separated the control samples with smaller scores (Fig. 21.5), and it had positive correlations with the thermogravimetric index (0.82), and O/H (0.82) and C/N (0.88) atomic ratios, and a negative correlation with the H/C (–0.90) atomic ratio. This is confirmation, by independent methods, that humic acids from anthropogenic soils can be characterized with regard to high stability in terms of both structural (NMR and elemental composition) and thermal properties.

The second principal component (PC2) corresponds to 21% of total variance. It is characterized mainly by a broad signal at 126 ppm and another at 170 ppm. The up-field shift of the aryl peak to 126 ppm is typical of polycyclic aromatic structures attributable to charred residues (Freitas et al. 2001; Knicker et al. 2005b). The scores of this PC were smaller for control samples and varied within the anthropogenic soils group (Fig. 21.5).

The third principal component (PC3) (Fig. 21.5) had 5% of the total variance and is characterized mainly by sharp alkyl (33 ppm), aryl (136 ppm) and carboxyl/amide (177 ppm) signals. Because of negative loadings in the region of N-alkyl groups, the 177 ppm signal can be attributed to carboxyl. Thus these features indicate peripheral incorporation of fatty acids to the aromatic backbone (González-Pérez et al. 2004a). This PC separated just one sample (data not shown).

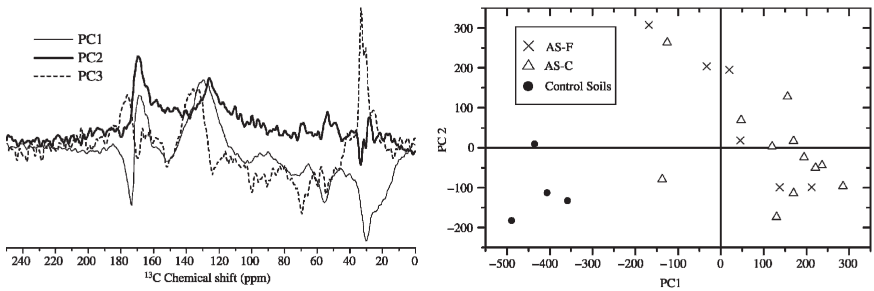

Fig. 21.5 Left: Loadings of PCA from full VACP spectra. Right: Scores of PCA from full VACP spectra. PC1, 2, and 3: principal components 1, 2, and 3; AS-F: anthropogenic soil under forest; AS-C: cultivated anthropogenic soil; control soils: non-anthropogenic soil

In resume, from PCA, using the VACP spectra, it has been possible to separate the different constituents of the humic acids, such as the carboxylated aromatic structures in the anthropogenic soils and those derived from plant sources (Fig. 21.5). The data show that the humic acids from anthropogenic soils have high contents of aryl and ionisable oxygenated functional groups, and the major functionalities from adjacent Control Soils are oxygenated functional groups from labile structures (carbohydrates, peptides, and with evidence for lignin structures). The humic acids in the anthropogenic soils can be considered to be more recalcitrant, and with more stable reactive functional groups. The recalcitrance, and the stable carboxyl functionalities associated with fused aromatic structures, the major contributors to the soil cation exchange capacity may, in part, explain the more sustainable fertility of the anthropogenic soils.

21.7 Conclusions

The results and references presented in this chapter indicate that the recent efforts of several research groups to obtain better NMR data are providing more consistent interpretations for the characterisation of soil organic matter. The advances made have shown that NMR is an important tool for the Soil Sciences. It allows a better characterisation of aromatic functionalities and their substituents; and a better definition of aliphatic functionalities, especially with regard to carbohydrate and aliphatic hydrocarbon groups. Such information will provide a better tracing of the humification process. It will also provide indications of environmental stability or lability, recalcitrance or reactivity, properties that are important for considerations of carbon sequestration and improvements in soil quality.

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Chapter 22
Opening the Black Box: Deciphering Carbon and Nutrient Flows in *Terra Preta*

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22.1 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 de índio* or Amazonian Dark Earths (ADE) (Woods and McCann 1999). *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 1,000 times more available phosphorus and up to ten times more total phosphorus than in adjacent soils (Lehmann et al. 2003).

Five years after Wim Sombroek, who can be considered the founder of research on *terra mulata*, passed away, his legacy is still alive in Wageningen, the city where he spent much 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 so called *eerdgronden* (*Plaggen* soils). The soil formation history of ADE 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 3,000 mg kg^{-1} (TW Kuyper, unpublished data, 2008) and ADE from 73 to 8,800 mg kg^{-1} (e.g. Costa and Kern 1999; Glaser 1999; Madari et al. 2003; Ruivo et al. 2003; Lehmann et al. 2003; Schaefer et al. 2004), whereas adjacent soils (non man-made) contain on average 150–300 mg kg^{-1} (Guttmann et al. 2006). C levels in Northern European sandy anthrosols vary from 1.3% to 2.8% (Blume and Leinweber 2004) which is lower than C levels in ADE which are between 2.8% and 9.0% (Costa and Kern 1999; Glaser 1999; Lehmann et al. 2003; Madari et al. 2003).

In this contribution we will present preliminary results of research on dynamic processes of ADE formation in space and time. Up to now, research on ADE has emphasized (static) properties of these soils rather than process rates (one exception

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

is Woods 1995). The question of which practices contributed to these changed properties of ADE, 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 food materials from nearby rivers as suggested by many also contribute to ADE properties. Little is known about the fluxes of nutrients and carbon, induced by the activities of the Amazonian populations that led to the formation of the fertile and productive ADE. As a consequence there is as yet no mechanistic underpinning of carbon and nutrient cycles in these soils. In order to gain understanding on their formation, the following questions seem pertinent:

1. What were the major inputs and outputs of the *terra preta* land use system?
2. Which processes caused the remarkable accumulation of C, N, and P in these soils?
3. What is the relative importance of the various processes for the accumulation of C, N, and P?
4. 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 into 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 Amazonian region, so ADE have generally remained productive for almost five centuries. We will apply the technique of nutrient and carbon balancing as a framework to gain understanding of the creation of ADE. Next to estimates of the balances of C, N, and P, we need to link these three elements in a joint stoichiometric framework (Sterner 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 pre-Columbian 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 ADE. Our data will show that deciphering the pathways along which ADE soils originated and were maintained and will need input from soil science, agronomy, archaeology, anthropology, and paleo-economy.

22.2 Methodology: Modelling of Nutrient Balances

22.2.1 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 (Fig. 22.1). 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 (Fig. 22.2), i.e. the soil processes occurring at field to village scale.

Based on several studies on ADE and work of Smaling c.s. (Smaling et al. 1987; Stoorvogel et al. 1993) an ADE nutrient balance was constructed (Fig. 22.1).

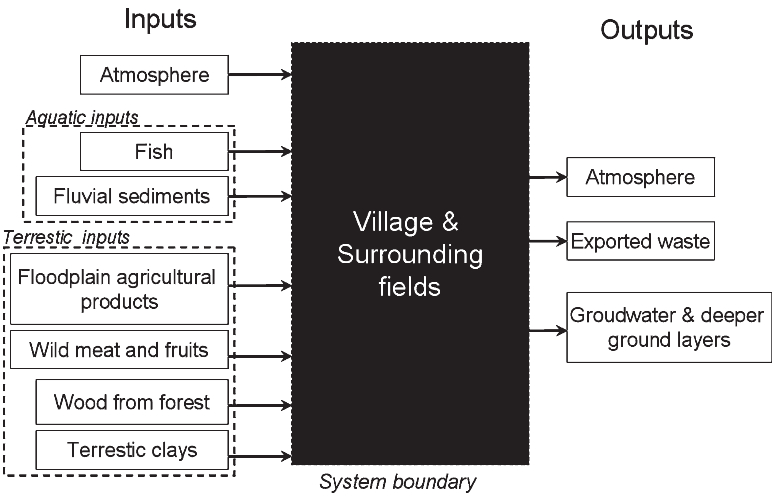

Fig. 22.1 Classical conceptual nutrient balance model in which the internal processes are not considered. All arrows represent flows of C, N, and P except the flows to and from the atmosphere, and probably the flow to the groundwater which mainly consist of C and N. Especially the flows of fluvial sediments for ceramics and wood imports, which are later transformed to charcoal, are unique to the ADE system

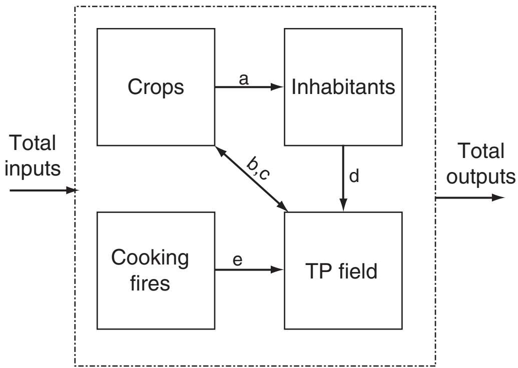

Fig. 22.2 Conceptual model of internal flows that play a role within the village during ADE cultivation. All arrows represent flows of C, N, and P and consist of (**a**) harvested products; (**b**) uptake of nutrients by crops; (**c**) nutrients from crop residues; (**d**) household waste (including fish bones) and excreta that are applied to the fields; and, (**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. 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 ADE system. People lived, cropped, and excreted their waste on the very same piece of land.

The data were assembled from a ADE site (54°26' W;3°36' S, on the Belterra plateau, near Tapajos River, Brazil) that was extensively described by Glaser (1999), and Woods and McCann (1999). This site is part of a huge expanse of ADE including both *terra preta* and *terra mulata* (Sombroek 1966).

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 2 ha 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 ADE sites, which should be subject to further research.

22.2.2 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 ADE 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.

22.2.3 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 Murrieta and Dufour (2004). For modelling purposes we simplified the diet of the inhabitants to three sources: (1) fish and other animals caught in the river (0.5 kg day^{-1} fresh weight); (2) home-grown cassava (0.9 kg day^{-1} fresh weight); and, (3) 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 22.1). For the cultivation of the needed cassava (33 Mg $year^{-1}$) 2 ha of land are needed under

Table 22.1 Chemical composition of products

	C	N	P	Ca	Mg
Cassava tuber[a]	18%	0.14%	0.02%	0.36%	0.02%
Cassava residue (leafs and trunks)[b]	12%	0.45%	0.07%	0.05%	0.06%
Papaya[a]	3.9%	0.10%	0.01%	0.02%	0.01%
Fish[c]	11%	2.4%	0.72%	1.1%	0.01%
Wood[d]	50%	0.37%	0.01%	0.2%	0.1%
Charcoal[e]	84%	0.18%			
Harvest index cassava[b]	0.6				
Carbonization coefficient of Cooking fires[f]	3%				
Loss fractions in village	0.72	0.4	0		

[a]USDA (2006).
[b]Kawano (1990).
[c]Sterner and George (2000), Hendrixson et al. (2007).
[d]Median value of data from Feldpausch et al. (2004), Vitousek et al. (1984).
[e]Adapted from Pastor-Villegas et al. (2006) P, Ca, and Mg content depend carbon coefficient changes.
[f]Own estimate.

low to medium growing conditions (Kawano 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 ADE (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 ADE. Most of the human waste (including excreta) would probably have been accumulated in the vicinity or better in the village on the ADE (in formation) (Erickson 2003; WI Woods, 2007, personal communication; Schmidt and Heckenberger, this volume). Based on excreta composition (Schouw et al. 2002) we estimate that 72% of the carbon in food that is imported to the village is respired and brought outside of the system and that the other 28% is incorporated in soil, contributing to the formation of ADE. 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 ADE. We assume no P losses due to the high P-fixing capacity of the Fe-rich Amazonian soils.

22.2.4 *Char from Forest Clearing and Cooking*

Char is one of the main inputs of ADE. 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 (e.g. Congo – 700 kg capita^{-1} year^{-1}) (Amous 1999). The char input from charring of the original biomass is estimated using figures from Brown and Lugo (1992), 281 Mg biomass ha^{-1} is assumed to be carbonized during smoldering 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.

22.2.5 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 negli-gible importance for the diet of native populations; (2) Erosion and sedimentation are negligible, because most of the Amazon is flat; and, (3) Building materials. The indigenous population used wood and 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. Also, 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. Mora (2003) did, however, find indications that major soil moving operations took place in an ADE 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 concentration in the ceramic that is abundantly found in ADE is from foods (particularly fish) that were 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.

22.2.6 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 ADE site was occupied and abandoned. In this model, three phases are distinguished. The following occupation history is hypothesized for the model ADE. First, the site was cleared, the biomass partly charred and cultivated for several years (2 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 this interaction between humans and their habitats that changed the Amazon from a pristine rainforest into a park landscape (e.g. 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 with European contact with the great decline in Amazonian populations, associated with settlement displacement. However, cessation of permanent land use did not lead to the end of ADE formation (see below).

We assume that the original highly weathered soil did not contain any (active) char before the start of the ADE formation. During the first year of the ADE 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. 2006). 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 22.6). 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 deficiency is uncommon on ADE (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 an ADE 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. (2005a).

The time of occupation of the ADE is calculated using P concentrations in the ADE soil, in an adjacent oxisol and the annual estimated P input. Furthermore we

Table 22.2 Amounts C, N and P (Mg ha^{-1}) in an oxisol and *terra preta* as measured by Glaser et al. (1999) (0–150 cm). 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

Table 22.3 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 Fig. 22.2). Only the ADE is considered as a sink, in the other components total outflow equals inflow

(kg ha^{-1} year^{-1})	C	N	P	Ca	Mg
Crops	4,982	98	16	69	12
Village	4,184	259	74	166	4
Cooking	17,868	128	5	60	20
Inputs to ADE					
Charcoal from cooking	536	1	5	60	20
Plant residues	1,993	75	12	9	9
Waste	1,153	155	74	166	4
Deposition		8			
Total	3,682	239	90	235	33
Outputs from ADE[a]					
Crop uptake		98	16	69	12
Total output		98	16	69	12
Soil surplus[b]	3,682	141	75	166	21

[a]The only output of ADE is crop nutrient uptake, gaseous losses of C and N, and N leaching are related to soil char content and therefore not shown here.
[b]Soil surplus is the amount of elements that is available for leaching or accumulation.

assumed that ADE formation started 1,000 years ago. Using these estimates together with difference in black carbon, total carbon, and nitrogen content between the ADE and the adjacent oxisol (Table 22.2), we derived the coefficients that determine the decomposition of char and the stabilization of non char soil C and N.

22.3 Results and Discussion

Table 22.3 provides insight in the size of the annual carbon and nutrient flows and their main components during the build up of ADE. The greatest C input to the entire system is wood while fish consumption causes greatest N and P inputs to the system.

Using the data from Tables 22.3 and 22.2 the occupation period was calculated to be 180 years. We checked this figure by exploring the stoichiometry of the inputs with ADE. 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 ADE sites (Teixeira et al. 2006).

Using the model described above (see Appendix for equations) we determined the conditions needed to generate an ADE within 180 years of occupation that after hundreds of years of abandonment shows the characteristics as shown in Table 22.2. 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 1 g char C can stabilize 3.1 g of non char C, the C-N ratio of the stabilized material is 15.9 (Table 22.5).

The strong stabilization of organic carbon and nitrogen by char causes carbon and nitrogen accumulation to continue even during (temporal) abandonment (Figs. 22.3, Table 22.4). 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 ADE formation because of higher pH and greater availability of P (Rondon et al. 2007). Furthermore, currently re-growing forests on oxisols are probably P and Ca limited (Feldpausch et al. 2004); however, on ADE soils being rich in P and Ca, the forests might become N-limited and hence no N might be left for stabilization.

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

Table 22.4 Element ratios. Net accumulation according to the soil data is the difference in nutrient content between the ADE and the adjacent oxisol as measured by Glaser (1999). Calculated accumulation is the accumulation calculated in the model

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[a]	1[a]	41[a]	0.4	3	8

[a]The parameters in Table 22.6 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).

Table 22.5 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 22.3)

Coefficients that determine C and N dynamics in ADE	
Decomposition coefficient char[a]	0.0005
The amount of C that can be stabilized by 1 g of partly oxidized char (g g^{-1})[a]	3.1
Carbon nitrogen ratio of stabilized material (g g^{-1})[a]	15.9

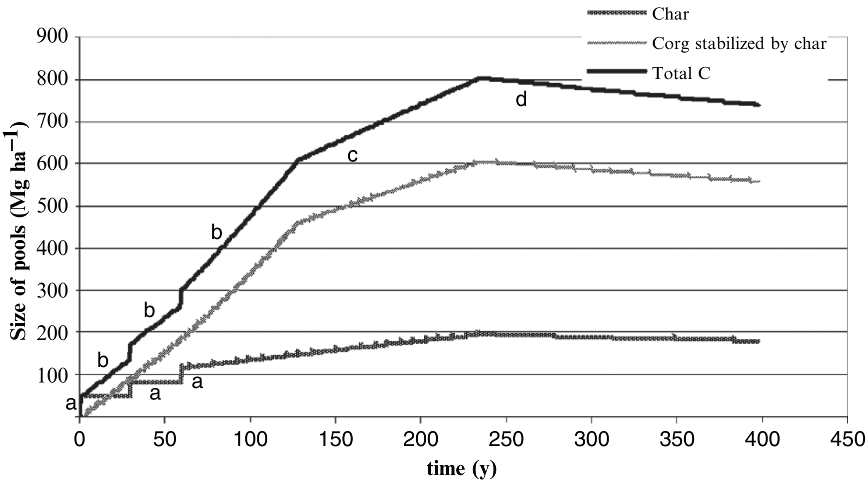

Fig. 22.3 Graph showing the amount of C in soil char (lower), and C stabilized by the char over time (middle) and total soil C accumulation (upper). The graph starts at zero because char and stabilized carbon before the start of ADE formation is not taken into account. In this graph the ADE site was 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 ADE site, no char is added anymore and soil C stocks slowly decrease

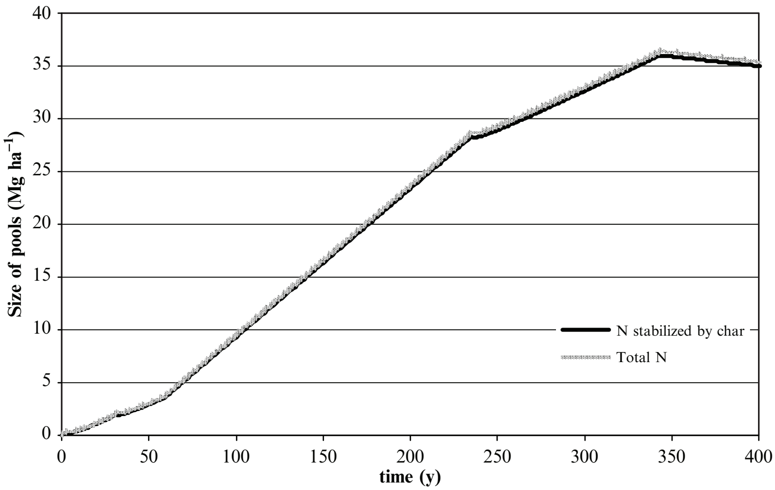

Fig. 22.4 Graph showing the amount of total soil N and N stabilized by the char over time. The graph starts at zero because char and stabilized N before the start of ADE formation is not taken in account. A slow accumulation occurs after the first clearing and charring of the vegetation. In this stage 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 kg N ha^{-1} $year^{-1}$). 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

Table 22.6 The coefficients used in the model described

Coefficients		
Decomposition coefficient char[a] ($g\ g^{-1}$)	0.0005	a
The amount of C that can be stabilized by 1 g of char ($g\ g^{-1}$)[a]	3.1	d
Carbon nitrogen ratio of stabilized material ($g\ g^{-1}$)[a]	15.9	e
C content woody biomass($g\ g^{-1}$)	0.50	f
Nitrogen carbon ratio char ($g\ g^{-1}$)	469	i
Wood leaves ratio litter ($g\ g^{-1}$)	0.19	h
C content leafy litter ($g\ g^{-1}$)[c]	0.46	g
Annual char input (after initial clearing) ($kg\ ha^{-1}\ year^{-1}$)[d]	536	CI
Annual carbon input to soil during ADE formation (kg C ha-1 $year^{-1}$)[d]	3146	CIN_t
Amount of litter dry biomass ($kg\ ha^{-1}\ year^{-1}$) of a forest with a standing biomass of 250 Mg ha^{-1}[e]	8300	LIT
Input of N by deposition and domestic wastes during ADE formation ($kg\ ha^{-1}\ year^{-1}$)[d]	241	NIN
Input of N by biological fixation during regrowth[f] ($kg\ ha^{-1}\ year^{-1}$)	80	NIN
Nitrogen removal on ADE during occupation ($kg\ ha^{-1}\ year^{-1}$)[d]	98	NR

[a]Calculated using Excel solver.
[b]Pastor-Villegas et al. (2006), Antal and Gronli (2003).
[c]Feldpausch et al. (2004).
[d]See Table 22.3.
[e]Gehring et al. (2005a).
[f]Szott et al. (1999).

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 ADE occupation or in N fixation during (temporary) abandonment do not change the coefficients displayed in Table 22.5, but they change the shape of the graphs above. Generally speaking, if less C and N is stabilized during ADE occupation more is stabilized during abandonment, between certain limits that are determined by the stabilization ratio of the char.

There is discussion whether ADE was formed intentionally. Some claim that ADE 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* (Sombroek 1966; Denevan 1996). *Terra mulata* is rich in char, but has much ceramics and shows often lower P levels (Sombroek 1966).

22.4 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.

22.4.1 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 and Mg, however, no char a depth of 4 m. 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 ADE 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 ADE formation. Phytolith research together with field research of traditional crops could bring us closer (see Bozarth et al., this volume). Normally, under tropical conditions household waste and excreta are decomposed very rapidly. 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 ADE? How much soil needs to be moved? How fast could the Amerindians have returned (if at all) to the same spot?

22.4.2 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 ADE formation as well as for understanding the relevance of ADE 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 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).

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Appendix: Equations in Nutrient Pool Model

Char in Soil over Time ($CHAR_t$ (kg ha^{-1}))

$$CHAR_t = CI + CHAR_{t-1} \cdot (1 - a \cdot (t - (t-1)))$$

CI annual char input (kg ha^{-1})
a stands for the decomposition coefficient of char (g g^{-1} year^{-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.

C Stabilization Capacity of All Chars in the Soil (SCCt (kg ha^{-1}))

$$SCC_t = c \cdot CHAR_t$$

c the amount of C that can be stabilized by 1 g 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.

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})

Carbon Input to Soil (CIN_t kg C ha^{-1})

During ADE Formation

$$CIN_t = (Waste + Residues) \cdot$$

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

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

During Regrowth After Abandonment

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

f • C content woody litter (g g^{-1})
g • C content leafy litter (g g^{-1})
LIT Annual mount 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· log t, t is time in years (Gehring 2005a)

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 ha^{-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})

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 ADE formation and biological fixation only during forest regrowth.
NR is nitrogen removal (kg ha^{-1}) which is harvest during ADE 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· 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.

Chapter 23
Charcoal Making in the Brazilian Amazon: Economic Aspects of Production and Carbon Conversion Efficiencies of Kilns

SN Swami, C Steiner, WG Teixeira, and J Lehmann

23.1 Introduction

Charcoal production worldwide is increasing for energy use in households and industry, but it is often regarded as an unsustainable practice and is linked to agricultural frontiers (Prado 2000). The production (Coomes and Burt 1999) and use of charcoal in agriculture is common in Brazil and widespread in Asia (Steiner et al. 2004).

The efficiency of biomass conversion into charcoal becomes important in conjunction with a newly proposed opportunity to use charcoal as a soil conditioner that improves soil quality on very acid and highly weathered soils (Lehmann et al. 2002; Steiner et al. 2004). This can be realized either by charring the entire aboveground woody biomass in a shifting cultivation system as an alternative to slash-and-burn (coined recently as slash-and-char by (Glaser et al. 2002; Lehmann et al. 2002) or by utilizing crop residues in permanent cropping systems. Charcoal formation during biomass burning is considered one of the few ways that C is transferred to refractory long-term pools (Glaser et al. 2001a; Kuhlbusch and Crutzen 1995; Skjemstad 2001). Producing charcoal for soil amelioration instead of burning biomass would result in increased refractory soil organic matter, greater soil fertility and a sink of CO_2 if re-growing vegetation (secondary forest) is used. A farmer practicing slash and char could profit from soil fertility improvement and C credits (if provided by a C trade mechanism to mitigate climate change), providing a strong incentive to avoid deforestation of remaining primary tropical forests.

Carbonised materials are formally authorized for use as soil amendment material in Japan, which is using 27% of its national charcoal production (50,835 t) for purposes other than fuel, more than 30.6% of which is used in agriculture (Okimori et al. 2003). In the past Japanese farmers prepared a fertilizer called “haigoe” which consisted of human waste and charcoal powder (Ogawa 1994). Charcoal is proposed to be an important component of the man-made and exceptionally fertile *terra preta* soils in the Amazon (Glaser et al. 2001b).

This study examines the labour requirements, costs, income, production process and efficiency of making charcoal in rural communities in the Amazon near Manaus, Brazil. The charcoal making process, biomass conversion efficiency, the

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek’s Vision*,

Fig. 23.1 Charcoal is soled together with Terra Preta along roads in the vicinity of Manaus, Brazil (Photo, C. Steiner)

proportion of charcoal waste accumulation and relation to agricultural activities under local small-holder conditions remains largely unknown. Therefore, we addressed the following questions: (1) How much does charcoal making contribute to the household income? (2) How efficient is the charcoal production under local conditions using brick kilns? and, (3) What are the opportunities for using charcoal waste for agriculture? We hypothesized that: (1) Charcoal making is an activity for the poorest households; (2) Access to markets is the largest constraint for small scale charcoal producers; (3) The conversion efficiency of wood to charcoal is low; and, (4) Significant amounts of charcoal waste is produced by charcoal making using brick kilns and can be used for agriculture (Fig. 23.1).

23.2 Materials and Methods

23.2.1 Study Site

Primary research was carried out in the Tarumã Mirim settlement situated at 21 km on the BR 174 highway that links Manaus, Amazonas to Boa Vista, Roraima. It was created in 1992 as an agricultural settlement by INCRA (*Instituto de Nacionalização*

Colonização e Reforma Agrária or the National Institute for Colonization and Agricultural Reform) and is situated between the streams of Tarumã Açu and Tarumã Mirim. The total area of the settlement is 4,291,076 ha, consisting of 1,042 lots of an average of 25 ha each, of which 944 lots were occupied as of July 2003. The location was chosen because local key informants, as well as secondary sources such as institutional and governmental reports, surmised that a large number of inhabitants make charcoal for sale. The settlement was originally created to promote the adequate occupation of the area through the absorption of potential farmers without land who live in marginalized conditions in Manaus. Around 75% of residents have been living there for 2–5 years, and approximately 70% of residents are from Amazonas State. There are many internal side roads, totalling 74 km, and all roads in the settlement are unpaved. Other areas in the region were also explored on an informal basis as a source of information on charcoal making activities near Manaus, including the banks of the BR-174 highway and the settlement Canoas/Rio-Pardo. The latter was created by INCRA for the same purposes as Tarumã Mirim.

23.2.2 Surveys

The households in the chosen settlement of Taruma Mirim were selected by driving along the main road and stopping at every three houses to solicit information on households that make charcoal within the nearest four or five houses. There is no census or other database of charcoal producers in settlements.

Interviews were conducted with the charcoal makers who were present at the time of the field visits. A total of 18 households who make charcoal were interviewed. First, a questionnaire was tested over the space of 1 month, and then revised in order to obtain more accurate information. The interviews solicited both quantitative and qualitative socio-economic information and were semi-structured in format and in-depth in nature. The qualitative information was verified by triangulation to the extent possible, including information from key informants, from public and government institutions, interviews with charcoal retailers in the city and written documents from various governmental and educational institutions. Economic returns, as well as more general information about production techniques, risks, labour requirements and the use of charcoal waste (powder, broken and unmarketable pieces) in agriculture were examined.

23.2.3 Biomass Conversion Efficiency

In order to assess the charcoal production progress and biomass conversion efficiency, four of the land owners interviewed were randomly selected and invited to assist measuring the weight of wood trunks, charcoal yield, remaining unburnt wood and charcoal waste (unmarketable broken pieces and powder). A balance with a capacity of 150 kg was used to weigh each bag individually. The C balance was examined by sampling disk shaped cross sections of wood trunks for each tree species that were loaded into each of the four kilns (hereon referred to as kilns A, B, C and D). A quarter of each of the cross sections was cut, dried, weighed and ground into a fine powder. Three composite samples from this fine powder were prepared for each species used in each one of the four kilns. The composite samples were analyzed for C content by dry combustion with an automatic C/N- analyzer (Elementar, Hanau, Germany) to determine the quantity of C entering each kiln in the form of wood. Randomly chosen charcoal samples were analyzed for their C content using the same analyzer.

The maximum temperature inside a kiln was measured using a brick marked with heat crayons and wrapped in aluminium foil. The bricks were placed inside the four kilns and remained there during the entire carbonization process. Ten crayon marks, each of a different colour, were made on each brick. Each crayon is manufactured to change colour at calibrated melting points in the range of 120°C to 600°C. At the end of the process, when the kiln was opened, the tile was retrieved to assess the changed colour according to the maximum temperature reached inside the kiln.

23.2.4 Statistical Analyzes

An ordinary least squares (OLS) linear regression was done to obtain an idea on what factors influence a household's charcoal productivity. A forward stepwise linear regression of the productivity (number of charcoal sacks produced) of a household was done.

23.3 Results and Discussion

23.3.1 Production Process

Charcoal is made in brick and earth kilns. Most kilns are located on the forest edge, thus facilitating easy access to the kiln feedstock. Although most charcoal producers have some knowledge of which tree species become good charcoal, they simply cut as much wood as needed to fill the kilns without any selection of tree species. However, some indicated a preference for wood from trees that had undergone considerable drying, as this wood tended to give more intact charcoal pieces. In a conventional kiln the water content strongly affects the reaction time and charcoal yield negatively, if not pressurized (Antal and Grønli 2003). The mean moisture content of the feed stock was 17%. Freshly cut wood from standing trees renders charcoal that tended to break and increase the formation of unmarketable charcoal powder. Thin branches and twigs are not used in this process since they are apt to burn and produce flames; hence, tree trunks and large, thick branches are preferred. After the kiln is filled a small fire is ignited at the kiln entrance. Later, the door is sealed with clay and the wood is left to undergo incomplete combustion (forming charcoal). The temperature inside the brick kiln was found to be between 470°C and 600°C. The combustion process can be regulated by sealing and opening vents with clay. Finally, the kiln and all the vents are sealed and coated in order stop the combustion process. Once the kiln has cooled sufficiently, it is opened and the charcoal placed in bags to sell.

23.3.2 Labour and Household Productivity

Those households making charcoal ($n = 18$) have been doing so for 3.4 years on average (±1.7) and 50% own one kiln, 33% own two kilns and 17% own three or more kilns. For the majority (56%) charcoal production is the only source of income. A kiln with a capacity to produce 100 sacks of charcoal costs between 45 and 67 USD (100–150 BRL) to build, including the costs of bricks and other tools; but the costs can be considerably higher if the charcoal producer hires labour for construction help. The model shows that household charcoal productivity increases significantly with the number of people working, the man-days of labour and the number of household income sources. A forward stepwise linear regression of the productivity (number of sacks of charcoal produced) of a household gives:

$$Y = -204.3 + 190.4a + 13.71b + 90.1c - 115.3d$$

Y = Monthly charcoal sacks produced per household
a = Number of people who are hired ($R^2 = 0.839$, $P < 0.05$)
b = Man-days of labour ($R^2 = 0.839$, $P < 0.05$)
c = Number of sources of income ($R^2 = 0.839$, $P < 0.05$)
d = categorical variable that indicates whether the charcoal is sold in Manaus (1) or not (0)

Charcoal making is a highly labour intensive activity that provides small returns (Table 23.1). The cost of raw materials for producing 100 sacks of charcoal is R$ 85 (38 USD). A charcoal producer takes, on average, nine man-days to make 100 bags of charcoal (1 day to cut wood, 1 day to fill and set fire, 3–4 days for pyrolysis supervision, 2–3 days to cool the kiln and 1 day to extract and bag the charcoal). Depending on whether he sells charcoal in the settlement or in the city, he earns either R$ 2.50 (1.1 USD) or R$ 6.50 (3.0 USD), respectively, for each bag of charcoal measuring the equivalent of four 20 L cans. Dividing the charcoal produced by the number of filled sacks at the producer gave a mean sack weight of 23.5 kg (Steiner et al. 2004) measured a mean sack weight of 15 kg at a roadside market.

Table 23.1 Economic returns and differences between solely charcoal makers (SC) and additional charcoal makers (AC)

	SC (*n* = 14)	AC (*n* = 4)
Average production costs per 100 sacks[b] (USD[a])	38.4	38.4
Man-days required to produce 100 sacks[b]	9	9
Average selling price per sack/ton (USD[a])	1.13/47.5	2.93/123.1
No. sacks/Mg produced per month	230 (±165)/5.5	643 (±200)/15.3
Net income per month from charcoal sales (USD[a])	172 (±150)	>1,200 (±90)
No. sources of income	1	>1
Charcoal production every month	Yes	No
Access to private transportation	No	Yes
Directly involved in production	Yes	No
Charcoal soled in Manaus?	No	Yes

[a]1 USD = 2.22 BRL (November 28 2005).
[b]Average sack weight at the producer is 23.8 kg.

All of the assessed charcoal making in the Tarumã Mirim settlement took place on the producer's own land. Two groups of charcoal producers could be distinguished (Table 23.1). The first group (solely charcoal makers, SC) is heavily dependent on charcoal as the principal source of income throughout the year. They make charcoal because their agricultural activities failed to provide them with an adequate income; hence, taking advantage of the natural vegetation (evergreen tropical rainforest). Their monthly income is highly variable; being influenced by their financial ability to hire labour, to pay for motor saw fuel, sacks to bag the charcoal and transportation. It was common to see settlers unable to meet many of the above conditions. All SC sell charcoal to middlemen since they have no access to transportation.

The second group (additional charcoal makers, AC) consists of those who are not dependent on charcoal as their principal source of income. Charcoal producers in this group have usually employment in the city. They produce charcoal as a supplement to their income and also to take advantage of deforestation by planting crops. All have access to private transportation that enables them to transport and sell charcoal in the city at higher prices and their income and productivity is not as variable as that of SC.

On the BR-174 highway (on which both settlements are located), considerable charcoal production is on lands belonging to large ranchers. The owners do not directly provide any income, instead letting charcoal producers utilize the wood in return for labour that clears his land. Once the land has been sufficiently cleared for agricultural production, the charcoal producer moves on to the next site where such an exchange can take place.

SC producers especially emphasized troubles to produce and market agricultural goods and all the producers in this group had trouble growing enough even at a subsistence level. The earnings from selling charcoal contributed much to purchase food from the city for such households. Neither group had a stable source of market based agricultural activities, although this settlement, like most others, was originally formed with the intention to provide land for agriculture to potential farmers.

23.3.3 Charcoal Market and Waste

In informal interviews at the charcoal market, charcoal sellers stated that for each of seven sales-posts, between 1,000 and 2,000 large sacks, and between 600 to 1,000 small sacks (~2 kg) of charcoal were sold every week. The charcoal sellers also stated that since they break down the charcoal into smaller pieces for selling, there is considerable powder left over. The powder is usually purchased by farmers of Japanese descent. Sacks of charcoal powder are sold for R$ 0.50 (0.23 USD) each. The selling can be considered as a way to get rid of the wastes, because only the price of the sack is gained. The charcoal sellers stated that typically all the powder is sold out.

23.3.4 Conversion Efficiency, Carbon Balance and Agricultural Use

The mean charcoal recovery by weight of wood biomass was 25.3% (n = 3) and the charcoal had a C content of 76.6%. Kiln B was an earthen kiln and had very little wood feedstock, which might explain the low conversion efficiency. The successful carbonization of the wood mainly depends on the condition of the kiln. Traditional kilns in Madagascar and Rwanda realize efficiencies of only 8–9%, while elsewhere efficiencies are in the range of 8–36% (reviewed by Antal and Grønli (2003). The mean C yield (C wood*100/C charcoal) was 41.6% (n = 3) and ranged from 31% to 56%. The mean proportion of charcoal waste was 12.3% of the charcoal produced at the production site and the C in the waste made up 3.7% of the wood C content (Table 23.2). Lehmann et al. (2002) calculated the average recovery of charcoal and C from woody biomass. They found that the average recovery of charcoal mass from woody biomass is 31%, the C recovery is 54% and the mean C content of charcoal is 76%.

Table 23.2 Biomass conversion into charcoal

Klin	Wood	Charcoal	Charcoal Waste	Unburned wood	Charcoal recovery by weight	Charcoal C content	C yield[a]	Charcoal waste C prop. of wood C	Charcoal waste prop. of charcoal
		Input (kg)						(%)	
A[b]	>4,339.3	1,160.8	140.5	351.4	<30.0	74.0	<47.2	<5.1	12.2
B[c]	1,731.9	256.7	64.5	0.0	18.5	76.6	31.0	6.2	25.2
C	5,359.0	1,059.1	86.8	90.6	21.4	82.9	37.9	2.7	8.3
D	4,010.7	1,394.5	52.3	166.7	36.1	72.8	55.9	2.0	3.8
Mean	>3,860.2	967.8	86.0	152.2	25.3	76.6	41.6	3.7	12.3

[a]Percentage of charcoal carbon from the carbon in wood. average c in biomass was 47%.
[b]Biomass input was not entirely assessed.
[c]Earth kiln.

Around Cali, Colombia, charcoal waste from local production was determined to be 30% to 40% of the total production (Lehmann et al. 2006). We determined a mean waste generation of only 12.3% at the producer. Given the considerable waste accumulation at the charcoal market in Manaus we assume that the percentage is much higher after transport, breaking of big logs and re-bagging.

None of the charcoal makers interviewed used charcoal powder as a soil conditioner in a systematic way. Also, it appears that many charcoal producers are not aware that charcoal powder is a commodity in the markets of Manaus, where it is bought by other farmers who have a cultural history of using it for instance to mix it with poultry feed (Steiner et al. 2004). Charcoal use might strongly depend on the ability to produce agricultural goods and, thus, depending on the ability of farmers to buy fertilizer and use fertilizer in a proper way. Most SC producers have not enough income to invest in their lands and an additional nutrient source is necessary to benefit from charcoal applications (Lehmann et al. 2003; Steiner et al. 2004). There are important differences between charcoal producers that influence whether charcoal wastes can be used in agriculture successfully from an economic point of view. SC producers may not find the use of charcoal for soil amelioration purposes to have much incremental benefits for them since they rely on charcoal sales for survival, are limited by labour and are lacking in capital assets that would enable them to reach the market and sell their goods (including crops) at higher prices. AC producers, however, have better economic means that may enable them to use charcoal and invest in long term soil fertility improvement. The charcoal waste or, indeed, some of the charcoal itself in powdered form could be used in agriculture without adversely affecting the household's well-being.

At a burn of forest being converted to cattle pasture only 2.7% of above-ground C being converted to charcoal (Fearnside et al. 2001). Seiler and Crutzen (1980) were the first to point out the potential importance of charcoal formation to the global C cycle. Fearnside et al. (2001) found that the average C content for charcoal formed by slash-and-burn was 73%, which is close to the C content of charcoal formed in the studied kilns. From the results of this study, forming charcoal in earthen kilns or brick kilns converts 31% to 56% of feedstock C into charcoal C. Hence, making charcoal with the specific purpose of using it or the waste as a soil conditioner could be one way to increase the amount of C in the soil; benefiting the farmer by providing him with a land clearing method that increases SOM in the form of recalcitrant black C and reducing the smoke emissions by controlled perennial (charcoal making is not restricted to the dry season) conversion. As charcoal waste is making up 2.0% to 6.2% of original C in the biomass (not including further waste creation during charcoal breaking, marketing and bagging) more C remains as refractory SOM in the soil as considering the slash-and-burn scenario even if just the waste were used for soil amelioration and the marketable pieces are sold. Charcoal waste accumulation in Colombia was determined to be 30% to 40% of the charcoal produced (Lehmann et al. 2006). Other sources report that 20% remains as charcoal powder and pieces (FAO 1991). AS producers seem likelier to have enough resources to establish a slash and char system. However, financial benefits provided by an international C trade mechanism would particularly enable and motivate SC producers to invest in soil fertility and, thus, in their own and the settlement's future.

Currently (November 28, 2005), 1 t of CO_2 is traded for 24 USD in Europe. One ton of charcoal produced in Amazonian kilns is the equivalent of 2.81 Mg of CO_2 (C content of charcoal (0.766) × (3.66) CO_2/C weight balance). Providing a SC producer access to the C trade market would raise the value of his charcoal from 48 USD per ton to 67 USD per ton. In this case it is more likely that SC producers implement a slash and char system than AC producers because the later are able to sell their charcoal for 123 USD per ton. According to Steiner et al. (2004) charcoal is sold by a producer with access to a road side market for 90 USD per ton. In reality, a bargaining process will determine how much C is used for soil amelioration (sequestration) or for energy use (fossil fuel substitution). Both cases reduce the amount of greenhouse gas in the atmosphere; the first by sequestering CO_2 and the second by avoiding emissions as long as the use of re-growing biomass is insured. According to Coomes and Burt (1999) fallows of between 8 and 12 years are sufficiently long for both charcoal production and agricultural cultivation and the regeneration of forest with primary forest species is much greater in areas that were not burned after felling and, instead, one used for charcoal production (Prance 1975). An access to the C trade market holds out the prospect to reduce or eliminate the deforestation of primary forest, because using intact primary forest would reduce the farmer's C credits. Fearnside (1997) estimated the above-ground biomass of unlogged forests to be 434 Mg ha^{-1}, about half of which is C. This C is lost if burned in a slash-and-burn scenario and lost to a high percentage if used for charcoal production. The C trade could provide an incentive to cease further deforestation; instead reforestation and recuperation of degraded land for fuel and food crops would gain magnitude. As tropical forests account for between 20% and 25% of the world terrestrial C reservoir (Bernoux et al. 2001), this consequently reduces emissions from tropical forest conversion which is estimated to contribute globally as much as 25% of the net CO_2 emissions and up to 10% of the N_2O emissions to the atmosphere (Palm et al. 2004). According to Lehmann et al. (2006) slash and char as alternative to slash-and-burn could off-set 12% of the annual anthropogenic C emissions caused by land use change. From our calculations a farmer is capable of increasing the soil C content on 1 ha in the top 0.1 m soil depth from 0.9% to 20% annually if just the waste were used in SC production system or all charcoal is used in an AC production system, respectively (Table 23.3). Already the low charcoal additions of 13.3 Mg C ha^{-1} improved tree height and stem diameter of *Inga edulis* significantly and was equivalent to fertilizer applications (Lehmann et al. 2002). Only 11 Mg ha^{-1} charcoal application could almost double the overall yield (four cropping cycles) from mineral fertilized plots in comparison from that achieved on mineral fertilized plots alone (Steiner et al. 2007).

The process of producing charcoal in kilns is also very hazardous to the health (Tzanakis et al. 2001), since the charcoal producer is exposed to heat and large amounts of charcoal powder and dust. Thus, any conscientious attempt to involve and encourage farmers to produce charcoal should investigate alternative production methods that are much less damaging to health and offer the advantage of

Table 23.3 Potential soil C increase and carbon sequestration value under different scenarios

Scenario % of charcoal for agricultural use	Annual amount of charcoal for soil (Mg)	Soil C increase 1 ha in top 0.1 m soil depths (%)	Potential carbon sequestration value (USD)
SC waste 12.3[a]	8.1	0.88	546
SC waste 35[b]	23.1	2.51	1,557
AC waste 12.3[a]	22.6	2.45	1,523
AC waste 35[b]	64.3	6.98	4,334
SC 100	66.0	7.17	4,449
AC 100	183.6	20.0	12,376

[a]12.3% of charcoal waste accumulation at the producer.
[b]Charcoal waste generation estimated by Lehmann et al. (2005).

utilizing by-products like energy and liquid fuels. The distillation of the pyroligneous acid fraction from the smoke is often part of the charcoal manufacturing processes in southern parts of Brazil (Glass 2001). Another system in development converts biomass into a hydrogen-rich gas producing charcoal as a by-product (Day et al. 2005). Such an integrated approach facilitates the utilization of any kind of wet biomass (crop residues, small branches and twigs) for energy and agricultural char production. Using other biomass sources for agricultural char production would not hamper the production of barbecue charcoal (from bigger logs for fossil fuel substitution).

23.4 Conclusion

There are important social and economic distinctions within charcoal producers at the household level. Charcoal making in most cases appears to be a "last resort" activity, especially among small farmers with few monetary resources. Most of these farmers would only consider charcoal making when under monetary pressure due to a failure of agricultural activities. For those who find themselves in such a situation, making charcoal from wood is a way to take advantage of the resources at their disposal in order to substitute for the income making capacity of agriculture. Yet others make charcoal to supplement other primary sources of income and are not reliant on charcoal for survival needs. This group has the financial strength for selling charcoal with high economic returns, as well as for agricultural production depending on fertilizer input.

Production of charcoal shows promise as an agent for C sequestration, especially given the quite efficient C conversion in brick kilns. Charcoal waste is a significant proportion of the total charcoal yield and can be used as soil conditioner to increase soil fertility and crop productivity in acid and highly weathered soils by transferring labile C into a refractory soil C pool. Even if the sold and burned charcoal does not sequester C it is still substituting fossil energy and, thus, reducing greenhouse gas emissions if a re-growing biomass source (secondary forest) is used instead of in-field burning. Amounts of charcoal waste produced at the production site are higher than charcoal produced by slash-and-burn events. A further large proportion of waste is generated during marketing and bagging of charcoal which is usually collected for agricultural purposes at the city market. More information is needed on the agronomic facilities, the potential to use alternative biomass sources and production of by-products to evaluate the opportunities for adopting a slash and char system. The access to a global C trade mechanism would facilitate charcoal use for soil amelioration and, thus, reducing climate change and further deforestation.

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Chapter 24
The Effect of Charcoal in Banana (*Musa Sp.*) Planting Holes – An On-Farm Study in Central Amazonia, Brazil

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24.1 Introduction

Agricultural production in the tropics is frequently limited by low soil fertility. Many tropical soils are rich in kaolinite and iron (Fe) and aluminium (Al) oxides, but relatively poor in soil organic matter (SOM), they frequently have a low cation exchange capacity (CEC), low pH, low calcium (Ca), and phosphorus (P) contents (Zech et al. 1990). In strongly weathered tropical soils, SOM plays a major role in soil productivity because it represents the dominant reservoir of plant nutrients (Tiessen et al. 1994; Zech et al. 1997). Generally SOM contains 95% or more of the nitrogen (N) and sulphur (S), and between 20% and 75% of the P in surface soils (Duxbury et al. 1989). Rapid mineralization of organic matter after clearing of forests and during continuous farming explains low fertility levels of many tropical soils under permanent cropping systems (Tiessen et al. 1994; Zech et al. 1990).

Conventional fertilization with mineral fertilizer (mainly N applied as urea or ammonium sulphate) is not very efficient on soils with low nutrient retention capacity (Alfaia et al. 2000). Heavy tropical rains leach easily available and mobile nutrients into the subsoil where they are unavailable for most crop plants (Giardina et al. 2000; Hölscher et al. 1997; Renck and Lehmann 2004). To overcome the poor nutrient supply the common agricultural practice in the tropics is slash and burn agriculture. Practiced by about 300 to 500 million people worldwide, (Giardina et al. 2000; Goldammer 1993) slash and burn contributes significantly to global warming (Fearnside 1997). This traditional agricultural practice is considered sustainable if adequate (up to 20 years) fallow periods follow a short time of cultivation (Kleinman et al. 1995). Long fallow periods make this technique land demanding and hardly any other crop than manioc can be cultivated by shifting cultivation in Central Amazon, without access to fertilizers.

The existence of an anthropogenic enriched dark soil (Amazonian Dark Earth [ADE] or *terra preta de índio*) proves that infertile Ferralsols and Ultisols in principle can be transformed to permanently fertile and productive soils. Such a transformation cannot be achieved solely by replenishing the mineral nutrient supply, because the soil organic matter is of prime importance for the prevention of nutrient

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leaching in these freely draining soils (Zech et al. 1990). The ADE's fertility is most likely linked to an anthropogenic accumulation of P, Ca, associated with bone apatite (Lima et al. 2002) and black carbon (C) as charcoal (Glaser et al. 2001).

Sustained fertility in charcoal containing ADE and the frequent use of charcoal as a soil conditioner (Steiner et al. 2004) in Brazil and mainly Japan (carbonized materials are formally authorized for use as soil amendment material in Japan) (Okimori et al. 2003) provided the incentive to study the effects of charcoal application to a highly weathered soil in Amazonia (Lehmann et al. 2003; Steiner et al. 2007). Slash and char as an alternative agricultural method producing charcoal out of the aboveground biomass instead of converting it to CO_2 through burning (Lehmann et al. 2003; Ogawa 1994; Steiner et al. 2004) could provide a significant carbon sink and could be an important step towards sustainability and SOM conservation in tropical agriculture. A previous pot experiment has shown soil charcoal amendments decrease N leaching and increase the efficiency of applied nutrients (Lehmann et al. 2003) and charcoal amendments significantly increased sorghum crop production in a field trial by C. Steiner and colleagues.

The trial was carried out in the local farming context in order to provide cheap sustainable options to improve crop yields in the tropics. In detail, our objective was to study the feasibility and effectiveness of charcoal application in the Amazon environment to improve soil quality for agricultural production.

24.2 Methods

In December 2001 the experiment was established within an existing and expanding banana plantation established on Oxisols north of Manaus on 99 km along the road BR 174 leading to Boa Vista. Four different treatments were applied and designated as: (1) Normal agricultural praxis (NAP); (2) NAP + 6.5 L (~2.2 kg) of charcoal powder; (3) NAP + 6.5 L charcoal in small pieces (sieved to obtain a particle size between 0.2 and 1 cm); and, (4) NAP + 13 L of charcoal mix (available as charcoal production waste from local charcoal producers = powder and pieces). The charcoal' nutrient content was low with 5.39, 0.03, 0.33, 1.02 and 0.36 g kg^{-1} N, P, K, Ca, and Mg contents respectively.

The experiment was designed as completely randomized with four replicates of each treatment and each treatment consisted of six banana plants. The normal agricultural praxis (NAP) is to plant bananas in planting holes 0.3 m deep and 0.45 m wide. The holes were filled with a mixture of 10 L fresh chicken manure (16.47, 6.89, 17.79, 16.68, 3.03; N, P, K, Ca and Mg contents respectively), 500 g powdered lime, 50 g micronutrient-mix (4.5 g Zn, 0.9 g B, 0.4 g Cu, 1.5 g Fe, 1.0 g Mn, 0.05 g Mo), 300 g simple super phosphate (23.22 g P) and soil. The other treatments received an additional charcoal amendment. The holes were established in lines with a distance of 2.5 m between the holes and 3.5 m between the lines in December 2001. Until harvest (February 26 to March 7, 2003) two further fertilizations were applied on the soil surface. In April 2002 60 g magnesium sulphate

($MgSO_4$), 80 g potassium chloride (KCl), 39 g zinc sulphate ($ZnSO_4$), 30 g FTE BR12 (micronutrients), 30 g Borax, 90 g ammonium sulphate ($(NH_4)_2SO_4$) and 60 g simple super phosphate. In July 2002 270 g KCl and 135 NH_4SO_4 were applied. On 22nd of April 2002 the bananas were planted as small clones (0.1 to 0.2 m plant size) of the variety *Caipira*. Six banana plants were planted per treatment in 4 replicates. On 17 December 2002 from each treatment and replicate four soil and leaf samples were taken to form one composite sample per treatment. Soil samples were taken from 0 to 0.2 m and 0.2 to 0.4 m depths for analyses of plant available P, K, Fe, molybdenum (Mo), zinc (Zn), manganese (Mn), and copper (Cu) (in Mehlich 1 extracts) and Ca, Al, and magnesium (Mg) (in KCl extracts), pH, effective CEC, base saturation (BS) and acidity (Al^{3+} + H^+) was determined (Claessen et al. 1997). Half a cross section of each third leaf from the top was sampled, dried, ground and analyzed for N (using the method of Kjeldahl and titration), P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn (Malavolta et al. 1997). The treatments NAP and NAP + charcoal-mix were established with six suction cups each. The suction cups were installed in an angle to be situated in 0.5 m depth (~0.2 m beneath the planting hole) for soil solution collection. Soil solution was taken on May 3rd, June 22nd and July 3rd 2002 for analysis of pH, conductivity, Mg, Ca and K. Micro-nutrients, Ca and Mg were determined by atomic spectrometry (GBL Avanta Σ Analitica, Australia) and Al by titration. Potassium was analyzed with a flame photometer (Micronal B 262, Sao Paulo, Brazil). The pH (WTW pH 330, WTW, Weilheim, Germany) and conductivity (HI 8733, HANNA Instruments) were determined in the solution.

At the first harvest from February 26 to March 7, 2003 the size and weight of the total bunch, number of single bunches per plant, weight of single bunch, number of fruits per single bunch, length of fruit, diameter of the fruit and the fruit diameter without peal was measured.

24.2.1 Bulk Density and Soil Water Retention Curve (SWRC)

In order to measure bulk density and soil water retention undisturbed soil samples were collected at each treatment and between planting lines, with three subsamples within each plot. On 17 December the samples were collected by hammering a steel cylinder (mean inner diameter = 6.96 cm, height = 7.18 cm, volume = 272.72 cm^3) into the soil surface. For bulk density assessment the samples were dried at 105°C for 48 h.

For the evaluation of SWRCs the steel cylinders were saturated in a shallow bath and, after saturation had been reached, water retention data were determined successively at 1.0 1.8, 2.0 and 3.0 pF ($\log_{10}$ cm H_20) using the tension-plate method. Details about the measurement of SWRCs with desorption method from soil cores are given by Klute and Dirksen 1986 and Mathieu and Pieltain (1998). All soil analyses were done at the laboratory of the Embrapa – Amazônia Ocidental station in Manaus.

24.2.2 Statistical Analyzes

Results were analyzed using the software SPSS (12.0) and completely randomized design with four replicates. The treatments were compared using one way ANOVA and Fisher's LSD test (least significant difference). Soil and foliar nutrients were correlated with pH using Pearson correlation with two-tailed test of significance. Only in two treatments (NAP and NAP + charcoal mix) suction cups were installed. Therefore the data were compared using a t-test.

24.3 Results and Discussion

24.3.1 Foliar Nutrient Contents

Charcoal amendments partly increased Ca, Mg, and S foliar nutrient levels significantly. Foliar Ca nutrition significantly increased up to 12.15 g kg^{-1} due to the application of powdered charcoal and charcoal mix. Mg was only significantly higher on plots receiving charcoal powder, and charcoal mix was the only amendment increasing foliar S. The levels of K, B, and Cu were lower if charcoal powder was applied (Table 24.1).The lower K uptake is surprising as Lehmann et al. (2003) found increased K uptake and supply due to charcoal application. With the exception of B and Mo, the solubility of inorganic forms of micronutrients decreases with increasing pH (Duxbury et al. 1989). Due to liming the soil pH was relatively high in all treatments (Table 24.2). It correlates negatively with foliar K (–0.574, P = 0.02 and –0.680, P = 0.004 for soil depths 0–0.2 m and 0.2–0.4 m, respectively) and positively with foliar Ca (0.560, P = 0.024 and 0.554, P = 0.026 for the soil depths 0–0.2 m and 0.2–0.4 m, respectively).

24.3.2 Soil Nutrients

Plant available elements despite Fe, Zn, and Cu tend to increase due to charcoal application. P, Na, Ca, and Mg correlate positively with soil pH, whereas Fe and Cu correlate negatively (data not shown). Organically complexed micronutrient metals, and perhaps also borate complexes with soil carbohydrates, are generally considered an important component of the labile reservoir of these elements in soils. In addition, soluble organo-metal complexes are often a major proportion of the micronutrients in soil solution and aid in the transport of micronutrients to plant roots. This is most important in high pH soils because, with the exception of B and Mo, the solubility of inorganic forms of all micronutrients decreases with increasing pH (Duxbury et al. 1989). Relatively high pH (6.03–6.54) was found in the banana planting holes in comparison to the untreated Oxisol (3.5–4.5). Only soil K

Table 24.1 Shows the mean foliar nutrient contents of banana plants. NAP = normal agricultural praxis, pieces = 6.5 L of charcoal pieces, powder = 6.5 L (~2.2 kg) of charcoal powder, 2CharMix = 13 L of charcoal production waste. Different letters in the same column indicate significant differences ($P < 0.05$) between treatments (Fisher's LSD test, n = 4)

	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
Treatment				($g\ kg^{-1}$)					($mg\ kg^{-1}$)		
NAP	24.99a	1.55a	21.20b	10.05a	2.04a	2.29a	39.05b	11.50b	67.00a	530.75a	13.75a
NAP + pieces	26.66a	1.57a	19.94ab	10.24ab	2.24ab	2.36ab	36.25ab	10.50ab	77.75a	585.50a	13.50a
NAP + powder	25.59a	1.64a	18.82a	12.15c	2.46b	2.26a	33.55a	10.00a	72.25a	569.25a	12.25a
NAP + 2CharMix	25.14a	1.59a	20.42b	11.83bc	2.14ab	2.58b	34.98ab	10.75ab	76.50a	643.25a	13.75a

Table 24.2 Mean plant available soil nutrient contents. NAP = normal agricultural praxis, pieces = 6.5 L (~2.2 kg) of charcoal pieces, powder = 6.5 L of charcoal powder, 2CharMix = 13 L of charcoal production waste. Different letters in the same column indicate significant differences ($P < 0.05$, if detected) between treatments (Fisher's LSD test, n = 5)

	Depth	pH	P	K	Na	Ca	Mg	Al	Acidity	CEC_{eff}	BS	Mo	Fe	Zn	Mn	Cu
Treatment	M	H_2O			($mg\ dm^{-3}$)				(cmolc)		(%)			($mg\ dm^{-3}$)		
NAP	0.0–0.2	6.06	965.5	395	116.3	1,278	81.10	0	5.57a	13.43	62.95	49.57	129.0	3,027	86.0	79.05
	0.2–0.4	6.03	863.9	136a	106.5	989	52.55	0	3.34	9.51	61.73	31.40a	110.0	504	33.2	18.06
NAP + pieces	0.0–0.2	6.50	1,272.8	581	217.5	1,399	90.21	0	2.99b	13.14	76.28	53.70	103.8	2,229	107.1	37.93
	0.2–0.4	6.44	1,098.3	161ab	154.5	1,364	78.67	0	2.94	11.71	74.43	40.69ab	129.0	1,367	75.5	50.92
NAP + powder	0.0–0.2	6.34	1,156.3	465	171.3	1,452	95.07	0	3.48b	13.91	71.63	56.91	94.0	2,879	95.6	52.09
	0.2–0.4	6.54	899.0	179ab	122.0	1,366	70.47	0	2.88	10,67	74.23	42.12b	108.3	430	37.5	13.01
NAP + 2CharMix	0.0–0.2	6.47	1,050.3	530	172.5	1,302	92.95	0	3.48b	12.81	72.63	49.81	102.5	2,745	114.9	56.33
	0.2–0.4	6.54	922.0	224b	125.9	1,243	72.60	0	2.98	10.79	73.53	36.37ab	112.3	1,194	62.3	27.01

Acidity = $Al^{3+} + H^{+}$; CEC_{eff} = effective cation exchange capacity; BS = base saturation.

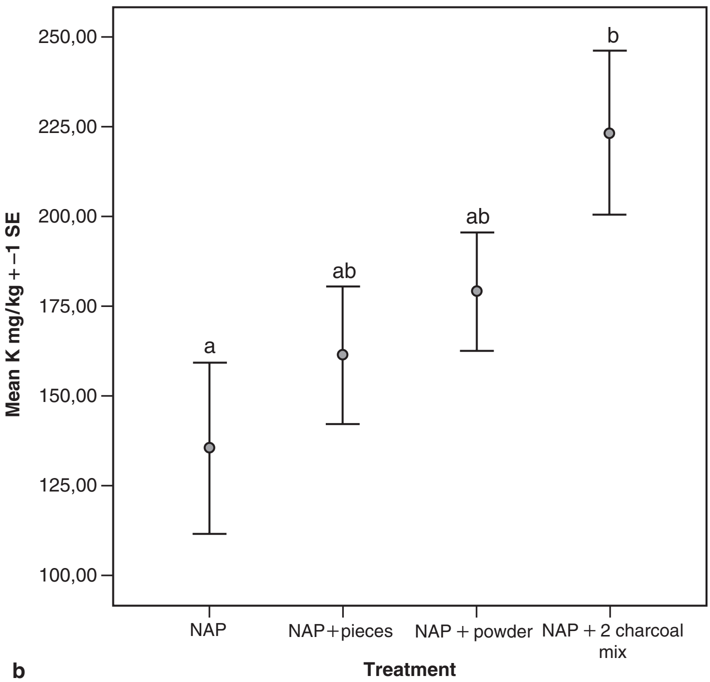

Fig. 24.1 Effect of charcoal application on plant available K in 0.2–0.4 m depth. The amount of charcoal applied as pieces and powder does not differ in weight but in surface area. NAP = normal agricultural praxis, mix = regular charcoal production waste double dosage (means ± standard error, letters indicate significant differences, Fisher's LSD test, $P < 0.05$, $n = 4$)

from 0.2 to 0.4 m increased due to charcoal applications and was found to be significant in planting holes amended with charcoal mix (Fig. 24.1).

Increased available K contents due to charcoal additions corroborate with findings by Lehmann et al. (2003). However the foliar K contents did not increase with increasing soil K contents. Either K in charcoal is not available or the number of replicates was not enough, or K was not a limiting factor for plant growth. All charcoal treatments significantly reduced acidity (0–0.2 m, Fig. 24.2).

No extractable Al was found in any treatment (Table 24.2) due to chicken manure and lime application. In a field experiment by (Steiner et al. 2007) chicken manure application of 47 Mg ha^{-1} also eliminated extractable Al and significantly lower extractable Al concentrations were found in charcoal amended and mineral fertilized soils in comparison to only mineral fertilized soils. Charcoal application increased legume production in a study by Topoliantz et al. (2005) due to decreased soil acidity and exchangeable Al and increased Ca and Mg availability. Complexing of organic matter (in this case, charcoal) with reactive Al and Fe surfaces would reduce the CEC, but has beneficial effects in that it blocks these sites and reduces

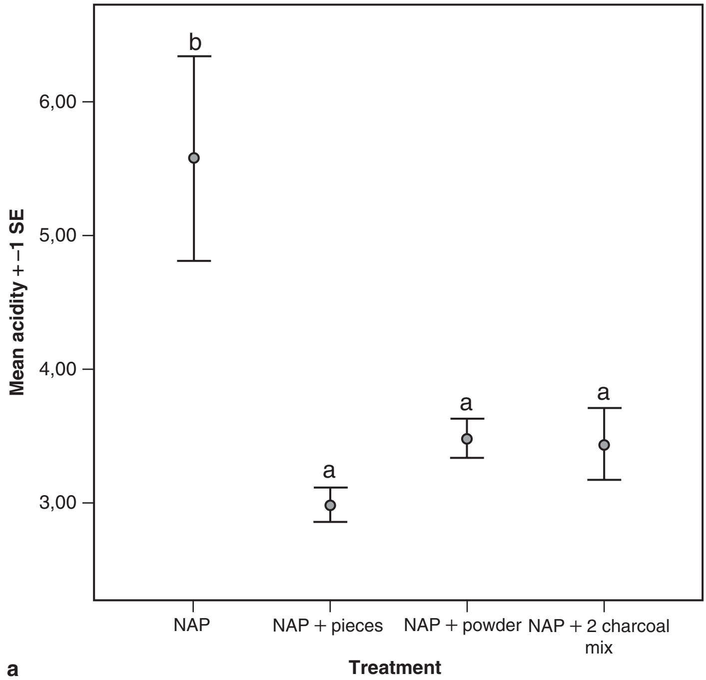

Fig. 24.2 Charcoal applications significantly lowered the acidity in the top 0.2 m soil depth. NAP = normal agricultural praxis, mix = regular charcoal production waste double dosage (means ± standard error, letters indicate significant differences, Fisher's LSD test, $P < 0.05$, $n = 4$)

the capacity of soils to fix phosphate and sulphate. Increasing SOM may also stimulate desorption of phosphate and sulphate by acting as competing anion (Duxbury et al. 1989). High acidity and Al toxicity can reduce yield severely affecting root growth, nutrient uptake and consequently plant biomass production (Sierra et al. 2003). Increases in soil nutrient contents were not significant because of a high standard deviation and low n number. Many more replicates are necessary to study the effects of fertilization on a farm where less attention is given to evenly distributed fertilizer as it is done on experimental fields.

24.3.3 Soil Solution

The suction cups used were not attached to a vacuum pump to maintain permanent vacuum. This led in fertilized soils and at high rainfall intensity to a dilution of the soil solution sampled, because suction cups which maintained their vacuum longer

Table 24.3 Nutrient contents, pH and electrical conductivity of the soil solution at three different sample times. NAP = normal agricultural praxis, Pieces = 6.5 L (~2.2 kg) of charcoal pieces, Powder = 6.5 L of charcoal powder, 2CharMix = 13 L of charcoal production waste. Significant differences ($P < 0.05$) are marked with *, t-test

Treatment	Date	n	pH	EC ($\mu S\ cm^{-1}$)	Ca ($mg\ L^{-1}$)	Mg ($mg\ L^{-1}$)	K ($mg\ L^{-1}$)
NAP	03.05.2002	4	6.07	650.2	2,745.9	1,592.6	291.9
NAP + 2CharMix	03.05.2002	4	6.32	1,185.8	2,477.9	791.3	112.0*
NAP	22.06.2002	4	5.93	317.0	478.3	119.5	34.0
NAP + 2CharMix	22.06.2002	6	5.46	384.3	1,122.0	498.7	149.5
NAP	03.07.2002	2	6.80	147.5	121.6	42.2	9.3
NAP + 2CharMix	03.07.2002	3	6.80	225.0	250.9	85.2	11.4

still sampled solution, whereas others stopped delivery at a potentially higher nutrient concentration.

Significant reduced K leaching was found at the first sampling period, but in regard to the small sample size and difficulties to maintain vacuum this result should be looked at with scepticism (Table 24.3). Lehmann et al. (2003) found decreasing leaching of mineral N fertilizer and a higher efficiency of nutrients if applied on charcoal containing soil.

24.3.4 Soil Physics

Bulk density did not differ between the treatments, but the bulk density in planting holes (0.82) was significantly ($P < 0.001$) lower than between planting rows (1.07). Bulk density and soil water retention clearly are influenced by soil disturbance due to the establishment of planting holes. The reduction of water retention between planting holes (Fig. 24.3) shows that soil management creates macro-pores. Charcoal amendment increased water retention (powder and charcoal mix) at 1.0 pF ($P = 0.1$, LSD test). The higher amount of water at lower pressure (pF 1.0) indicate that charcoal amendment enhance soil pores with a radius of approximately 0.015 mm. Either charcoal promoted the aggregation of soil with pores of this size or charcoal's porosity itself was responsible for this increase.

24.3.5 Harvest

The first harvest was relatively small with a mean total bunch weight of 13 kg. The following harvests are usually higher and provide more valid data. The harvest did not show any significant difference between the treatments. Other experiments with sorghum (*Sorghum bicolor* L. Moench) did prove a significantly increased biomass and yield production due to charcoal application at the second harvest or following harvests (Steiner et al. 2007), but the following harvests could not be assessed because of the projects limited time.

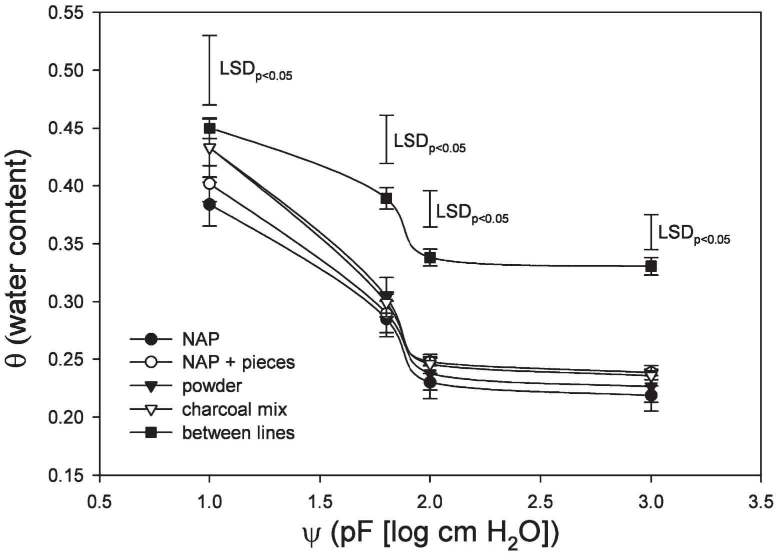

Fig. 24.3 Soil water retention curves under increasing pressure. The error bars indicate the standard error and the LSD (least significant difference) is marked ($P < 0.05$, $n = 3$)

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Chapter 25
Characterization of Char for Agricultural Use in the Soils of the Southeastern United States

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25.1 Introduction

Char produced from the pyrolysis of biomass has potential as an agricultural amendment in low fertility soils. Much of the interest in its use as an agricultural amendment has been stimulated by research discussed in this book and the previous volumes on the role of charcoal in *terra preta* soils. Results from studies conducted in South American and African tropics on acidic, highly-weathered Oxisols with low organic carbon (C), cation exchange capacity (CEC), and base saturation indicate that addition of charcoal has significantly influenced nutrient cycling, soil biology, and crop productivity (Glaser et al. 2002; Lehmann and Rondon 2006; Oguntunde et al. 2004). Increased yields and biomass have been reported for various legumes (Iswaran et al. 1980; Lehmann et al. 2003; Topoliantz et al. 2005) and for corn (Lehmann and Rondon 2006; Oguntunde et al. 2004). Increased productivity may be related to available nutrients (Glaser et al. 2002; Lehmann et al. 2003; Steiner et al. 2007), or increases in pH (Topoliantz et al. 2005; Steiner et al. 2007), and CEC (Steiner et al. 2007; Liang et al. 2006), as well as changes in water relations and soil biology (Glaser et al. 2002; Steiner et al. 2004). Although most studies report increased plant productivity with charcoal addition, plant biomass decreases have been observed, particularly at high application rates (Glaser et al. 2002). These responses could be related to nitrogen immobilization through high C:N ratios and sorption of NH_4 and NO_3 (Lehmann and Rondon 2006).

The southeastern United States is an important agricultural area. The state of Georgia alone has approximately 4.3 million hectares of corn (*Zea mays*), soybean (*Glycine max*), cotton (*Gossypium hirsutum*), and peanuts (*Arachis hypogaea*) in production and 9.6 million hectares of forestland largely in loblolly pine (*Pinus taeda*) production (USDA 2002; Georgia Forestry Commission 2007). The growing interest in biofuels is increasing demands on row crop production and may also increase demand on forestlands. The Ultisols of the southeastern United States are similar to tropical Oxisols with low organic C concentrations of less than 1%, low CECs of approximately 5 cmol kg^{-1}, and low base saturation of usually less than

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30% (Perkins 1987). Char from energy production through pyrolysis may provide an opportunity to increase the productivity of southeastern soils, similar to the way charcoal functions in *terra preta*. However, because char characteristics vary with feedstock and pyrolysis conditions (Harris et al. 2006; Antal and Gronli 2003), a better understanding of the influence of these factors on char characteristics and the effect of different chars on soil processes in the southeastern United States is needed.

25.2 Pyrolysis Conditions and Char Characteristics

Char or charcoal corresponds to black carbons that result from the incomplete combustion (pyrolysis) of biomass. Black carbon consists of graphite-like planes (graphene layers) that show varying degrees of disorientation. The resulting spaces between these planes constitute porosity.

The capacity of char to remove impurities from solutions and gases has been known for many centuries. This is due to the porous nature of the material (Barkauskas 2002) and to the surface chemical properties including the type and number of functional groups (Stoeckli et al. 2004). Charcoal has chemical reactivity due to the existence of unsaturated valence (active sites) at the edges of the aromatic planes. The ratio of these active sites in relation to the inert carbon atoms within the graphene layers increases as the surface area increases. Heteroatoms, such as oxygen, hydrogen or nitrogen also have a strong influence on the mechanisms of the adsorption process. Oxygen is the most important heteroatom and is part of chemical groups that have both Lewis base properties such as chromene and pyrone or acidic properties such as anhydrides, lactones, lactols, phenols, carbonyls, and carboxyls. The presence and quantity of these groups affect the capacity of char to add to the cation or anion exchange capacity of the soil and other soil productivity properties. Charcoals are known to sorb cations (Lima and Marshall 2005) and also anions when basic surface oxides are present due to exposure to the atmosphere (Boehm 1994). These sorption capacities may create the potential for char to retain needed nutrients in the low exchange capacity soils of the southeastern United States.

25.2.1 Feedstocks

The mineral content of char depends upon the nature of the feedstock and can influence the surface chemistry by interaction with electrons of the aromatic rings and through electron paramagnetism (Benaddi et al. 2000). Ash complicates interpretation of surface phenomena of carbon. Ash solubility in water is variable, making the analysis of surface groups difficult at higher ash concentrations. Insoluble metal oxides can be involved in the charge development on the carbon surface and become charged in aqueous suspension; consequently, these are considered part of the active surface sites.

Feedstock particle size also affects char yield from pyrolysis. At low pyrolysis temperatures, larger particle sizes favor longer inter-pore residence time for volatiles, thus increasing char yield (Antal and Gronli 2003).

25.2.2 Pyrolysis Conditions

Important parameters that determine quality and yield of the carbonized product are the rate of heating, final temperature, and the gas environment (Bansal et al. 1988). A low heating rate during pyrolysis leads to lower volatilization and higher char yields. This creates char with higher carbon contents but does not affect char microporosity. In addition, chars developed at low heating rates are heavier and denser than those from high heating rates. This may be an advantage for agricultural use in terms of handling properties.

The final temperature during pyrolysis typically ranges between 400°C and 600°C, and does not exceed 800°C. Guo and Rockstraw (2007) observed that surface area and porosity did not develop at temperatures <300°C and that from 300°C onwards, the concentration of acidic surface groups decreased with increasing temperature. The decrease occurred more quickly between 300°C and 400°C, and slowed after 400°C, probably due to an equilibrium between decomposition and formation of strong acidic surface groups, or because most of the temperature-sensitive strong acidic groups had disappeared. Iyobe et al. (2004) reported that thermolysis of cellulose or lignin occurred actively at 400°C to 500°C, with the formation of acidic functional groups, such as carboxyls and phenolic hydroxyls. The amount of acidic functional groups continued to decrease with pyrolysis temperatures >600°C. Hydroxide (C-OH), C = O, and C-H groups are largely lost at temperatures >650°C, and most of the aromatic and C-H groups are decomposed above 750°C (Antal and Gronli 2003). Above 950°C chars are almost like graphite with little active chemistry on its surfaces resulting in a decreased ability to sorb cations. Asada et al. (2002) reported that char obtained by carbonizing bamboo at 500°C had the highest removal effect for NH_3 compared to carbonizing at 700°C or 1,000°C. In general, these data indicate chars produced at lower temperatures (400–500°C) may hold the greatest promise for agricultural use in terms of nutrient holding capacity.

The gas environment during pyrolysis also exerts considerable influence on char properties. Lower carrier gas flow rates result in longer residence time of vapors in the char matrix, which allows for char-catalyzed secondary reactions to occur. Steam may increase the presence of oxygen in surface functional groups (Strelko et al. 2002).

25.2.3 Comparison Between Traditional Two-Step Pyrolysis and Activation with One-Step Steam Pyrolysis

Typically chars produced at temperatures around 400°C to 600°C do not have the well developed surface areas seen in activated carbons because of tars deposited on the solid surface that restrict pore structures. Steam activation at temperatures between 800°C and 1,100°C physically removes these residues and opens pores. After activation, chars have higher surface area and adsorption capacity as well as a better pore size distribution (Gregova et al. 1994; Alaya et al. 2000).

The combination of this two-step process into a single step, which involves pyrolyzing under steam conditions, may increase surface area and increase adsorbent properties, and requires less energy and time. Steam pyrolysis at low temperatures (600°C) has been shown to increase micropores with the ratio of micropore volume to total pore volume approaching 95% (Alaya et al. 2000). These authors suggest that steam enhances the evolution of volatile molecules at lower temperatures and prevents the cracking of volatiles. In addition, gasification (conversion of solids to gases) is induced much earlier (600°C compared to 800°C to 900°C in non-steam environments) and results a more porous carbon skeleton. Chars produced at lower temperatures with steam may have a more active surface chemistry; however, the literature is not clear about the impacts of one-step processing on nutrient properties and surface chemistry.

Based on available literature on char and activated carbons, it appears that chars produced at low pyrolysis temperatures with steam may hold the greatest promise for agricultural use due to lower production costs, higher surface functional groups for sorption, and a denser product. Because chars produced at lower temperatures with steam may have some degree of activation due to the steam, we refer to char produced under these conditions as activated chars.

25.3 Agricultural Characteristics of Activated Char

25.3.1 Feedstock and Pyrolysis Condition Effects on Nutrient Status

Analyses of activated char from common feedstocks in the southeastern United States confirm the effect of feedstock and temperature on char composition. Total nutrients were analyzed in activated chars produced from peanut hull (PN), pine chip (PC), and hardwood (HW) feedstocks pyrolyzed at low temperatures (380°C, 400°C, and 420°C) with steam in a small furnace, and poultry litter (PL) at 400°C in a batch reactor in a steam flow environment (Table 25.1). At these pyrolysis temperatures, the initial nutrient content of the feedstock had a larger effect on activated char nutrient concentration than pyrolysis temperature (Table 25.1, Fig. 25.1).

Table 25.1 Total carbon and nutrient concentrations for feedstocks on an as is basis and activated chars (AC) produced from those feedstocks at 400°C with steam

	Peanut hull		Poultry litter		Pine chips		Hardwood	
Constituent	Feedstock	AC	Feedstock[a]	AC	Feedstock	AC	Feedstock	AC
C (%)	47.7	65.5	N/A	41.7	46.5	67.0	44.7	70.3
N (%)	1.44	2.00	3.80	3.70	0.05	0.14	0.20	0.30
C:N	33	33	N/A	11	949	543	224	234
S (%)	0.13	0.13	0.42	1.18	0.02	0.02	0.02	0.02
P (mg kg^{-1})	732	1,620	11,930	33,580	30.0	235	92.9	278
K (mg kg^{-1})	6,340	15,372	19,339	45,593	436	1,973	937	2,409
Ca (mg kg^{-1})	1,880	4,420	17,900	46,760	418	1,686	794	2,709

[a]Average Georgia broiler litter concentrations analyzed by the University of Georgia Agricultural and Environmental Services Laboratory.

N/A – not available.

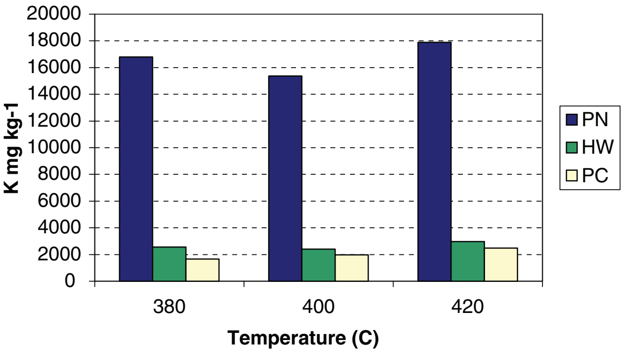

Fig. 25.1 Total potassium in activated char produced from pine chips (PC), hardwoods (HW), and peanut hulls (PN) pyrolyzed with steam at three temperatures

At these low pyrolysis temperatures, total N concentrations in the activated chars were similar to that of the initial feedstock (Table 25.1), and particularly high in the PL and PN activated chars at 3.7% and 2%, respectively. The PL activated char concentration was higher than that reported by Lima and Marshall (2005) for active carbon produced from boiler litter (0.75%) although the N concentration of the poultry litter feedstock was similar at 3.26%. The broiler litter active carbon was produced at 700°C and activated with steam at 800°C, which may have volatilized more N. The N concentrations in PC and HW activated char were similar to those reported for pinewood (0.11%) and oak board (0.18%) charcoal by Antal and Gronli (2003).

Although the N concentration of the PN activated char is potentially high enough to offer a substantial nitrogen input and the C:N ratio is relatively low (33, Table 25.1), the N does not appear to be readily available. Nitrogen mineralization studies were conducted with PN and PC activated chars produced in a pilot scale pyrolysis unit at 400°C with steam. Peanut hull activated char C and N concentrations were 72.85% and 1.90%, respectively in the activated char from the pilot plant, and PC activated char C and N were 76.99% and 0.17%, respectively. Nitrogen mineralization was very low in incubations (24-days at 25°C, 55% water filled pore space) of infertile, low C Tifton soils (fine-loamy, siliceous, thermic Plinthic Kandiudults) amended with these PN and PC activated chars at 11 and 22 Mg ha^{-1} equivalent rate (Table 25.2). There was no statistical difference in the change in NH_4^+ -N concentrations between the control and activated char amended soils (p = 0.05). There was a trend for higher NO_3^--N concentrations in the PN amended soils, but only the PN 11 Mg ha^{-1} rate was statistically different from the control.

We saw similar indications that N in the high N activated char was not plant available in the first year of field trials on similar Tifton soils with irrigated corn (Gaskin et al. 2006). Peanut hull activated char was incorporated to a depth of 15 cm in microplots (1.8 × 2.2 m) at rates of 0, 11 and 22 Mg ha^{-1} in a factorial combination with two rates of nitrogen fertilizer (0 and 213 kg N ha^{-1}) surface applied as ammonium nitrate. Earleaf N concentrations during the first growing season only showed a highly significant effect (p = <0.0001) due to N fertilizer. The mean N tissue concentrations in the PN activated char/no N fertilizer treatments averaged 1.13% for the PN 11 and 1.52% for the PN 22 treatment, and were similar

Table 25.2 Mean change after a 24-day incubation in NH_4^+-N and NO_3^--N in Tifton soils amended with peanut hull (PN) and pine chip (PC) activated char at 11 and 22 Mg ha^{-1}. Values in parentheses correspond to one standard deviation. Letters within the same column indicate statistical difference at the p = 0.05 level

Feedstock	*n*	ΔNH_4-N (mg kg^{-1})	ΔNO_3-N
PN 11	4	1.49 (0.24)	5.53b (0.65)
PN 22	4	0.94 (0.78)	5.08a (0.62)
PC 11	4	1.19 (0.36)	3.62a (0.51)
PC 22	4	1.44 (0.26)	4.41a (0.16)
Control	4	1.37 (0.38)	3.26a (1.66)

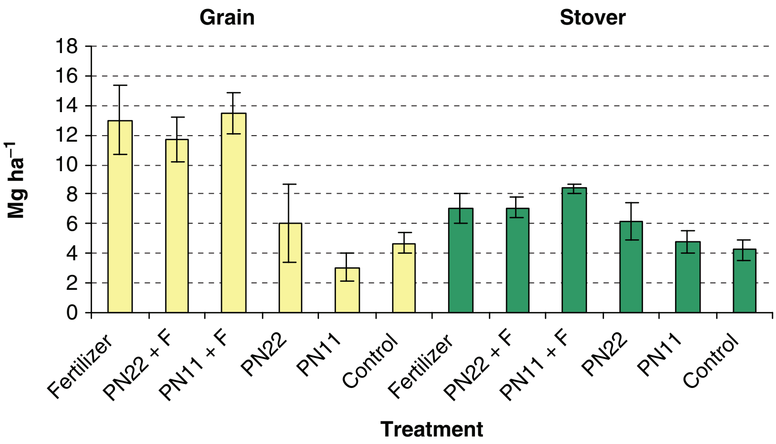

Fig. 25.2 Corn grain yield and stover (dry wt basis) from Tifton soil plots amended with peanut hull activated char at 11 Mg ha^{-1} (PN 11), peanut hull activated char at 22 Mg ha^{-1} (PN 22), 213 kg N ha^{-1} as ammonium nitrate (F), peanut hull activated char at 11 Mg ha^{-1} + N fertilizer (PN 11 + F), peanut hull activated char at 22 Mg ha^{-1} + N fertilizer (PN 22 + F), and an unamended, unfertilized control

to the control (1.40%). Nitrogen tissue concentrations in the N fertilized treatments averaged 2.91%. There was a highly significant (p = <0.0001) response to N fertilizer for both grain yield and stover (Fig. 25.2), but no significant (p = 0.7197) response due to activated char rate for grain yield. There was a significant (p = 0.0241) effect of activated char rate for stover yield. These preliminary data indicate, although some N in PN activated chars may be mineralizing, it may be insufficient and not readily available to microorganisms in the short-term (24-days) and not highly plant available over a growing season (approximately 4 months).

The activated char may serve as a source for other nutrients, particularly K, as indicated by the higher Mehlich-I K concentrations in the soil of the PN activated char amended plots at the end of the first growing season (Table 25.3).

25.3.2 Feedstock and Pyrolysis Condition Effects on Cation Exchange Capacity

The PN, PC, and HW activated chars (Table 25.1) were analyzed for CEC using a modified Na-acetate /ethanol/NH_4-acetate compulsory replacement method (Sumner and Miller 1996) with sodium analyzed by atomic absorption spectrophotometry. To avoid interference by ash, activated chars were leached with deionized water before analysis. In this preliminary study, there was a trend for a higher CEC at 400°C (Table 25.4).

25.3.3 Feedstock and Pyrolysis Condition Effects on Sorption Properties

Subsamples of the PC and PN activated chars (Table 25.1) pyrolyzed at 420°C were ground to <420 µm, washed with deionized water to remove soluble salts and air-dried. Activated chars were added to Tifton soils at the rate of 0.05 g activated char g^{-1} soil and phosphorus sorption isotherms were determined using batch techniques.

Table 25.3 Mehlich-I K concentrations in Tifton soil amended with factorial combinations of peanut hull activated char at 11 (PN 11) and 22 (PN 22) Mg ha-1 and 213 kg N ha^{-1} as ammonium nitrate (F). Values in parentheses correspond to one standard deviation. Letters within rows indicate statistical difference at p = 0.05 level. N = 4

Depth (cm)	Control	Fertilizer	PN 11	PN 11 + F	PN 22	PN 22 + F
	(mg kg^{-1})					
0–15	28.3a (8.7)	33.2a (12.6)	53.2b (6.8)	49.2b (9.9)	74.1c (11.0)	65.9c (14.3)
15–30	21.3a (4.4)	24.0a (8.4)	43.2b (4.1)	38.4b (7.4)	68.2c (11.3)	51.0c (7.0)

Table 25.4 Mean cation exchange capacity =/– standard deviation in peanut hull (PN), pine chip (PC) and hardwood (HW) activated chars produced at three pyrolysis temperatures with steam

Feedstock	Temperature 380°C	400°C	420°C
	(cmol kg^{-1})		
PN	36.7 +/– 0.76 (*n* = 4)	44.0 +/– 0.35 (*n* = 2)	28.0 +/– 5.26 (*n* = 4)
PC	18.6 +/– 1.34 (*n* = 3)	27.0 +/– 0.60 (*n* = 2)	16.5 +/– 2.42 (*n* = 4)
HW	22.6 +/– 0.04 (*n* = 2)	22.9 +/– 3.21 (*n* = 2)	14.1 +/– 0.34 (*n* = 2)

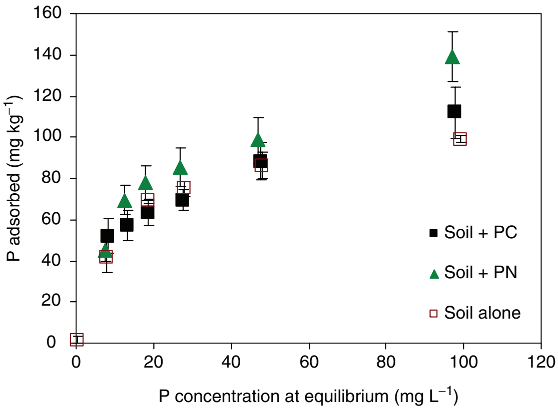

Fig. 25.3 Phosphorus adsorption isotherm form a Tifton soil amended with pine chips (PC), and peanut hull (PN) activated chars pyrolyzed at 420°C with steam at 0.05 g activated char g^{-1} soil

Soil-activated char mixtures were equilibrated with five concentrations of P (0, 5, 20, 50, and 100 mg P L^{-1}) in 0.01 M $CaCl_2$ matrix. The capacity and intensity of sorption by soil varied with the type of activated char added to soil. The amount of P sorbed was highest in soil amended with PN activated char, while the lowest P sorption occurred in unamended soil (Fig. 25.3). All systems showed a sharp increase in adsorption at low equilibrium P concentrations but sorption eventually reached a plateau. This is a characteristic of an L-*curve* isotherm where the adsorbate (P) has high affinity for the sorption sites but sorption diminishes regardless of the amount of adsorbate as surface area decreases (Sposito 1989). Such a relationship suggests a strong interaction between the P and the exchange surfaces and that the overall sorption was dependent on the properties of both components (Giles et al. 1960; McBride 1994).

25.4 Summary

Soils in the southeastern United States typically have low C concentrations, CEC, and base saturation. Studies of *terra preta* soils show charcoal has an important influence on these soils productivity, and reviews of the activated carbon literature illuminate some of the physical and chemical mechanisms involved. Activated chars may have the potential to supply nutrients, sorb cations and anions. The literature and our data indicate pyrolysis conditions and the feedstock have considerable effects on char characteristics. Our studies on activated chars produced from feedstocks commonly available in the southeastern United States indicate that their CECs can potentially increase the ability of low C loamy sands to retain nutrients. Some activated chars also have the potential to increase P sorption. It is unknown at this point if there would be subsequent desorption of P by char and what affect this may have on crops.

Preliminary studies indicate that activated chars with a relatively high N content such as those obtained from peanut hulls were not able to supply enough N for corn during the first year of cropping, but contain mineral nutrients such as K that are available to crops. Our preliminary work indicates activated char addition may have potential agricultural benefits, but a better understanding of how char from various feedstocks and produced under different pyrolysis conditions change soil processes and crop response is needed.

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Chapter 26
Black Carbon (Biochar) in Rice-Based Systems: Characteristics and Opportunities

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26.1 Introduction

The total amount of crop residues produced each year in rice-based systems of Asia can be roughly estimated at about 560 million tons of rice straw and about 112 million tons of rice husks (based on 2005 production, a harvest index of 0.5, and a husk/paddy ratio of 0.2). These residues constitute a valuable resource, but actual residue management practices do not use their potential adequately and often cause negative environmental consequences. In the past decades, increasing opportunity costs of organic fertilizer use and shortened fallow periods due to cropping intensification caused a continuous decline in the recycling of crop residues (Pandey 1998). Residue burning is widely practiced and causes air pollution, human health problems, and considerable nutrient losses. The declining return of organic materials to soils does not seem to affect soil quality in mostly anaerobic systems (rice-rice) with good soils but residue recycling is important to maintain soil fertility on poor lowland soils, in mixed cropping systems (rice-upland crop), and in upland systems (Dawe et al. 2003; Ladha et al. 2003; Tirol-Padre and Ladha 2006). Global climate change raises further questions about rice residue management. Decomposition of organic matter in flooded rice is always related to emissions of methane, which is about 22 times more radiatively active than CO_2, and rice-based systems are estimated to contribute 9% to 19% of global methane emissions (Denman et al. 2007). In addition, the rapidly increasing interest in renewable energy sources adds new options and consequences for rice residue management and rice-based systems.

An opportunity to address these issues in a completely new way arises from research on anthropogenic soils in the Amazonian region called *terra preta de índio* (Sombroek 1966). These soils are characterized by high contents of black carbon (carbonized organic matter, biochar) most probably due to the application of charcoal by Amerindian populations 500 to 2,500 years ago. They are also distinguished by a surprisingly high and stable soil fertility contrasting distinctively with the low fertility of the adjacent acid and highly weathered soils, which was at least partially attributed to their high content of black carbon (Lehmann et al. 2003). The high stability of black carbon in soils and its beneficial effect on soil fertility led to the

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

idea that this technology could be used to actively improve poor soils in the humid tropics (Glaser et al. 2001; Lehmann and Rondon 2006). However, most studies in this context concentrated on extensive production systems, on crops other than rice, and on wood as the source of black carbon. But black carbon can be produced by incomplete combustion from any biomass and it is a by-product of modern technologies for bioenergy production (pyrolysis).

Therefore, rice residues could be used to produce energy and thereby lower fossil energy consumption and related CO_2 emissions. The black carbon by-product could serve to recycle nutrients and maintain or even improve soil fertility. And the high stability of carbonized residues could help to reduce greenhouse gas emissions from rice-based systems and sequester carbon in rice soils. In this context, our study intended to: (1) give an overview of available information on carbonized rice residues; (2) test the agronomic effect of carbonized rice residues applications; (3) investigate the stability of carbonized rice residues under the special conditions of rice-based systems; and, (4) introduce one option demonstrating the link to energy production from rice residues.

26.2 Material and Methods

26.2.1 Field Experiments

Field testing of the effect of carbonized rice residues on rice growth and soil characteristics was conducted in three different environments: an irrigated lowland site with two rice crops per year (IRRI research farm in the Philippines; 14°11' N, 121°15' E; 21 m asl), a monocropped rainfed upland site (Siniloan, Philippines; 14°28' N, 121°29' E; 310 m asl), and a monocropped rainfed lowland site (Ubon Ratchathani, northeast Thailand; 15°14' N, 104°51' E; 127 m asl). Soil types were haplic Umbrisols at the IRRI farm, humic Ferralsols at Siniloan, and gleyic Acrisols at Ubon (FAO 2006). All sites have a tropical monsoon climate with an average rainfall of 2,027 mm a^{-1} at IRRI, 3,330 mm a^{-1} at Siniloan, and about 1,550 mm a^{-1} at Ubon. A completely randomized design with three replications was used at all sites and treatments were

T1: no rice husk, no fertilizer
T2: no rice husk, medium fertilizer rate
T3: 4.13 kg m^{-2} carbonized rice husk, no fertilizer
T4: 4.13 kg m^{-2} carbonized rice husk, medium fertilizer rate
T5: 4.95 kg m^{-2} untreated rice husk, no fertilizer
T6: 4.95 kg m^{-2} untreated rice husk, medium fertilizer rate

Carbonized and untreated rice husk were applied once at the establishment of the trial (wet season 2005) and incorporated to about 0.15 m depth. Fertilizer rates were site-specific and were 60–8.2–25 kg NPK ha^{-1} at IRRI, 60–25–25 ha^{-1} kg NPK at Siniloan, and 40–12–10 kg NPK ha^{-1} at Ubon. Fertilizer P and K were applied basal and N was applied in two equal splits at early tillering and panicle initiation. Varieties used depended on the site: IR72 at IRRI, APO at Siniloan, and KDML105 at Ubon. At IRRI and Ubon, rice was transplanted after puddling, whereas direct seeding without puddling was used at Siniloan. Grain and straw yield and grain moisture content were determined at harvest for 5 m^2 in each subplot. Total organic carbon (TOC; Nelson and Sommers 1996) was determined for top-soil samples (0–0.15 m depth) at the beginning, in the middle (not in the first season), and at the end of the cropping season. Selected samples were also analyzed for total N, P, K, Ca, Mg, and Si (Bremner 1996; Soltanpour et al. 1996). Bulk density was determined at the end of the cropping season in each subplot and for two depths (0–7.5 and 7.5–15 cm, three repetitions in each subplot).

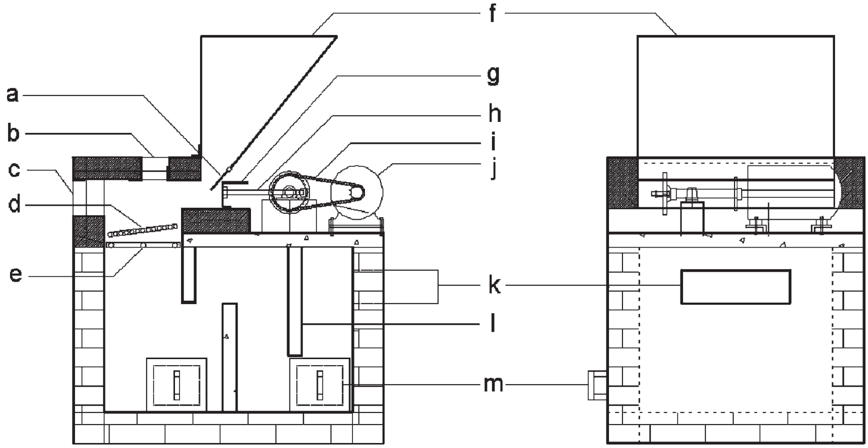
26.2.2 Mineralization Experiments

Mineralization of untreated and carbonized rice husks was quantified in laboratory incubations using samples from two wetland soils (calcaric Fluvisols) in the tidal zone of the Elbe River in northern Germany. The site "Assel" was at the shoreline of the river being flooded at high tide. The vegetation was dominated by *Typha angustifolia*. The second site ("Haseldorf") was a diked grassland that was sampled at the rim of a shallow drainage channel. Samples were taken in April 2006 from the uppermost 20 cm. Three different treatments (no addition of organic matter, addition of 2.5% (w:w) carbonized rice husks, and addition of 2.5% (w:w) untreated rice husks) were incubated under oxic and anoxic conditions. To enhance availability, the amended organic material was milled prior to addition to the soil. Samples for anoxic incubations were processed in a glove box under N_2. 50 g of field fresh sample were filled into glass bottles that were closed airtight with rubber stoppers. The headspace (500 ml) was evacuated and replaced by N_2 to establish oxygen-free conditions. Headspace pressure and gas concentrations (CO_2, CH_4) were measured repeatedly by gas chromatography to calculate CH_4 and CO_2 production rates. For oxic incubations, 50 g soil samples (50% of maximum water-holding capacity) were filled into 1 L vessels. A small beaker with 2 ml of 2 M NaOH was introduced to trap the CO_2 produced. Vessels were closed airtight containing an atmosphere of ambient air. At regular intervals, vessels were opened, a new CO_2 trap placed in the vessels, the headspace exchanged with air to compensate for consumed oxygen, and the soil moisture adjusted if necessary. The CO_2 produced was quantified by acid distillation with 0.1 N HCl after transferring the content of the CO_2 trap into 5 ml of a 0.5 M $BaCl_2$ solution. All treatments were replicated four times. All samples were incubated at 28°C in a temperature-controlled incubator for 9 months (oxic incubations) and 1 year (anoxic incubations), respectively.

26.2.3 Rice-Hull Furnace Development and Testing

The introduction of double cropping systems often leads to increased demand for mechanical rice dryers because the traditional sun drying of paddy is either not possible or causes high grain quality losses during the wet season harvest. Mechanical drying of rice requires the energy equivalent of 10–15 L of kerosene per ton of paddy. Rice husks as a by-product in the milling process are free or cheap and do not produce net CO_2 emissions when burned. They are therefore an obvious energy source for paddy drying or power production. Such technology is used by large mills for example in Thailand which increasingly burn rice husks for power production and sell the carbonized remains for various purposes. However, existing furnaces for small to medium-size rice mills have poor rice-husk feeding mechanisms, resulting in high labor requirement, an uneven burning process and temperature, and low furnace efficiency, and the flue gas often contains smoke and fly ash.

A new semi-automatic down-draft rice-husk furnace, developed by IRRI (Philippines), Hohenheim University (Germany) and Nong Lam University (Vietnam), for small to medium-size rice dryers, has an adjustable automatic feed mechanism for setting the retention time of the rice husk inside the burning chamber (Fig. 26.1). The piston pushing the husk through the combustion chamber removes the ash simultaneously. By increasing the feed rate and thus decreasing the



a Flap
b Primary air inlet
c Ash outlet
d Grate
e Secondary air holes
f Feed hopper
g Piston
h Connecting rod
i Speed reducer drive
j Electric motor
k Flue gas outlet
l Baffles
m Inspection hole

Fig. 26.1 Details of the commercial prototype of the rice husk furnace (modified from Chandrasekar 2005), developed by IRRI (Philippines), Hohenheim University (Germany), and Nong Lam University (Vietnam) retention time of the rice husk in the burning chamber, the degree of husk burning (i.e. carbonization) can be adjusted. Various prototypes of the furnace were tested in the Philippines and in Vietnam and optimized with respect to furnace efficiency, labor efficiency, and CO emissions. The furnace can be produced locally but requires electricity for the automatic feed mechanism and a simple electronic controller setting the piston movement frequency.

26.3 Results and Discussion

26.3.1 Literature Review on Use and Characteristics of Carbonized Rice Residues

According to personal experience and mostly gray literature (e.g. FFTC 2001; Bulford 1998; PhilRice 2002), carbonized rice residues are produce and used in several Asian countries; however, few research studies on this topic were published. The widespread and old practice of burning rice straw in the field indicates that black carbon from incompletely burned (i.e. carbonized) rice residues could be an important source of soil organic matter in rice soils, as was shown for a range of other soils (Schmidt and Noack 2000), but no comparable studies have been conducted for rice soils. Only in Japan, where carbonized rice husk known as *Kuntan* has been used in various ways for centuries, have several studies been published. Handbooks on the use of Kuntan in agriculture were published as early as the 1910s in Japan. Traditionally, it is used as a cover material for rice nurseries and as a soil amendment in home gardens. Since the 1970s, Kuntan has received increasing attention as a component of growth media in soil-less culture and is frequently used today for the production of ornamental plants (Tanbara et al. 1973; Kato et al. 1996; Islam and Ito 2000).

Carbonized rice husks are a very light material with a microporous structure and a bulk density of about 0.150 g cm^{-3} (Nakajima 1986). The structure of rice husks is preserved in the carbonization process but carbonized husks break easily, especially if carbonized at high temperatures. Carbonization significantly improves the water-holding capacity of rice husks because water-repellent substances such as tars are volatilized in the process (Oshio et al. 1981). The chemical properties of Kuntan vary considerably depending on the temperature and the duration of the carbonization process. The first effects in the carbonization process are the loss of moisture and the decomposition of starch, hemi-cellulose, and cellulose into saccharides. Most saccharides are further decomposed into carbon dioxide until the temperature of carbonization reaches 400°C. Water-repellent substances such as tar are volatilized at temperatures around 500°C (Oshio et al. 1981; Yanagita et al. 1997). Carbonization of rice husks does increase the concentration of most elements present, and causes the husk to become alkaline (Table 26.1). Cation exchange capacity (CEC) of Kuntan reaches its maximum at carbonization temperatures of

Table 26.1 Selected chemical characteristics of rice husk (RH) and carbonized rice husk (CRH) adapted from Oshio et al. (1981) and comparison with untreated and carbonized rice husk used in field experiments and a typical charcoal sample

Material	pH	C	N	P	K	Ca	Mg	Si	CEC
		(g kg^{-1})							(cmol kg^{-1})
RH untreated	6.7	399	5.8	0.4	5.0	–	–	–	11.2
CRH, 300°C × 10 min	7.1	456	7.8	0.5	6.6	–	–	–	9.5
CRH, 400°C × 10 min	9.2	526	6.1	1.0	15.9	–	–	–	18.8
CRH, 500°C × 10 min	10.0	531	6.0	1.0	15.9	–	–	–	18.1
CRH, 600°C × 10 min	10.8	546	6.0	1.2	16.5	–	–	–	16.7
RH untreated[a]	6.8	362	6.9	1.4	4.5	0.6	0.8	95	–
CRH[a]	8.6	398	12.3	4.5	10.3	1.5	2.5	204	–
Charcoal[a]	9.0	805	9.4	1.2	11.2	11.8	1.3	1	–

[a]Average data of untreated rice husk and carbonized rice husk used in the field experiment and from a charcoal sample (deciduous tree).

about 400°C. For comparison, Table 26.1 also shows analytical results from the untreated and carbonized rice husk used in the field trials described below, which are similar to the values reported by Oshio et al. (1981). The comparison with a charcoal sample indicates that charcoal has higher concentrations of C and Ca but much lower concentrations of Si (Table 26.1). Newly prepared Kuntan is microbiologically sterile due to the high temperatures prevailing in the process but its microporous structure provides habitats for microorganisms. According to field observations, Kuntan has anti-pathogenic functions, possibly related to fungicidal constituents (Miyakado et al. 1977). Application of a Kuntan layer of 1–3 cm on animal dung reduced ammonium gas emissions by 50% to 89% (Matsumoto et al. 1994). Yamada et al. (1992) found that the application of Kuntan (35 t ha^{-1}) with and without compost increased soil water-holding capacity and yields of spinach and Chinese cabbage, and lowered the irrigation requirements. Kuntan placement in ridges (10% of the ridge volume) promoted soil aeration and water-holding capacity, and decreased CO_2 concentration surrounding the roots, thus increasing the yield of sweet potato by 40% (Islam et al. 2000). Yield-increasing effects of Kuntan application on upland rice in West Java were reported by Ratna et al. (1996) and Sophal et al. (2006) found positive effects in lowland rice of Cambodia.

26.3.2 *The Effect of Black Carbon from Rice Residues in Field Trials*

Given the experience of black carbon production and use in Japan, we used carbonized rice husks for our experiments. Black carbon production from rice residues was based on a simple method used by Japanese farmers. The rice husk (about 1 m^3) was piled up around a small fire in a burning chamber with a chimney, and the carbonization advanced from the inside to the outside. When the rice husk pile was black on the outside, the husks were spread out, sprayed with water, and then dried in the sun. The weight loss during this process was determined by placing samples of untreated rice husks in a steel mesh in the pile during carbonization. On average, this indicated a weight loss of 68% during carbonization, and the density increased from 0.117 g cm^{-3} for untreated rice husks to 0.140 g cm^{-3} for carbonized rice husks. Elemental concentrations measured in untreated and carbonized rice husks are given in Table 26.1. They indicate considerable losses of C (65%) and N (43%), whereas losses of Si, P, K, Ca, and Mg were small (calculated based on weight loss and elemental concentration).

In total, about 17.9 t ha^{-1} carbon were applied with untreated husks (treatments T5/T6) and about 16.4 t C ha^{-1} with carbonized rice husks (treatments T3/T4). The treatment effect on total organic carbon (TOC) concentration is shown in Fig. 26.2. Non-homogeneous incorporation of the applied rice husks in the top soil is indicated by large standard deviations from the treatment mean for the first two samplings at IRRI. The initially very high TOC concentration for T5/T6 in Siniloan was most probably caused by an incomplete and shallow incorporation of the untreated rice husks. At IRRI, TOC values for T5/T6 reached the level of the control treatments (T1/T2) at the start of the second cropping season (February 2006), indicating fast and nearly complete mineralization of the added residues. In Siniloan, TOC values for the T5/T6 treatments stabilized at an intermediate level between the control treatments (T1/T2) and the treatments in which carbonized rice husks were applied (T3/T4) from the end of the first cropping season onward. Only soil samples from the first rice season were analyzed for Ubon and only the treatments T3/T4 showed an increased TOC concentration. The application of carbonized rice husks (T3/T4) increased TOC significantly and lastingly at all sites. Using bulk density measurements and TOC concentrations, we estimated the treatment-dependent total amount of TOC at the end of the 2006 wet season (end of the 2005 wet season at Ubon) (Table 26.2). Comparison of average TOC amounts between the control treatments T1/T2 and T3/T4 suggests that little or none of the applied carbonized rice husk was mineralized at IRRI and Siniloan, whereas losses of about 6 t ha^{-1} are indicated at Ubon. In contrast to that, the comparison between the control treatments T1/T2 and T5/T6 suggests that all applied untreated rice husks were mineralized at IRRI, more than 90% were mineralized at Ubon, and about 60% were mineralized at Siniloan.

Average grain yields were highest at IRRI (irrigated system) and considerably lower at the rainfed upland (Siniloan) and lowland site (Ubon) (Table 26.3). In most cases, fertilizer application (treatments T2, T4, and T6) increased grain yields significantly but non-significant increases or even decreases were observed at Siniloan. Neither at IRRI nor at Siniloan did the application of untreated or carbonized rice husks have a significant yield-increasing effect. Only at Ubon did the application of carbonized rice husk significantly affect rice yield, and this effect was stronger in the second season.

The characteristics of the carbonized rice husk used in the field experiments are comparable to values reported by Oshio et al. (1981) (see Table 26.1) and the carbon recovery (35%) and weight loss (68%) were similar to values estimated for

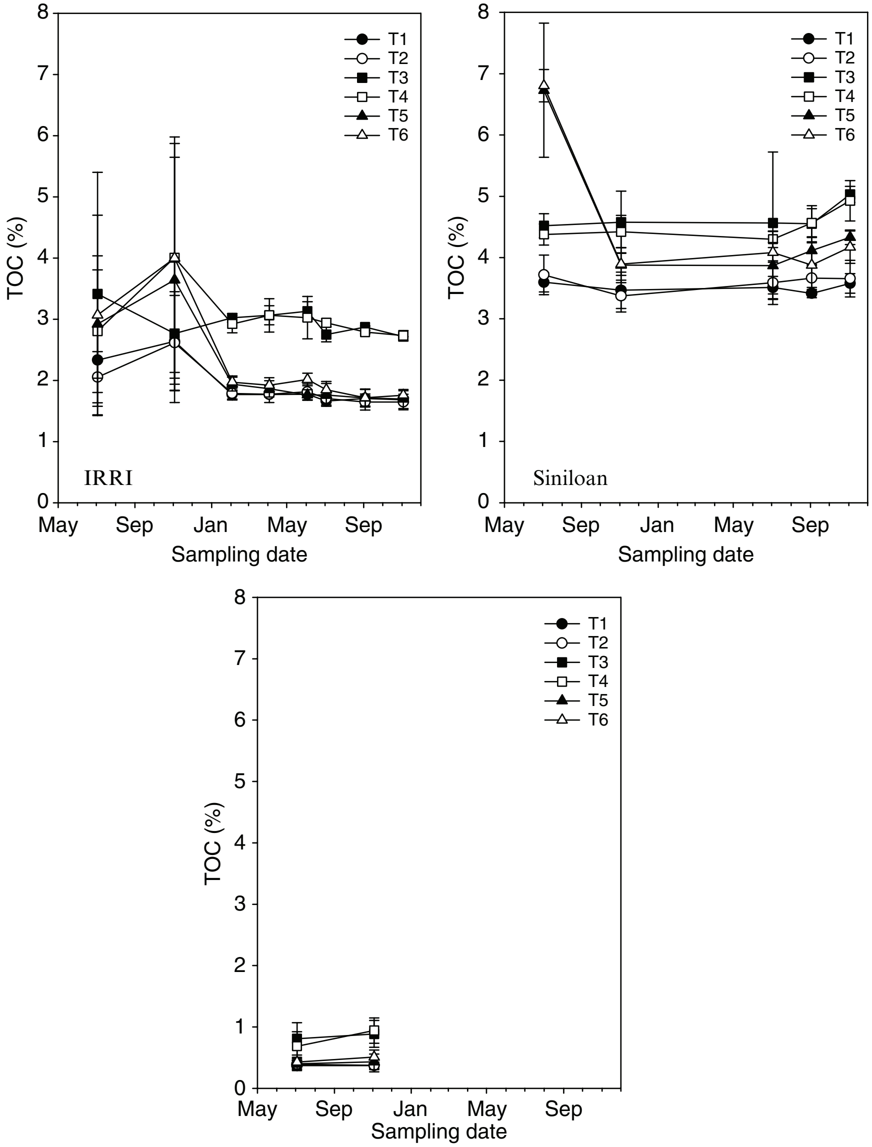


Fig. 26.2 Development of total organic carbon (TOC) concentration in the topsoil (0–0.15 m) for all treatments of the field experiments at IRRI, Siniloan (both in the Philippines), and Ubon (northeast Thailand). Data presented cover a period of 1.5 years, with the exception of the Ubon site, where only data from the first season were available

simple charcoal production methods (Lehmann and Rondon 2006) and the rice husk furnace described below (see Fig. 26.4), respectively. The technique used to carbonize rice husks for the field experiments did produce considerable amounts of smoke and the husk analysis showed that apart from carbon substantial amounts of nitrogen are emitted. Therefore, this technique cannot be recommended at a larger

Table 26.2 Bulk density of the soil (B_d) and concentration and amount of total organic carbon (TOC) in the topsoil layer (0–0.15 m) for all treatments of field experiments at the end of the wet season 2006 at IRRI and Siniloan, and at the end of the wet season 2005 in Ubon

Site	Treatment	B_d (g cm^{-3})	TOC (wt%)	TOC (t ha^{-1})	ΔTOC[a] (t ha^{-1})
IRRI	T1	0.98	1.71	25.1	
	T2	0.98	1.65	24.2	
	T3	0.98	2.87	42.0	16.2
	T4	0.95	2.79	39.7	
	T5	0.94	1.71	24.2	−0.6
	T6	0.93	1.72	23.9	
Siniloan	T1	0.91	3.58	48.6	
	T2	0.90	3.66	49.2	
	T3	0.88	5.03	66.5	16.8
	T4	0.88	4.93	65.0	
	T5	0.85	4.33	55.0	5.2
	T6	0.85	4.17	53.2	
Ubon	T1	1.43	0.373	8.0	
	T2	1.48	0.377	8.4	
	T3	1.41	0.887	18.7	10.6
	T4	1.33	0.943	18.8	
	T5	1.39	0.435	9.0	1.8
	T6	1.44	0.511	11.0	

[a]Average difference between the control treatments T1/T2 and T3/T4 and between the control treatments T1/T2 and T5/T6.

Table 26.3 Grain yields at 14% moisture content for all treatments of field experiments at IRRI, Siniloan (both in the Philippines), and Ubon (northeast Thailand). Only at the irrigated IRRI site was wet-season (WS) and dry-season rice (DS) grown

Site	Treatment	2005 WS grain yield (t ha^{-1})[a]	2006 DS grain yield (t ha^{-1})[a]	2006 WS grain yield (t ha^{-1})[a]
IRRI	1	3.84cd	2.89b	3.02c
	2	5.22ab	4.82a	4.94a
	3	3.81d	2.68bc	2.89c
	4	4.72bc	4.79a	4.32ab
	5	4.14cd	2.32c	2.50c
	6	5.81a	4.41a	4.04b
Siniloan	1	3.01a		3.01a
	2	2.56[b]a		3.19a
	3	3.52a		3.30a
	4	2.83[b]a		3.29a
	5	3.42a		3.02a
	6	2.74[b]a		3.39a
Ubon	1	2.63b		2.18c
	2	3.31ab		2.63b
	3	2.73b		2.76b
	4	3.71a		3.33a
	5	2.61b		2.27c
	6	3.10ab		2.88b

[a]Yield results from one site and followed by a common letter are not significantly different according to the tukey-kramer test with $p < 0.05$.
[b]Excessive nitrogen supply with negative effects on grain yield was indicated by lodging.

scale. With the exception of nitrogen, nutrient losses during the carbonization process were limited and the application of carbonized rice residues could thus contribute to the recycling of nutrients.

The total amount of untreated and carbonized husks applied in the experiments was relatively high if compared to usual rates of organic matter used in agronomic trials. This high rate in one initial application was mainly chosen to facilitate tracing of the applied carbon and because the purpose of carbon sequestration would require substantial carbon application rates. It is important to note that the chosen rate does not represent an optimal rate for rice growth, which is unknown and would depend on several factors, including soil properties and concurrent nutrient and organic matter additions (Lehmann and Rondon 2006). Good agronomic effects in other crops have been achieved with rates between 0.4 and 8.0 t C ha^{-1} (Lehmann and Rondon 2006) and negative effects of rates below 20 t C ha^{-1} have not been reported.

A main objective of the field trials was to investigate whether carbonized rice residues are resistant to bio-degradation in a range of rice environments. Sites differed in cropping intensity (IRRI > Siniloan/Ubon), soil preparation (with or without puddling), duration of aerobic conditions and/or soil drying (Ubon > Siniloan > IRRI), and indigenous soil fertility (IRRI > Siniloan > Ubon). Across sites, fertilizer treatments did not significantly affect the bio-degradation of untreated or carbonized husks. Important factors for a rapid bio-degradation of soil organic matter (SOM) are a neutral to alkaline soil pH, good soil water supplies, high indigenous or external nutrient supplies, intensive soil tillage, and soil temperatures of 30–35°C; SOM stabilizing factors are interactions with clay minerals (strongest for three-layer minerals) and sesquioxides (Zech et al. 1997; Neue et al. 1990). Consequently, fast and complete bio-degradation of untreated rice husk (49.5 t ha^{-1} applied!) was observed at IRRI (neutral pH, good nutrient supply, intensive tillage), whereas only partial mineralization was observed at Siniloan (low pH, low nutrient availability, high sesquioxide content) (Fig. 26.2, Table 26.2). The data from Ubon (low pH, low nutrient availability, coarse texture) are not yet complete but seem to be intermediate. In contrast to these results, the observations for applied carbonized rice husk suggest that no or very little bio-degradation occurred at IRRI and Siniloan (Fig. 26.2, Table 26.2). At Ubon and after one cropping season, the estimated amount of C from carbonized husk in the topsoil (10.6 t C ha^{-1}) is much below the applied amount (16.4 t C ha^{-1}) but this is most likely due to a transport into the subsoil and TOC profiles are targeted for all sites in the coming season.

Positive yield and/or biomass responses resulting from carbonized wood (charcoal) applications were reported repeatedly and attributed to direct nutrient additions, higher nutrient retention and availability, increased exchange capacity, improved soil physical characteristics, and positive effects on soil microorganisms (Lehmann and Rondon 2006; Glaser et al. 2002). Our results indicate that yield-increasing effects of carbonized rice husk applications were limited to poor soils in water-limited environments (Ubon). In such systems, the relative improvement of soil fertility will be highest, whereas the improvement of soil quality will be small on fertile soils. It was also observed that the yield-increasing effect of charcoal increased over the first few years after application (Rondon et al. 2006), indicating that the applied charcoal increased its positive characteristics such as surface oxidation leading to increased cation exchange capacity (Cheng et al. 2006). The yield data from Ubon and Siniloan (Table 26.2) suggests such a trend but at least one more season will be necessary to confirm this development.

26.3.3 Bio-degradability of Carbonized Rice Residues in Incubation Experiments

The addition of untreated rice husks to surface soil samples of two fluvisols from northern Germany resulted in an immediate increase in microbial organic matter mineralization (Fig. 26.3). In all incubations, CO_2 and CH_4 production rates were highest at the beginning of the experiment and decreased rapidly, reaching up to 16-fold lower values after 9 months (aerobically) and 1 year (anaerobically). The Assel soil showed a stronger response to untreated rice husk addition since aerobic CO_2 production rates increased by a factor of 2.6 (2.0 for Haseldorf), anaerobic CO_2 production by a factor of 3.6 (2.0 for Haseldorf) and methane formation by a factor as high as 6.9 (1.8 for Haseldorf). Furthermore, the total additional carbon mineralized, calculated as the difference between the amount of CO_2 and CH_4 released from the control treatment and the rice husk treatment, was higher in the Assel soil (aerobically 544 μmol gdw^{-1}, anaerobically 672 μmol gdw^{-1}) than in the Haseldorf soil (aerobically 499 μmol gdw^{-1}, anaerobically 237 μmol gdw^{-1}) (Table 26.4). In contrast, if carbonized rice husks were added, no significant increase in CO_2 and CH_4 production was found. Only when comparing initial aerobic mineralization rates in the Assel soil did the addition of carbonized rice husks affect carbon mineralization rates, both positive (anaerobic CO_2 formation) and negative (aerobic CO_2 formation and CH_4 formation). But the latter effect was transient and final rates and total CO_2 and CH_4 formation over the whole incubation period did not differ significantly between the treatments with and without the addition of carbonized rice husks.

The aerobic degradation of soil black carbon (BC) has been proven by direct and indirect approaches; however, the mineralization pathways and fate of the degradation products are still unclear. Based on the abundance of BC in soil plots affected and those being protected from fire, Bird et al. (2000) found evidence that BC can be turned over in well-aerated tropical soils on a decadal to centennial time scale. A rapid degradation or translocation of BC was also proposed for boreal soils affected by burning (Czimczik et al. 2003). However, the fate of the degraded carbon remained unclear. Hockaday et al. (2006) studied degradation products deriving from about 100-year old charcoal particles in a temperate forest soil and found evidence that particulate BC is transferred into the soluble organic matter fraction and may be further oxidized by soil microorganisms. The potential of aerobic microorganisms to degrade high-molecular-weight humic substances from BC to low-molecular-weight compounds has been shown repeatedly especially for low-rank coal (Fakoussa and Hofrichter 1999; Hofrichter et al. 1999). Although it

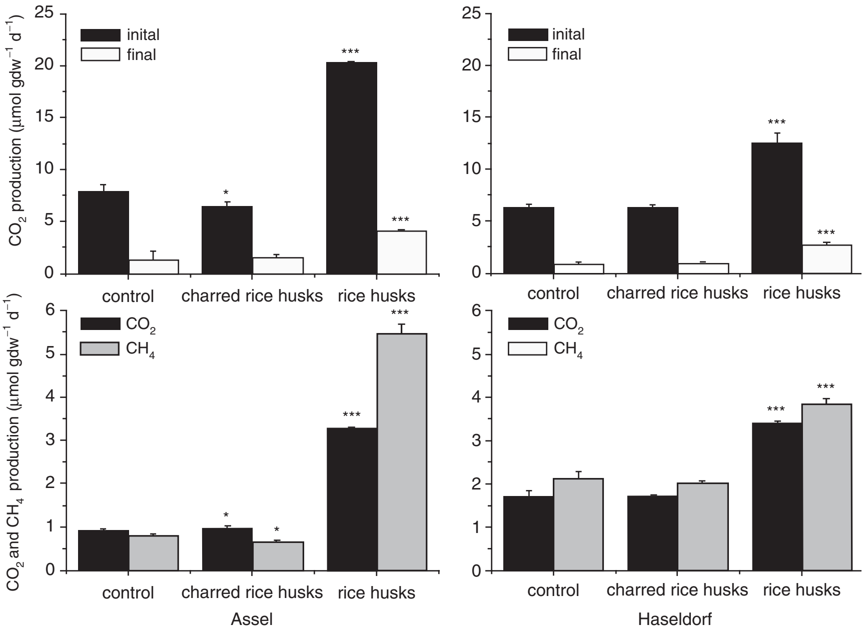


Fig. 26.3 Carbon mineralization rates in incubation experiments with two fluvisols from the Elbe River, i.e., Assel (left panels) and Haseldorf (right panels). Soils were incubated under oxic (upper panels) and anoxic (bottom panels) conditions. Initial rates (black columns) and final rates (white columns) at the end of the experiment are presented for oxic incubations. Initial methane (black columns) and carbon dioxide (gray columns) production rates are presented for the anoxic incubations. The three different treatments were the control (without addition of organic matter), charred rice husks (addition of 2.5% charred rice husks), and rice husks (addition of 2.5% untreated rice husks). Significance levels indicated are * = $p < 0.05$, *** = $p < 0.001$

became clear that BC may be degraded to soluble organic matter by microorganisms, proof for a microbial mineralization to CO_2 is still lacking. Baldock and Smernik (2002) used artificial soil, inoculated with microbial cultures, to determine the affect of heating on the chemical composition and microbial degradability of Red pine timber. When this wood was heated above 200°C, the chemical composition changed significantly but the microbial degradation of the respective products became almost negligible. Incubation experiments similar to our approach generally gave no evidence for substantial CO_2 production from charred organic matter. Cheng et al. (2006) studied biotic and abiotic charcoal oxidation from black locust (*Robinia pseudoacacia* L.) under laboratory conditions using samples of a Brazilian savanna soil (Anionic Acrustox). They did not find any indication of microbial oxidation over an incubation period of 120 days. Quantification of CO_2 production from volcanic ash soils amended with charred grassland plant material did not indicate any degradation of black carbon over a period of 40 weeks (Shindo 1991). But even if the final fate of carbon from carbonized organic material remains unclear, it is evident that the addition of BC material to aerobic soils does not substantially increase the release of CO_2 on an annual time scale.

Table 26.4 Amount of CO_2 and CH_4 produced (in µmol gdw^{-1}) over a period of 9 months (aerobic) and 1 year (anaerobic), and initial carbon content for all treatments. Values in parentheses denote the standard deviation

	Assel			Haseldorf		
	Control	Carbonized rice husks	Untreated rice husks	Control	Carbonized rice husks	Untreated rice husks
Oxic						
CO_2	378.7	372.1	922.5**	353.4	395.0	852.8***
	(±58.7)	(±66.83)	(±198.7)	(±20.2)	(±37.8)	(±16.9)
Anoxic						
CO_2	88.0	95.5	399.4***	135.4	124.1	245.1***
	(±9.7)	(±7.7)	(±22.2)	(±9.8)	(±8.7)	(±20.2)
CH_4	104.6	97.0	465.4***	163.6	138.5*	290.7***
	(±14.3)	(±12.4)	(±27.6)	(±11.8)	(±10.7)	(±28.2)
C_{org} (%)	3.4	5.7	5.3	4.1	5.6	5.3

Significance levels of difference between treatments for each soil are * = $p < 0.05$, ** = $p < 0.01$, and *** = $p < 0.001$ using the t-test and SatSoft STATISTIKA 7.1.

Under anaerobic conditions, organic matter is mineralized in terrestrial soils mainly to CO_2 and CH_4. The addition of untreated rice husks to the two fluvisols resulted in a strong increase in CH_4 and CO_2 production, demonstrating the potential of the soils to rapidly decompose fresh organic carbon. After 1 year, 23% of the carbon added as untreated rice husks to the Assel soil was transformed to CH_4 and 20% to CO_2. Since CH_4 is a much more powerful greenhouse gas than CO_2, anaerobic carbon degradation was of particular interest. However, the addition of carbonized rice husks did not increase the amount of both CH_4 and CO_2 released and we have no indication for an anaerobic degradation of BC in our incubations. Transformation of BC under anoxic conditions has been studied mainly on coal and there is evidence that coal or some of its components might support microbial activity, including methane production (Detmers et al. 2001; Krüger et al. 2007). On the other hand, significant anaerobic turnover of BC is impeded by several reasons. High-molecular-weight BC, containing condensed aromatic ring structures, has to be dissolved and cleaved into low-molecular-weight compounds to allow microbial degradation, but known enzyme systems for BC degradation depend on molecular oxygen (Fakoussa and Hofrichter 1999). Furthermore, the anaerobic degradation of light polycyclic aromatic hydrocarbons by microorganisms has been described under nitrate- and sulphate-reducing conditions (Galushko et al. 1999; Rockne et al. 2000); however, this process is very slow and it seems unlikely to occur with significant rates in the case of hydrophobic particulate BC being composed of condensed aromatic structures. Consequently, Middelburg et al. (1999) reported the degradation of BC in marine sediments only under oxic but not anoxic conditions on a time scale of 10–20 kyear. In summary, our results of laboratory incubations give no indication that the addition of carbonized rice residues leads to a significant additional liberation of CO_2 and CH_4. Although carbonized organic matter may be degraded in oxic soils, turnover could not be detected on an annual time scale. Degradation rates under anoxic conditions are expected to be even slower, considering the absence of a strong oxidant needed for cleavage of condensed aromatic ring structures of BC.

26.3.4 Integrated Use of Rice Residues in Rice-Based Systems

The evaluation of the new rice-husk furnace prototypes (Fig. 26.1) in 2006 by IRRI and the Philippine Rice Research Institute (PhilRice) in the Philippines and by NLU in Vietnam has shown that the new furnace concept has many advantages over conventional rice-husk furnaces and in particular over air heaters that use kerosene burners as a heat source.

Because of the continuous feeding of the husk by the piston, heat generation was even and combustion smoke-free. In conventional furnaces, the operators feed new rice husk and remove the ash on average every 5 min, which generates temperature variations and temperature peaks in 5-min cycles. In the new furnace, a constant drying air temperature of 43°C can be easily maintained and with optimum settings the carbon monoxide content of the flue gas is less than 0.03% (Fig. 26.4). Fly ash

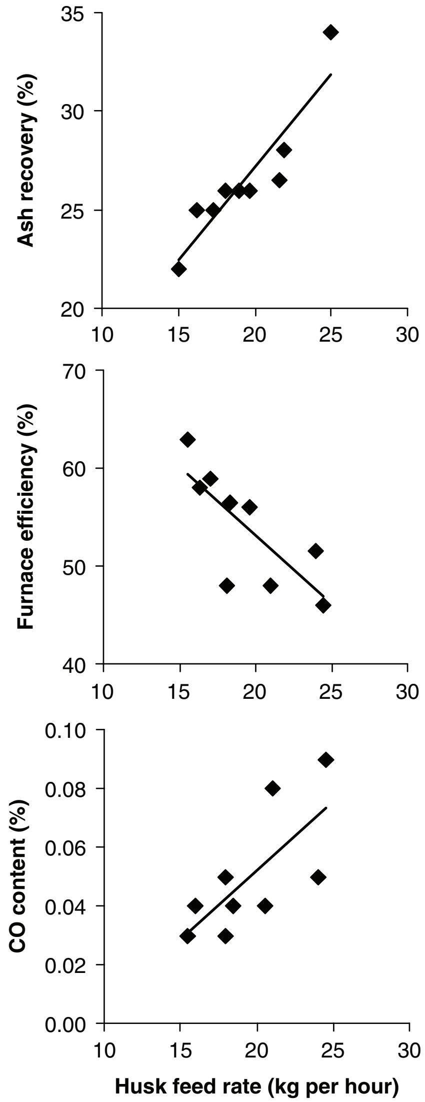


Fig. 26.4 Ash recovery (in w% of fresh rice husk), furnace efficiency, and carbon monoxide content in the flue gas as a function of feed rate of the improved rice-husk furnace. The furnace was designed for medium-size rice dryers with a capacity of 4 t per batch

often contained in the flue gas of other furnaces is prevented because of the downdraft principle and remaining small amounts of fly ash are separated by specially designed baffles in the burning chamber.

In a typical dryer with 4 t capacity, every batch of paddy is usually dried for around 8 h. For this, up to 60 L of kerosene are used in conventional dryers, which can be replaced by 120 to 200 kg of rice husk in the new rice-husk furnace. Per batch dried, this translates into savings of at least 192 kg of CO_2 emissions. Furnace efficiency reached up to 63% (Fig. 26.4), which is a good value for a small-scale furnace, ensuring low rice husk consumption. Rice husks are available at rice mills, where most drying takes place, at no cost, thereby reducing energy costs. Further cost savings result from the much reduced labor requirements because the new furnace is fed only every 60 min (compared with every 5 min in conventional furnaces) and the operator does not need to remove the ash.

Initial tests conducted at IRRI in the Philippines indicated that the new furnace can also be used for the production of carbonized rice husks by increasing the husk feed rate. This causes a reduced retention time for husks inside the furnace, leading to incomplete combustion. Increasing the feed rate from 15 to 25 kg h^{-1} increased the ash (i.e. the carbonized rice husk) recovery from 22% to 34% but decreased furnace efficiency from 63% to 45% by reducing the amount of heat available for drying (Fig. 26.4). The CO content in the flue gas increased from 0.03% to 0.09% with the higher feed rate but still remained within acceptable limits. The ash from experiments with a higher feed rate had few gray ash particles, which increased its market value as carbonized rice husk in the Philippines. The weight loss at the higher feeding rates was similar to the weight loss observed during the production of carbonized rice husk for the field experiment, indicating that both processes resulted in a similar product. The main effect of the lower furnace efficiency is an increase in labor cost because more frequent feeding of the hopper is needed, whereas free rice husks keep fuel costs low. Where possible, sale of the carbonized rice husks could compensate for the higher labor costs.

It can be concluded that the benefits of the new rice-husk furnace design include clean and even combustion, fuel efficiency, environmental friendliness, lower costs, and the option to produce carbonized rice husks as a by-product from paddy drying. Consequently, commercialization of the new technology has started in the Mekong Delta of Vietnam, with three commercial units installed in 2006 at rice mills and farmer cooperatives for rice dryers with a batch capacity of 4 t. Further adaptive research is ongoing to adjust the furnace for rice dryers with a batch capacity of 8 t since operators in Vietnam are shifting to the bigger dryers.

26.4 Conclusion

This study intended to verify the basic components of black carbon technology for rice-based systems. The results indicate that black carbon amendments from carbonized rice residues can increase the fertility and productivity of poor soils but may have little effect on fertile soils, and that such amendments appear to be relatively stable in various soils and rice environments, thereby providing an option to reduce greenhouse gas emissions and to sequester carbon in rice-based systems. We also showed that the combined use of rice husks for energy and black carbon production can be achieved easily, especially because the collection of rice husks is naturally integrated into the rice production process. This is not the case for rice straw which constitutes the bulk of rice residues. Given the low bulk density of straw, only solutions at the village level seem feasible but suitable technologies such as pyrolysis are still in the development stage and would probably need considerable investment.

Apart from such technological and related political questions, a remaining agronomic question is how the transformation of most crop residues into energy and "inert" black carbon would affect "normal" soil organic matter and soil fertility. However, this question needs to be addressed by all bioenergy technologies based on crop residues and black carbon technology has good potential to offer sustainable solutions.

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Chapter 27
City to Soil: Returning Organics to Agriculture – A Circle of Sustainability

G Gillespie

27.1 Introduction

The current politically based model of economics seldom recognises all theelements of an economy and indeed has ignored to the peril and destructionof many communities that the basis of any economy is its soil. Any communityis literally built from the ground up. It is the quality of the soils of all nationswhich determine their viability, both in economic and social terms. Communityis built on agriculture. It always has been. Agriculture, in turn, is responsiblefor up to 70% of the industrial inputs of some economies (Chino 2001). If you have no soil you have no industry, if you have no soil, you have no community.

The basis of the relationship between a community and its soil – a community and its farmers, will be the relationship which determines the future stability and survival of humanity. The simple act of returning organic waste to agricultural soil has long been recognised as a logical and fundamental practice in many settled communities around the world. Indeed it is this very practice which contributed to the development of all the successful agricultural models of human history (Diamond 1999).

Many native communities from Australia to the Amazon, Africa to Asia have records both historical and recent which indicate that the return of organic materials as manures, scraps and charcoal is as old as humanity itself. The only thing which has changed perhaps is how focused and intentional this process has become with our increased knowledge of soils and science.

The return of organic material to agriculture, far from being the simple disposal process it is today, provided a link between the community and the soil. It was an intentional and conscious attempt to maintain a link between the individual and their food producer. As much as any other action, it was an act of respect. Perhaps it was this intentional activity, along with planting seed and nurturing plants to feed the community, which reinforced the notion of a settled community life – of health, of comfort and safety.

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

27.2 The Urban-Rural Disconnect

Issues relating to land degradation, soil quality and food production are generally seen by the urban majority as problems of the farmer. Little thought of the farmer is ever given by the shopper in the city supermarket to the source of their food and the effects that this constant drain on the land has on future production. Yet, history tells us that all communities which have lost the connection between the paddock and the plate, between the health of the soil and the people it feeds have not survived (Diamond 2005).

An innovative program in Queanbeyan, New South Wales, Australia has developed a system to reduce contamination levels in household organic waste bins, reward householders and provide quality composted product to farmers – and all with a model based on simple off-the-shelf technology (Stensletten 2004a, 2004b). The trial project was designed to deliver high quality compost to farmers and to demonstrate that the financial benefits that farmers gained from the product could be used at the front end to ensure clean source separation. It also demonstrated that a large percentage of the money currently used to dispose of waste to landfill could be redirected to beneficially reuse compost on farms.

Australia currently spends amore than $3 billion per year putting 33 million tonnes of waste into landfill (Meredith 2005). Around 60% of the material put into landfill is organic (Gillespie 1994). Yet, at the same time many areas of surface soils in NSW have organic matter level of less than 1% (NSW EPA 2000a, 200b). If correctly composted, this organic material could be returned to agriculture, with financial benefits to the farming community. This trial set out to demonstrate that to achieve this; we only need to make a few simple changes to our waste collection systems.

The cost of disposal of waste to landfill in the larger cities is around $100 per tonne and is rising every year. Even in small-unattended country landfills, when all costs are included the true cost of disposal per tonne is around $60 to $70 per tonne (Silich 1999).

The national fertiliser bill at the farm gate in Australia rises every year. So every tonne of organic material returned to agriculture will reduce this fertiliser bill and the corresponding levels of nitrous oxide they produce. Much of the degradation and structure loss in Australian soils is caused through falling levels of soil carbon and micronutrients. These in turn cause reduced microbial activity in the soil – part of the very activity that releases nutrient to the plant.

Research in 1997 by Anthony Ringrose-Voase of the Australian CSIRO research laboratories in Wagga Wagga, Australia, clearly demonstrated that falls in the levels of organic material is soil are directly attributable to decreases in the value of both crops and farm land. For every .1% of organic carbon lost from the soil the farmer loses $11.60 per hectare in the value of the crop and $79 per hectare in the value of the land. This process is entirely reversible by returning organic carbon back to the soil. This work has been more recently reinforced in Western Australia through the use of biochar in crops (Blackwell 2007).

Everything we do, everything we export, relies on the quality of our soil and its ability to produce. In the State of New South Wales, Australia, 70% of the land is affected by at least one form of land degradation; almost 30% is severely to very severely affected (NSW EPA 2000a, 2000b).

27.3 Grasping the Opportunity

The majority of projects associated with the management and recycling of wastes are focused on problem solving, diverting material from landfill and the costs associated with solving the problem.

This project is also focused on diverting material from landfill, but with the added incentive of providing increased benefits through agricultural use of the end product, providing additional wealth, which is then provided back to the participants in the system. This project is about realising an opportunity rather than solving a problem. The agricultural benefits of using quality organic material in agriculture are:

1. Increased yield
2. Reduced water use
3. Improved soil structure
4. Increased microbial activity
5. Reduced fertilizer costs
6. Reduced erosion
7. Carbon sequestration
8. Improved land value

This project commenced in February 2003. The council green waste collection and composting service had been found in an earlier study to be cost neutral (Annis 2000), due to in part to such factors as lower costs for upkeep of the Council's own garden and park assets and reduced disposal to landfill.

A trial on the property "Mooncoin" was commenced in March 2003 to investigate the effects on soil properties, yield and moisture retention, using various applications of the processed organic material as treatments. The commercial value of these effects to the farmer is of principal importance in marketing the product.

Concurrently, a document released internally by the New South Wales Department of Environment and Climate Change outlined a number of potential benefits with using recycled organic products. This document, "Life Cycle Inventory and Life Cycle Assessment of Windrow Composting Systems" is now available through the Department of Environment and Climate Change web site. http://www.environment.nsw.gov.au/education/spd_org_pubs.htm#8

The "Mooncoin" trial was designed within this context to pursue broader principles of sustainability, and to expand upon the idea that recycling of organic material has benefits and value to agriculture and the community beyond the saving of landfill costs. To deliver these benefits it was necessary to be capable of producing a quality uncontaminated composted product. Free of glass, plastic and metal. To produce an uncontaminated product requires clean, source-separated materials as an input. This therefore required a collection system to be developed to address contamination in household collected green waste bins.

The council already has reactive and educational measures in place to address contamination in green waste bins, but some considerable effort is still required to remove contamination after the material has been collected. The project named "City to Soil" attempted to address this issue upfront, by engaging with the source: The householders, who do the separation of materials for recycling.

A householder directed information campaign, before and after attitude surveys, and contamination audits were undertaken in an effort to bring about and monitor any changes during the trial period (Carlsund 2004). The project was confined to a discrete area of Queanbeyan of some 800 households. Minor modifications were made to the collection system to identify complying and non-complying bins, and to deliver rewards. The data collected from the trial indicates shifts in attitudes and concepts, and contamination was substantially reduced.

A benchmarking study for recycling and waste in Queanbeyan was undertaken to further highlight the benefits of the practice in economic terms. This demonstrated considerable financial benefit for the farmer (Hawley 2004). This project demonstrated that it is possible to take some part of the total financial value generated by using quality composted product in agriculture and to return it to the householder to ensure that organic waste bins, put out by the householder, are contamination free. The first stage of this project, the agricultural trial on the property "Mooncoin" was commenced in February 2003. The collection and rewards elements of the trial were completed in June 2004. Evaluation of the effects of the composted product is continuing.

27.4 Soil Health

This project sought to demonstrate that falling levels of organic materials in agricultural soils could be addressed in part by engaging the rural and urban communities together in a trial, which sought to increase soil health by returning quality composted products to agriculture. Increased soil health brings benefits to the farmer by increasing yield and income and to the broader community by ensuring agricultural sustainability for future generations.

The project aimed to minimize alterations to existing systems in collection, processing and on-farm application. Using very simple bar-code technology and rear loading vehicles, a householder credit system was devised, which reduced contamination by 40% (Stensletten 2004a, 2004b). This in turn, lead to cleaner, compost product with more direct application for the farmer, with no concern for contamination.

27.5 Innovation

This project was unique; in that although it used very simple existing equipment in collection, processing and product delivery, it resulted in a process that rewarded all participants in the system. The "City to Soil" project was designed as a model, which could be modified and remodeled to suit any regional, rural or urban center.

The project used a low-tech approach to collection, processing and delivery. It used standard hand-held scanners to record the bin bar code of any household that placed a bin, free of contamination on to the kerbside. The main innovative aspect of this project is that it identifies all the financial benefits of applying quality organic material to agriculture and then returns part of that value to the household for clean source separation of the product in the first place.

27.6 Costs and Benefits

The cost of landfill in the region where the trial was conducted, near Canberra, Australia's National capital, is $80 per tonne. The cost of disposal of waste to landfill for Sydney, the State Capitol, varies from around $100 per tonne up to $150 per tonne. Yet, it is possible for a commercial processor to manufacture quality compost to Australian Standard AS4454 and carry the product at least 200 km in any direction for a cost of $50 per tonne (Carlsund 2004). This means that the product can be delivered to the farm gate for less cost to the community than disposal to landfill.

As this trial demonstrated, however, when the farmer applied the product in his vineyard, his productivity in the trial area increased dramatically. In the cool climate wine area where this compost was applied the sale value of the grapes on this vineyard was approximately $1,300 per tonne. In the trial area the application of compost at a rate of 10 cm depth gave an increase in yield of 182% – a value of more than $17,000 per hectare.

Given that these wine grapes were young, it is still expected that in the long term, when the vines are more mature, the grapes would still produce an increase in yield from the 10 cm of compost used. This would mean that if the farmer paid a rate of $30 per tonne for the compost, the application cost would have been around $900, but it would have returned a profit of $3,900 or a net profit of $3,000 per tonne. The sale value of the compost could be returned to the community as community rewards and prizes to encourage clean, source separation of household product.

This project uses the same funds, which were previously used to landfill organic products to return them to useful function within agriculture. At the same time it generates profit and reward for all who participate. This project is about the triple bottom line of social economy. The yield from the grapes in 2005 from the area with 10 cm of compost was still an 82% improvement over the control.

27.7 Replication

Farming is a mineral extractive industry. It can take a vast array of minerals and nutrients to grow a plant. Yet where strict industrial chemical farming is practiced many farmers only return three chemical nutrients to the soil. Any soil will progressively suffer under this constant degeneration. The extraction process can also affect the organic levels of soils, reducing the materials on which soil biology lives, thus slowly killing the soil. This project has many positive outcomes in that it is about having people in the waste and fertilizer industries transport and sell a different range of products while providing a basis for long-term sustainability in agriculture.

As national communities we must resolve to change to more sustainable methods of agriculture and as we do we must demonstrate that farming can be sustainable and that it can involve the entire community. The "City to Soil" model will fit into any community. It will broaden the market to include not only the fertilizer companies, but also the farmer and the general community, engaging them all in sustainable food production.

27.8 City to Soil Values

Environmental	Cost/benefit	Farm	Social
Reduced waste to landfill	Compost can be made and transported to the farm for less cost than disposal to landfill	Increased yield Reduced water use	Urban-rural soil and food relationships
Reduced run-off and contamination from landfill		More efficient water use Improved soil structure	Community Education Community buy-in
Reduced methane from landfill	On farm benefits provide $ input value for community rewards	Increased microbial activity	More jobs in every rural and urban community
Reduced weed dumping in public spaces		Reduced fertilizer costs	More on-farm employment distributing product
Environmental collection benefits of kerbside, rather than household to landfill	Cost savings on fertilizer	Reduced erosion Carbon sequestration	Increased business activity in recycling
	Better return on investment for community waste handling dollar		Ties directly into Sustainable Schools program

The initial "City to Soil" project focused on the domestic aspects of organic waste and their return to agriculture. As such it demonstrated the fundamental link between a community and its soil. Once this link is established, it is possible to utilize not only household organic materials in this process, but all forms of organic waste in a range of different products. A community committed to recycling in their home will also be committed to recycling in the workplace provided the correct system is put in place.

It is also possible to see that the issue is of such a scale and such scope that a range of products need to be made to solve the soil degradation problems of an overpopulated world. We need to lead the development of these products with good science, demonstrating the right product for the particular soil, the correct application rate for the crop.

In addition to composts we need charcoal, biological products, seaweed products, rock dust products and all manner of agricultural inputs which are both safe and healthy. It is possible to expand this project to include a range of organic materials inputs and product types, appropriate to both the condition of the soil and the underlying market.

27.9 Expanding the Program

To identify the product type, material sources, carbon benefits, agricultural profits and the community connection, a larger project will shortly commence which covers a range of crop and soil types in a range of regional centers. The larger project, under the name "Groundswell" will use several innovations to enable both the collection of food waste and a new distribution system to ensure that the finished product gets to the farm gate with the minimum of cost and the maximum of profit to the farmer.

Food will be collected from households using a cornstarch liner bag in a 6L kitchen bench top bin. These bags will carry a code to identify the individual house. These bags once sealed will go into a larger 240L wheeled cart or bin and collected through the usual means. Once the organic material arrives at the processing site, one of the bags will be removed and opened. If it contains no contamination, that household, identified by the bag code, will receive a substantial prize.

Each of the bags used in the system will also provide the individual home with a partial community or carbon credit. A second innovation will provide for the collector, the processor and the farmer to operate as a collective. This will ensure that the investment that the household makes in waste removal will get the processed, finished product to the farm gate at minimum cost. The collective will then set the price of sale to its members, as determined by the return in productivity.

In this model the organic output is collected as an agricultural input. Other sources of input for the manufacture of biochar, compost and foliar fertilizers will come from industrial and agricultural sources, with a similar system of rewards applying for clean source separated product. These rewards will be generated through improved agricultural benefits.

The emphasis of any process which uses organic material in agriculture must be on source-separation of organic materials. Legislation in many areas rightfully protects agricultural soils from the application of contaminated materials. Any product used in such a system; biochar, compost or liquid fertilizer must be clean and free from contamination.

27.10 Conclusion

The world is now struggling with the recognized enormity and consequences of Climate Change. A new range of drivers will determine how we respond to these consequences in the future, but above all is that one driver upon which the term 'sustainable' is founded. That driver is a future for our children and likewise the generations, which may follow them. All generations, all humanity, all biodiversity relies on the thin skin of the earth, the soil. We have clearly demonstrated through history that if we do not return to the soil the things which we borrow from it, it will degrade and die.

There is a profitable nexus between waste management and soil management. An opposite to landfill in landcare. An alternative to waste streams in clean streams. The nexus in the solution to these problems has a common source. – The soil.

The removal process of waste management is a service with a cost, which will always be. It is how we treat these goods once they are collected that will determine our future. We can have pollution; acidification, contamination and waste or we can turn our efforts and expenditure toward agricultural benefit, clear air, clean water, healthy soil, healthy food and healthy communities.

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Chapter 28
Terra Preta Nova – Where to from Here?

J Lehmann

28.1 Introduction

Terra preta de índio (also called Amazonian Dark Earths or ADE [a term introduced by Woods and McCann 1999]) is one of the most fascinating and intriguing re-discoveries in modern soil science. Its study led to a shift in our understanding about pre-Columbian civilizations (Neves et al. 2003) and provides a plausible explanation for a much greater carrying capacity of the highly weathered Amazonian soils than hitherto anticipated. ADE soils have sustained a high fertility (Lehmann et al. 2003b) as expressed in their elevated nutrient availability and organic matter contents for hundreds to thousands of years after they were abandoned by the populations that caused their appearance. Could it be that these soils were purposefully created by Amerindian populations to improve the productivity of the soil as suggested by some (Woods et al. 2000; Neves et al. 2003)? And, could the emergence of ADE even be the reason for the development of civilization in the Amazon with more numerous and more complex societies than was anticipated until recently (Heckenberger et al. 2003)? How did they do it? The answer to that question may also teach us valuable lessons for sustainable landuse management in our time.

However, the lessons that ADE can teach us do not hinge upon the fact whether or not the Amazonian populations intentionally created these fertile soils for improving soil productivity for agriculture or whether they are an accidental byproduct of habitation. We can even draw the most important conclusions without ever knowing how ADE was actually created. These lessons can be gleaned from the properties of ADE today and the fact that these were in some way ‘created’ at a particular point in history a long time ago. As we can understand it today, the most important aspect of ADE is its high nutrient availability and high organic matter content. The goal of the recent efforts in ADE research has therefore been to find the answer to the question how it is possible that these favorable properties can still be observed after such a long period of time. What is unique about ADE that explains its sustainable productivity? Some of these lessons will be discussed in the first part of this chapter. In the second part, one of these lessons will be discussed

WI Woods et al. (eds.), *Amazonian Dark Earths: Wim Sombroek's Vision*,

in more detail with respect to the development of a new soil and biomass management approach: biochar agriculture for environmental management.

28.2 Terra Preta as a Training Ground

A multitude of lessons have been learned from ADE research to date, and many more will certainly emerge over the coming decades. These lessons reach from getting a better understanding of the basic biogeochemistry of soil such as its organic matter cycles (Glaser et al. 2003), the long-term nutrient dynamics (Lehmann et al. 2003b), or its biological diversity (Thies and Suzuki 2003); but also lessons about the management of fertile soils with respect to weeds (Major et al. 2005) or agrobiodiversity (Clement et al. 2003); and ADE research provided important clues for the prehistoric soil management through archaeological excavations (Neves et al. 2003) as well as the study of contemporary ways to manage the fertility of ADE (Hecht 2003).

28.2.1 Soil Biogeochemistry

Possibly, the most important lesson that has already been successfully adapted into research for future soil management is the occurrence of large amounts of biochar (also called charcoal, biomass-derived black carbon or pyrogenic carbon) in ADE (Glaser et al. 2001). It is by now well established that the stability of organic matter in ADE is based on the macromolecular composition derived from biochar (Solomon et al. 2007). The high stability of biochar has been recognized for many soils worldwide (Preston and Schmidt 2006), largely through the analyses of the C^{14} age of the naturally occurring biochar fraction of soil organic matter. ADE provides a visible proof for the stability of biochar in soil: the age of the biochar can be related in a qualitative way to the occurrence of biochar. If more than 50% of the organic matter of a surface soil is composed of biochar as shown by Liang et al. (2006) with an age that can be traced back to activities occurring for example about 1,000 BP as observed in many ADE, then it can be concluded that this carbon pool is cycling very slowly in relation to the rest of the organic matter. However, a turnover time can not be obtained, as no approach has so far demonstrated how the original amounts of biochar can be estimated to calculate a mass balance. Possibly with the collection of more dates of ADE appearance in conjunction with their molecular characterization will provide opportunities for estimating biochar turnover. This will hinge upon the progress of archaeological excavations in the Amazon.

Another opportunity that the defined time of biochar accumulation in ADE provides is the study of the changes of biochar over time. Such studies are much more difficult to conduct in soils with natural and recurring biochar accumulation that show average ages. Biochar fractions would need to be physically separated, which is laborious and does not lead to well-defined age classes due to the continuum of biochar properties (Krull et al. 2006). Several other opportunities to obtain sites with defined biochar deposition exist for example from charcoal accumulation for fuel production in the vicinity of pig iron ovens which was a common practice throughout the eighteenth and nineteenth century in the Eastern and Midwestern U.S. (Schallenberg 1975). These kilns were in operation for only several decades at a time that provide relatively distinct deposition periods. Other examples are dark earths sites in Europe (Schmidt et al. 1999), in Africa (Brooks and Smith 1987; Fairhead and Leach, this volume), or Australia. But rarely will such an opportunity be found as in ADE with ages ranging from 500 to 8,000 BP in sufficient numbers and in a relatively small area to allow age comparisons to be made.

One of the most striking features of ADE apart from biochar is their high concentrations of available phosphorus and calcium. In most cases these will stem from accumulation of fish residues and are therefore composed of biogenic calcium phosphates (Lehmann et al. 2004). ADE therefore offers the possibility to study biogenic calcium phosphates and their dissolution over long periods of time. First results indicate that most of the calcium phosphate disappears 2,000–3,000 years after its accumulation, with a shift from crystalline hydroxy-apatite to tri-calcium phosphate to less crystalline di-calcium phosphate. Similar studies of molecular changes over long periods of time may be done for trace metals such as manganese, copper or zinc which are also abundant in ADE. No studies exist on organic nitrogen forms in ADE especially in conjunction with biochar, most likely due to the analytical challenges associated with N-15 NMR techniques (Smernik and Baldock 2005).

Much hope and discussion has been associated with the biology and specifically the microbiology in ADE. It is by now clear that ADE indeed harbors a population of microorganisms that is unique compared to adjacent soils (Yin et al. 2000; O'Neill et al. 2006). However, the microbial composition should rather be seen as a result of the unique habitat that ADE provides than a cause for ADE. It will not be possible to extract a 'magic microbial potion' from ADE that can be used to recreate ADE. Nonetheless, the unique microbial population may perform functions that change soil nutrient and carbon dynamics in ways that promotes the sustainability of ADE. Not the identification of a specific organism but the function of a group of organisms would need to be investigated. This is a challenge to be resolved in the future.

ADE does not always provide a suitable experimental opportunity to test certain hypotheses. For example, the reason why the microbial community structure is specific to ADE may be very difficult to identify. ADE is a very complex mixture, and any of its components may have an impact on microbial life, or possibly only a few or only one of them. Yet this conclusion will most likely not be obtained from the study of ADE, but probably only from controlled experiments. In the case of biochar, ADE research provides one of the decisive starting points for investigation of microbial diversity. Only high-resolution spatial measurements will in the future be able to unequivocally link certain organisms or their groups to the occurrence of biochar. Whether functional information can be obtained through this type of observation such as turnover or the use of certain food sources or the production of certain metabolites, is debatable. Again, only controlled field experiments outside of ADE will be able to link the presence of biochar with a certain microbial community and their function.

28.2.2 Blast to the Past

Archaeological studies are fundamental to answering some of the most interesting questions that guide both research on soil biogeochemistry in ADE as well as lessons for future soil management. For example, changes of biochar properties or phosphorus forms over time as discussed above can only be investigated with solid information about the time of ADE formation. The same is true for comparisons between ADE sites that differ in environmental or edaphic properties or simply for a generalization of certain ADE properties studied at a limited number of sites. An ADE soil that formed 2,000 years ago such as Açutuba will necessarily have different chemical properties than an ADE that formed 1,000 years ago such as Lago Grande (Liang et al. 2006). Without proper age identification and context of formation, interpretations of ADE characteristics are in many cases very difficult.

Even though the positive proof of a purposeful creation of ADE by Amerindian populations and the techniques involved are not vital to most of the lessons learned from ADE research as pointed out above, still, such information may not only provide new insights for future soil management and lend validity to the lessons learned, but would naturally also revolutionize our view of pre-Columbian civilization as started by Heckenberger et al. (2003) among others. Positive proof may be difficult to develop for times gone bye. But some evidences appear to be starting points for further investigation. For example, in an ancient settlement at a site called Lago Grande (Neves et al. 2003; Arroyo-Kalin, this volume), a defensive wall separates a small peninsula from the mainland. The peninsula shows clear signs of habitation with development of ADE with a depth of in some places up to 2 m, accumulation of potshards and a central plaza area without ADE (EG Neves, 2008, personal communication). The interesting observation is that ADE can also be found outside the defensive structure. Is this an indication that ADE outside the village walls are rather agricultural land? Again, a close collaboration between archaeologists and soil scientists is crucial to the success of such investigations.

28.2.3 Terra Preta Nova?

Many of these insights from archaeology and soil biogeochemistry may and some already have led to practical recommendations for future landuse – a vision put forward by Wim Sombroek (Sombroek 2001; Sombroek et al. 2002) as *terra preta* *nova. Terra preta* in its entirety, however, may not be a model for sustainable land use or only under certain circumstances that are likely of local rather than global importance. For one, ADE have widely differing properties that are a reflection of the location (hydrological, geological, as well as biological regime) as well as the management in pre-Columbian as well as recent times. Consequently, no ADE "as such" exists but soils that are classified as belonging to a group of soils that share the same anthropic origin, but can have variable properties (Kämpf et al. 2003). Secondly, in most instances ADE contain remnants of a multitude of additions from for example biochar (Glaser et al. 2001), animal manures, human excrements, human and animal bones (Neves et al. 2003), aquatic plants (Mora 2003), fish residues (Gilkes et al. 2004; Lehmann et al. 2004), turtle shells (Sombroek 2001), and many others. It is hard to imagine that such a complex mixture will yield a useful management suggestion. Nor do all of these ingredients provide critical contribution to the sustainability of ADE. One such ingredient and possibly the one that makes Terra preta "tick" is biochar, which is being developed into a soil management approach.

We should, therefore, rather be talking about *terra preta nova* technologies than about producing *terra preta nova per se*.

28.3 Biochar Agriculture for Environmental Management

The first and so far most important outcome of a *terra preta nova* technology is the purposeful management of biochar as a soil conditioner. Although, biochar has been produced by humans extensively and for very long periods of time for a variety of purposes including metallurgy, filtration, or artistic drawing (Harris 1999), its use as a soil amendment is less well documented. Limited circumstantial evidence suggests that adding biochar to soil has also been part of nursery or kitchen garden management and the beneficial effects of biochar in soil have been recognized for some time, as well. For example, the President of the Highland Agricultural Society of Ohio writes in 1850: "We have evidence upon almost every farm in the county in which I live, of the effect of charcoal dust in increasing and quickening vegetation. The spots where charcoal pits were burned 20, and some say even 30 years since, still produce better corn, wheat, oats, vegetable, or grass, than adjoining lands" (Trimble 1851). Some scientific work explaining biochar soil management dates back to the beginning of the last century with studies on the effect of biochar on tree seedling growth (Retan 1914; Fig. 28.1) or a very thorough study on the soil chemical and physical processes affected by biochar (Tryon 1948). Only relatively recently, however, research into the chemical properties of ADE (e.g. Glaser et al. 2001) triggered a proliferation of scientific studies related to the effects of biochar on soil fertility (e.g. Topoliantz et al. 2002; Lehmann et al. 2003a; Oguntunde et al. 2004, and several others). The following discusses possible ways forward for the framework in which biochar could operate, and articulates several visions of biochar use in the future.

Fig. 28.1 Seedlings of white pine grown in the nursery (from left to right): without biochar additions, and with biochar added 2 years before, 6 months before or at time of seeding (Retan 1915)

28.3.1 Biochar as a Routine Management in Agriculture

Can biochar become a routine management option in agriculture? The basic principle why biochar acts as a valuable soil amendment is by now well established and mainly builds on its recalcitrance in soil and its ability to retain nutrients (Glaser et al. 2002; Lehmann and Rondon 2006). Other properties that are much less understood are the effects on soil biology (Lehmann and Rondon 2006), which may have substantial yet hitherto largely unquantified benefits for crop productivity (Lehmann 2007a). Due to these soil-changing effects, biochar should be primarily considered as a soil conditioner and not as a fertilizer. Biochar improves the essential soil functions for long periods of time, but does not replace the need for nutrient additions through either inorganic or organic fertilizers.

Some types of biochar can, however, contain significant amounts of soluble nutrients, which may under certain conditions improve plant nutrition and productivity by direct nutrient addition. Biochar made from chicken manure is especially rich in calcium and phosphorus (J Lehmann, unpublished data), and most biochars contain large amounts of soluble potassium (Lehmann et al. 2003a). The yield increases in response to such direct fertilization effects are most likely comparable to those achieved by adding nutrients separate from biochar. However, for some types of biochar the release may be slower and the nutrients may be less prone to leaching losses than if added separately, and should be investigated in the future. The yield benefits achieved by such direct nutrient additions are a welcome short-term benefit, but are not a proof of the sustainability of biochar soil management and may in some instances even obscure the more important long-term effects. In that sense, pot experiments have more value in testing for allelopathic effects that may decrease crop yield, in quantifying the immediate benefits of reduced leaching or gaseous losses and in tracking the short-term changes of biochar in soil.

In any event, nutrients have to be applied each cropping season to compensate for yield export and possible losses by for example volatilization, leaching or erosion. Since biochar is intended to be a sustainable amendment, a combination of a function of nutrient delivery and long-term improvement of soil organic matter is not a mandatory and possibly not even an appropriate strategy. One-time and large applications of biochar may be the preferred strategy where rapid soil improvement is required, feedstock is not regularly available (as in a shifting cultivation scenario), or the economics favor one-time applications through possibly reduced costs of transportation. This would preclude a combination with fertilization as an annual intervention.

However, low amounts of annual biochar additions in combination with inorganic or organic fertilization is a possibility that could have advantages under certain conditions. For example, the production of biochar can be combined with a precipitation of ammonium bicarbonate on its surfaces which may be energetically and possibly economically advantageous for creating a nitrogen-rich biochar. A combination of low amounts of biochar and fertilization may offer procedural and, hence, economic advantages in that the same pass for applying fertilizer to soil also adds the biochar. Whether this is a useful strategy will most likely depend on the specific cropping system and farming equipment used to apply fertilizers. A third aspect that can be mentioned is the verification of carbon sequestration needed to justify carbon credits. The fertilizer distribution system can double as a verification tool. In addition, a biochar-fertilizer mixture will most likely be inappropriate as a fuel source and risks of diversions from the intended sequestration are unlikely.

The vision of biochar as a routine management tool in agriculture should be explored in large-scale field operations and must include full economic and environmental assessments. Biochar should also be adopted by the organic grower community and be allowable as a certified organic soil management where the integrity of the biochar product can be guaranteed.

28.3.2 Biochar for Sustainable Recapitalization of Soils

Biochar leads to a secure recapitalization of soil organic matter that can improve crop productivity through a one-time and large application to soil. A recapitalization with biochar may be especially attractive for improving the agricultural production base on highly degraded soils as often found in tropical regions. Biochar should therefore be explored for sustainable development in rural areas of developing countries.

What is the most likely long-term productivity of a one-time and large application compared to annual and small applications? If biochar is assumed to be completely recalcitrant to microbial decay, such a one-time application most likely achieves significantly greater cumulative yields over the long term than annual applications as shown in Fig. 28.2. Even by considering that biochar actually

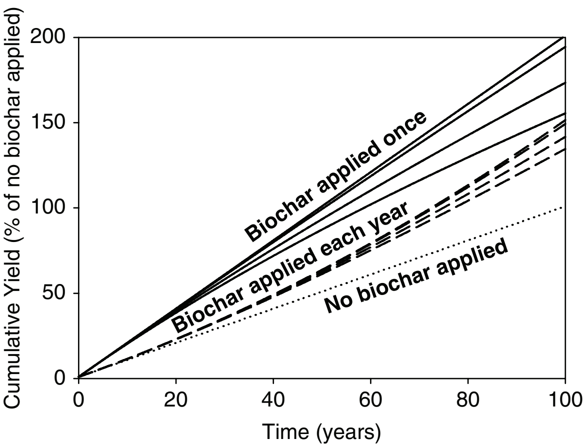

Fig. 28.2 Cumulative yield over 100 years comparing one-time application of biochar with a hypothetical doubling in yield (solid lines) and the repeated application of the same total amount with a yield increase proportional to annual biochar additions (dashed lines), compared to an unamended control (dotted line). Four scenarios were calculated: no decomposition of biochar, a half life of 500, 100, and 50 years (from top to bottom for both biochar scenarios)

decomposes over time, one-time applications still appear to be superior to annual applications with respect to yields. With a biochar half life of 500, 100, and 50 years, 91%, 76%, and 60% greater yield increases can still be achieved if the biochar is applied once at the beginning than annually over the same period of time. This calculation exercise also demonstrates that biochar does not need to have a half life of several thousand years to be considered a long-term soil improvement. Already with a half life of 100 years, 73% and 42% compared to the yield improvement without biochar decomposition would be achieved during a 100-year period for one-time or repeated biochar applications, respectively. A half life of 100 years is currently considered a low estimate for biochar and biochars will most likely have longer half lives of up to several thousand years (Preston and Schmidt 2006), depending on biochar and ecosystem properties.

Such a calculation assumes that yield increases are proportional to the amounts of biochar applied. This assumption may not necessarily be correct as shown for a greenhouse experiment with beans on a highly weathered savanna soil (Rondon et al. 2007). It also assumes that biochar is equally effective in improving soils immediately after it was applied to soil and after a long period of time such as 100 years. However, it is known that recently produced biochar has a low ability of retain cations and attains cation exchange capacity only over time (Lehmann 2007a), in most cases during a period of months to a few years (Cheng et al. 2006). On the other hand, biochar appears to maintain a high cation exchange capacity over the long term of centuries and millennia as shown by analyses of biochar contained in ADE (Liang et al. 2006). Therefore, the most likely effect of time on biochar properties also favor a one-time and large application over annual and small applications.

Some situations may even dictate one-time applications as in the case of the already mentioned shifting cultivation scenario: biomass is only available in large quantities at the land clearing stage that can produce sufficient amounts of biochar to recapitalize soil organic matter (Lehmann and Rondon 2006).

It should not be forgotten, however, that nutrient additions are still required to compensate for nutrient exports. In a situation as for example seen in Africa with high prices for fertilizers especially in land-locked countries such as Malawi (Sanchez 2002), a slight increase in the efficiency of applied nutrients could make a large difference to farm economies. In 2003, the farmer price per ton of urea in the United States was $227, whereas 1 t of fertilizer cost $336 in Nigeria and even $828 in Angola (Gregory and Bumb 2006). In such a situation, short-term financial support by international agencies or foundations to recapitalize soil productivity through biochar additions may achieve a long-term and sustainable impact. This may be an important aspect in a climate of typically short funding cycles and changing priorities that many organizations face.

The costs, however, may be substantial. If all 255 million hectares of soils which in 1990 were estimated to be degraded by agriculture in Africa (Oldeman et al. 1991) were to receive 10 Mg ha^{-1} of biochar to jump start production, the rather large sum of $255 billion was required (at a price of $100 per tonne of biochar). These are high but not insurmountable costs even though they are four times the amount that the UN Hunger Task Force projects to eliminate hunger world-wide during the coming 5 years (Sanchez and Swaminathan 2005). Costs can be reduced by prioritizing sites where biochar additions are economically or environmentally most effective, and by determining with greater accuracy the critical amount of biochar necessary. The latter will certainly be a function of crop species and location (Lehmann and Rondon 2006). To be successful, such a large undertaking requires careful planning and consideration of the local conditions.

Such a recapitalization is also secure. Once biochar is incorporated into soil, it will not accidentally disappear, can not be sold, or used for different purposes. For comparison, investments in livestock can be risky, as animals can die of disease, be sold for short-term benefits, be stolen or killed. Similar considerations apply to investments in woodlots for timber production. Biochar in soil on the other hand, becomes a long-term environmental asset that sustainably improves the agricultural production base and will create revenues for very long periods of time, as exemplified by ADE. The task ahead is to determine the opportunity costs and financial benefits of adding biochar to soil for a large-scale recapitalization campaign.

The time that biochar will remain in soil is difficult to generalize for reasons of feedstock and environmental variability (Lehmann 2007a). Yet decomposition occurs gradually and can be predicted for a certain situation, and even comparatively rapid decomposition will still achieve most of the expected yield increases over the long-term as shown by Fig. 28.2. Leaching is certain to transport some portion of the added biochar into the subsoil, which may be advantageous for improving subsoil fertility and rooting depth. On the other hand, such a transport will decrease biochar concentrations in the topsoil where most crops have their roots and where most nutrients are taken up. At present, the vertical transport is thought to be negligible on the short term of a few years (Major et al. 2007), and will only change subsoil biochar contents significantly over long periods of time likely exceeding decadal or centennial time frames. Erosion of biochar is different in this respect and may have a significant yet largely unquantified impact on the effectiveness of biochar (Rumpel et al. 2006).

A risk-averse recapitalization program of degraded soils is an intriguing vision for the poorest regions of the world. With such a large-scale intervention, biochar to soil could significantly contribute to achieving two of the eight Millenium Development Goals of the UN by 2015: eradicate extreme poverty and hunger, and ensure environmental sustainability. Biochar is able to directly address actions 3, 4, and 7 of the UN Hunger Task Force (Sanchez and Swaminathan 2005). It is a promising approach for the suggested entry point by the Task Force to invest in soils as a battle against world hunger.

28.3.3 Biochar for Mitigation of Climate Change

The case for biochar as a promising approach for the mitigation of climate change has been made previously (Lehmann et al. 2006; Lehmann 2007b). Some aspects of this strategy require renewed careful consideration and are briefly discussed here. One, the conversion of biomass into biochar can either be primarily a net withdrawal of carbon dioxide from the atmosphere or a net emission reduction or both. For example, the harvesting of bioenergy crops such as fast-growing trees or grasses and their conversion into biochar in conjunction with replanting of the vegetation is primarily a withdrawal. The conversion of crop residues, however, that would decompose within short periods of time (Jenkinson and Ayanaba 1977) into biochar is both a net withdrawal and an emission reduction. In contrast, the lower evasion of nitrous oxides (Yanai et al. 2007) and lower fertilizer requirements for crops due to biochar additions to soil constitute an emission reduction that is not linked to a withdrawal of atmospheric carbon dioxide. These distinctions help in framing the discussion about the impact of biochar on greenhouse gas balances and carbon trading.

Second, even though about 75% of the biomass weight is typically lost during charring, only about 50% of the carbon is emitted (Fig. 28.3). Most of the mass driven off results from losses of oxygen and hydrogen. The resulting biochar shows up to double the concentration of carbon, yet the pyrolysis process itself always leads to a short-term net evasion of carbon. This has to be considered when designing biochar projects. The loss is assumed to be compensated for by the greater recalcitrance against microbial decay over the long term (Lehmann et al. 2006).

Third, in order for conversion of biomass into biochar to constitute a net sink, the amount of biomass that was charred has to be regrown. Deforestation and biochar production, for example, is not a net sink, but a net source of carbon dioxide, since about half of the carbon in biomass is emitted during pyrolysis (Fig. 28.3). This

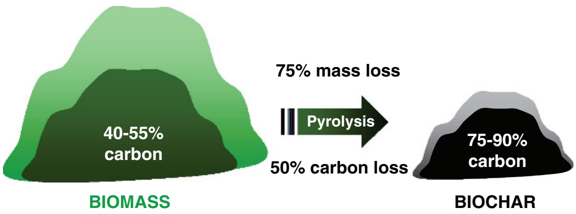

Fig. 28.3 Typical conversion of biomass (such as trees, grasses, green wastes) into biochar. The carbon and mass losses can vary significantly depending on the type of feedstock and the pyrolysis conditions (e.g. temperature, moisture, sweep gas)

emitted carbon can be captured in a bioenergy process (Lehmann 2007a), but will eventually be returned to the atmosphere under any scenario (Lehmann 2007b).

Fourth, whether or not biochar additions lead to emission reductions depends on the change in practice. The already mentioned use of otherwise living trees for biochar production results in a net source of greenhouse gas emissions. However, if the change in practice is from shifting cultivation that uses slash-and-burn to a slash-and-char practice (Lehmann et al. 2002), about half of the emissions are avoided and the change in practice results in emission reductions. In another example, the use of crop residues for biochar production instead of leaving them in the field for eventual complete decomposition to carbon dioxide, constitutes an emission reduction, as well (Gaunt and Lehmann 2007). Therefore, careful carbon and energy accounting is required to assess the impact of pyrolysis technologies on greenhouse gas emissions under a particular scenario.

28.4 The Terra Preta Nova Phenomenon

More than providing the decisive incentive to question common beliefs about the limitations of ancient landuse in Amazonia (Heckenberger et al. 2003; Neves et al. 2003), ADE has ignited the interest in sustainable soil use practices of today's agriculture. ADE can be credited of having inspired the most recent and widespread efforts in exploring biochar as a soil amendment, even though biochar was recognized as a soil improver for a very long time. Also, ADE has in general put soils at center stage and spurred the interest of a wide range of environmentalists. It has captured the imagination of a broader audience and may contribute to creating a greater interest in soils in the future. In some instances, sound soil management has been dubbed *terra preta* management, irrespective of whether or not a specific approach builds on insights gained by studying ADE properties or believed to mimic Amerindian soil management. These public responses have created a 'Terra preta nova phenomenon' of unexpected proportions.

The term *terra preta* has almost become a marketing tool. Companies are starting to promote their products using this term without demonstrating any obvious understanding whether it actually builds on ADE properties or ancient management. Given the ongoing research on the biochar aspect alone (Lehmann 2007a), this may not even be possible at this moment. The translation as ‘dark earth’ evokes images of fertility and sustainability combined with the mysterious and inexplicable. *terra preta* soil management may be perceived as gaining legitimacy by the suggested heritage of what ancient and supposedly sustainable land management did in harmony with the environment. It may also come with less ideological baggage than organic agriculture and could therefore be more easily accessible to a larger audience.

How ADE research and development will be carried forward is difficult to predict. Biochar gained its own momentum particularly in the context of climate change discussions (Lehmann 2007b). *Terra preta* currently combines a notion of solid scientific insight and perceived ancient wisdom with the hope for a solution to some of the most pressing environmental problems. In the end, only an unbiased view can truly capitalize on the lessons that ADE can teach.

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Index

D

E

F

G

H

I

J

K

Color Plates

Fig. 2.2 Aerial photograph of the Hatahara Site. It is possible see the scarp of the bluff and the Solimões River. The irregular oval line delimits the habitation zone of the site (Photo by E. Neves 1999)

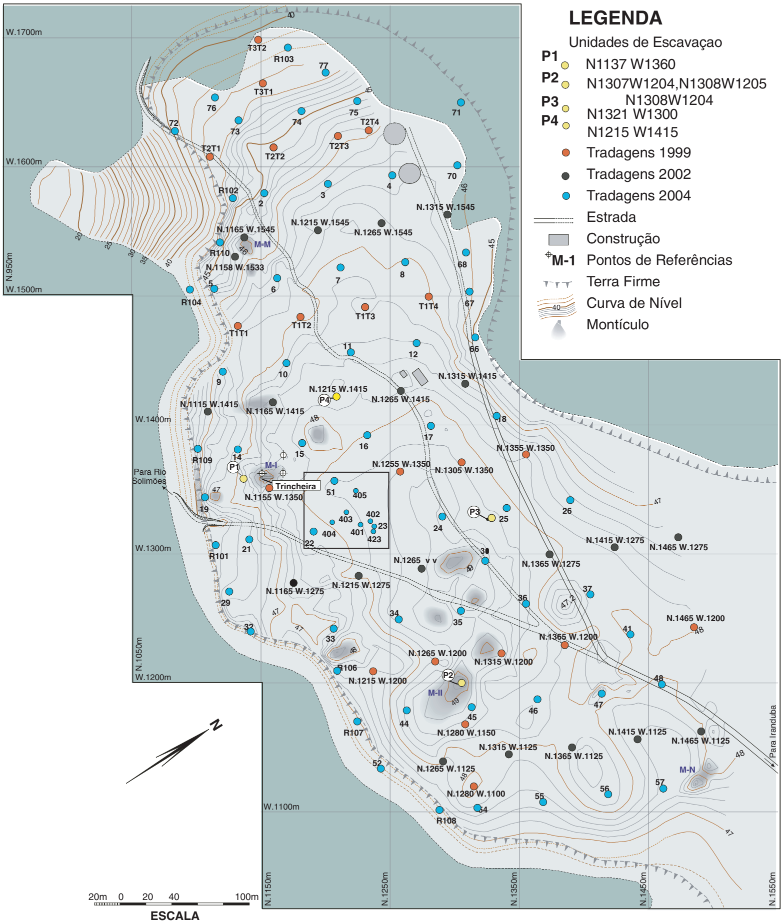

Fig. 2.3 Fieldwork at the Hatahara site. The 103 auger pits are shown in red (recollected in 1999), blue (2002), and black (2004). The yellow indicates units excavated

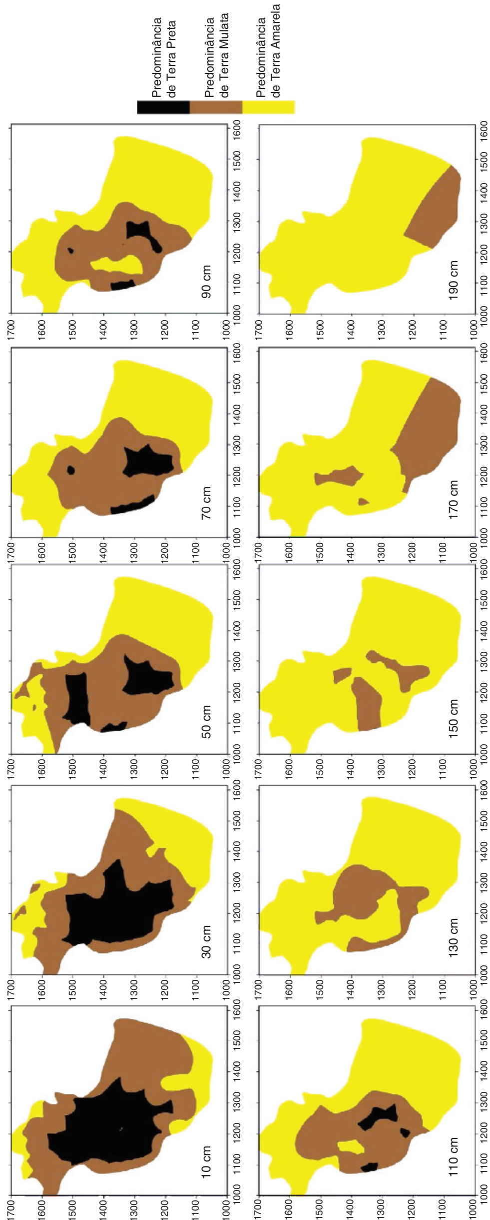

Fig. 2.4 Hatahara site soil color distribution. Soil color behavior through the artificial levels

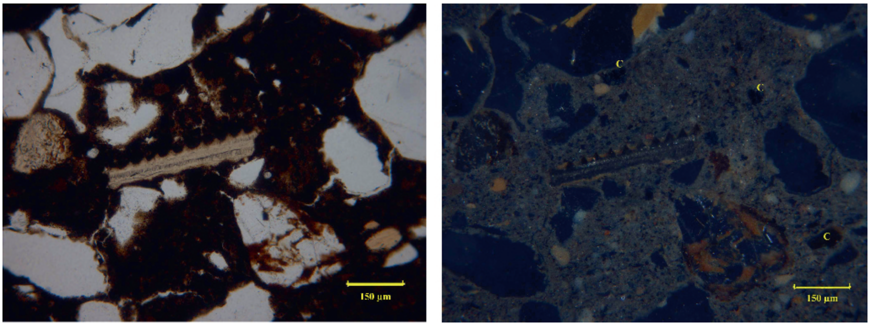

Fig. 5.1 Small bone and charcoal (C) fragments in A horizon sediments of the Lago Grande site. Left: PPL. Right: OIL

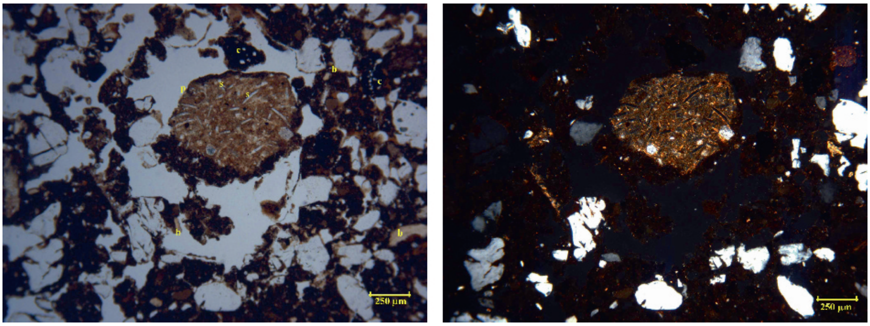

Fig. 5.2 Rounded, sponge-spicule (S) tempered pottery fragment (**p**) from the A horizon of the Hatahara site (Left: PPL; Right: XPL). Note charcoal (C) and bone (B) fragments

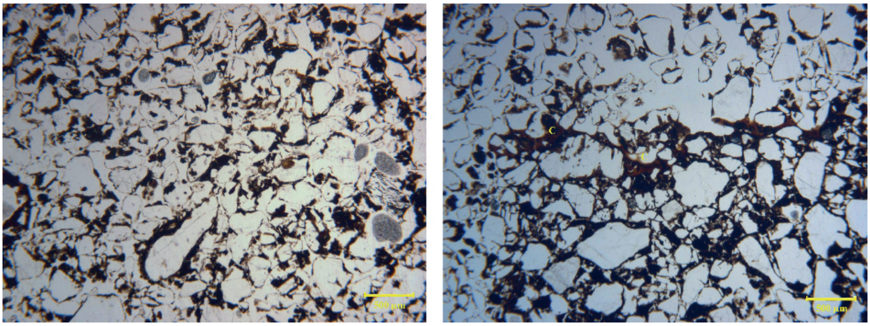

Fig. 5.3 Left: grain-supported microstructure in the A horizon of Açutuba (PPL). Right: matrix-supported ped within grain-supported microstructure in the A horizon of Açutuba. Note illuvial clay coatings (C) on matrix-supported ped (PPL)

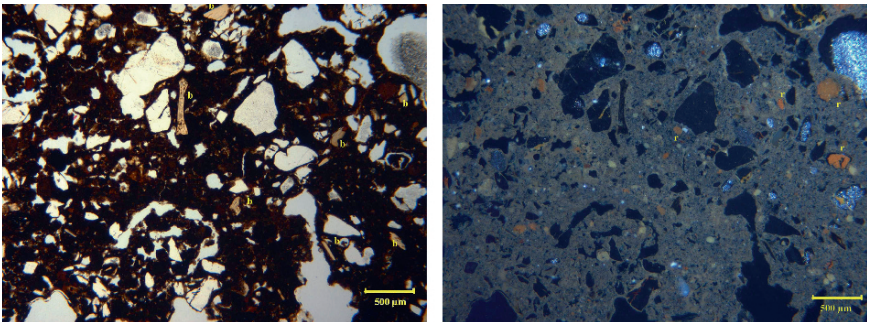

Fig. 5.5 Microscopic bone (**b**) and rubified clay aggregates (**r**) in a Type II clayey fabric. A horizon sample, Lago Grande site (Left: PPL; Right: OIL)

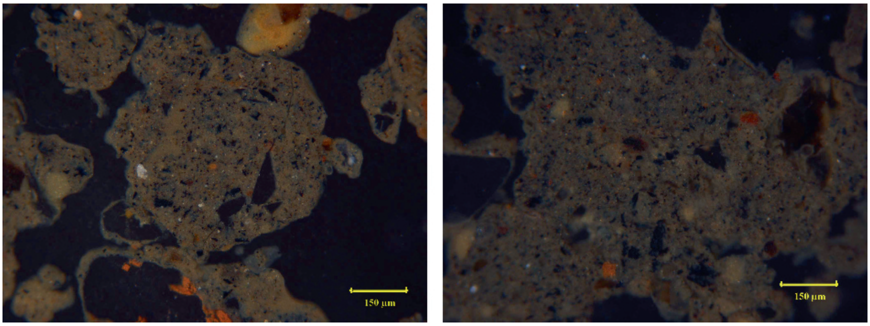

Fig. 5.7 Left: Type I (LG-3.2) and, right: Type II (LG-3.1) fabrics at the Lago Grande site (Profile LG-3, OIL). Note similar density of microscopic charcoal. More opaque grey colours are observed on the right but these are not well expressed in photographs. A higher Mn:Al ratio can be computed for 10–20 cm vis-à-vis 30–40 cm in this profile

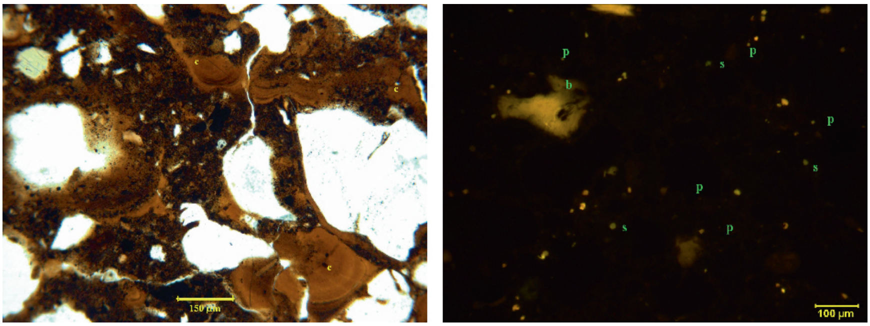

Fig. 5.9 Indirect evidence for ash in A horizon samples at Hatahara. Left: Dusty illuvial clay coatings (**c**) in Profile HA-5 (PPL). Right: auto-fluorescent bone fragments (**b**), sponge spicules (**s**) and silica phytoliths (**p**) in profile HA-3 (UVL)

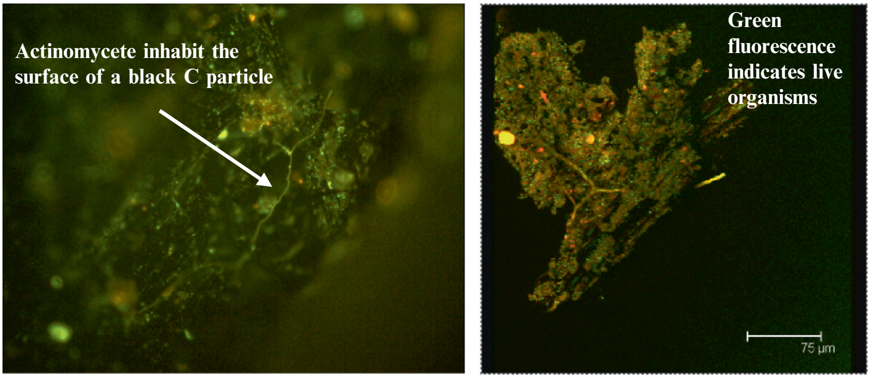

Fig. 15.2 Confocal microscopy of black carbon from ADE using fluorescent microscopy images demonstrated the presence of live (in green) microorganisms on BC surfaces, indicating that BC can serve as a habitat for microbes, despite its chemical recalcitrance, despite its chemical recalcitrance

Fig. 15.3 Global positioning system (GPS) for the ADE soil from Balbina Lake (Central Amazon) - 1°30'26,4';S and 60°05'34';W and for the adjacent soil - 1°30'27';S and 60°05'33';W. There is a typical high vegetation richness above the *terra preta* soils, as shown from Fig. 15.1. On the left, it is shown how the soil cores were collected at different depths

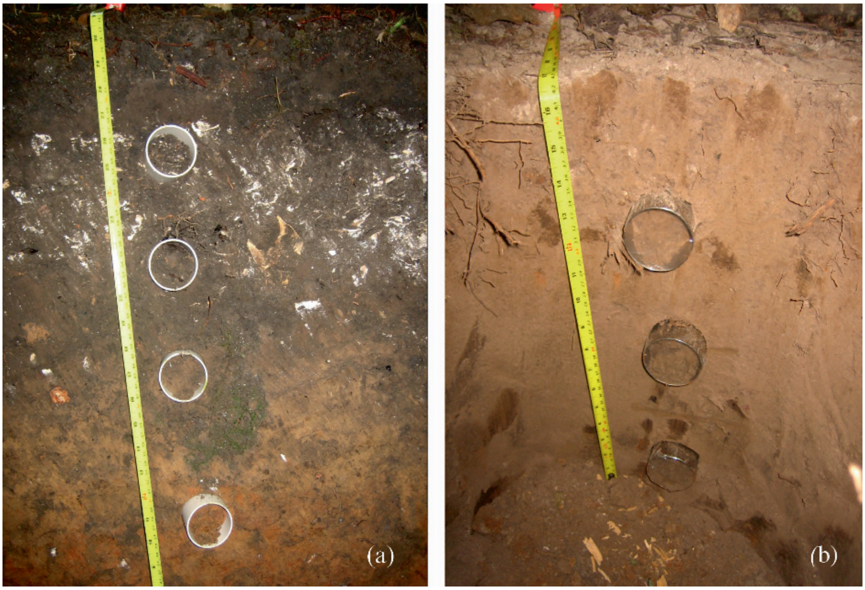

Fig. 15.4 Global positioning system (GPS) for the ADE soil from the National Forest of Caxiuanã (Eastern Amazon), with global positioning system (GPS) data for the ADE (Mina I) of 1°40'45,5';S and 51°20'71';W

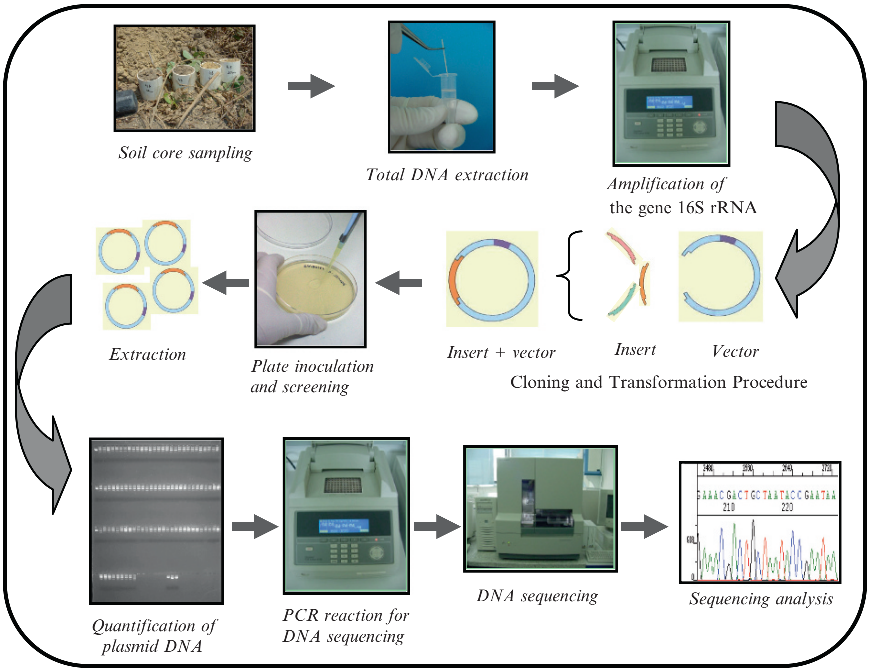

Fig. 15.5 Main steps for the bacterial 16S rRNA clone library construction

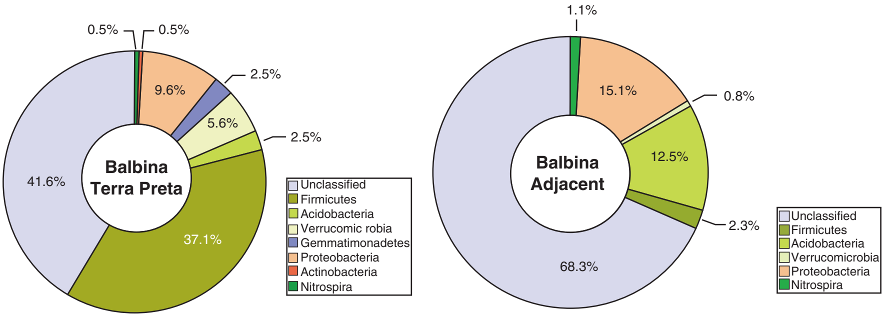

Fig. 15.6 Clone libraries from ADE (Terra Preta) soil and its adjacent soil from Balbina Lake (Central Amazon)

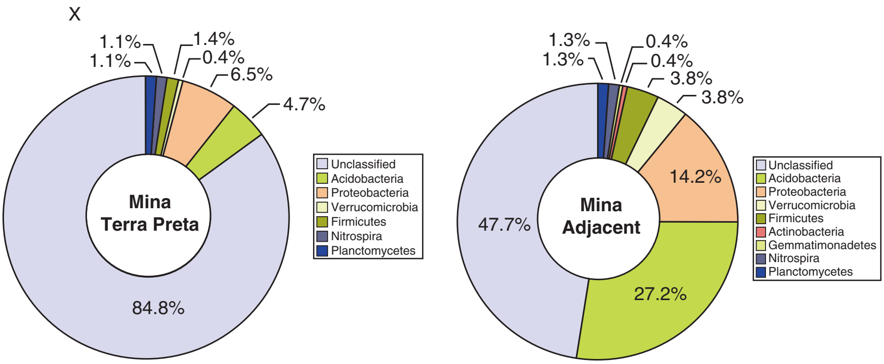

Fig. 15.7 Clone libraries from ADE (Terra Preta) soil and its adjacent soils from the Caxiuanã National Forest (Eastern Amazon)