Pre-Columbian land use and its modern legacy in the Purus-Madeira Interfluve, Central Amazonia

Submitted by Regina Gonda to the University of Exeter

as a thesis for the degree of

Doctor of Philosophy in Archaeology

In September 2018

I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Regina Gonda

2018

ABSTRACT

To combat environmental degradation and change, it is imperative that the rainforests are protected and sustainable land use practices are developed in Amazonia. A better understanding of the role of humans in shaping Amazonian environments and the extent to which the forests have been resilient to anthropogenic disturbance is critical to determining the current state of these ecosystems.

This research provides the first reconstruction of late pre-Columbian to early post-Columbian land use and its environmental legacy in the Purus-Madeira Interfluve, Central Amazonia.

Soil profile samples were collected across a transect approximately 600 km in length between Manaus and Humaitá, covering a large ecological gradient from dense canopy forests to open canopy forests, as well as dry, upland areas (*terra firme*) and small riverine settings. Archaeobotanical phytolith and terrestrial palaeoecological samples were analysed from four contexts: (i) primary forests; (ii) oligarchic forests dominated by economically useful trees in the *terra firme* rainforest on natural soils; (iii) an anthropogenic forest with Brazil nut trees on anthropogenic soil; and (iv) a previously undocumented archaeological site next to the Brazil nut stand.

The outcome of this study provides evidence that the extent of the pre-Columbian environmental impact was larger than previously thought, and this shows that humans managed these forests in various ways to varying intensities.

The data therefore helps to identify the long-term role of human-environment interactions in Central Amazonia and provides valuable information for future environmental and land use regulation policies.

ACKNOWLEDGEMENTS

What a journey this was.

When I finished my MSc, I planned to do PhD research on a desert, probably in Jordan, as I had spent a summer excavating there during my master's program. Who could have imagined that I would end up doing my PhD in the world's largest rainforest? I have experienced and learned so much during these years, and they have undoubtedly also been the most challenging years of my life. But, now that I am sitting in the PGR office writing this acknowledgement and reflecting back on the past four years, I know that I am actually very fortunate. I have had the opportunity to travel to some incredible places, meet some amazing and inspiring people, gain knowledge and confidence in archaeology and terrestrial palaeoecology, and pick up valuable skills. I am thus forever grateful to the people and organisations who have helped me along my PhD journey, and who have contributed in many ways to the making of this thesis.

My PhD project was funded by the European Research Council (ERC) as part of the Pre-Columbian Amazon-Scale Transformations (PAST) project, coordinated by José Iriarte and Denise Schaan.

My sincere thanks go to my lead supervisor, José Iriarte, for giving me the opportunity, training me, helping me to formulate my research design, and supporting me during these four years. Your enthusiasm for your subject and "everything is possible" attitude have been truly inspirational for me.

I would also like to thank my second supervisor, Dunia H. Urrego, who helped me with the research design, statistics, kept me on track, and was constantly supporting me in general. Your positive and solution-oriented mind-set always reminded me that there is an answer for every problem.

Lilian Rebellato kindly agreed to lead the application for the IPHAN permit to carry out the archaeological research. Umberto Lombardo of the Universitat Pompeu Fabra, Barcelona, was a huge help in interpreting my terrestrial palaeoecology data. Jonas Gregorio de Souza generously gave his time to make the GIS maps included in this study.

The team of the PAST project, especially Yoshi Maezumi, Mark Robinson, Jonas Gregorio de Souza, and Sarah Elliott, not only taught me a lot about archaeology, palaeoecology, and archaeobotany but became my friends. I would especially like to mention Yoshi here, my "roomie", who is one of the brightest young researchers I have ever met and has become one of my best friends. Thank you for constantly encouraging, supporting, and inspiring me.

Doing fieldwork in the Amazon Rainforest was an incredible experience, but I could not have done it without the enormous amount of help I received from many people and organisations. First of all, I would like to thank Charles Clement of the National Institute of Amazonian Research (INPA) for welcoming me to INPA and advising me on my fieldwork. Charles also discussed the fieldwork findings and organised for the soil samples to be shipped from Manaus to São Paulo and Exeter. My PhD project was initially based on and inspired by the work of INPA's Carolina Levis on anthropogenic forests in Amazonia. Both Carolina and Flavia Costa (also at INPA) helped me greatly by discussing my plans for field research and designing the project.

I could not have organised everything for my fieldwork in Manaus so smoothly without having met Lóránd Jelényi, who has becone a great friend of mine. Lóránd helped me with bureaucracy, renting a car, buying equipment and food in Manaus, and he also found my field assistants. He and his family were just all-round fun to be with and made my short stay in Manaus unforgettable.

Izaias Brazil, the PAST project's field botany expert, helped greatly with executing the modern vegetation inventories. My field assistants, Irmão, Veca, and Diego, not only worked hard on the test pits in the rainforest, but they also built shelters, hunted, caught fish, and generally looked after me. It has been one of the most beautiful experiences of my life to live on a traditional Amazonian houseboat, play with pink river dolphins, survey the landscape along the Igapó-Açu River, and discover my first archaeological site. I would like to thank the Igapó-Açu community for their hospitality, as well as all the local people along the BR-319 road who gave us shelter and food during our journey.

I would also like to thank Paulo Eduardo de Oliveira for welcoming me to his lab in the Institute of Geosciences at the University of São Paulo for six weeks, so that I could begin processing my soil samples. I would like to acknowledge Jenny Watling who has been following my PhD journey from the beginning, made me feel at home in São Paulo, and has been a great friend since we first met. In addition to Jenny, all the PGR students I met in São Paulo made my stay in the city very memorable.

Aside from those already listed, I am also grateful to a number of colleagues with whom I had interesting discussions in relation to this work. I should mention here Daiana Travassos, Lautaro Max Hilbert, Andre Junqueira, Manuel Arroyo-Kalin, Phil Riris, Eduardo Machicado, Sanna Saunaluoma, and Rafael Milheira, amongst others.

My PhD experience would not have been complete without the special PGR community at the Department of Archaeology in Exeter: Malene Lauritsen, Alice la Porta (my PhD buddy from day one), Felipe do Nascimento Rodrigues, Dóra Szabó, Belinda Tibbetts, Emily Johnson, Matt Knight, Ethan Greenwood, Adrian Oyander Rodriguez, Theresa Kamper, Katie Edwards Bonnett, Leah Moradi, Jemma Singleton, Brice Girbal, Carlos Salgado Ceballos, and many others with whom I enjoyed beers or just had a chat in the corridor. You all contributed to the success of this project. My best Hungarian friends for more than 15 years, Emese Polgár and Ágnes Takács-Hajnal, have always cheered me on. I miss you ladies a lot, and I am grateful for having you in my life.

In addition to family and friends, I received invaluable help from the Exeter University’s Wellbeing Centre during the hardest time of my life after my father passed away earlier this year.

I would not be writing this acknowledgement today if I did not have a supporting and loving family. I would like to acknowledge the support of my close and extended family: my mother, my late father, my brother, my godparents, my cousins, and my late grandmother. I dedicate this thesis to my mother, Zsuzsanna, who is the strongest woman I know, and my late father, András, who was always fascinated by nature and adventure and would have been beyond proud of me if he had the opportunity to see me submit this thesis. I also dedicate this thesis to my late grandmother, Gizella, who we lost just a couple of weeks before I handed in this thesis. You and Dad taught me to love the land and grow our own food, and thus you planted that little seed in my heart that in the end evolved into this thesis studying land use in the past and its legacy.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVATIONS

b.s.	below surface
ca.	*circa*
cf.	*confer/conferatur*
ADE	Amazonian Dark Earth
CBH	Circumference at breast height
DBH	Diameter at breast height
ICPN	International Code for Phytolith Nomenclature
LGM	Last Glacial Maximum
NKMNP	Noel Kempff Mercado National Park
NMDS	Nonmetric multidimensional scaling
NPA	Non-palm arboreal (phytolith)
PMI	Purus-Madeira Interfluve
SOM	Soil organic matter
UID	Unidentified (phytolith)

Domesticated forests, wild gardens... In short, if we think of the Amazon as landscape, an arena of agency rather than a constraining wilderness, we might get somewhere.

David Cleary
(2001)

INTRODUCTION

The common myth which dominated much of twentieth century research on Amazonia was that its rainforests were pristine: only small bands of hunter-gatherers roamed the vast rainforests, and they had only negligible impact on the landscape (e.g. Steward, 1949; Meggers and Evans, 1957). Although this misconception about Amazonia survives in the public perception, the “pristine myth” has been debunked by the scientific community (Denevan, 1992, 2001; Erickson and Balée, 2006; de Souza et al., 2018; Heckenberger et al., 2003; Heckenberger and Neves, 2009; Levis et al., 2017; Levis et al., 2018; Myers, 1992; Pärssinen et al., 2009; Posey, 1985). Most researchers now agree that intensive land use occurred on the *várzea* (floodplains), but it is also recognised that past human impact on Amazonia might have been heterogeneous (Barlow et al., 2012a; Bush and Silman, 2007; Piperno et al., 2015), and there remains much disagreement about the extent and the spatiotemporal scale of pre-Columbian land use regimes in *terra firme* (non-flooded upland) forests far from the main river channels and in other areas that have not been extensively studied (Heckenberger et al., 2003; Barlow et al., 2012b; Tollefson, 2013; Bush et al., 2015).

Models of land use on *terra firme* can be divided into two main views. The traditional view, called the “tropical forest culture” (Steward, 1949) or more recently the “standard model” (Viveiros de Castro, 1996), holds that *terra firme* forest features mainly poor, leached soils and scarce game, which inhibited the development of permanent and complex societies (Meggers and Evans, 1957; Meggers, 1954). On the other hand, recent archaeological evidence indicates that both the riverine and non-riverine areas experienced significant pre-Columbian cultural development. For example, the geoglyph area in Western Amazonia (Saunaluoma, 2010; Schaan, 2010), as well as archaeological remains on the Upper Xingu River (Heckenberger et al., 2008) and in the Upper Tapajós Basin in Brazil show that human exploitation of *terra firme* forests was more complex and larger in scale than previously thought. This view is supported by ethnobotanical studies that demonstrate that traditional interfluvial communities were remarkably skilled forest managers, who created highly diverse, complex, and sustainable forms of food production. They combined horticulture and agroforestry, which they supplemented with hunting, fishing, and gathering (Balée, 1994; Killion, 2013; Peters, 2000; Posey and Plenderleith, 2002). Historical ecologists argue that this was probably true for pre-Columbian communities as well (Balée, 2010; Clement, 2014; Denevan, 1998, 2001; McKey et al., 2010), who enhanced the ecological diversity of the forests (Levis et al., 2017; Levis et al., 2012; Maezumi et al., 2018), improved the properties of poor soils by the intentional or unintentional creation of archaeological sites called Amazonian Dark Earth (ADE) sites (Smith, 1980; Erickson, 2003; Neves et al., 2003; Schmidt and Heckenberger, 2009), and transformed landscapes on a regional scale (Erickson, 2006; Erickson and Balée, 2006; de Souza et al., 2018; Heckenberger et al., 2008). Some researchers suggest that the ability of humans to enhance their environments served as a sustainable basis for long-term sedentism, resulting in the development of socially complex societies between *ca.* 1000 BC and AD 1000 in the *terra firme* forests across Amazonia (Denevan, 2012a; Troufflard, 2013).

However, although the non-flooded *terra firme* areas constitute 95% of Amazonia, we still know very little about their human history (Piperno and Pearsall, 1998a; Stahl, 2015). These areas have been left unexplored due to the traditional archaeological view that they were uninhabitable, as well as to the logistical challenges to surveying these landscapes (Levis et al., 2013).

In recent years, studies have begun targeting human-environment interactions in the *terra firme* forests in the Purus-Madeira Interfluve (PMI), stimulating much debate. This interfluve is a unique region to study the modern legacy of past land use, as a terrestrial palaeoecology study by McMichael et al. (2012b) concluded that there was only a sparse pre-Columbian human presence that had minor long-term impacts on vegetation cover. Conversely, based on modern forest inventories in the PMI, Levis et al. (2012; 2017) argue that large forested areas, previously thought to be pristine, reflect historical forest management and modern-day composition enrichment. Unfortunately, none of these studies has combined archaeological and palaeoecological methods (Mayle and Iriarte, 2014). The discipline-specific methodological approach adopted inprevious research is not suitable to revealing the relationship between past human land use practices and long-term environmental impacts. This has resulted in intense debates in the recent literature (Bush et al., 2015; Clement, 2014; Clement et al., 2015; Piperno et al., 2015; Stahl, 2015). Additionally, past land use strategies and their environmental impact have not been connected with the modern vegetation composition of certain landscapes, which has raised further questions regarding methodologies for studying the modern legacy of pre-Columbian subsistence (Barlow, 2012b; Forline, 2008). More recently, however, predictive modelling on the extent of human impact in lowland Amazonia has suggested a high probability of the presence of ADE archaeological sites in the interior of the PMI (McMichael et al., 2014; Palace et al., 2017). By combining archaeobotany, terrestrial palaeoecology, and modern forest inventories, this thesis explores the promising results that come from using an interdisciplinary approach to resolve the debate on the extent and modern legacy of landscape modification in the PMI. The data gathered and analysed in this thesis provides a deeper understanding of the distribution and usage of ADEs and other anthropogenic areas in the interfluves, and it offers new insights into the long-term impact of indigenous communities on these landscapes.

Aims and scope of the research

This thesis aims to investigate the geographical extent and impact of pre-Columbian subsistence strategies on the modern vegetation composition and soil properties in the middle PMI. Combining archaeobotany, terrestrial palaeoecology, and modern vegetation inventories, this project takes a multidisciplinary approach and was designed to find evidence for long-term interactions between pre-Columbian societies and their environmental settings (habitats). Data on the modern vegetation composition was collected, as well as samples from soils under primary forests, oligarchic forests, an anthropogenic forest with Brazil nuts (*Bertholletia excelsa*), and an archaeological site (see Chapter 3). These were used to reconstruct human-environment interactions in the PMI during the late Holocene. No absolute natural baseline is presumed at the sites; instead, the landscapes are approached as the products of past environmental processes and anthropogenic activities. The research questions that will be answered are the following:

1. Were the forests and soils of the PMI modified by humans in late pre-Columbian times (*ca.* AD 1000–1492)?

2. If yes, what kind of subsistence strategies were applied, and what was the nature and geographic scale of their impact?
3. Did pre-Columbian land use have a lasting effect on forest composition and soil properties in the PMI?

This study covers an approximately 600 km-long transect in the PMI. The contexts that were studied to answer the research questions fall into four broad management types with growing anthropogenic impact: (1) primary forests on natural soil with no known forest management in the past; (2) oligarchic forests on natural soils and forests dominated by useful species; (3) anthropogenic forest with Brazil nuts on anthropogenic soil (brown ADE); and (4) the Couro Velho archaeological site with brown and black ADE soils in a small riverine setting. The site selection was based on the results of the following publications: Levis et al. (2012), McMichael et al. (2012b), McMichael et al. (2014), and personal communication with Carolina Levis, Charles Clement, and Flavia Costa, all at INPA.

This thesis is organised into six chapters following this Introduction. Chapter 1 presents a short overview of the palaeoecology and environmental changes in the Amazon Basin during the late Pleistocene and Holocene, the time when humans first occupied Amazonia. This is followed by a discussion of current understanding of land use, subsistence strategies, anthropogenic landscape transformations, and archaeological sites in Central Amazonia in Chapter 2. Chapter 3 presents this thesis' materials and methodology. First, the rationale behind site selection is introduced, then the fieldwork methods and laboratory analyses are described. Chapter 4 describes the results obtained from fieldwork and laboratory analyses. Chapter 5 discusses these results using a multiproxy approach, followed by the statistical analysis of the modern floristic inventories and part of the phytolith data. Finally, in Chapter 6, the conclusions drawn about ancient subsistence practices and their long-term environmental impacts in the PMI are presented and contribute to current archaeological understanding of some previously unexplored landscapes in lowland Amazonia.

CHAPTER 1

Palaeoecology of Amazonia since the Last Glacial Maximum

This chapter discusses the palaeoecological research that has been conducted in the Amazon Basin, and the geoglyph region specifically. All dates mentioned in the text are calibrated, unless stated otherwise.

The Amazon Basin is the part of South America drained by the Amazon River and its tributaries, and it covers an area of about 7,500,000 km^2 across the countries of Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname, and Venezuela (Goulding et al., 2003). The Amazon River is at least 6400 km long and has more than 1100 tributaries (*ibid.*). Tributaries are smaller rivers that do not flow directly into the ocean or sea but feed the river's main stem, the primary downstream segment of the river. Most of the basin is covered by the Amazon Rainforest, also known as Amazonia, a 5,500,000 km^2 area of dense tropical forest. This is the largest rainforest in the world and harbours around 390 billion individual trees that are divided into 16,000 species (ter Steege et al., 2013).

The palaeoecology and palaeoclimate of Amazonia both influenced the long-term development of natural flora and fauna. This consequently dictated the natural resources available to early settlers at the end of the Pleistocene, as well as the development of settlements and agriculture throughout the Holocene (Roosevelt, 2014). Therefore, it is important to take them into consideration when studying human occupation, land use, and their long-term impact. However, current reconstructions of Amazonian palaeoclimate and palaeovegetation are based only on proxy data and have therefore resulted in oversimplified cold-warm, wet-dry dichotomies being posited (Bush and Silman, 2004).

1.1 Late Pleistocene

It is widely accepted among terrestrial palaeoecologists that the average temperature was *ca.* 5 ˚C colder in Amazonia during the late Pleistocene than today's climate; however, there is still debate about whether the climate was cold and dry or cold and wet (Bush and Silman, 2004).

An early theory, namely the "refugia theory", stated that the tropical tree taxa of the Amazon Basin were forced into small isolated refugia during glacial periods (e.g. Haffer, 1969; van der Hammen and Absy, 1994; Prance, 1987). The assumption has been that these refugia were surrounded by expansive savanna vegetation communities that formed due to the significantly drier climate during the last glaciation (Prance, 1987). Fossil pollen evidence presented to support this theory has, however, been widely criticised, as sites with long sediment records are generally found across widely dispersed localities and contain no or very small amounts of Last Glacial Maximum (LGM) sediment. Additionally, there are too few radiocarbon dates for these sites to produce a well-defined chronology (Ledru et al., 1998).

Although they do not provide direct evidence for the existence of a forest refugium, Absy et al. (1991) argue that the LGM climate in south-east Amazonia was drier than in modern times based on a 60,000-year-old pollen sequence from Lake Carajás. The drier climate was supported by increased amount of Poaceae pollen and lower lake levels between 22,000–11,000 BP, which suggests the expansion of savanna ecosystems into the territory of forest ecosystems. Later, a pollen sequence from a lake core obtained from Katira Creek, Rondônia, confirmed this hypothesis, showing a clear shift from forest to savanna vegetation in the area around 41,300–18,500 BP (van der Hammen and Absy, 1994). Colinvaux and De Oliveira (2000), however, argue that the LGM was not necessarily drier than today's climate in southeast Amazonia and suggest that the dry periods in the sediment cores from Katira Creek were actually natural sedimentary hiatuses. They further argue that a reduction in precipitation during the wet season may have caused drops in lake levels, but this was not enough to considerably change the regional vegetation (*ibid.*).

Other palynological evidence suggests a cold LGM in Amazonia, but the climate was probably not drier than the present day (Behling, 1998). In this study, Behling interpreted the occurrence of *Podocarpus* populations in a sediment core from Lagoa da Curuça at the Amazon's mouth as evidence for significant cooling at low latitudes during the Late Glacial period. The pollen record from this core indicates dense and tall tropical rainforest during the Late Glacial period and does not support the spread of savanna ecosystems in this region during this period. Similarly, in the less seasonal north-west Brazilian Amazon region, the pollen record of Lake Pata also demonstrates the stability of the biome in the area for the last 40,000 years, as the region was constantly occupied by closed forests (Colinvaux et al., 1996). Examining the records more closely, the study's pollen data show strong signals for *Podocarpus* and other cold-adapted taxa, such as *Humiria, Weinmannia, Ilex,* Melastomataceae, *Hedyosmum*, *and Rapanea*. It is suggested that these cold-adapted taxa, which are today found at higher elevations, did not replace but rather enriched the tropical forest vegetation (*ibid*.).

Bush et al. (2004) also study the sediment sequence of Lake Pata together with other sediment sequences from surrounding lakes to investigate palaeoclimatic and vegetation change in the last 170,000 years in the Hill of Six Lakes region. At lakes Pata, Verde, and Dragão, the fossil palynological, charcoal, cation, and pigment data indicate the presence of uninterrupted mesic (moderately moist) forests throughout the last Ice Age, despite the evidence for continuous fluctuations in precipitation. Gross stratigraphy, algal remains, and palaeochemistry suggest that these fluctuations were cyclic and correlating precessional orbital variations (Bush et al., 2004). However, in the same paper goes beyond the forest/savanna debate and follows the argument of Colinvaux et al. (1996), suggesting that, although forest cover was uninterrupted during the Pleistocene, its composition changed in the late Pleistocene and more montane floral elements were present instead of the typical lowland forest biome, which suggests a cooling of 4–5 ˚C (*ibid.*).

The pollen record from an off-shore core in the Amazon Deep-Sea Fan further supports the theory of continuous forest cover during the Last Glacial period. Haberle and Maslin (1999) state that using the sediment record of a deep-sea core to reconstruct plant migration directions and rates during the LGM in the Amazon Basin has advantages compared to lake or bog cores, as the geographically scattered locations do not provide high-resolution fossil pollen data for the whole Amazon Basin. However, the Amazon Fan extends more than 700 km seaward of the continental shelf, therefore it collects pollen on a bigger geographical scale. The core, called the ODP Site 932 core, provides a 50,000-

year-long pollen record for vegetation from the Amazon Basin. *Alchornea,* Melastomataceae*,* Myrtaceae, and Moraceae/Urticaceae are dominant taxa in the pollen record between 40,200 and 19,800 BP. However, the fossil pollen record also shows peaks in cold-adapted Andean taxa, such as *Podocarpus* and *Hedyosmum*, at the LGM, a time when the treeline was lowered to about 2000 m above sea level in response to a cooling of up to 7 °C in the Andes (*ibid.*).

Besides palynological records, other source of evidence also suggest continuous forest cover during the late Pleistocene and early Holocene. For example, stable carbon isotope studies also demonstrate the dominance of C_3 (forest) vegetation from about 17,000 to 9000 BP in southern Amazonia, which suggest colder and wetter conditions (Pessenda et al., 2001). This study was carried out on a 200 km transect along the highway BR 319 on the border between Amazonas and Rondônia states, Brazil. Further, the stable isotope results also show that C_4 (savanna) vegetation cover grew in the middle Holocene (*ca.* 9000–3000 BP) suggesting warmer and drier circumstances, but from about 3000 BP forest vegetation dominated again. Another stable carbon isotope study in the same area found the same pattern: forest vegetation in the early Holocene, the expansion of savanna vegetation during the middle Holocene, then the advancement of C_3 vegetation again from about 3000 BP (de Freitas et al., 2001).

To synthesize findings on climate and vegetational changes during the late Pleistocene, it is evident that changes were not uniform across the entire Amazon Basin. In the zones between ecotones on the northern and southern margin of the Amazon Basin, savanna vegetation replaced forest in some areas during the LGM; however, most of the Amazon Basin remained forested during this time, though changes in the forest composition occurred due to the spread of dry and cold-adapted species in seasonal regions (Mayle et al., 2004). General circulation models for the LGM (Ganopolski et al., 1998; Hostetler and Mix, 1999) also suggest that the palaeoclimate was complex and that changes to precipitation patterns were differed between areas. Hostetler and Mix's (1999) predictive model suggests a reduction in wet season rainfall, but no changes or even a slight increase of dry season rainfall (June–July–August) in southern Amazonia, December–January–February in northern Amazonia). These observations, coupled with palaeoecological data, indicate that climate and precipitation changes were asynchronous and spatially variable across Amazonia (Behling, 1998; Bush and Silman, 2004).

1.2 The Holocene

Although the Holocene climate has not been characterised by the extreme climatic fluctuations of the Last Glacial period, it has been significantly variable. Millennial-scale climate variability during the Holocene has possibly been mainly influenced by solar activity, but other factors, such as the hydrological cycle, the ocean heat content, and atmospheric greenhouse gases, may have played role as well (Anderson et al., 2007).

The transition between the Pleistocene and Holocene seems to have been slightly cooler than today's climate, and, together with increased precipitation and CO_2 concentration, it resulted in forest expansion (Mayle et al., 2004). At the same time, the onset of rising sea levels resulted in a higher water table and the formation of Lago Tapajós around 11,000 BP. This is a wide, deep lake along the Lower Tapajós in Central Amazonia, although it should be noted that the cores below 42 m used to reconstruct the lake’s history are quite low resolution, due to coarse sand deposited on the water body’s bottom before it was flooded (Irion et al., 2006). Based on the pollen data, it seems that closed-canopy and riparian forest vegetation were dominant throughout the Holocene in this area (*ibid.*). The increased humidity and temperature at the onset of the Holocene is indicated in pollen records in from the Amazon Fan and Lake by a drop in cold-adapted Andean taxa (Bush et al., 2004; Haberle and Maslin, 1999).

The Early–Mid-Holocene brought aridity to Amazonia again. At the beginning of the Holocene, the cold-adapted *Podocarpus* disappears from the pollen record, suggesting a warming of the climate in the north-western Brazilian rainforests (Colinvaux et al., 1996). Indeed, at Lake Pata, temperature change is probably also responsible for the appearance of the palm *Mauritia*, which became prominent only with warming Holocene temperatures (*ibid.*). One hundred km from the Eastern Cordillera in the Colombian Amazon, sediment cores from Laguna Loma Linda, located at an altitude of 310 m in the transitional zone between the savannas of the Llanos Orientales and the Amazonian rainforest, suggest that savanna vegetation dominated the area between about 8700 and 6000 BP, indicating significantly lower precipitation with stronger seasonality. Poorly-developed gallery forests along the drainage system also attest to low precipitation (Behling and Hooghiemstra, 2000). The pollen record shows that the dominant taxa during this period were Cyperaceae, *Ludwigia, Polygonum*, and

Sagittaria, which indicates that the water table was low. Only a few woody savanna taxa, such as *Curatella* and *Byrsonima*, were present in the sediment core, and gallery forests along the drainage system were poorly developed. Based on the abundance of charcoal fragment in the core, the study's authors suggest that the savanna vegetation was burnt frequently (*ibid*.).

Later in the Holocene, the vegetation of the southern part of Amazonia was also characterized by the expansion of savanna and dry forest vegetation formations, with fire increasingly frequent between *ca*. 7800 and 3200 BP, and charcoal evidence from the Bolivian Amazon also indicates that this reduction in precipitation caused an increase in forest fires (Mayle et al., 2004). However, about the same time (from *ca.* 6400 BP) in the Colombian Amazon, the rainforest expanded again at the expense of savanna taxa, and conditions became even wetter from 3500 BP. Rainforest and gallery forest taxa, such as Moraceae/Urticaceae, Melastomataceae, *Alchornea, Cecropia*, and *Acalypha*, were abundant, whereas Poaceae reduced in frequency (Behling and Hooghiemstra, 2000).

The mid-Holocene aridity, savanna expansion, and drying out of shallow lakes are reported from more sensitive areas in south-eastern and south-western Amazonia (Absy et al., 1991; Mayle et al., 2000). Absy et al. (1991) suggest that the extension of savanna vegetation was most extensive at Lake Carajás around 6000 BP, suggesting a dry climate in this region where fire, attested by the abundance of charcoal remains, played an important role. Burbridge et al. (2004) studied sediment cores from Laguna Chaplin and Laguna Bella Vista in the Noel Kempff Mercado National Park (NKMNP) in the north-eastern Bolivia lowlands (south-western Amazon Basin). They conclude that the savanna ecosystems persisted until the mid-Holocene, with vegetation composition comprising mainly *Mauritia flexuosa* and/or *Mauritiella armata* palms, as well as the obligate savanna species *Curatella americana.* Semideciduous dry forest most likely bordered lakes in upland, non-flooded areas, such as the quartzite ridge, as indicated by the presence of *Anadenanthera, Astronium fraxinifolium, Astronium urundeuva,* and *Gallesia* pollen. Although the vegetation underwent significant changes in species composition during the early and mid-Holocene, savanna and dry forest remained the dominant vegetation form.

From the mid-Holocene, mixed evergreen and semideciduous forests started to expand, and an increase in Moraceae/Urticaceae around 2240 BP and a decrease in charcoal mark the southerly expansion of rainforest taxa in response to wetter conditions. Additionally, macrofossil charcoal has also been recovered from cores of this period, which indicates the presence of fire prone vegetation (Burbridge et al., 2004). These results have been confirmed by Mayle et al. (2000), which also focused on data from the NKMNP, suggesting that the climate was drier than today until about 2790 BP. This means that lake levels were lower and savannas dominated by *C. americana* and levees were seasonally inundated. Additionally, Moraceae-dominated gallery forests lined the nearby river. During this time, sediment-accumulation rates varied remarkably in the Bolivian lakes studied by Burbridge et al. (2004). At Laguna Bella Vista, deposition during the mid-Holocen, was slow at 0.02 mm yr^{-1}; however, the sedimentation rate was much higher in the early and late Holocene at 1.0 and 0.2 mm yr^{-1}, respectively. In contrast, the sedimentation at Laguna Chaplin was slow (0.02 mm/year) until *ca.* 6900 BP when the sedimentation rate became ten times faster.

This aridity in the more seasonal areas of Amazonia is not visible in either the sediment sequence of Lago Tapajós (Irion et al., 2006), or lakes in less-seasonal central Amazonia ((Bush, Miller, Oliveira, & Colinvaux, 2000)), though subsequent analyses of other lakes in this region suggest some lowering of water levels between *ca.* 6400 and 4600 BP (De Toledo, 2004, quoted in Irion et al., 2006).

In the sediment core from Lago Tapajós, the rate of sand sedimentation, as well as the concentrations of many chemical elements, declined, and the rate of deposition also slowed between 25 and 16 m depth (*ca.* 5500–3000 BP). The reduced sand content and slower sedimentation suggest a low-energy deposition environment, possibly resulting from reduced flow or less erratic discharge (Irion et al., 2006). During this period, an increase in Poaceae by *ca.* 20% was also observed; however, this is consistent with landscapes that contain a mosaic of vegetation types, though it can also be a sign of local anthropogenic disturbance (*ibid.*). Burbridge et al. (2004) argue that evidence for dense indigenous populations throughout much of the Bolivian Amazon before the Columbian Encounter raises the possibility that human activity may have contributed to regional vegetation dynamics.

The late Holocene marked the establishment of modern rainforests at the expense of savanna vegetation in most part of the Amazon Basin. At the border between the savannas and forests in the Colombian Llanos Orientales, the forest started to expand from *ca.* 3500 BP, which is suggested to be the result of increasing precipitation (Behling and Hoogheimstra, 2000). This expansion is deonstrated by the increased presence of *Hedyosmum* pollen, probably *Hedyosmum bonplandianum*, in the sediment sequence, which suggests increased disturbance and/or wetter climatic conditions. Behling and Hoogheimstra (2000) conclude that it is plausible that the area around Loma Linda would have remained forested throughout the late Holocene with lesser human impact.

Burbridge et al.’s (2004) study suggests that seasonally-flooded savannas dominated the lower areas of the Bolivian Amazon around Laguna Chaplin until about 2000 BP in which *M. flexuosa* and/or *M. armata* palms and the ubiquitous savanna species *C. americana* were prevalent. The pollen record indicates that humid evergreen rainforests expanded to cover most of the area within the past 2000 years, a suggested by declining Poaceae and increasing Moraceae pollen, whereas the charcoal record shows a decrease in natural fires. The sharp increase in Moraceae pollen percentages to present-day levels of 40% around 650 BP suggest the establishment of modern rainforest vegetation around Laguna Chaplin. A similar pattern is seen at Laguna Bella Vista; however, the timing is slightly different. The retreat of savanna and expansion of dry forest vegetation occurred between *ca*. 6800 and 3200 BP, and the establishment of modern rainforest began *ca.*2000 BP (*ibid.*). The continuous oscillation from savanna to evergreen forest throughout the Holocene can be explained if there was a gradual increase in mean annual precipitation and reduction in the length or severity of the dry season since the mid-Holocene (*ibid.*).

In southern Amazonia, carbon isotope results show the expansion of C_3 vegetation at the expense of savanna since about 3200 BP in the transect between Humaitá and Porto Velho. De Freitas et al.’s (2001) results also supports Absy et al.’s (1991) pollen study, which found that the development of modern forest vegetation in southern Serra dos Carajas (south-eastern Amazon) started around 3000 BP. Carbon isotope studies also attest to the same vegetation pattern in this area (Pessenda et al., 1998). Another carbon isotope study shows that, during the transition between the middle Holocene and the present, the climate in Roraima State, Brazil, at the northern limit of the Amazon Basin became more humid; however, forest fires still occurred regularly, which is indicated by the presence of numerous charcoal remains, dated to *ca.* 3230–1790 years BP (Desjardins et al., 1996). The climate change-driven increase in precipitation during the late Holocene may have played a significant role in one of the largest expansions of any linguistic family in the world. Iriarte et al. (2017) argue that the wetter conditions favoured the southerly extension of the forested areas and consequently the agricultural expansion of the Guarani forest-farming culture about 2500 BP. In south-west Amazonia, precipitation increased again from the mid-Holocene, especially after *ca.* 3000 BP, and forested vegetation started to expand (Mayle et al., 2004).

Many of the above studies about palaeovegetation dynamics indicate that it is difficult to distinguish natural changes in vegetation due to climatic forces caused by human-induced modifications in the landscape during the Holocene, and research designs and methodological approaches have a large impact on studies' outcomes. Behling and Hooghiemstra (2000), for example, argue that, although climatic circumstances should denote continuous forest cover in the Colombian Llanos Orientales from about the mid-Holocene, grass savanna has expanded again over the last 2300 years, and *Mauritia*-dominated palm forests developed in the area, suggesting increased human impact on vegetation. Burbridge et al. (2004) suggest that, although there is no direct pollen evidence of palaeo-Indian agriculture (e.g. maize) around their study area in Bolivia's NKMNP, anthropogenic soils suggest there has been a long-term human presence in this landscape. However, there is also evidence for dense populations of indigenous peoples before European contact throughout much of the Bolivian Amazon, which raises the possibility that human activity may have contributed to large-scale vegetation changes (e.g.,Denevan, 2001).

Many other scholars have suggested that humans played a major role in shaping the Amazonian forests. For example, ter Steege et al. (2013) suggest that widespread pre-Columbian forest management is a compelling hypothesis to explain the hyperdominance of some species in Amazonia, especially those that are extensively used by modern indigenous people (*Hevea brasiliensis*, cacao, and many palms) or associated with ADE sites (*Attalea butyracea*, *Attalea phalerata*, *M. flexuosa*). Similarly to this hypothesis, Levis et al. (2012, 2017, 2018) argue that the modern forest composition in large areas of Amazonia is the result of past forest management. Clement et al. (2015) suggest that by the time of the Columbian Encounter Amazonia was able to harbour a large, socioculturally diverse human population due to plant and landscape domestication. Landscape domestication was the most pronounced in relation to large, densely populated late pre-Columbian settlements *ca.* 1200–AD 1600 (Heckenberger et al., 2003, 2008). Balée's (2013) work in *terra firme* forests in the Brazilian portion of Amazonia implies that at least 11.8% of these forests is of anthropogenic origin, comprising palm forests, Brazil nut forests, forest islands, etc. Balée also argues that the liana forests that cover about 1,000,000 km^2 of the Brazilian Amazon may be secondary forests, the result of extensive fire events probably of human origin (Balée and Campbell, 1990).

CHAPTER 2

The Archaeology of Amazonia

This chapter discusses the main archaeological theories and the current state of archaeological knowledge that present research is based upon. First, the development of different models of land use in *terra firme* areas are outlined. This section is followed by a discussion of different land use strategies and their archaeological implications, as well as long-term environmental impact. In the final section, archaeological finds in Central Amazonia are presented.

2.1 Models of land use on *terra firme* areas

Although most scholars of the Amazon agree that the Amazonian floodplains were important centres of socio-cultural and technological development in pre-Columbian times, the extent of human impact on areas in Amazonia’s interior, further away from the main river channels, is still highly debated (Barlow et al., 2012a; Bush and Silman, 2007; Piperno et al., 2015). Particularly regarding the vast *terra firme* areas that constitute 95% of Amazonia, there seems to exist an opposition between archaeologists and anthropologists, who support large areas being utilised and transformed (“domesticated”) by pre-Columbian societies, and ecologists, palaeoecologists, and botanists, who argue that these areas experienced only minimal if any human impact prior to 1492 (Clement, 1999; Clement et al., 2015; Barlow et al., 2012a; Bush et al., 2015; Heckenberger et al., 2003; McMichael et al., 2017; Piperno et al., 2017; Tollefson, 2013; Watling et al., 2017a). Therefore, this overview focuses on the development of different models regarding the number and impact of pre-Columbian inhabitants in the interfluvial forests.

There are two main models of land use on the *terra firme*: the standard model (environmental determinism) and the cultural ecology model (Myers, 1992; Neves, 1999; Viveiros de Castro, 1996).

2.1.1 The standard model and its critique

The first attempt to document Amazonian populations in modern times came with Steward's "standard model" in *The Handbook of South American Indians* published by the Smithsonian Institute between 1940 and 1947 (Steward, 1940-1947). In this six-volume series, Steward synthesized the ethnographical and anthropological tradition of the mid-twentieth century and transformed it into a new discipline called "cultural ecology" that was fed by geographical and environmental determinism. He designated the indigenous Amazonian groups as belonging to a "tropical forest culture" and described such cultures as slash-and-burn horticulturalists who lived in small, autonomous villages, occupying an intermediate evolutionary position and limited by technological and environmental constraints (Steward, 1949). This model was also called the "standard model" (Viveiros de Castro, 1996) or "standard paradigm" (Stahl, 2002) and was based on sparse archaeological data and assumptions based on historical or contemporary indigenous groups.

Steward (1949) initially assumed that the tropical forest culture fed from the traits of the more complex circum-Caribbean culture. Later, he also considered the lowlands adjacent to the eastern Andes as another possible source of this cultural tradition. In any case, these models portrayed Amazonia as marginal to South American cultural history (Neves, 1999). Steward's model portrayed contemporary Amazonians as people who lived in a mature equilibrium with their limiting environment. Additionally, as this environment was homogenous throughout the Amazon Basin, its cultures were thus also "strikingly uniform". Although Steward was an anthropologist and did not test his hypotheses through archaeological excavations, his work has had long-lasting influence on the way archaeologists interpret their data (Neves, 1999).

Betty Meggers, an influential archaeologist and conteporary of Steward from the Smithsonian Institute applied his views in her landmark paper of 1954, in which she correlated the cultural development of indigenous populations with their environmental circumstances and, more importantly, the agricultural potential of the rainforest. She supported Steward's (1949) theory that the prehistoric inhabitants of Amazonia most probably came from the west as a result of the Andean cultural expansion and quickly diminished in the jungle of the lowlands. Meggers proposed the law of environmental limitation on culture and claimed that, "the level to which a culture can develop is dependent upon the agricultural potentiality of the environment it occupies." In 1971, she published her theoretical manifesto *Amazonia: Man and Culture in a Counterfeit Paradise.* In this volume, she argued that the Amazon's lush vegetation hides significant limitations for all living organisms, including humans, placing a ceiling on pre-Columbian population density and social complexity.

More than 20 years later in 1996, a revised version of this volume was published (Meggers, 1996). The only change was that Meggers added an epilogue in which she states that the evidence accumulated over the past two and a half decades did—contrary to other archaeologists' claims—further strengthen her theory. Throughout her career, Meggers has approached Amazonia as a "counterfeit paradise" and argued that its prehistoric inhabitants were restricted by harsh climatic conditions, poor soil quality, and a lack of protein, which kept them socially and technologically primitive and prevented them from having any signfiicant impact on the forests (Meggers, 1954, 1971, 1993, 1996, 2011; Meggers and Evans, 1957). In her view, the indigenous slash-and-burn horticulturalists lived in equilibrium with the forest.I In other words, this was the highest state of cultural and social complexity they were capable of reaching and sustaining (Meggers, 1971).

Based on these theories, the concept of Amazonia as the last pristine wilderness populated by small bands of hunter-gatherer groups was actively promoted by the global conservation movement that increasingly gained ground in the 1970s and 1980s (Bezerra, 2015; Denevan, 2012b). Indeed, while the Amazon is recognised for its unrivalled biodiversity, it does present several obstacles to human population growth, particularly in terms of its poor soils and scarcity of game animals (Lathrap, 1970, Meggers, 1993). Although her interpretation of pre-Columbian Amazonian life and anthropogenic impact diverged from Megger's in many ways, Roosevelt (1980) also identified poor soils as a limiting factor. Similar to Meggers, Roosevelt concluded that the development of complex pre-Columbian societies, especially in *terra firme* settings, was restricted by the poor soils. It is true that 75% of soils in the Brazilian

Amazon are categorised as oxisols and ultisols, which are deep, acidic, highly-weathered, leached formations with toxic levels of aluminium (Moran, 1993; Furley, 2006; Falcão et al., 2009; Cochrane and Sánchez, 1982), therefore they are unsuitable for sustainable agricultural production. However, human manipulation of soils and crops can overcome these obstacles (Balée and Gély, 1989).

Balée and Gély (1989) also points out that, beside the infertile soils mentioned above, 8% of Amazonia is covered by more fertile soil types, such as Alfisols, Mollisols, and Vertisols. Additionally, this 8% does not include the anthropogenic soils (section 2.3). Lathrap, 1970 notes that Amazonian soils should be looked at in terms of how we want to use them. Indigenous groups had a range of plants to cultivate and the ecological knowledge to choose which plant would be better to grow depending on the soil properties. Techniques to improve soil fertility other than creating ADEs have also been described: the Kuriuku on the Upper Xingu River created mounds from soil to change its texture (Carneiro, 1983); the prehistoric farmers of French Guiana improved soil ferility (Iriarte et al., 2012); the Llanos de Mojos in Bolivia (Erickson, 1995) built raised fields for better drainage and aeration during rainy season (Erickson and Balée, 2006); and other indigenous groups tend to protect plants that promote nitrogen fixation in the soils (Hecht and Posey, 1989).

The other controversial subject regarding the highest level of social complexity that can be reached in lowland Amazonia is the availability of protein. The scarcity of game in *terra firme* is a factor that Gross (1975) argued to be another large hindrance to the landscape's human carrying capacity. He noticed that ethnographic accounts of several Amazonian groups documented protein intake below those of modern minimum acceptable levels, which leads to conditions of high residential mobility and diminished health. It was also argued that the number and variety of risk avoidance behaviours practiced by modern indigenous groups (e.g. high mobility, cultivar diversity, taboos on consumption, mandatory sharing, long-distance exchange, and infanticide) are cultural responses to low carrying capacity (Meggers, 1993). Both Gross and Meggers, however, failed to consider the role of vegetable protein (e.g. palms, Brazil nuts, cashews) in indigenous diets and the very diverse sources of animal protein (big game, small game, aquatic resources, reptiles, insects, etc.) in the tropical rainforest (Beckerman, 1979).

Stahl (2002) raises the question: if tropical forest cultures have successfully adapted to the imposed limitations of their environment and are able to maintain a sustainable livelihood, why are the resources they use still being perceived as scarce or limited? Meggers' answer to this question focuses on the climate's variability, namely the severe periodic droughts caused by large El Niños that appear every few hundred years and limit agricultural productivity, food production, and consequently the development of cultures (Meggers, 1994; Schimmelmann et al., 2003). Meggers (1994) identified discontinuities in lowland Amazonian ceramic sequences *ca.* 1500 BP, 1000 BP, 700 BP, and 400 BP, which she correlated with dramatic drops in rainfall that she explained had catastrophic consequences on local subsistence strategies. She further argues that these periodic droughts might have forced the repeated human dispersals reflected in the linguistic and genetic diversity of surviving indigenous lowland South American populations (*ibid*.).

In contrast, Stahl (2002) denies that these drought events had such a significant impact on the Amazonian ecosystems and consequently on humans. He argues that, although it is true that rainfall has fluctuated since the Pleistocene, there has always been enough to support the Amazonian lowland forest ecosystems and their inhabitants, and there has been no sign of abrupt changes or savanna-like ecosystems forming. In *Maya Subsistence: Studies in Memory of Dennis E. Puleston* edited by Kent V. Flannery, Denevan's (1982) statement echoes Meggers' claims about Amazonian agricultural potential and limitations on cultural development, arguing:

> …there are no environmental limitations to the development of agriculture, only cultural limitations. 'Agricultural potential' is a cultural phenomenon; it is not something inherent in nature that can be measured, that exists independent of culture (Denevan, 1982: 181).

These words foreshadowed much-needed changes in the way Amazonian archaeology theory and practice was conducted.

2.1.2 The new paradigm in Amazonian archaeology

The archaeological theory and methodology formulated by Meggers and Evans (1957) was attacked from many angles. Meggers' views were criticised early on, with claims that her law of environmental limitation on culture was vague and untestable (Hirshberg and Hirshberg, 1957). Meggers and Evans (1957) investigations on the Marajo Island at the mouth of the Amazon River was critiqued as fundamentally misleading, as it was clearly designed to locate and excavate exactly what the two researchers wanted to find in Amazonia: small sites with shallow occupational layers (Peters, 2000). Despite these critiques, Meggers and Evans work in the 1950’s set the tone for Amazonian archaeology for decades.

From the 1980s, however, a new generation of scientists with a fresh view on the human history of Amazonia brought new concepts into the prevailing discourse. Anna Roosevelt, for example, continued Meggers work on the Marajó Island. Her decades-long work combining archaeological excavations with geophysical surveys revealed that the Marajó culture lasted nearly 1000 years (Roosevelt et al., 1991). With this work, Roosevelt challenged theories based on environmentally deterministic precedents and provided evidence that the pre-Columbian Amazon was able to sustain more complex human culture. During the following years, there was a shift in archaeological theory and practice, as it became increasingly evident that the emergence and persistence of “simple” or “complex” social structures could not be explained using only environmental factors without also considering long-term historical and social dynamics (Viveiros de Castro, 1996).

2.1.3 The historical ecology perspective and its implications for investigating *terra firme* areas

To overcome the problem of understanding the size and magnitude of indigenous landscape modification and domestication, William Balée established the ”historical ecology” approach that he describes as:

> a new interdisciplinary research program concerned with comprehending temporal and spatial dimensions in the relationships of human societies to local environments and the cumulative global effects of these relationships (Balée, 2006: 75).

Instead of seeing humans as adapting to environments, historical ecology focuses on the “interpenetration" of culture and environment, which are in constant interplay (Balée, 1989, 2006). The main ideas of historical ecology are:

1. Much, if not all, of the human biosphere has been affected by human activity;
2. Human activity does not necessarily lead to the degradation of the environment or its improvement;
3. Different socio-political systems have different effects on the biosphere, and on the trajectory of subsequent socio-political systems;
4. Human groups and cultures, together with landscapes and regions, can be understood as a total phenomenon (Balée, 2006).

Apart from the interdisciplinarity, the most important aspect of the historical ecology approach is the time depth that it studies. Historical ecology sees modern landscapes as palimpsests of ecological and cultural processes, the results of co-evolutionary development. Stahl (2008) stresses the importance of the historical ecology approach by adding that the cultural landscapes created by the ancestors of today's indigenous groups continue to sustain contemporary populations and underlie much of what is considered by many to be "nature". Stahl (2002) summarises the main differences between the standard model and the historical ecology approach as emphasising the environmental heterogeneity and variability in agricultural adaptation, deeper time scales for human occupation, endogenous cultural complexity, and higher population densities. Applied historical ecology, therefore, can supply the reference conditions of time depth and traditional knowledge to restore past landscapes, as well as support biodiversity conservation and management, rational development, and indigenous rights.

However, while the tenets of historical ecology remain widely accepted among Amazonian scholars, others warn that the way data is obtained and interpreted must be done very carefully even with a well-prepared research framework. For example, there is still an ongoing debate over the ages of "old" anthropogenic forests and whether they can be attributed to the activities of pre-Columbian populations, post-Columbian populations, or both. Indeed, Palace et al. (2017) recently questioned the time depth suggested by Levis et al. (2017) for the age and extent of anthropogenic forests (forests enriched with useful species) in the Amazon Basin. It is not clear whether an elevated density of useful species was the result of ancient agroforestry practices, the impact of post-Columbian industrialisation (e.g. the rubber boom), natural processes, or a combination of natural and anthropogenic factors (ter Steege et al., 2013).

The importance of unravelling the “historical” part of historical ecology is also illustrated by a study which deals with the vast areas of palm stands in Maranhão State in north-eastern Amazonia. The babaçu palm (*Attalea speciosa*) is very important to the Guajá Indians in this region for many reasons (fuel, food, fiber), and Balée (1989) and others have assumed that palm forests are relics of pre-Columbian landscape transformations; however, Forline (2008) argues that this species’ distribution in Maranhão corresponds to areas that have experienced relatively recent human impact. From the establishment and subsequent abandonment of colonial sugarcane plantations to the post-contact adoption of swidden agriculture by the Guaja tribe and the introduction of modern industrial practices, this area was heavily utilised after European contact (Forline, 2008; May et al., 1985). Thus, Forline (2008) argues that babaçu forests are primarily an artefact of recent migration and settlement, and they must be viewed in terms of recent history. Similarly, a vast region of western Amazonia was opened up for rubber extraction in the 1800s, which resulted in a huge influx of caboclos (mixed-race farmers) who practiced swidden agriculture and altered species composition across large swathes of these interfluvial zones (*ibid*.).

On the other hand, historical ecology has played a vital role in revealing the intricate and sometimes very subtle ways that humans alter their environment, and the approach has done much to promote the knowledge and agency of indigenous peoples (Stahl, 2002). It has opened up perspectives for a very different way of looking at and thinking about the interplay between cultural and natural elements, as well as the shaping of our environment, not only in Amazonia, but also elsewhere in the world (e.g. Feiss et al., 2017; Ingrouille, 1995; Swetnam, 1999). By having humans play an active role in human-environment interactions, the approach has also highlighted the need to consider all structures of human activity—policy, economy, society, and culture—as constantly interacting with the environment, and it has provided a model for a unified understanding of landscapes. While such an understanding is arguably much harder to achieve for the past than the present (Whitehead, 1998), historical ecology has nonetheless introduced new avenues and ideas for research in the arena of human-environment interactions.

2.1.4 *The várzea-terra firme* dichotomy and the bluff model

In early Amazonian archaeology, the *várzea-terra firme* dichotomy was another way to demonstrate the advantages of living on the floodplains, which have abundant resources compared to living in the interfluvial forests, which have poor soils and scarce game. In earlier works, the bulk of the archaeological record constituted riverine sites (e.g. Denevan, 1996; Lathrap, 1970; Meggers, 1971; Roosevelt, 1980), and the literature contained a strong assumption that the intensive exploitation of the floodplains recorded in the first European accounts in the sixteenth century reflected the greater desirability and ecological potential of the floodplains compared to the interfluves. Nonetheless, this theory of cultural development—proposed by Lathrap (1970)—was based on the fact that there large quantities of nutrient-rich sediment deposits are left on the floodplains after the annual floods recede. Either manioc (*Manihot esculenta*) (Lathrap, 1970) or maize (*Zea mays*) (Roosevelt, 1980) cultivation on these fertile alluvial soils was thought to be the catalyst for the development of the large, complex societies that eventually spread along the major tributaries of the Amazon river due to population pressure (Lathrap, 1970).

In the same year as Lathrap, Carneiro (1970) introduced a new ecological hypothesis considering the origin of the state, which suggested that environmental constraints, especially agricultural productivity and the territorial limitations on the floodplains, lead to the rise of chiefdoms. Carneiro did not dismiss the productivity of the hinterland, however, demonstrating that subsistence economy based on manioc had the potential to support large, dense populations on the Upper Xingu (Carneiro, 1983).

The “floodplain model” proposed by these authors was still environmentally deterministic, as it stemmed from the idea that the rise of social complexity was dependent on the abundance of natural resources (Viveiros de Castro, 1996; Roosevelt, 1999). Indeed, environmental dichotomy implied cultural dichotomy as well. Roosevelt et al. (1991) even stated that the native groups inhabiting the hinterlands were more vulnerable to acculturation and extinction through European contact. It has, however, been argued that, although there is some truth in this assumption, the growing archaeological evidence suggests that the *várzea-terra firme* dichotomy is overemphasised. Cleary (2001) argues that the interfluvial areas were also inhabited by pre-Columbian societies and underwent anthropogenic landscape modification processes, but the sheer size of these areas means that this impact is less visible than on the floodplains where space is more concentrated.

Although the notion that cultural complexity originated within Amazonia was highly novel, the early models failed to recognise the diversity of environments present in the Amazon. As Moran (1993) insisted, the region's pedological, botanical, and zoological variety do not fit into the simple *várzea-terra firme* opposition, because the floodplain ecosystems are complex and very diverse throughout the length of the Amazon River and its tributaries. Similarly, the *terra firme* is not an enormous block of landscape, but it consists of various kinds of forests, savannas, and other ecosystem formations. Stahl (2002) states that, as it is not possible to think about the vast interfluvial areas constituting 95% of lowland Amazonia as a uniform environment, we also cannot approach the indigenous people inhabiting these forests as if they are the same everywhere.

Denevan's bluff model

In 1996, William Denevan proposed a new model for population concentration and land use in the Amazon Basin. Although this new model is also based on the *várzea-terra firme* dichotomy, it puts much more emphasis on the importance of upland areas in the subsistence strategies of the native Amazonians. From the accounts of early travellers, ethnohistorical studies, and archaeological evidence, Denevan recognised that, although the fertile soils of floodplains were cultivated seasonally along the main river channels, the large settlements and anthropogenic soils were situated on bluffs above the *várzea*. He argued that, because of regular annual floods and extreme periodic flooding, the *várzeas* were high-risk habitats that made them suboptimal for large, established settlements. In his model, Denevan also proposed that the *terra firme* areas adjacent to the settlements had been subjected to intensive cultivation as agroforestry systems that were also integrated with permanent gardens and swiddens (Denevan, 1996).

2.2 Pre-Columbian land use strategies

2.2.1 The population of Amazonia pre-Contact

In order to estimate the geographical extent of the Amerindians and their impact on Amazonian landscapes, it is important to first estimate how many people lived in Amazonia before 1492. However, this question represents one of the biggest challenges for Amazonian archaeology. The most widely-quoted estimate for prehistoric populations in the Amazon is Denevan's (2003) estimate—made based on the relevant archaeological, historical, environmental, and agricultural evidence available at the time—which suggests at least five to six million people in Greater Amazonia and at least three to four million in the Amazon Basin. Other estimates posit this number somewhere between two and 10 million at the time of contact with Europeans (Clement, 1999; Meggers, 1993; Myers, 1988; Petersen et al., 2001; Roosevelt et al., 1996).

Contrary to the lack of agreement on the population number pre-1492, most researchers agree that, during the first centuries after contact with Europeans, human populations in the Americas declined by around 90–95% as a result of of Old World diseases, warfare, and slavery (Clement, 1999). Dobyns (1966) refers to the introduction of Old-World pathogens—e.g. smallpox, measles, whopping cough, influenza, etc. —to the New World as one of, “the world’s greatest biological cataclysms”. Stahl (2002) has proposed that the current inhabitants of the interfluvial areas might be considered the remnants of prehistoric forager groups that avoided contact with Europeans or other floodplain populations and survived by dispersing in the uplands to escape the European invasion.

Since the exact number of pre-Columbian inhabitants is unknown, it is also difficult to estimate the impact they had or pressures they placed on Amazonian ecosystems (Erickson, 1995). Clement (1999) argues, for example, that native Amazonians were cultivating or managing as least 138 plant species by the time of European contact. These plants needed constant human intervention to maintain genetic stocks. However, after the sharp decline of the native Amerindian population, the majority of this genetic heritage plausibly vanished.

To achieve a finer picture of the past, archaeologists tend to use ethnohistorical data as a crutch to support their hypotheses about pre-Columbian life in Amazonia. Indeed, ethnohistorical data can serve as evidence that indigenous people are capable of successfully practicing large-scale land management and creating anthropogenic landscapes. Modern practices can thus be used as a baseline for evaluating the past (Cleary, 2001). However, their direct, uncritical projection back to pre-Columbian times can lead to misinterpretations. Denevan (1992) notes in his paper, "Pristine Myth: The Landscape of the Americas in 1492", that, when piecing together archaeological, ethnohistorical, and fieldwork data, the difference between Amazonian landscapes pre- and post-1492 is huge. He thus argues that human presence was probably less visible in 1750 than it was in 1492. The following section presents some of the observations from ethnohistorical and ethnobotanical perspectives of land use practices employed by indigenous Amazonians on *terra firme* areas.

2.2.2 Ethnohistorical and ethnobotanical studies in the interfluvial forests

While Balée worked among the Ka'apor people, he made an interesting observation that led him to propose his "agricultural regression" hypothesis (Balée, 1994). He found that small-scale agriculturalists among the Ka'apor people have more words for plants and animals than foragers do. However, since the foragers live closer to and engage more frequently with wild animals and plants, they should need much more extensive naming inventories. This led Balée to the conclusion that the ancestors of these foragers might have been agriculturalists, but, due to environmental, cultural, or other stresses—e.g. European contact—they had returned to a nomadic hunter-gatherer lifestyle. In other words, present-day Amazonian foragers did not adapt to a pristine environment but utilised the cultural landscapes their agriculturalist ancestors left behind. Denevan (2001) proposes a similar argumentthat he calls "de-evolution". He argues that landscape elements like ADE and the anthropogenic forests are artefacts of intensive land use from pre-Columbian times. This is particularly the case for areas where hunter-gatherer groups live today (Denevan, 2003).

In contrast, other scholars claim that not every indigenous group went through a process of "agricultural regression". Costa (2009) disputes the uniformity of Balée's model, arguing that the Kanamari in the western Brazilian

Amazon gave up farming for a short period between the late 1930s and early 1970s. During this period, the Kanamari became increasingly mobile, but, instead of returning to foraging, they became involved with the Amazonian rubber boom. Costa further argues that, for this group, giving up agriculture and becoming more mobile was a means to reconnect with their ancestors' way of life, to rediscover who they originally were. Giving up sedentism, therefore, should not be seen as a backwards steps in the development of group social and cultural complexity; it is not a way of life that humankind cannot return from.

In his book *Indigenous Management of Tropical Forest Ecosystems: The Case of the Kayapó Indians of the Brazilian Amazon*, Posey (1985) describes how the Kayapó Indians on the Xingu River utilise, conserve, and even create new tropical forest islands (*apêtê*) in their territory. He observed that the Kayapó had deep knowledge of the forest's ecology and were adept at creating using semi-domesticated and domesticated plants. He refers to their land use practices as integrated management, as they not only utilised forest plants but also created plant communities close to their village that served as habitats for wild animals to hunt. The group even kept semi-domesticated bees.

With Posey's work (Posey, 1985; Posey et al., 1984), an influential case was made for incorporating indigenous knowledge into rational development schemes for Amazonia. The Ka'apor Indians of eastern Amazonia, extensively studied by Balée (1989, 1993, 2013), created "cultural" or "anthropogenic" forests that had different species compositions to old-growth forests. The species that appear in such forests are typically manipulated and show no reduction in natural diversity. Cultural forests in Ka'apor territory (including babaçu, Brazil nuts, lianas, palms, and bamboo) constitute at least 11.8% of total upland forest in the Brazilian Amazon (Balée, 1989: 14). Such studies demonstrate that contemporary indigenous Amazonians are able to transform and utilise their environments in ways that ensures they produce sufficient food and their diets are healthy.

An issue regarding indigienous diets that has been raised has similarly been contested by ethnographic studies. Meggers' (1993) and Gross' (1975) arguments that the inhabitants of lowland Amazonia suffered from protein deficiencieshas been debunked by evidence for the historical and current use of insect and plant proteins in indigenous Amazonian diets (Posey and Plenderleith, 2002). Additionally, Balée (1989) observed that the Ka'apor hunted large game, though there was a taboo on the hunting of capybara.

One of the implications of these ethnographic and ethnobotanical studies is that nature cannot be considered to provide a ceiling that restricts the potential for population growth or the emergence of social complexity, since nature can also be a product of human action and not a neutral external variable (Neves, 1999). This also supports the criticism of Lathrap's (1970) ecologically determinist models that suggested only the alluvial floodplains could serve as major centres of early cultural developments, such as plant domestication and ceramic production, while the interfluvial forests could only accommodate foraging groups. The following section discusses recent archaeological finds from interfluvial areas and argues that, in addition to contemporary indigenous groups, pre-Columbian societies were also able to thrive on landscapes they had completely transformed in the *terra firme* forests.

2.2.3 Archaeological studies in interfluvial areas

In addition to modern ethnobotanical and anthropological studies, recent archaeological evidence indicates that signfiicant pre-Columbian cultural development could have taken place in both riverine and interfluvial areas. The cases of the geoglyph area in western Amazonia (Saunaluoma, 2010; Schaan, 2010), the Upper Xingu region in Mato Grosso State, Brazil (Heckenberger et al., 2008) and the Upper Tapajós Basin (de Souza et al., 2018) show that human exploitation of the *terra firme* forests was more complex and larger in scale than previously thought.

Ethnobotanical studies similarly demonste that traditional interfluvial communities were remarkably skilled forest managers who created highly diverse, complex, and sustainable systems of food production. Theses communities combined horticulture and agroforestry, supplemented by hunting, fishing, and gathering (Balée, 1994; Peters, 2000; Posey and Plenderleith, 2002). Historical ecologists argue that this was probably also true for pre-Columbian communities (Balée, 2010; Clement, 2014; Denevan, 1998, 2001; McKey et al., 2010). Their activities will have enhanced the richness of forest species (Levis et al., 2012), improved poor soils through the intentional or unintentional creation of ADEs (Erickson, 2003; Neves et al., 2003; Schmidt and Heckenberger, 2009;

Smith, 1980), and transformed landscapes on a regional scale (Clement et al., 2015; de Souza et al., 2018; Erickson, 2006; Erickson and Balée, 2006; Heckenberger et al., 2008). It has been suggested, that the ability of humans to enhance their environments served as a sustainable basis for long-term sedentism, resulting in the development of socially complex societies between *ca.* 1000 BC and AD 1000 in the *terra firme* forests across Amazonia (Denevan, 2012a; Troufflard, 2013).

Archaeological and palaeoecological investigations in south-west and western Amazonia

The earthwork tradition in south-west Amazonia on the border of Brazil and Bolivia paints a very diverse picture of pre-contact archaeology. Different types of earthworks have been studied, including the impressive but uniform earthworks that probably served as borders for enclosed areas or sometimes canals in Bolivia's Riberalta region (Saunaluoma, 2010) and the enormous geoglyph constructions in Acre State, Brazil (Pärssinen et al., 2009; Schaan, 2007; Schaan et al., 2012). One of the big challenges that scholars face regarding these earthworks is that only archaeological remains have been found, therefore there remains debate surrounding how these earthworks were built in places that have historically been thought of as inhabited by simple, small hunter-gatherer groups. These discoveries challenged previous assumptions about the cultural development, social organisation, and numbers of indigenous people in the Amazon (Pärssinen et al., 2009; Schaan, 2007).

In Amazonian archaeology, the presence of highly fertile anthropogenic soils, also known as ADE (section 2.3) are generally accepted as signs of densely populated areas, sedentism, and intensive land use in pre-Columbian times (Kern et al., 2003; Heckenberger and Neves, 2009). The surprising absence of ADEs in *terra firme* areas in south-western Amazonia, however, indicates either a small population and sporadic use of sites or a different trajectory in pre-Columbian Amazonian subsistence strategies.

Phytolith, charcoal, and stable carbon isotopes (Watling et al., 2015; Watling, 2017a) suggest that the native people of this region utilised both domesticated plants (maize, squash) and wild plant resources (mainly palms). Such studies also suggest that these forests have been managed for the last 6000 years at least; however, regional-scale deforestation is strictly a modern phenomenon (Watling et al., 2017a). In contrast, Carson et al. (2014) argue that earthwork builders took advantage of a naturally-open savanna landscape which existed due to drier-than-present climatic conditions prior to *ca*.2,000 years ago. These conditions would have necessitated far less labour-intensive work. The authors conclude that this finding implies a much lower population density than previously thought.

Theories that western Amazonia was not inhabited during the early Holocene were questioned by Posey (1985), who suggested that forest islands in the savanna were the product of human activities.. Posey's interpretation was later critiqued by Parker (1992), who believed that many anthropogenic features were not the result of the Kayapó's intervention but that of the Brazilian Air Force, while the forest islands were the natural products of secondary succession following the abandonment of cropping, as opposed to deliberate management. The discovery of early Holocene shell middens in the Llanos de Mojos of western Amazonia challenged these assumptions. As the middens are located in the forest islands, Lombardo et al. (2013) suggest that early hunter-gatherer groups actively changed the landscape to overcome difficulties in a changeable environment.

The later inhabitants of the Llanos de Mojos transformed the landscape even further, which Erickson (1995, 2006) argues cannot be called adaptation or alteration but was rather the creation of a different anthropogenic landscape. Indeed, by burning and clearing vegetation, building earthworks and ring-diches, raising agricultural fields, creating forest islands and artificial wetlands, etc., this landscape cannot be considered natural. Even though indigenous people created a completely anthropogenic landscape, they did not degrade it, but may have increased local biodiversity in some cases (Erickson, 2006).

A combined palaeoecological and archaeobotanical investigation by Whitney et al. (2014) reveals a more detailed land use history of the Llanos de Mojos. At El Cerro raised-field site, raised fields were constructed after the removal of savanna trees, and gallery forests were used to improve soils so that they were suitable for maize cultivation. Fire was a crucial tool to manage the vegetation on and around the raised fields. Around AD 1300, the agricultural strategy had changed; fire as a management strategy was abandoned, and more diverse domesticated (e.g. sweet potato) and wild resources (e.g. Inga fruits) were exploited. By the time of the European's arrival, the raised fields were mainly abandoned, but sweet potato cultivation remained important until about AD 1800 (Whitney et al., 2014).

Based on these findings, it is likely that western Amazonia sustained large populations that were organised in villages and towns dispersed across the savannas and forests (Denevan, 2001; Erickson, 2006; Erickson and Balée, 2006; Walker, 2008). Furthermore, it is possible that this pre-Columbian economy expanded to a size where it was able to produce agricultural surplus for trade and exchange (Cleary, 2001).

In addition to archaeologists, palaeoecologists have also been highly interested in conducting research in western Amazonia, specifically to seek signs of pre-Columbian impact on Amazonian landscapes; however, their methodologies and interpretations have sparked much debate. In a series of articles, McMichael et al. (2011, 2012a, 2012b) report on their analysis and interpretation of many soil cores extracted from randomly-selected locations in central and western Amazonia. Only a small amount of charcoal was recovered from the soils, and the phytolith assemblages contained very few cultigens or other useful plants. Based on these results, the authors question the “cultural parkland” hypothesis supported by Heckenberger et al. (2003) and Erickson and Balée (2006). Their palaeoecological methodology, however, sparked lively discussion and was criticised as being unsuited to detecting all types of human impact on the landscape (Stahl, 2015).

Investigations in southern Amazonia

The Upper Xingu region

The Upper Xingu region of the southern Amazon is located in Mato Grosso State, Brazil. It represents another remarkable example of landscape domestication in a *terra firme* setting. Heckenberger et al. (2008) describe complex settlement and land use patterns from late pre-Columbian times in the region. They refer to these as galactic clusters—small, independent villages linked to a common regional peer polity by roads that probably share features of techno-economy, socio-political organisation, and ideology. The Arawak, an early agricultural group, colonised the basin by AD 500–800 and created a semi-intensive resource management system focused on manioc production, which was combined with arboriculture, such as encouraging the growth of palms, and probably extensive wetland management. Heckenberger et al. (2008) and Heckenberger and Neves

(2009) suggest that contemporary land use seems similar to what they found in the archaeological record.

The Upper Tapajós Basin

In a recent paper, de Souza et al. (2018) present the results of their investigation in the Upper Tapajós Basin. Using remote sensing and excavation techniques, de Souza et al. report the discovery of 81 new sites in this previously-uncharted region. The majority of these sites contain ceramics and ADE, suggesting the long-term occupation of this area. Some of the ditched enclosures were big enough (up to *ca.* 360 m in diameter) that they probably served as fortified villages. In addition to these ditched enclosures, ring villages have been also discovered in the Upper Tapajós Basin. These new discoveries fit well with what is already known about site complexes on the Upper Xingu and south-western Amazonia, suggesting that the entire southern rim of Amazonia, an approximately 1800-km stretch, was once occupied and transformed by pre-Columbian societies.

Recent debates on the size of pre-Columbian populations and their environmental impact on interfluvial areas

Data from the geoglyph area, the Llanos de Mojos of Bolivia, the Upper Tapajós Basin, and the Upper Xingu region show that human exploitation of *terra firme* forests was more complex and conducted on a larger scale than previously thought. The urbanised societies of the interfluves developed intensive land use strategies and influenced their environment in a way that is still evident (Clement et al., 2015; Heckenberger and Neves, 2009). However, debates on agricultural strategies and the prehistoric impact on the interfluves have recently been reignited. Watling et al. (2017) published new results on the environmental impact of geoglyph builders in Acre State, Brazil, using phytolith, charcoal, stable carbon isotope data to reconstruct the environmental history of this known archaeological area. The results imply that bamboo forest has dominated the area for at least the last 6000 years, and only small, temporary clearings were made when the geoglyphs were built.

The authors argue that the low concentration of charcoal in the soil profiles means that the area did not see systematic, widespread deforestation. However, they maintain that it simultaneously does not imply the absence of other landscape management practices. Piperno et al. (2017) question all of Watling et al.'s (2017) main statements and argue that, when applying a similar methodology in their previous studies (McMichael et al., 2012b; Piperno et al., 2015) they also found no evidence for large-scale forest burning and clearing, but they interpret this as the sign of small, sporadic, and localised human impact on the forest.

2.3 Amazonian Dark Earth

The shift in how scholars thought about the carrying capacity of the rainforest and the popularisation of the historical ecology approach coincided with another major turning point that influenced the way people perceived nature and culture in Amazonia: the discovery of ADEs (*terra preta do Indio*). As mentioned in section 2.1.1, approximately 75% of soils in Amazonia are classified as oxisol (46%) or ultisol (29%). These soils are characterised as unsuited to agricultural purposes because of their low concentration of exchangeable base cations, low-activity clay minerals, minimal extractable phosphorus, high acidity, and thus high concentration of exchangeable aluminium and manganese that can be toxic to crops (Sanchez, 1976).

In contrast to these natural soils, ADE soils are anthropogenic in origin and are characterised by very thick, black or brown A horizons. They have high amounts of total calcium oxide (1810 mg kg^{-1}) and phosphorous pentoxide (4900 mg kg^{-1}), as well as a lot of organic matter and biological activity. Soil pH ranges from 5.2 to 6.4, and extractable phosphorous is generally above 250 mg kg^{-1}, while zinc and managanese are above 200 and 450 mg kg^{-1}, respectively (Falcão et al., 2009). This thick surface layer often includes large numbers of pottery sherds, sometimes in addition to other artefacts and charcoal (Lehmann et al., 2003). Due to these properties, ADEs are very fertile and have even been suggested to be self-perpetuating anthrosols (Woods and McCann, 1999).

ADEs formed throughout the Amazon in pre-Columbian times through the intentional or unintentional accumulation of charcoal and household waste (e.g. Arroyo-Kalin, 2009; Glazer and Woods, 2004; Lehmann et al., 2003; Smith, 1980). They were reported and described at the end of the nineteenth century but did not receive much attention (Cleary, 2001). Later, scholars attempted to establish the origin of these soils, and there have been several conflicting theories. As they were originally only found at the top of plateaus, Camargo (1941) believed that these soils were natural, namely that they formed on late Tertiary or early Quaternary period volcanic ashes from the Andes. Other theories of natural origin included formation in Tertiary lakes (Falesi, 1974) or more recent ponds (Cunha Franco, 1962) through sedimentation. Since most ADE sites are associated with potsherds, bones, ash, and other settlement refuse, Smith (1980) and others suggested that they were primarily prehistoric middens. It is now widely accepted, however, that these soils were not only used by local populations but are a product of indigenous soil management (e.g. Arroyo-Kalin, 2009; Fraser et al., 2011b; Sombroek, 1966; Smith, 1980), and, once established, both black and brown ADEs would have been used for cultivation, as they still are today (Denevan, 1998).

ADEs are considered to be cultural in origin due to criteria outlined by Woods and McCann (1999). The identifying features are:

1. similarity in texture between ADE and soils in the immediate vicinity;
2. similarity between the subsoil underlying ADE and that of surrounding soil;
3. occurrence of ADE in a variety of physical landscape settings;
4. (4) co-occurrence with ceramic and lithic debris;
5. a chemical signature commonly associated with human habitation. It has been established that there is a high correlation between archaeological sites and ADEs (Neves, 1999; Neves et al. 2003).

Further, since archaeological sites are typically assumed to be prevalent along whitewater river channels, which host high biodiversity of plants and fish species (Junk et al., 2011), efforts to conduct archaeological surveys on and map ADEs has been concentrated in the close vicinity of these rivers (Winklerprins and Aldrich, 2010).

The earliest ADE soils were reported in the Upper Madeira region at Teotônio (*ca*. 6500–6400 cal BP) by Watling et al. (2018) and at Garbin (*ca.* 8400–7000 cal BP) by Caldarelli and Kipnis (2017). However, most known ADE sites in Amazonia are about 500–2500 years old (Neves et al., 2003). Neves et al. (2003) raise three hypotheses on why most ADE sites are not older than 2500 years:

1. older sites diminished due to environmental/pedological processes;

2. ADE formation actually began only around 2,500–2,000 years BP, when population expansion and agricultural intensification is considered to begin in Amazonia;
3. the soil organic matter (SOM) in most older ADE sites has been mineralised, and their dark colour faded, leaving only inorganic artefacts, therefore they are very difficult to detect.

The ADE sites range in size from less than two to several hundred hectares, with the majority (80%) about 2 ha (Winklerprins and Aldrich, 2010). Earlier, it was estimated that ADEs constitute 6000–18,000 km^2, of the Amazon Basin, equivalent to 0.1%–0.3% of the area of lowland Amazonia (Sombroek et al., 2003), but, as researchers discover new ADE sites, the overall estimate continues to rise. Recently, McMichael et al. (2014) used predictive modelling to suggest that ADE sites likely cover *ca.* 154,063 km^2 or 3.2% of lowland Amazonia. However, the updated version of this model by Palace et al. (2017) suggests that ADEs cover approximately 6,000,000 km^2 of the Amazon Basin. Some scholars even presume that, once all existing ADEs have been located, the proportion of its total land cover will exceed 10% of the Amazon (Mann, 2002).

ADE soils have been found at many locations in several parts of the Amazon: Peru (Denevan, 1996); Colombia (Eidt et al., 1984); and French Guiana (Vacher et al., 1998). Most ADE sites have been identified on river bluffs above the *várzeas* of whitewater rivers, with an average size of 20 ha (McCann, 2001; Smith, 1980), however much larger sites, up to 350 ha, have also been reported (Smith, 1980). However, Levis et al. (2013) argue that floodplains of blackwater and clearwater rivers—usually tributaries of the major rivers—are as good as the *várzeas* for habitation. Consequently, research projects should focus more on these areas, because there is a high possibility that archaeological sites and anthropogenic soils will be found.

In addition to riverine settings, ADEs also occur on *terra firme* areas. Indeed, numerous ADE sites have been reported in interfluvial *terra firme* forests in Brazil, including an area of of 50,000 ha between the Tapajós River and Rio Curuá-Una (Smith, 1980). These sites are usually much smaller than the bluff sites (*ca.* 0.3–0.5 ha), and anthropogenic layers are often shallower, which suggests a shorter period of occupation (Denevan, 2001). There are, however, examples of large ADE sites in the interior areas as well. For example, the site

Oitavo Bec on an inner plateau south of Santarém is larger than 120 ha (Woods and McCann, 1999), while interfluvial black and brown ADEs sites measuring around 30–50 ha and dating to AD 1000–1500 have been reported in the more remote Upper Xingy Basin by Heckenberger et al. (1999).

ADE soils are highly variable in their physical and chemical properties according to geographical region, parent material, soil formation factors (including human and natural processes), cultivation practices, plants growing on them, etc. (Falcão et al., 2009). There are also continuing debates about their origins beyond simply being anthropogenic. Whether ADEs were created intentionally and which processes contributed to their formation is still not clear, but research shows that there are different types of ADEs that have distinctive properties and developed under different influences.

It is established that black ADEs were settlement areas and are the result of soil enrichment due to the decomposition of village refuse. Hence, the anthropogenic layer of such ADEs consists of large quantities of pottery sherds and other human-made artefacts (Woods and McCann, 1999). In contrast, Woods and McCann (1999) found ADEs that were have been uniform middens; they had brown soils with few or no artefacts surrounding black soil patches. The authors argue that most ADEs cannot be associated with habitation sites but were the result of pre-Columbian farming and therefore had different properties. While the black soils were referred to as *terras pretas* (black ADEs), Woods and McCann (1999) named the brown soils *terras mulatas* (brown ADEs) following Sombroek (1966) and suggested that brown ADEs were formed by long-term agricultural activity including in-field burning, mulching, and composting. In addition to the colour difference, brown ADEs have significantly lower calcium and phosphorous levels and contain much less cultural material than black ADEs (Woods and McCann, 1999). Arroyo-Kalin (2012) has also suggested that there is a clear gradient from higher to lower pH, availability of organic carbon, and availability of soil nutrients from black ADEs to brown ADEs to oxisol catena.

ADEs are usually highly fertile, and they are able to maintain their productivity under long-term cultivation (Lehmann et al., 2003; Madari et al., 2003). Field observation of perennial crops on both black and brown ADE sites in central Amazonia has shown that, even during very dry seasons, crops not only survive but also do not suffer severe damage in terms of growth and productivity (Falcão et al., 2009). Although, recent research suggests that the vegetation on ADE soils, despite all of its valuable properties, has lower biomass and is more vulnerable to drought (Palace et al., 2017),. there are other examples of the extraordinary qualities of these anthropogenic soils. These include Petersen et al. (2001), who report ADEs in the central Amazon that have been continuously cultivated for 40 years without fertilizer.

In a similary way, black ADEs are high in black carbon, which has been proposed to be the likely reason for the stability of organic carbon (Glaser et al., 2001). They also have elevated cation exchange capacity, higher pH values, higher moisture-holding capacity, and nutrient availability—especially nitrogen, phosphorus, calcium, and potassium (Glaser et al., 2001; Lehmann et al., 2003; Sombroek et al., 2002). The elevated nutrient content was attributed to decomposed fish residue, turtle shells, weeds and sediment from rivers, manure, and kitchen waste other than fish (Erickson, 2003; Neves et al., 2003; Lehmann et al., 2003). For this reason, ADEs are frequently associated with specific and more intensive forms of agriculture (Fraser and Charles, 2008; Fraser et al. 2011a; German, 2003).

Even though many indigenous farmers recognise ADEs as particularly valuable for modern agriculture (Smith, 1980), the same farmers consider their formation to be the result of burning the standing vegetation (aka slash-and-burn) (German, 2003). ADEs, however, do not seem to form through shifting cultivation strategies but under more intensive farming (Clement et al., 2015; Denevan, 2001). One well-documented example of soil-enrichment techniques practiced by modern Amazonian people, the Kayapó of southern Para, fits with the observed pattern for the composition of ADE deposits. These enrichment techniques are connected to the improvement of soils on cleared fields rather than midden formation around villages (Hecht and Posey, 1989). Unfortunately, in other areas of the Amazon, ancient knowledge about the creation of these soils by native Amazonians seems to have been lost (German, 2003).

Although the processes leading to the formation of ADEs is still not completely clear, it is believed that these special soils play an important role in sustainable land management (Glaser et al., 2001) or the mitigation of climate change (Sombroek et al., 2002). Lehmann et al. (2003) argue that ash from burning above-ground biomass (slash-and-burn) when clearing the forest for new agricultural fields is an important fertilizer for Amazonian soils; however, the benefits do not last for more than a few years. In contrast, the “slash-and-char” technique, which involves incomplete combustion of the organic material, involves charring biomass from only the planned cropping area and adding it to the soil. This produces more stable organic carbon and therefore more fertile soils for a longer time. Thus, Lehmann et al. identify the slash-and-char technique as a sustainable alternative to the destructive slash-and-burn. Experiments like this have since inspired technological developments and given rise to new concepts, like *terra preta nova* (creation of modern ADEs) and biochar (Maia et al., 2011; Sombroek et al., 2002).

Regardless of where the future of ADE research leads, it cannot be denied that its discovery has transformed the way pre-Columbian Amazonia is seen and how future research projects will be planned. Most notably, ADEs have rewritten our understanding in the following ways:

1. the existence of fertile anthropogenic soils in the interfluvial forests challenged the dominant assumption that the Amazonian uplands were inhabitable (Erickson, 2003; Neves, 1999; Viveiros de Castro, 1996);
2. the discovery of ADEs showed that a landscape's carrying capacity and agricultural potential can be overcome by humans, and these are not fixed, immutable concepts (Denevan, 2001);
3. the ancient Amazonians enhancing the biodiversity of the forest in anthropogenic areas has challenged the idea that humans are only destructive and demonstrates the potentially positive contribution of humanity to nature (Denevan, 1992; Hiraoka et al., 2003; Junqueira et al., 2010).

2.3.1 Vegetation on ADEs

The importance of ADEs not only lies in their extraordinary properties for cultivation. Even if abandoned and left uncultivated, ADEs can serve as agrobiodiversity reservoirs: areas with considerable concentrations of genetically diverse native, exotic, and domesticated species . This is due to long-term human activity (Clement et al., 2003). Recent botanical studies show that growing vegetation on ADEs is quite distinct from doing so in adjacent, natural areas. Research in the middle Madeira region shows that the species richness of secondary forests on ADEs is generally lower, but they harbour higher densities and greater species richness of useful/edible species than non-ADE soils (Fraser et al., 2011a; Levis et al. 2012).

In general, ADEs are characterised by lower canopy vegetation, a more closed understorey, and the presence of some indicator species (Junqueira et al., 2010; Palace et al., 2017). Woods and McCann (1999) have observed Brazil nut, cacao, cupuaçu (*Theobroma grandilorum*), and samauma (*Ceiba pentandra*) growing on ADE sites along the Lower Amazon River. Botanical inventories carried out in riverine caboclo communities of the Middle Madeira by Junqueira et al. (2010) have identified 11 indicator species for ADEs, including three palms, caiaué (*Elaeis oleifera*), urucuri (*Attalea cf. phalerata*), and murumuru (*Astrocaryum murumuru*). ADEs also have distinctive weed population (Major et al., 2003). The definition of a weed is quite ambiguous, especially in these traditional cropping systems. Although some weed species found on ADE soils have important uses as a food, medicine, fibre, dye, or construction material, many are treated as weeds, as they compete with economically-important crops. For example, plants like mallow (*Malva* sp.) and Caesar's weed (*Urena lobata* L.) are used for their fibre or edible fruits, while guava (*Psidium guajava* L) and canapum (*Physalis angulata* L.), aka the cut-leaf ground-cherry, are commonly found on ADE swiddens in the central Amazon and are considered weeds (Major et al., 2003). Experiments on weed dynamics conducted on ADE soils and adjacent non-ADE soils by Major et al. (2005) revealed that weeds covered ADE soil 45 times more rapidly than adjacent soils, and there were 11 times more weed species. The weed communities on ADE were similar to each other, including many species typically associated with environments that have been highly disturbed by human activities, such as *Cyperus* spp., *Phyllantus niuri*, and *Croton lobatus.* These weed communities were quite different from those on adjacent non-ADE soils.

2.4 Anthropogenic forests

The existence of complex societies in Amazonia has challenged the standard paradigm, and new theories have thus emerged regarding prehistoric demography and settlement patterns, including size, location, and duration, based partly on assumptions about food productivity. There is, however, still little archaeological, ethnohistorical, and ethnobotanical data on food production to support these claims (Denevan, 1998).

It was believed originally that modern slash-and-burn, shifting cultivation was also the dominant farming system in pre-Columbian times (Meggers and Evans, 1957), even though descriptions of shifting cultivation are rare throughout the Americas prior to about AD 1600 (Denevan, 1992). Denevan (1992) argues that, in prehistoric times, the native Amazonians only had stone tools, and clearing large patches for long-fallow cultivation in the rainforest with stone axes was both impractical and almost impossible. His experimental studies indicate that clearing the forest with a stone axe required 60 times more energy and time than to clear it with a stone axe. Denevan further argues that, in lowland Amazonia, stones that would have been suitable to make axes were very rare (Denevan, 2001).

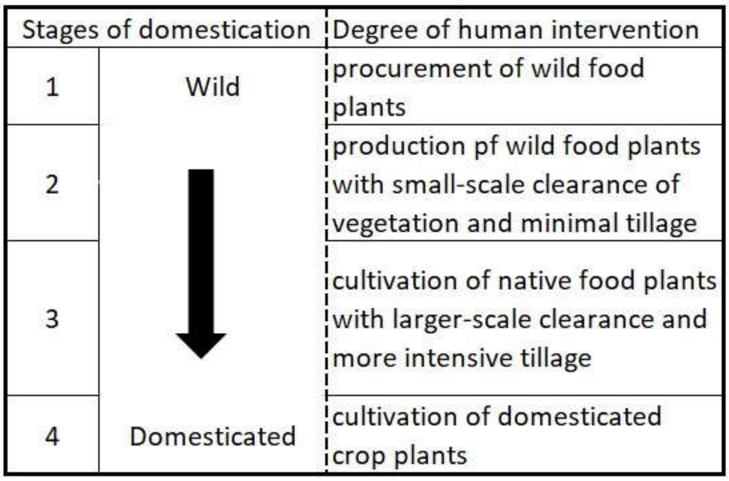
But what was food production like before 1492 in lowland Amazonia? In this subchapter, archaeological, archaeobotanical, ethnobotanical, ethnohistorical, and modern botanical studies focusing on cultivation systems in tropical rainforests are examined. First, however, terms like agriculture, horticulture, domestication, landscape domestication, and agroforestry will be introduced.

“Agriculture” literally means the cultivation of “ager”' (tilled, cleared field) (Wiersum, 1997). The term refers to the “grain model” that concerns cereal domestication in Mesopotamia, around the Mediterranean, and ancient rice-based civilisations from India to China (Michon and de Foresta, 1997). In this classical model of plant domestication, humans extract a genetically-diverse wild plants from their complex ecosystems and create genetically-simplified plants that only survive in homogenous, artificial systems (Michon and de Foresta, 1997).

“Horticulture”, or the “garden model” means the cultivation of “hortus”, a garden containing multiple species of trees and tuberous crops. Domestication according to the gardem model involves a gradual transfer of the natural environment. Many horticultural species that produce fruits, vegetables, or ornamental flowers have origins in natural forests, and most of these tree gardens can be confused with natural forests by even agronomists and horticulturists (Michon and de Floresta, 1997; Wiersum, 1997).

The words “domestication” and "to domesticate" come from the Latin “domus” which means either “house” or to, "cause to feel at home; naturalize" (see the *Shorter Oxford English Dictionary on Historical Principles*, 2002). Until the nineteenth century, the wild-domestic dichotomy was often used in Western philosophy, archaeology, anthropology, and biology in its static sense to describe stages of being (Cleary, 2001). Later, domestication was referred to as a process, a dynamic progression between these two extremes (Wiersum, 1997).

Harris (1989) proposed a model of plant domestication focusing on the way plants are treated with increasing human interventions. Thus, this model typically represents the “field crop” model of domestication (Fig. 2.1):



Stages of domestication		Degree of human intervention
1	Wild	procurement of wild food plants
2	↓	production pf wild food plants with small-scale clearance of vegetation and minimal tillage
3		cultivation of native food plants with larger-scale clearance and more intensive tillage
4	Domesticated	cultivation of domesticated crop plants

Figure 2.1: Harris’ (1998) model of plant domestication (modified from Wiersum, 1997).

Due to increasing human pressure, the plant’s genetic code goes through changes. The degree of this change in the targeted population was categorised by Clement (1999) as follows:

1. *Wild*: A naturally evolved population whose genotypes and phenotypes have not been modified by human intervention.
2. *Incidentally Co-Evolved:* A population that lives within a domesticated population and probably undergoes some degree of genetic change but without human selection. Weeds are good examples for this category.
3. *Incipiently Domesticated:* Human modification and selection have already started on this population; however, its average phenotype is still closer to the wild population.

4. *Semi-domesticated*: A population that has been already significantly modified by human selection and management; however, the plant would still survive in the wild without the help of human intervention.
5. *Domesticated*: The genetic variability of this population—due to human selection and intervention—is very small, therefore these plants would no longer survive in the wild, only in human-created artificial environment.

To date, the examination of the various dimensions of domestication have mainly dealt with grain crops. Relatively little attention has been given to the process of domestication of other crops, such as trees (Clement, 1999; McKey et al. 2010). However, the domestication of tree crops cannot be assessed without taking into consideration their surrounding environments and the changes these go through (Clement, 1999; Latinis, 2000). Therefore, a landscape-scale approach seems to give a more comprehensive view of tree crop domestication.

The expression “domestication of the landscape” was introduced by Hynes and Chase (1982) to describe the case of Australian Aborigines. They observed that, during the process of plant domestication, the environment and ecosystem where the target plant lives also change. This process is also called "co-domestication” (Wiersum, 1997) or “landscape domestication” (Clement, 1999). Landscape domestication is a process in which human intervention and manipulation result in changes in the landscape’s ecology and the demographics of plant and animal populations, with the outcome of a more productive and congenial landscape for humans. Terrell et al. (2003) add that, if we want to understand how landscapes are domesticated, we need to know what species are being harvested there and also what is being done to harvest them. Wiersum (1997) goes further with this argument, stating that there are three elements that change during this process: (1) the plant that is being harvested; (2) its environment in order to get a bigger yield; but also (3) the harvester that adapts its way of living to the lifecycle of the harvested plant. This latter element is evident in animals changing migration routes or humans moving winter and summer camps according to where there is more food in the landscape. OIin other words, domesticated landscapes are the ones where the creatures inhabiting them know how to live there (Wiersum, 1997).

In Clement (1999), the intensity of manipulation during the process of landscape domestication is classified by the following categories:

1. *Pristine:* A landscape in which humans have not manipulated plant or animal populations.
2. *Promoted:* In this category, desirable plant populations and individuals are encouraged through minimal forest clearance (e.g. around camp sites or trails) or with the dispersal of seeds. These minimalist interventions can, however, have long-lasting effects on the biotic composition of an area. Fire can be used for these activities. This corresponds to Wiersum's (1997) "conserved forest" category: the acculturalization phase. In this phase, valuable species or patches of forests are controlled.
3. *Managed:* The difference between promoted and managed landscapes is the degree of human manipulation. In this category, the abundance and diversity of food or other useful plant populations may be further encouraged through partial forest clearance, expansion of the forest fringes, transplanting desirable individual plants, planting individual seeds, taking steps to enhance plant growth, and reducing competition from non-useful plants. The changes in the biotic components of these landscapes can, again, last long after abandonment. Balée's (1989) anthropogenic forest types, e.g. palm, bamboo, liana forests, and forest islands belong to this category. In other words, these types of forests are Wiersum's (1997) "modified forests" in which management practices are enhanced to increase the (re)productive potential of valued species.
4. *Cultivated*: Complete transformation of the biotic landscape to favour the growth of one or a few selected food plants and other useful populations through any combination of forest clearance and burning, localised or extensive tillage, seedbed preparation, weeding, pruning, manuring, mulching, and watering. The biotic components of this very artificial landscape do not survive long after human abandonment, because the changes that favour the growth of the human selected populations also favour the growth of weeds and the invasion of other secondary forest species; however, it takes a long time to return to a

natural state. This category is Wiersum's (1997) "transformed forests", and it is the phase of cultivation of genetically modified tree crops.

"Agroforestry" is a land use system in which woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used in the same management unit as agricultural crops and/or animals, either in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economic interactions among the different components (FAO, 2015).

Although very little is known about the subsistence strategies of the early colonists in Amazonia, some botanical remains and stable carbon isotope data suggest that they initiated the development of cultural forests in Amazonia in the form of upland palm forests (Roosevelt, 2014). Terrell et al. (2003) suggest that prehistoric and modern foragers are so knowledge about the biotic and abiotic elements of their environment that they required no extra knowledge to farm; transitioning to agriculture was not the next big step but a continuation of existing knowledge. Therefore, arboriculture—the anthropogenic cultivation of forests as a traditional subsistence strategy—is difficult to understand if foraging and farming are treated as separate and distinct ways of putting food on the table.

In the development of agroforestry systems, the utilisation of fruit crops starts with the collection of wild forest products and protection of the natural forests. It ends with the cultivation of domesticated tree crops in a highly-managed forest. Throughout this process, both the human energy input and production gain increase. Wiersum (1997) argues that more attention has been given to the beginning and end phases of domestication, but since domestication not only affects individual species but is the co-domestication of forests and trees, our understanding of the various intermediate phases represented in indigenous forest management and agroforestry systems remains limited (Clement, 1999; Terrell et al., 2003).

Indeed, especially in tropical forests, plant domestication refers to two inter-related aspects: the plant itself targeting its morphology and production pattern, and the ecosystem in which the plant lives being shaped in a way that the plant gets the most benefits from it (Michon and de Floresta, 1997). It is also important to note that the steps in the development of agroforestry systems cannot simply be seen as progressive steps moving from simpler to more complex ones. These different forest management intensities and strategies can co-exist in a complex, interactive matrix (Balée, 1989; Terrell et al., 2003).

The explicit emphasis on the work of Balée and others concerning the dynamic co-production of people and landscape represents a significant shift from the hegemony of environmental determinism and offers a basis for reconsidering traditional view of adaptation. It takes into consideration human agency, as well as the biophysical environment in which it acts.

Following this line of thought, Peters (2000) describes different management systems based on the successional status of vegetation and the intensity of human intervention in these systems:

1. *Home gardens*: Multistorey mixtures of trees, shrubs, vines, and herbaceous plants that are maintained as an annex to a house. It contains both edible fruits and medicinal plants, spices, ornamentals, etc. Home gardens are highly managed because of easy access. Maintenance involves periodic weeding or brushing, selection and planting of important plants or genotypes. Most home gardens are fertilised with household refuse, organic material from weeding, and ashes from kitchen fires. If livestock is present, manure may also be added. Due to intensive management, the soils are much more fertile than on the adjacent, less intensively managed or unmanaged areas. After a few generations of trees, the surviving relicts of cultigens and herbaceous plants in home gardens become engulfed by the developing forest. However, fruit and nut trees (especially those that were obtained from the local forest and were not introduced or domesticated species) remain, and their abundance will be higher than in the adjacent areas, because they are growing on very fertile soil without human intervention.
2. *Managed fallows*: Fallows are tracts of forests that are left to recover after several years of cultivation. Managed fallows are designed to facilitate and enrich the successional process. In fallows, the manipulation can produce lasting if almost imperceptible changes in the forest. Monocyclic fallows are the most common type: small patches of forest are cut and burnt, and the clearing is planted with agricultural crops, such as manioc or maize. Other useful species, both

domesticated and semi-domesticated ones are also introduced at this time. After one or two years of crop production, the site fills with young secondary growth enriched with fruit trees, construction materials, and medicinal plants. In short fallows, the cycle is four to eight years, but the Kayapó of central Brazil (Posey, 1984) leave the forest to regrow for 20 years or even longer (Posey et al., 1984). Polycyclic fallow systems are allowed to grow until there is a mature forest. Fruits, fibres, and medicinal plants are periodically harvested, but there is never a final cut or clearing of the site. Over time, they become managed forest orchards.

3. *Managed forests*: To the untrained eye, managed forests look like natural or primary forests. They can be produced from old fallows, young fallows, home gardens, or intact forests. Management techniques include weeding, planting useful species stems, coppicing, and protecting desirable volunteer species. Fertilisation, mulching, and pruning can also occur. Ecologically, managed forest systems represent the endpoint of successional process on a site. In the most productive managed forest—compared to unmanaged forests—the overall species richness is lower due to cyclic burning and weeding, but useful species richness is higher. This conclusion is supported by the studies of Junqueira et al. (2010) and Palace et al. (2017).

To emphasise the complexity of food production systems in prehistoric Amazonia, Denevan (1998) describes a semi-permanent short fallow system that is integrated and rotated with permanent gardens and managed agroforests, both dominated by useful perennial trees, especially fruit trees. There are numerous mentions of the importance of fruit trees in the sixteenth-century accounts, and Clement (2006) also agrees that the management of semi- or fully domesticated fruit trees contributed significantly to raising the human carrying capacity of Amazonian ecosystems.

Management of fruit forests in the humid tropics has been a general trend. Latinis (2000) argues that, in South-East Asia and the Pacific, arboriculture was a separate class of subsistence economy, not a peripheral component of swidden, horticulture, or agriculture; highlighting its importance as a core subsistence strategy. In the tropical forest of central Africa, recent studies suggest that exploitation and even management of wild resources (especially fruit trees) played a larger role in subsistence strategies and had a longer history than previously thought (Oslisly and White, 2007). Archaeological research conducted in Gabon and Cameroon shows that the distributions of some economically-useful tree species, e.g. oil palm (*Elaeis guineensis*) and mango (*Magnifera indica*), are closely correlated with prehistoric and historic occupation sites (see citations in Oslisly and White, 2007). A combination of archaeological and palaeoecological data indicates that arboricultural practices had started to develop as early as the Early Iron Age (2500–1400 BP) the tropical forests of Central Africa.

Many scholars consider today's forest composition and distribution in several areas of Amazonia to be remnants of prehistoric agroforestry systems (Junqueira, 2010; Levis et al., 2012, 2017; Latinis, 2000; Oslisly and White, 2007). In *Resource Management in Amazonia: Indigenous and Folk Strategies*, Balée (1989) attempted to categorise oligarchic forests by hyperdominant species that may be indicators of prehistoric forest management practices and, he argued, may provide clues for archaeologists and palaeoecologists as to the extent and degree of prehistoric human impact on the Amazonian rainforest. These are outlined briefly here.

2.4.1 Palm forests

Palms are amongst the most frequently noted disturbance indicators on Amazonian archaeological sites. Palms, which do seem to be prominent in vegetational cover or undisturbed archaeological sites on *terra firme*, include babaçu (*A. speciosa* Mart.), tucumã (*Astrocaryum vulgare* Mart.), mucujá (*Acrocomia* cf. *eriocantha* Barb. Rodr.), and caicué (*E. oleifera* (H.B.K.) Cortes).

Babaçu palm forests cover almost 200,000 km^2 of Amazonia (May et al., 1985), and they seem to usually be artefacts of intensive disturbance and removal of previous primary forests. Babaçu can dominate burned forest clearings because of its cryptogeal germination. Its kernels and mesocarps are important dietary items.

Tucumã has a dispersal strategy similar to the babaçu palm. Wessels Boes (1965, cited in Balée, 2013: 40) described this palm as a species that is "never" encountered in undisturbed forest and is a "good" indicator of previous human occupation in Suriname. The fruits of the tucumã attract tapirs and agoutis. Cultural uses of tucumã include as fibre for skirts, hammocks, and infant carrying straps. The seed is used for making arrows, specifically the joint between the arrow shaft and steel point.

Mucujá, or macaúba, is commonly encountered on ADE sites. This palm fruit is a very important dietary item for some Amerindians. Caicué, a native Amazonian oil palm, is frequently found on ADEs. The peach palm (*Bactris gasipaes* Kunth) is the only Neotropical palm that was domesticated by Native Americans (Clement et al., 2010; Galluzzi et al., 2015). This domestication process resulted in different landraces, some with large, starchy fruit that was good for fermentation, while others were oilier amd better for snacks (Clement et al., 2017).

2.4.2 Bamboo forests

The estimated extent of forest dominated by bamboo (*Guadua glomerata* Munro) on south-western Amazonian *terra firme* is *ca.* 165,000 km^2 (Smith and Nelson, 2011), and, although many scholars believe that they are anthropogenic forests (e.g. Balée, 1989; Watling et al., 2017), others argue that their widespread dispersal in this region can be explained ecologically and geographically (McMichael et al., 2014; Piperno et al. 2017). It is, however, widely accepted that bamboo plays an important role in the lives of contemporary Amerindians, and it was probably the same for pre-Columbian communities too. The foraging Guajá people exploit bamboo to make arrow points, but bamboo forests are also associated with past Ka'apor settlement sites (Balée, 1989). Bamboo forests in the Jararaca and Pindaré regions are quite possibly the of past horticultural activities by the Ka'apor and Guajajara. Watling et al. (2017) report that, based on archaeobotanical analysis, the geoglyph builders in Acre State, Brazil, have likely exploited bamboo forests for thousands of years.

2.4.3 Brazil nut forests

Brazil nut (*B. excelsa*) represents the most important non-timber product in Amazonia (Shepard and Ramirez, 2011). Forests dominated by Brazil nut trees, called castanhais, only occur over an area of 8000 km^2 near Marabá. The presence of Brazil nuts is frequently associated with ADEs (Balée, 1989) in

Amazonia, as it is a light-loving species that tends to colonise clearings (Mori and Prance, 1990). Kayapó Indians plant Brazil nuts, because they are direct food sources and also attract game to hunt. Apart from humans, the nut is dispersed mainly by agoutis, which are also strongly associated with swiddens, various types of successional forests, and babaçu forests.

Phenotypes observed in certain Brazil nut populations suggest a degree of selection and incipient domestication or semi-domestication (Shepard and Ramirez, 2011). The distribution and possible cultivation of the Brazil nut in the eastern portion of the Amazon Basin could be partly associated with the intensification of agriculture (mainly bitter manioc and the development of ADEs), especially in the beginning of the first millennium AD (Neves et al., 2003). The earliest evidence of Brazil nut consumption comes in the form of carbonised Brazil nuts identified at Pedra Pintada, an upper Palaeolithic cave site in the central Brazilian Amazon that was occupied some 11,000 years ago by ancient hunter-gatherers (Roosevelt et al., 1996). Brazil nuts are important indicators for archaeologists and palaeoecologists studying the impact of pre-Columbian societies on forests, because these trees can live for 500–1000 years, so their pre-conquest distribution can be mapped based on their modern distribution (Clement et al., 2010).

2.4.4 Liana forests

Liana forests cover about 100,000 km^2 of Brazilian Amazonia (Pires,1973, cited in Balée, 1989). They prefer low acidity, highly fertile soils and are also associated with anthropogenic soils (Moran, 1993). It has been proposed that the formation of liana forest is a kind of disclimax, possibly a consequence of swidden agriculture using fire in “natural” successional processes (Balée, 1989; Balée and Campbell, 1990). Liana-dominated forests have also been found on ADE soils, suggesting that the forests had recovered after intensive cultivation (Smith, 1980).

2.4.5 Other forests

Balée (1989) mentions three other anthropogenic forest types on *terra firme* that are important. Bacuri (*Platonia insignis*) is a long-lived disturbance indicator, and its fruit is an important food for the Ka’apor. A great concentration of cacao has been found on Marajó Island and is thought to be pre-Columbian. Finally, pequi (*Caryocar villosum*) forests are an important food source for indigenous people in the Upper Xingu Basin.

2.5 Investigations of ADE sites in central and south-west Amazonia

This section summarises the chronologies of ceramic traditions in central (Fig. 2.2) and south-west Amazonia, as well as available data from archaeological surveys in central Amazonia along the Purus River and in the *terra firme* forests.

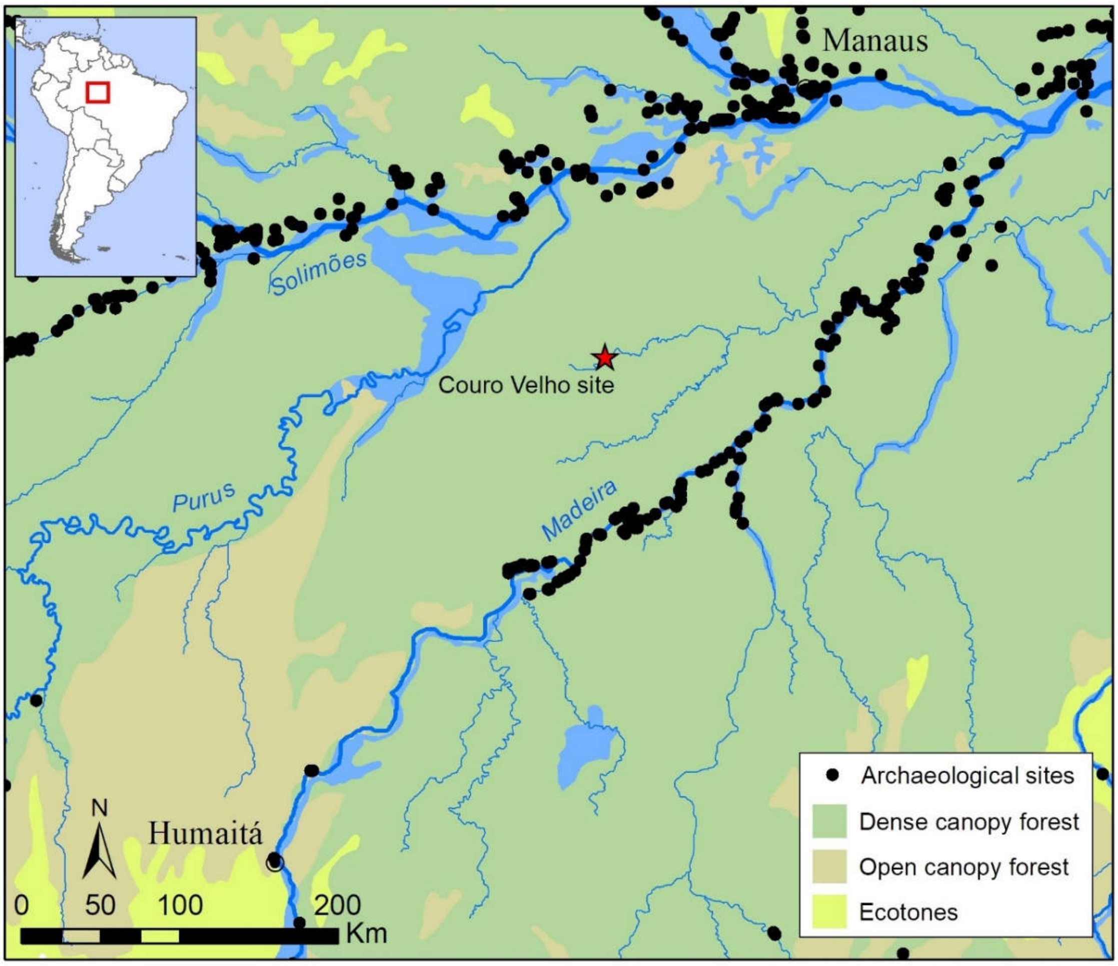


Figure 2.2: The location of the Couro Velho site (red star) in relation to other known ADE sites in central Amazonia. The vegetation classification is after IBGE (1992).

2.5.1 ADE sites in the central Amazon

Since 1995 in central Amazonia—this region roughly centres on the confluence of the Rio Negro and Rio Solimões, and includes the uppermost reaches of the

Rio Amazonas—the Central Amazon Project (CAP) has been studying pre-Columbian indigenous archaeology in different environmental settings, including floodplains, uplands, river plateaus, and lakes and lagoons (e.g. Heckenberger et al., 1999; Petersen et al., 2001). The project's findings suggest that cultivation intensification, combined with the growth of Amerindian populations in late prehistory, led to the formation of ADE soils from about the onset of the first millennium AD and then to fully sedentary life (e.g. Neves et al., 2003, 2004; Petersen et al., 2001). The project has also found that ADE sites in this region were probably continuously occupied for decades and longer. Occupation may even have lasted for centuries, which contrasts with Meggers' (1996) claim that ADE sites evolved during short term occupation (Heckenberger et al., 1999; Neves et al., 2003).

The archaeological phases and dating framework used in central Amazonia are presented in Table 2.1. The phases include the Açutuba phase, which is considered to begin in the early first millennium AD and overlaps at the end with the Manacapuru phase towards the fifth century. Manacapuru is affiliated with pottery of the Barrancoid (Incised rim) tradition, which extended into the eighth century, when it overlaps with the start of the Paredão phase. The Paredão phase ends around the late twelfth–early thirteenth century, overlapping with the onset of the Guarita phase, which is part of the Polycrome tradition. The Guarita phase then continues until the fifteenth century (Arroyo-Kalin 2009).

During their investigations in central Amazonia, Neves et al. (2004) found that ADE soils develop more rapidly than previously thought. Earlier, Smith (1980) hypthesised that the rate of ADE formation is approximately 1 cm per 10 years of intensive occupation. Neves et al. (2004), alternatively, suggest more rapid ADE development, and that population density alone was the key factor that stimulated formation of these anthropogenic soils. The researchers present data on the timing and rate of ADE formation at three archaeological sites to prove their hypothesis.

Osvaldo is a single occupation site with ceramics belonging to the Manacapuru phase from the Barrancoid tradition (Lathrap, 1970; Heckenberger et al., 1999). Osvaldo is located on a bluff along the southern shore of Lago do Limão opposite a modern village of the same name. Radiocarbon dates suggest that ADE formation during the Manacapuru occupation happened fairly quickly: about 70 cm of ADE formed within a century in the seventh century AD.

Hatahara is much larger than Osvaldo, with the ADE covering approximately 16 ha. It is located on a river bluff above the Solimões River near the town of Iranduba. There were probably three discrete occupations at this site, starting with a distinctive ADE layer from the Manacapuru phase, covered by another thick ADE layer produced by Paredão and Guarita occupations (Amazon Polychrome tradition) (Lathrap, 1970). At this site, several mounds were found. The general pattern of ADE formation at Hatahara is similar to that at Osvaldo: it developed rapidly. Though the ADE largely formed during the Guarita and Paredão occupations, its development began during the earlier Manacapuru phase.

The Lao Grande site is located on a bluff and, similar to Hatahara, several mounds have been identified here, but no burials have been found. Somewhat differently, the darkest ADE layer was buried at a depth of *ca.* 90 cm b.s. This depth also correlates with the highest density of pottery sherds in the profile. Radiocarbon dates from this stratum indicate that occupation of the deposit lasted several hundred years from *ca.* AD 700–800 to approximately AD 1000. Neves et al.'s (2004) data show that ADE formation was rapid at the beginning of the initial building process—*ca*. 40 cm in 100 years—however, this may be partly due to the mound construction.

ADE sites on the Lower Negro at Açutuba show great variability in the sizes and locations of sites: small and medium sites (*ca*. 2–10 ha of ADE) were found in diverse ecological settings, including major rivers, side channels, small to medium streams (*igarapés*), and *terra firme* lakes (Heckenberger et al., 1999). The largest sites in this area have been found on river bluffs in line with Denevan's bluff model (1996). The primary habitation areas with ADE soils 30–80 cm deep expand over 30 ha, which implies that blackwater habitats can sustain large populations for extended periods. Since floodplains near blackwater rivers have not previously been considered suitable for intensive agricultural production, the example of Açutuba indicates that arable *terra firme* land (Denevan, 1996) and rich aquatic resources (Henderson & Crampton, 1997) provided the economic foundation for these large, settled populations. Heckenberger et al. (1999) suggest that Açutuba was probably occupied by a large, sedentary population throughout the Christian era and maybe even earlier.

Table 2.1: Chronology of ceramic traditions and archaeological phases in central and south-west Amazonia (based on Neves and Petersen, 2006; Heckenberger et al., 1999; Arroyo-Kalin, 2009; Miller et al., 1992; Watling et al., 2018).

Ceramic tradition	Dates (cal BP)	Archaeological phase	
		Central Amazonia	SW Amazonia
Amazon Polychrome	*ca*. 900–400	Guarita	Borba and Jatuarana
Local development?	*ca*. 1500–900	Paredão	Jamari
Barrancoid (Incised Rim) tradition	*ca*. 2500–1000	Manacapuru and Açutuba	Axinim, Curralinho and Poco
Pre-ceramic	*ca*. 5500–2800		Massagana
Pre-ceramic/pre-ADE	*ca*.9500–9400		Girau

2.5.2 ADE sites along the Madeira River

The first systematic archaeological survey was conducted along the Madeira River by Simões and Lopes (1987). Their project's objective was to complement previous research on the Dos Marmelos and Guaporé rivers, two tributaries of the Madeira, in order to understand pre-Columbian cultural and migration routes between modern Brazil and Bolivia. The project covered the lower and middle Madeira region within the umbrella project, the National Archaeological Research Program in the Amazon Basin (PRONAPABA).

The results of the fieldwork included the discovery of 31 new archaeological sites (Fig. 2.3) belonging to the Borba, Axinim, and Curralinho archaeological phases, which are affiliated with two ceramic traditions: the Barrancoid tradition and the Guarita phase of the Amazon Polycrome tradition (see Table 2.1).

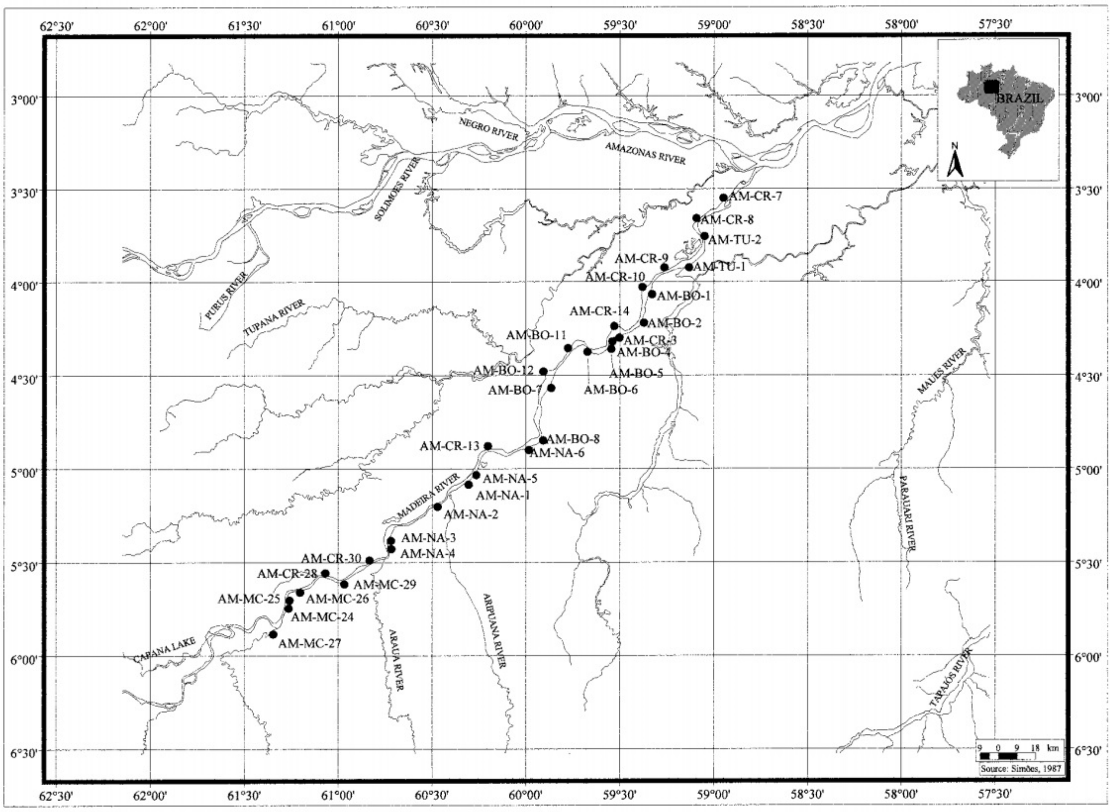


Figure 2.3: Distribution of archaeological sites along the Madeira River (map from Simões and Lopes, 1987, in Kern et al., 2003)

Similar to ADE sites in the central Amazon, ADE sites belonging to the Borba phase of the Polycrome tradition have mainly been found on river bluffs, sometimes up to 20 m above the water level. In general, the sites are elliptical in shape and range in size from 100x60 m to 500x200 m. The sites are found under secondary forests or in deforested areas with capoeira and roça vegetation. The depth of ADE soils is an average of 80 cm. No burials have been found at the sites.

Sites belonging to the Axinim phase (Barrancoid tradition) are also found on the bluffs, 15–23 m above the water line, and are elliptical in shape. The size of the sites ranges from 150x80 m to 600x300 m, with an average ADE thickness up to 50 cm. At one of the sites, an urn was found containing bone fragments. Many ADE sites have been disturbed by modern agriculture.

Sites that belong to the Curralinho phase have been found in areas with secondary forests and capoeira or roça vegetation, or that are at the edge of urban areas. Similar to the Borba and Axinim phases, Curralinho sites are also elliptical and situated on river bluffs, and sizes vary from 150x120 m to 600x300 m. The average thickness of ADE layers is around 70 cm. Some sites have been partially destroyed by modern agriculture or looting. Only sites of the Curralinho phase have been radiocarbon dated to the range AD 840–1450. Based on the artefacts, Simões and Lopes (1987) state that the Axinim phase seems to be contemporaneous with the Curralinho phase.

The Upper Madeira and its tributaries played an important role in the domestication of some species. Clement et al. (2015) strongly suggest that the centre of the domestication for manioc was the Upper Madeira Basin. Additionally, peach palm and one chilli species (*Capsicum baccatum*) were probably also domesticated in this area.

Teotonio is a site situated on a river bluff on the right bank of the Madeira River, south-west of the modern city of Porto Velho. The site represents the oldest ADE soil formation in the Brazilian Amazon, and has been subjected to archaeological research since the 1970s, when Miller et al. (1992) first excavated and described the site. The earliest radiocarbon dates are associated with the pre-ceramic and pre-ADE Girau phase *ca*.9500 cal BP), then ADE soils started to form in the pre-ceramic Massangana phase (*ca*. 6500 cal BP) (Watling et al., 2018). Three consecutive ceramic occupations were also identified from *ca.* 3000 BP onwards (Açutuba, Jamari, and Jatuarana) (Almeida and Kater, 2017).

Based on the archaeobotanical data, Watling et al. (2018) suggest that landscape domestication and the management and exploitation of wild resources (e.g. palms and tubers) had already begun during the Girau phase, which is pre-ADE. Food production and landscape domestication then intensified and ADE started to form in the Massangana phase, for which archaeobotanical data revealed the cultivation of squashes, beans, and leren (*Calathea allouia*), in addition to the exploitation of wild resources.

2.5.3 ADE sites in *terra firme* settings in central Amazonia

Archaeological studies along major rivers and new discoveries of large sites in transitional forests on Amazonia's southern border strongly suggest that the region was exposed to more human impact than previously thought (see section 2.2.1; Watling et al., 2015; Heckenberger et al., 1999; Prümers and Jaimes Betancourt, 2014; de Souza et al., 2018). Even though 90% of the Amazon Basin's river network is composed of medium and small rivers (Mayorga et al.,, 2005), most studies in Central Amazonia have only looked at pre-Columbian settlements along the largest rivers (Winklerprins and Aldrich, 2010).

The first systematic landscape survey for archaeological sites in *terra firme* areas took place along the Trans-Amazonian highway between Altamira on the Xingu River and Itaituba on the Tapajós River (Smith, 1980). Half of the sites on this transect were 200 m away from any perennial stream or river (Fig. 2.4). These sites are usually smaller than the ADE sites along the main rivers, *ca*. 0.3–5 ha. They are found on diverse soil types (e.g. *Terra roxa*, latosol, red-yellow latosol) and with diverse modern land use (e.g. indigenous agricultural fields, coffee and manioc plantations, mature forests, or campinha). The maximum depth of ADE ranged from 20 to 87 cm b.s., although pottery sherds were found between 10–20 cm b.s. at all sites.

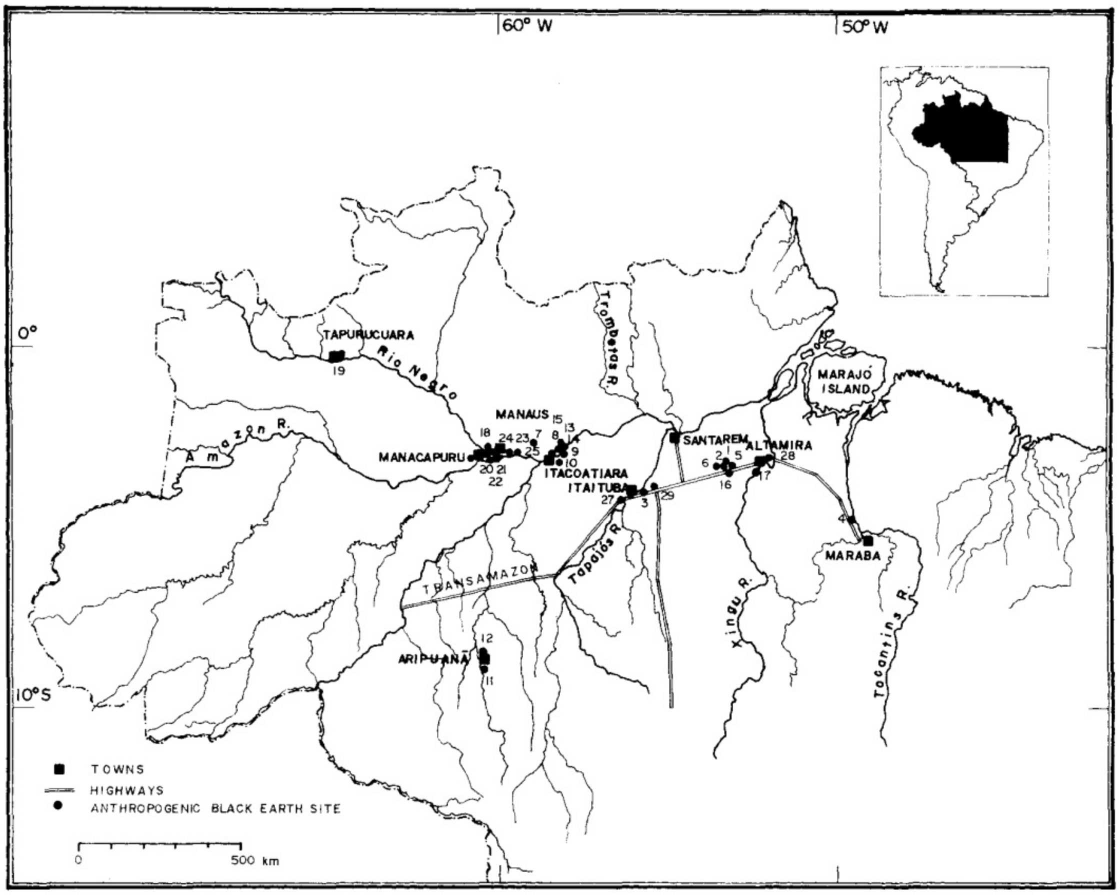


Figure 2.4: ADE sites mentioned in Smith (1980). Sites mentioned in this section are numbers 1, 2, 5, 6, and 29.

Another survey at areas far from major rivers was conducted by Levis et al. (2013). They show that, in some cases, there are more ADE sites along tributaries than major rivers in central Amazonia. They speculate on the reason for this, suggesting that tributary riverbanks tend to be more stable, and there can be more fish in blackwater rivers—which constitute the majority of tributaries—than in whitewater rivers. Tributaries also often have as many Brazil nut stands as are found along main rivers, and these stands are often associated with archaeological sites, suggesting that these habitats were important in pre-Columbian times (Thomas et al., 2015).

Although large riverine habitats have definitely been favoured locations for permanent settlements, it has been argued that people who lived away from major rivers also had perfectly adequate diets and could maintain healthy levels of protein intake (Beckerman, 1979; Beckerman and Lizarralde, 2013: 233), contrary to a major earlier argument against the possibility that permanent settlements could have been located far from major rivers (Gross, 1975; Meggers, 1954).

As outlined in section 2.3, a socio-cultural shift and sudden population growth correlate with the rapid development of ADE sites in central Amazonia. These substantial changes, especially the growth of populations that saw settlements with thousands of people sometimes living together (Clement et al., 2015), may have led to increased warfare and disease transmission (Petersen et al., 2001) that forced some groups to move away from the more obvious habitats (Beckerman and Lizarralde, 2013: 224–226; Roosevelt, 1993). Despite the lack of archaeological work that has been conducted on ADE sites along small rivers and tributaries, research to date shows that it is likely that pre-Columbian groups expanded the boundaries of human influence to a large extent, and a much larger portion of the Amazon Basin than has previously been acknowledged was once occupied and modified by these societies.

CHAPTER 3

Materials and Methods

This chapter describes the contexts that were studied for this thesis and introduces the field techniques and laboratory analyses that were applied.

The contexts studied in the PMI fall into four broad management categories that are today experiencing growing anthropogenic impact (Fig. 3.1, Table 3.1):

1. Primary forests on natural soils that have experienced no known forest management in the past (M05, M06). These areas serve as a control, a baseline by which anthropogenic impact is measured against that in the other study areas.
2. Oligarchic forests on natural(?) soils—forest dominated by useful species (M02, M11).
3. Anthropogenic forest with Brazil nuts on brown ADE—Brazil nut stands.
4. Couro Velho archaeological site with brown and black AD.

As was established in the Introduction, this thesis' study area in the PMI was not approached as a pristine landscape but the result of previous environmental and anthropogenic activities. Given this approach, the multidisciplinary methodology suggested by Mayle and Iriarte (2014) was chosen to fully understand the interplay between environmental and anthropological forces in the development of soils and land cover through time. This interdisciplinary approach helps to reveal past processes in the landscapes in a way that pure archaeological or palaeoecological studies would not be able todo. As a recent example, Maezumi et al. (2018) successfully reconstructed the history of landscape management and polyculture agroforestry at the mouth of the Tapajós River in the eastern Amazon. By combining pollen and micro charcoal analysis from lake cores,

Table 3.1: Contexts studied in this thesis.

Primary forest on natural soil	Oligarchic forest on natural(?) soil	Anthropogenic forest on brown ADE	Archaeological site on brown and black ADE
M05, M06	M02, M11	Brazil nut stand next to Couro Velho	Couro Velho

Minimal human impact in the past ⟶ Maximum human impact in the past

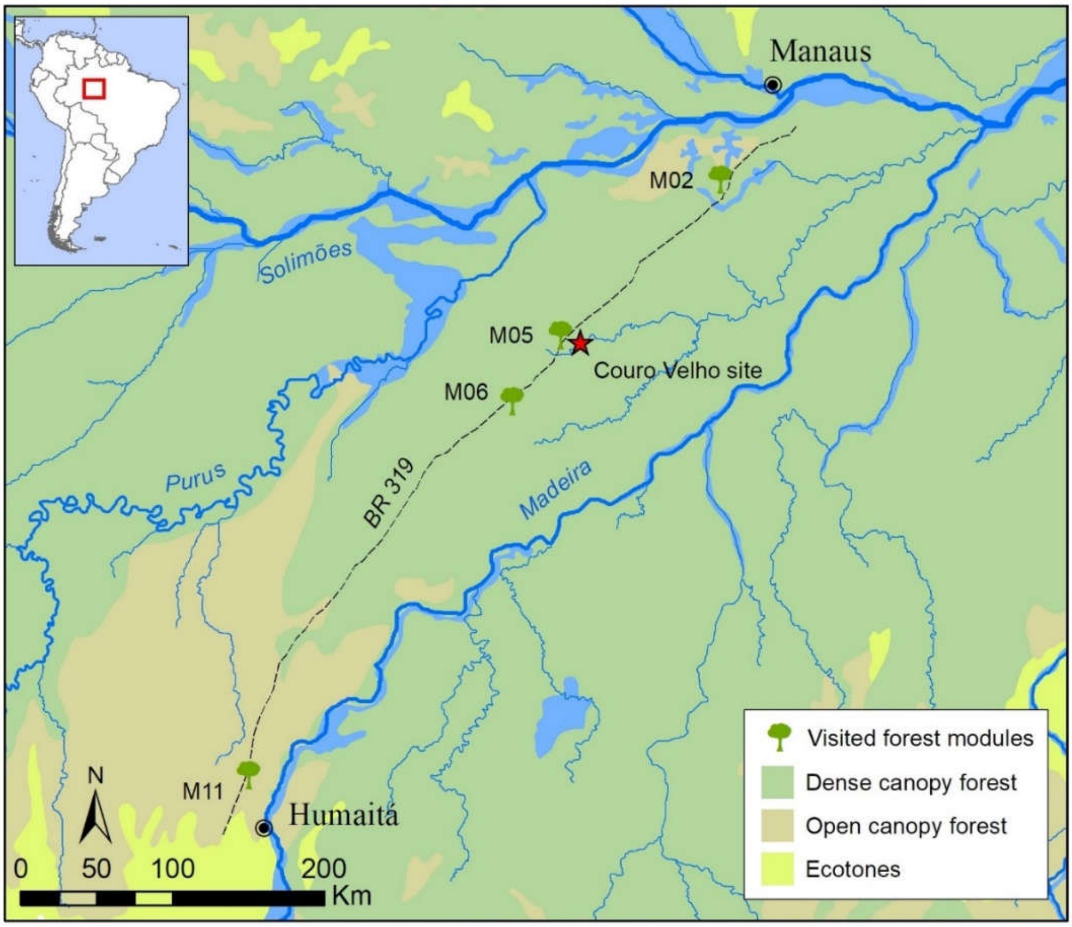


Figure 3.1: Spatial distribution of the sampling sites in the PMI. Trees symbolise the PPBio forest modules that were visited for this thesis, and the red star shows the location of the Couro Velho archaeological site and Brazil nut stand. The vegetation classification is after IBGE (1992).

archaeobotanical analysis from soil profiles, archaeological excavation, and modern vegetation inventories, the authors were able to identify evidence for persistent anthropogenic landscape modifications over the last 4500 years that resulted in the hyperdominance of edible species.

In this thesis. the multidisciplinary approach combined archaeological, terrestrial, palaeoecological, and modern botanical methods that involved fieldwork (modern botanical surveys and soil profile descriptions) and laboratory analyses (radiocarbon dating and phytolith, geochemical soil, macro charcoal, and stable carbon isotope analyses). The archaeological investigation and the radiocarbon dating allows the extent and nature of human occupation to be examined, while the phytolith, soil geochemical, and macro charcoal analyses produced valuable data regarding the long-term impact of pre-Columbian societies on the study area's environment. The botanical survey serves as a useful modern reference by which it is possible to compare changes in the vegetation through time. While phytolith analysis is excellent for detailed study of vegetation at the local level, stable carbon isotope data is a fast and convenient method to generate a broader picture of vegetation dynamics at different study sites.

In total, six sites were studied (Fig. 3.1), and 368 soil samples were collected. The soil samples were analysed for their phytolith assemblages, geochemical compositions, macro charcoal contents, and stable carbon isotope signatures. Radiocarbon dates were obtained from four samples.

3.1 Fieldwork methods

During July and August of 2015, field work was conducted for one month in the PMI to collect soil samples from soil profiles and to perform vegetation inventories at four Brazilian Program for Biodiversity Research (PPBio) forest modules (see Pezzini et al., 2012). The modules are managed by INPA and are distributed along along the BR-319 highway between Manaus and Humaitá in Amazonas State, Brazil—a *ca.* 600 km transect that spans different environmental settings. Based on the controversial results for past human impact on *terra firme* forests reported in Levis et al. (2012), McMichael et al. (2012b), and through personal communication with INPA's Carolina Levis and Fabia Costa, four forest modules along the BR-319 for study.

These forest modules constitute two primary forest sites with minimal or no human impact in the past (M05, M06) and two potential oligarchic forests—forests that have an unusually high density of useful species and, therefore, were probably managed by people in the past—according to Levis et al. (2012) (M02, M11). During fieldwork, a short landscape survey was conducted along the Igapó-Açu River, a small tributary of the Madeira River that flows across the PMI, to search for signs of past human land use and archaeological sites. The landscape survey was based on McMichael et al.'s (2014) predictive mdoel. as well as on personal communication with Carolina Levis and Charles Clement at INPA. Brazil nut trees and palms were spotted along the river and a new archaeological site called Couro Velho was discovered. The site is an ADE site with brown and black ADEs, and it is accompanied by a Brazil nut stand. These two new sites, Couro Velho and the Brazil nut stand, were then added to the existing study sites.

Table 3.2: Coordinates of all sampling points.

Sampling site	Sampling Point	Coordinates (degrees, minutes, seconds)	
		South	West
M02	P1	03°41'14.4"	60°19'53.7"
	P2	03°40'58.1"	60°19'25.8"
	P3	03°40'40.1"	60°18'57.1"
	P4	03°40'21.5"	60°18'30.4"
M05	P1	04°36'55.3"	61°14'41.0"
	P2	04°36'35.0"	61°15'00.5"
	P3	04°36'17.4"	61°15'21.6"
	P4	04°35'50.7"	61°15'56.8"
M06	P1	04°59'04.7"	61°34'14.4"
	P2	04°59'21.7"	61°33'47.8"
	P3	04°59'40.0"	61°33'20.6"
	P4	04°59'57.3"	61°32'54.4"
M11	P1	07°12'41.8"	63°07'41.5"
	P2	07°12'55.6"	63°07'11.6"
	P3	07°13'07.4"	63°06'43.1"
	P4	07°13'36.4"	63°05'43.0"
Couro Velho (TP1)	P2	04°38'47.3"	61°09'05.0"
	P3	04°38'47.9"	61°09'05.9"
	P4	04°38'47.1"	61°09'05.2"
	P5	04°38'46.9"	61°09'04.7"
	P6	04°38'46.8"	61°09'04.4"
	P7	04°38'47.0"	61°09'05.1"
Brazil nut stand (CAST)	CAST1 P2	04°38'42.4"	61°09'15.2"
	CAST2 P1	04°38'44.0"	61°09'10.2"

3.1.1 Introduction to the PPBio forest modules

The PPBio information system was launched by the Brazilian Federal Government in 2004 (Pezzini et al., 2012). Its purpose is to research abiotic and biotic elements of the forests. It is organised by sites (modules), which are usually represented by a grid with 10–72 uniformly distributed plots (Fig. 3.2).

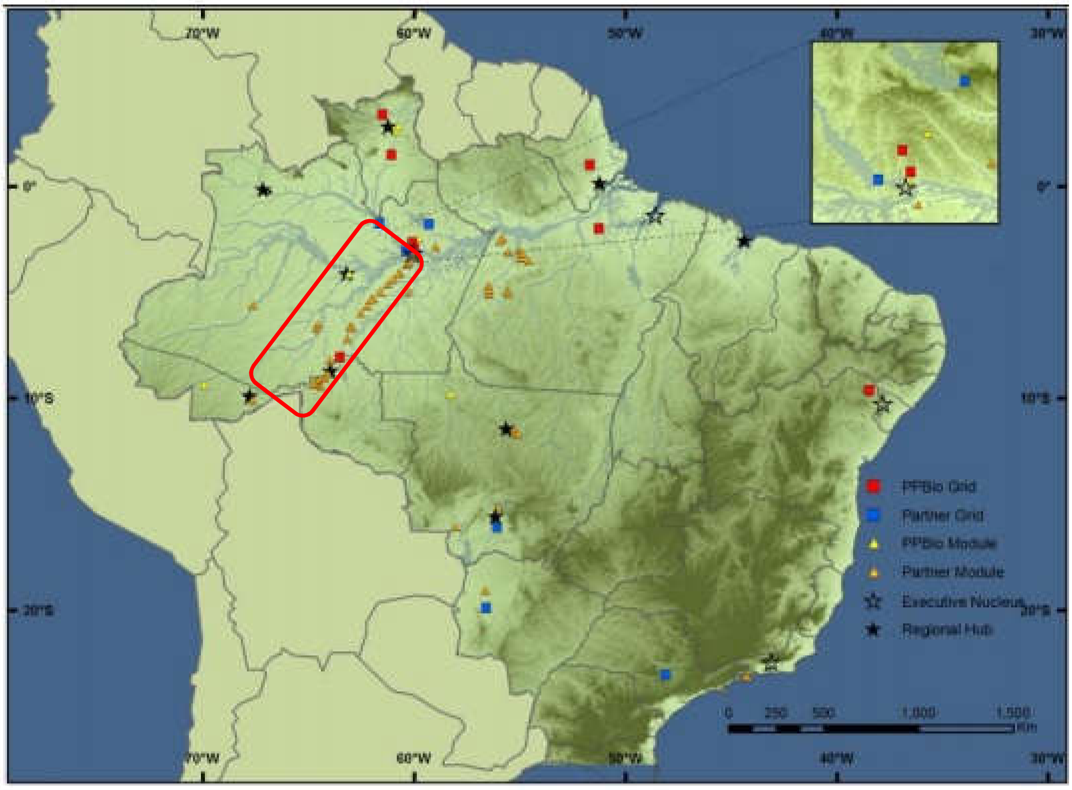


Figure 3.2: PPBio forest grids and modules (Pezzini et al., 2012), the red rectangle shows the locations of the forest modules in the PMI.

In the PMI, PPBio forest modules were established along the BR-319 highway. In these forest modules, 10 irregularly-spaced forest plots were established along a U-shaped trail (five on each side of the U), 1 km apart from each other. The plots have 250 m-long centre lines that follow elevation contours, and each plot's shape varies with the topography to follow the central contour line. The width of the plots varies according to the biological group being sampled. The width is narrowest for herbs (2 m) and the widest for trees (DBH>30 cm) and lianas (DBH>1 cm) (Fig. 3.3).

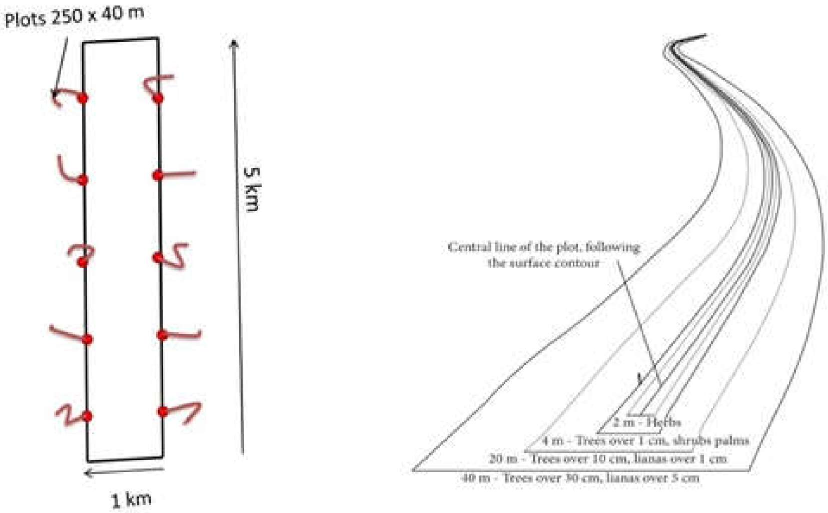


Figure 3.3: Schematic representation of a terrestrial forest module showing the distribution of plots and different plot sizes used for sampling plants (Pezzini et al., 2012)

3.1.2 Sampling strategy at the PPBio forest modules

At each study site (Fig 3.4), four forest plots were selected for sampling. The aim was to sample plots next to each other in a row on the northern trail (Fig. 3.5) in every forest module. However, in the case of the M11 module, the northern trail had been disturbed by illegal loggers, therefore the forest plots on the south trail were studied. On this trail, however, the fourth forest plot was inaccessible, so the fifth forest plot was added to the first three plots.

Sampling methodology in the PPBio forest modules

Since it is forbidden to disturb the vegetation inside the forest plots, the sampling points and vegetation inventory areas were set up opposite them 10 m away from the trail (Fig. 3.5). This meant that the sampling points were on the same elevation level as the PPBio plots, which would make results from their vegetation and soil comparable with this thesis' results.

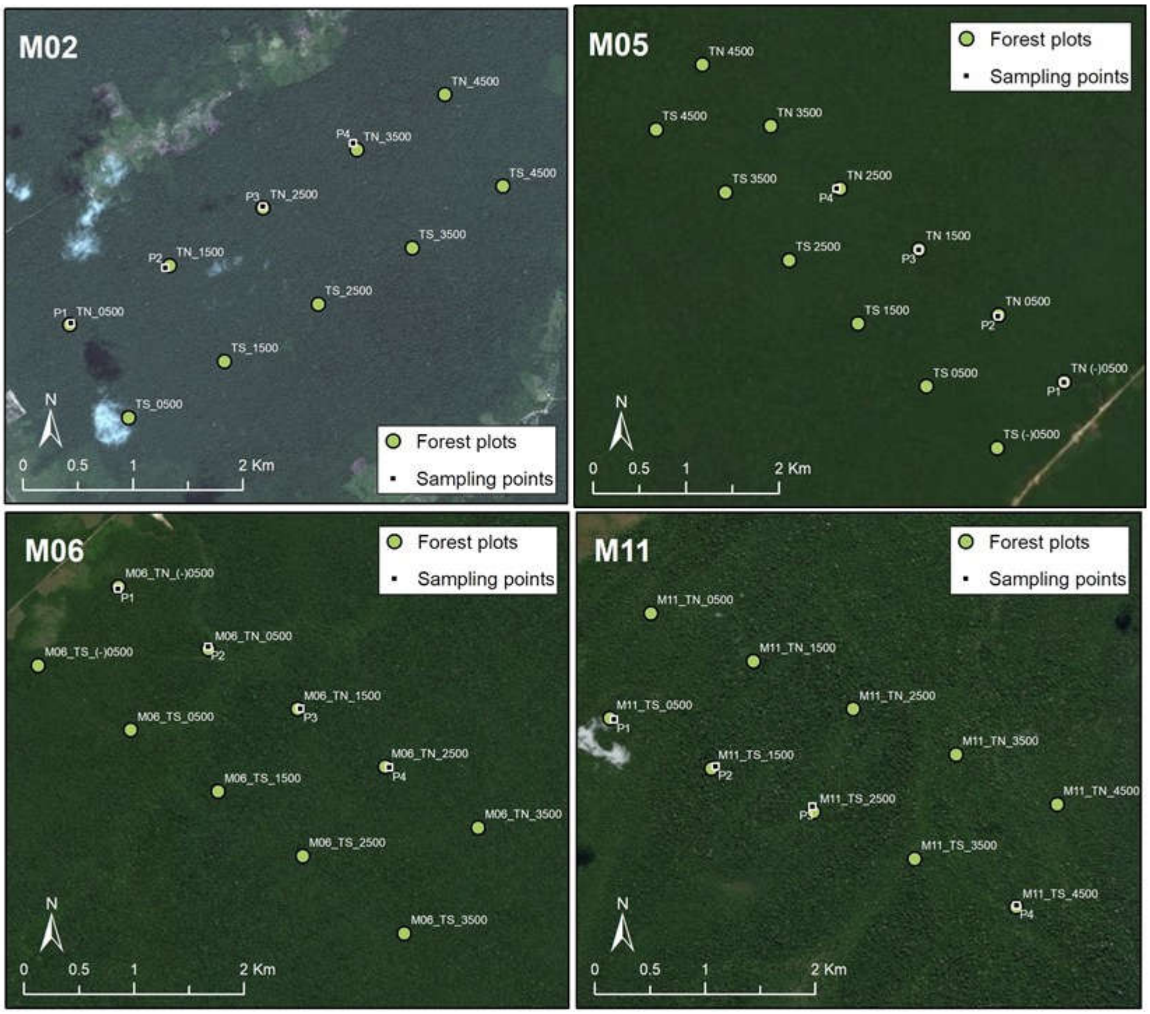


Figure 3.4: The visited PPBio forest modules and the locations of the forest plots that were studied.

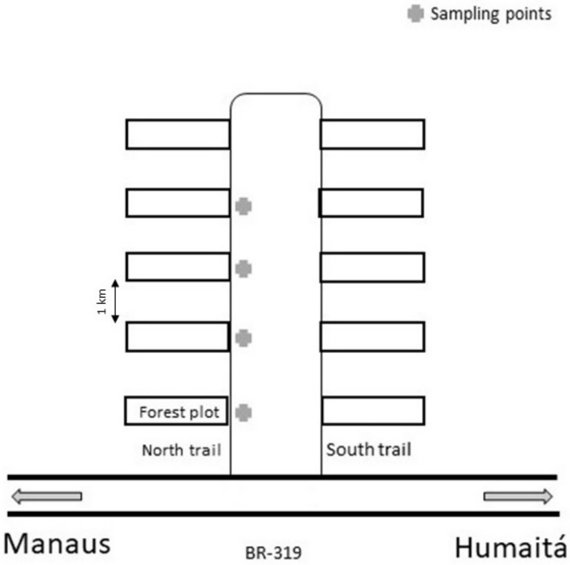


Figure 3.5: Schematic representation of the sampling points in a forest module.

Figure 3.6: Schematic representation of a sampling point opposite to the PPBio forest plot.

The vegetation plots were set up as 10x10m squares, divided into four smaller quarters (Fig. 3.6). All live trees and palms with DBH≥10 cm were recorded, and the species were identified by the PAST project's taxonomic specialist, Izaias Brazil (Fig. 3.7: A). In each vegetation plot, a test pit was opened in the bottom right quarter of the to collect the soil samples. Since the aim was to reach pre-Columbian layers and these are around 50 cm b.s. in the PMI (McMichael et al., 2012b), the soil pits measured 100x150x75 cm. Each soil profile was carefully cleaned, a drawn record was made, photographs were taken, and the stratigraphy was described. After documentation, around 300 g of soil was removed from a column at intervals of 5 cm using a freshly-cleaned trowel. The soil was then transferred directly into labelled sample bags. Where evidence of bioturbation was seen, care was taken to sample around it to avoid contamination. Altogether, 16 samples were taken from each soil profile (Fig 3.7: B). All four PPBio forest modules were sampled using the same methodology, therefore a total of 16 soil pits were opened, and 256 soils samples were collected.

Figure 3.7: (A) Botanist Izaias Brazil (in white) and a field assistant performing a vegetation inventory, (B) soil samples taken from a soil profile (photos by the author).

3.1.3 Sampling at the Couro Velho archaeological site

Couro Velho is situated in the area of the Igapó-Açu Sustainable Development Reserve Conservation Unit. The reserve is located between the Purus and Matupiri rivers in Amazonas State and covers an area of about 400 ha. A total of 55 families (200 people) live in six communities along the BR-319 highway and Igapó-Açu river. The main economic activities are agriculture, fishing, and tourism. The vegetation can be divided into two main types: savanna (*campina*/*campinarana*) and forest vegetation. The forest vegetation has two subtypes: *várzea*—floodplain forest—and *terra firme*—upland forest. The local fauna is remarkably rich due to the sparse human population, with 165 species of fish, 22 species of frog, 11 species of snake, 16 species of lizard, 287 species of bird, 23 species of mammal, and three species of crocodile identified in the area (Governo do Estado Amazonas, 2014).

Couro Velho is a small (>1 ha) site with anthropogenic soils (brown and black ADE soils), and it is located on the river bluff along the Igapó-Açu River in the middle of the interfluve (Fig. 3.8). The site is locally known and used as an abacaba palm (*Oenocarpus mapora*) planation, a palm used for its oil (Fig. 3.9).

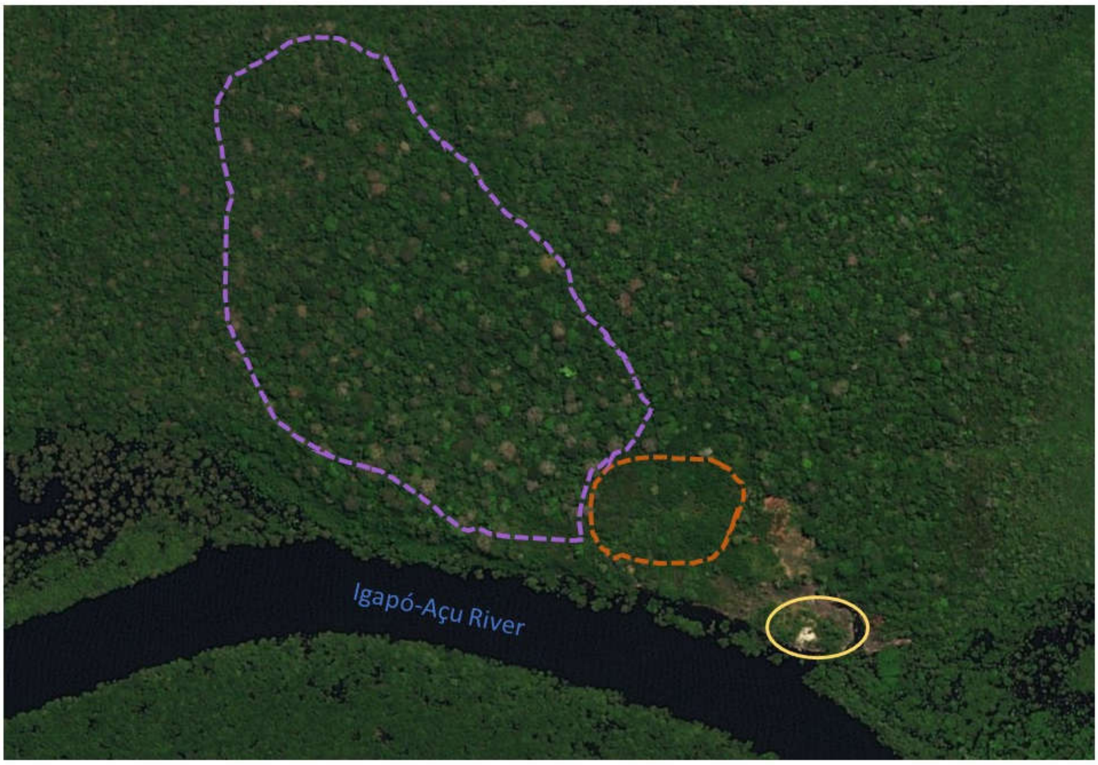


Figure 3.8: Satellite image of the tentative area covered by the Couro Velho site (orange), the Brazil nut stand (purple), and the location of modern inhabitants (yellow) (Image created using Zoom Earth (https://zoom.earth/) September 2018).

Figure 3.9: Modern abacaba plantation at the Couro Velho site (photo by the author).

Other species that are indicators for ADE were also identified, like açai (*Euterpe oleracea*), coffee (*Coffea canephora*), and a member of the yam family cará do Índio (*Dioscorea trifida*) (Clement et al., 1999). A tree, locally known as pau (*Handroanthus*), was also identified, and locals reportedly use the bark for medicinal purposes and its wood for hunting bows. Ceramic sherds and other burnt clay remains (possibly the residue of pottery production) were evident on the surface at the site, especially near the riverbank where the soil has been eroded.

Around the actual settlement area (black ADE), a larger brown ADE area was discovered where farming activities probably took place. Small test pits were excavated to examine the extent of the core black ADE. Much of the brown ADE is lying under an anthropogenic forest patch, a Brazil nut stand, where 50 individual Brazil nut trees were counted. The largest brazil nut tree in the grove has a DBH of 455 cm, and, although there are issues associated with dating Brazil nut trees based on trunk diameter, this individual may be *ca.* 1000 years old (Peres and Baider, 1997; Shepard and Ramirez, 2011).

Three 10x10m plots to examine vegetation were established on site: two in the Brazil nut stand and one on the ADE. All live trees and palms with DBH≥10 cm were recorded. The species were identified by Izaias Brazil, and all Brazil nut trees were mapped using a hand-held GPS. On the black ADE, besides the regular plant inventory, useful and ADE indicator species that were <10 cm at DBH were also identified.

Altogether, five soil profiles were opened in the settlement area (brown and black ADEs), and two profiles were opened under the Brazil nut stand on brown ADE. The two Brazil nut stand profiles were situated 150 m from the core area and each other, constituting a 300 m-long transect (Fig. 3.10). The same sampling strategy used for the PPBio forest plots was utilised, and a total of 112 soil samples were collected. All the soil profiles were mapped with a hand-held GPS device and were documented and sampled the same way as the profiles in the PPBio forest modules.

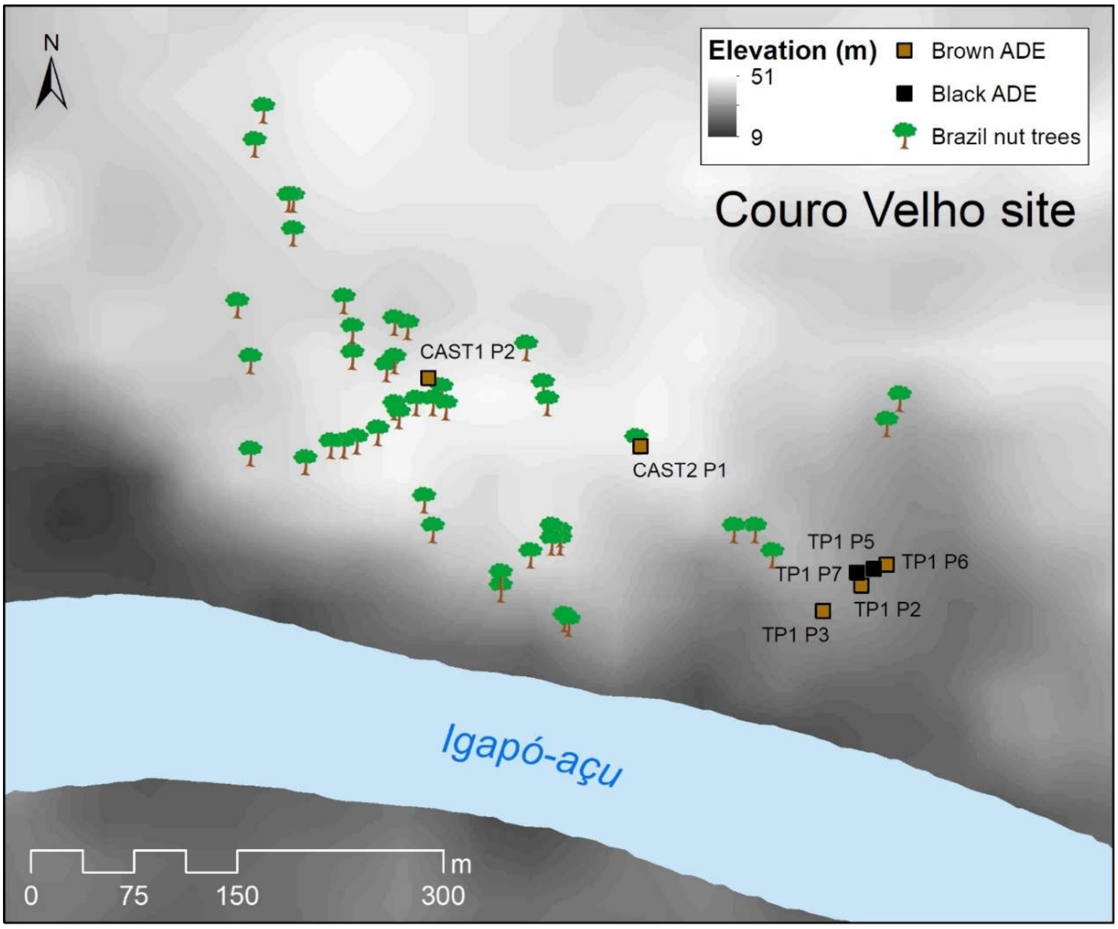


Figure 3.10: Location of soil profiles and the Brazil nut stand at Couro Velho.

3.2 Laboratory methods

This section provides a general description of the method for selecting the soil samples for laboratory analyses. The use of phytoliths for archaeobotanical studies are then discussed before moving on to describe the laboratory procedures for phytolith extraction and the identification method used in this thesis. Soil geochemical analysis, macro charcoal analysis, stable carbon isotope analysis, and radiocarbon dating are also presented (Table 3.3).

Since 368 samples collected exceeded what was possible to process and analyse within the scope of this PhD project, the sample size was reduced, though it was ensured that the high spatial and environmental variability of the study sites and sampling points was retained.

For the phytolith analysis, two soil profiles were selected from every PPBio site to study. This selection was based on an initial phytolith analysis where samples from 5 cm b.s., 40 cm b.s., and 75 cm b.s. were processed from each profile to measure the abundance of phytoliths in the soils. This initial assessment

Table 3.3: List of all soil profiles with performed field and laboratory procedures.

Site affiliation	Site location	Profile name	Vegetation inventory	Soil samples	Laboratory analyses				
					Phytolith	Soil geochemistry	Macro charcoal	Stable carbon isotope	Radiocarbon dating
PPBio Primary forest 1.	M05	M05 P1	X	X	X	X	X	X	
	M05	M05 P2	X	X					
	M05	M05 P3	X	X					
	M05	M05 P4	X	X					
PPBio Primary forest 2.	M06	M06 P1	X	X					
	M06	M06 P2	X	X					
	M06	M06 P3	X	X					
	M06	M06 P4	X	X		X		X	
PPBio Oligarchic forest 1.	M02	M02 P1	X	X					
	M02	M02 P2	X	X	X	X		X	
	M02	M02 P3	X	X					
	M02	M02 P4	X	X	X				
PPBio Oligarchic forest 2.	M11	M11 P1	X	X					
	M11	M11 P2	X	X	X	X		X	X
	M11	M11 P3	X	X					
	M11	M11 P4	X	X	X				
Brazil nut stand	CAST1	CAST1 P2	X	X	X	X	X		
	CAST2	CAST2 P1	X	X	X	X			
Couro Velho	TP1	TP1 P2	X	X		X			X
	TP1	TP1 P3	X	X		X			X
	TP1	TP1 P5	X	X	X	X	X		X
	TP1	TP1 P6	X	X		X			
	TP1	TP1 P7	X	X	X	X	X		X

was useful to identifying which profiles contained sufficient amounts and varieties of phytoliths to conduct a full analysis of the phytolith assemblages for the whole profile. However, interestingly, from the four initial control profiles at M05 and M06, only one profile (M05 P1) contained enough phytoliths for a detailed analysis (an outline of causes of low phytolith quantities in soil samples is provided in section 3.2.1).

Consequently, five profiles from the PPBio forest modules were analysed (M05 P1, M02 P2, M02 P4, M11 P2, M11 P4). At the Couro Velho site, four of the seven profiles were analysed for phytoliths—two brown ADE from the Brazil nut stand and two black ADE from the core area—to represent the variability of anthropogenic soils in the phytolith record. The selected profiles represent a 300 m-long transect across the site, from the middle of the Brazil nut stand to the core.

Soil geochemical analysis was performed on four profiles from the PPBio forest modules and seven profiles at Couro Velho. In the case of the PPBio profiles, the aim was to analyse the profiles that are also analysed for phytoliths to make a multidisciplinary interpretation possible. In the case of the ADE soils, all soil profiles were analysed to better understand intra-site variability of anthropogenic soils.

The aim of the macro charcoal analysis was to confirm the use of fire in the creation of anthropogenic soils. The M05 P1 profile served as a control profile, providing a natural baseline for the analysis. In addition to this profile, one brown ADE profile from the Brazil nut stand (CAST1 2) and two black ADE profiles (TP1 P5, TP1 P7) from the Couro Velho site were examined for their charcoal.

Stable carbon isotope analysis was carried out on samples from one profile at every PPBio forest module. Regarding this analysis, the rationale was to gain an overall understanding of the stability or instability of the vegetation through time and space. This comparatively cursory analysis was then complemented by the more detailed phytolith analysis.

Radiocarbon dates were obtained from profiles where the phytolith or geochemical analysis revealed a large-scale change in the profile. For example, in the case of M11 P2, the phytolith, stable carbon isotope, and geochemical analyses revealed a shift in both the land cover and soil properties. Therefore, this profile was selected for dating to make it possible to correlate the changes in this profile with those evident in other studies in the area. Additionally, four profiles from the Couro Velho site (TP1 P2, TP1 P3, TP1

P5, TP1 P7) were also dated to identify the timeline of initial occupation, the start of ADE formation, and the period of intensive site use .

3.2.1 Phytolith methods

Justification

Phytoliths are microscopic opal silica bodies—the term “phytolith” derives from the Greek word meaning “plant stone” —that form in a plants’ leaves, stems, roots, and inflorescences (Piperno, 2006). The formation of phytoliths starts with monosilicic acids which are present in the groundwater and absorbed by plants through their roots. A combination of genetic and environmental factors lead to the formation of silica bodies, which develop into specialised silica-accumulation cells and inter-cellular spaces, providing support, rigidity, and structural defence mechanisms for the plant. Since different plant taxa have different internal structures, this sometimes results in phytoliths with different shapes and sizes, which can be diagnostic for a specific plant (Pearsall, 2000; Piperno, 2006).

Phytoliths have been used to reconstruct palaeoclimate and palaeoenvironments in a variety of sediments (Lu et al., 2007 and references therein). Studies show that it is also possible to distinguish between, for example, forest and savanna vegetation based on their phytolith assemblages (Iriarte and Paz, 2009). Dickau et al. (2013) suggest that several lowland Amazonian forest formations can be characterised by their phytolith assemblages. Phytolith analysis has proved to be a reliable method for identifying various types of domesticates, particularly in regions of poor macrobotanical preservation (Piperno, 2006; Piperno and Pearsall, 1998b). Therefore, it is a valuable tool to investigate the domestication and distribution of plant species in lowland Amazonia.

The advantages of studying phytoliths include:

- In most cases, phytoliths are deposited *in situ* where the host plant dies, thus serves as a local fossil record (Piperno, 2006). This is important to this thesis, which examines landscape history at a fine spatial resolution and assesses the impacts of past human land use in certain areas of the interfluve. In contrast, fossil pollens, for example, are better suited to detecting changes in vegetation at the regional scale. Phytoliths can travel longer distances during wind-blown fires (Fredlund and Tieszen, 1997) and alluvial transport, but forest fires are rare in the forests in and surrounding the PMI (Bush and Silman, 2007), so the effect is probably negligible. Additionally, this study utilises terrestrial soil profiles, meaning that alluvial transport of phytoliths should not affect the results.

- Phytoliths are often preserved in the absence of other palaeobotanical data, as they are very durable and able to survive the corrosive, acidic soils of the tropics for thousands of years (Alexandre et al., 1999). This contrasts with fossil pollens the preservation of which requires waterlogged conditions.

There are also some disadvantages of phytolith analysis which have to be taken into consideration in the discussion of the data. The taxonomic resolution of phytoliths is discussed by Piperno (2006) in depth, and a salient issue is that phytolith analysis is sometimes forced to rely on suites of morphotypes that are produced by a large number of families (e.g. globular granulates). The poor resolution of such samples make distinguishing many arboreal and other dicotyledonous taxa difficult, especially in forested areas.

Despite this, although multiplicity in eudicot phytolith assemblages still exists, various tropical eudicot families have been found to produce phytoliths diagnostic to family or genus level. These include Cannabaceae (*Celtis* sp.), Moraceae, Burseraceae, and Annonaceae (Piperno, 1989, 2006). Further advances have allowed a number of lowland Amazonian vegetation formations to be differentiated by their phytolith assemblages (e.g. Dickau et al., 2013; Watling et al., 2016).

Among monocots, grasses (Poaceae) produce phytoliths diagnostic to subfamilies and genus (Piperno and Pearsall, 1998b), and sometimes even species level. For example, maize (*Z. mays*) produces different diagnostic morphotypes in different parts of the plant (Iriarte, 2003; Pearsall, 1978; Pearsall et al., 2003; Piperno and Pearsall, 1993). However, in a recent study, another important domesticated Poaceae, rice (*Oryza* sp.), was identified in south-western Amazonia by its diagnostic phytolith morphotype (Hilbert et al., 2017). Some non-Poaceae monocot families also produce diagnostic phytoliths, including palms (Arecaceae), sedges (Cyperaceae), Heliconiaceae, and Marantaceae (Piperno, 2006).

Regarding palm phytoliths, recent work carried out by Morcote-Ríos et al. (2016) has confirmed that the size and shape of palm phytoliths can inform the identification and distinction of Amazonian palm species to some degree.

According to Hyland et al. (2013), the rate of biomass production and therefore silica uptake is different between plant types, and this impacts their phytolith production as well. This can result in potential biases towards identifying some taxa over others. of the authors highlighted this issue by pairing soil phytolith assemblages and local vegetation assemblages in the central United States, which showed that soil phytolith assemblages averaged a 29% bias towards grass morphotypes compared to actual aboveground vegetation. Indeed, Piperno (2006) also suggests that grasses produce more phytoliths than (temperate) hardwood trees. Additionally, some work implies that certain depositional environments, including certain soil types, may be less suitable for phytolith preservation due to oxidisation or clay-adhesion (e.g. Fredlund and Tieszen, 1997). Hyland et al. (2013) suggest a strong correlation between phytolith assemblage bias and soil type, since soil types are closely linked to vegetation type, which has been shown to be a significant source of phytolith production bias.

Post-depositional processes can also affect phytolith preservation and phytolith assemblages in stratigraphic layers. For example, colluvial deposition—the movement and deposition of terrestrial sediments at the base of hillslopes by either rain-wash, sheet-wash, slow continuous downslope creep, or a variable combination of these processes—can influence the movement of phytoliths in the profile. However, in the PMI, the regional topography is relatively flat, with elevation ranging between 27 and 80 m above sea level. The topography is even gentler at the local scale: between 1 and 3 m above sea level (Sombroek, 2000), therefore this issue will have had a minor influence on terrestrial sediment deposition.

A similar issue is bioturbation, which is the mixing of sediments from different depths due to the activities of animals and plant roots. This can cause problems when it comes to the interpretation of the stratigraphic phytolith record in forested sites (Hart and Humphreys, 2003). Taking special care during documentation and sampling of a soil profile, however, can mitigate this problem, particularly as bioturbation is often explcitly identifiable due to changes in the soil's colouration.

Column experiments on phytolith translocation in loamy and sandy soils due to water percolation were conducted by Fishkis et al. (2010). Their study shows that phytolith transportation in sandy soils as a result of water seepage was significantly higher than in the control soil. However, water percolation did not have an impact on phytolith movement in loamy soils. The authors conclude that phytolith size has a great impact on translocation by percolation: phytoliths with diameter <5 μm exhibit significantly deeper movement by percolation than phytoliths with diameter >5 μm. The degree of translocation caused by this process is unresolved (Madella and Lancelotti, 2012). Contrary to Fishkis et al.'s (2010) findings, an earlier study by Fisher et al. (1995) found that once phytoliths are deposited in the soil, they remain generally stationary. Since the soil profiles analysed in this thesis contain mainly loamy soils, phytolith translocation via water seepage, if a problem, would not impact the phytolith analysis.

Finally, chemical intervention on phytoliths during pedogenesis may also affect soil phytolith assemblages, leading to dissolution and subsequent silica recycling (Madella and Lancelotti, 2012). PH and composition can be a source of taphonomic bias, especially if the upper soil horizon is highly acidic (Hyland et al., 2013). Piperno (1988), alternatively, shows that the presence of free iron and aluminium oxides in highly-weathered tropical soils like those of central Amazonia may enhance phytolith durability, since these free oxides can be absorbed by the phytolith, which makes them less prone to dissolution. However, since phytoliths are produced in different parts of the plants, some will be less durable than others. Thinner phytoliths are much less durable than those which are formed inside of cells and represent solid infillings. These include ones that are formed as casts of cells and cell wall incrustations, such as epidermal sheets (Piperno, 1988; Alexandre et al., 1997).

In sum, grasses and other monocots produce significantly more phytoliths than trees and woody forest vegetation, and soils with acidic upper horizons and significant clay accumulations are more likely to have experienced taphonomic biases, such as the chemical destruction or physical adsorption of phytoliths. These issues must be considered when describing and interpreting this thesis' results.

Phytolith extraction

Phytoliths were extracted using the wet oxidation method described by Piperno (2006). A summary of the laboratory procedures is given below.

From each sample, 100 ml of soil was mixed with 1 teaspoon sodium hexametaphosphate and 900 ml warm water. The mixture put on the shaker for 12–24 hours to disaggregate the soil. The clay fraction was then removed using a gravity sedimentation process. This involved placing the disaggregated samples in 1000 ml beakers that were then topped up with water and allowed to stand for a minimum of one hour. The heavy sand and silt fraction thus sank to the bottom of the beaker, whereas the clay fraction was left floating at the top and could then be poured off. This process was repeated a minimum of 10 times or until the water had been cleared from the clay.

The next step involved separating the sand and silt fractions of the sediment using the wet sieving method. The separation of these fractions faciliates distinguishing and identifying diagnostic phytoliths under the microscope. The silt fraction particle size was <50 µm (A fraction) and the sand fraction particle size was >50 µm (C fraction). For each sample, about 2 cm^3 silt and 2 cm^3 sand were transferred into separate test tubes to be chemically washed. First hydrochloric acid (37%) was added to remove carbonates and some of the iron oxides. When any visible reaction had stopped, the hydrochloric acid was washed out of the samples in a centrifuge (1700 rpm) for 10 minutes until the water turned clear.

To ensure that the phytoliths would be clearly visible under the microscope, organic matter was also removed from the samples. For this step, the samples were treated with nitric acid (60%) and heated up to 100 ˚C for a minimum of 3–4 hours. A small amount of potassium chlorate was added regularly to the sediment to serve as a catalyst and help the reaction. When the nitric acid turns a clear yellow or yellowish green colour, this signifies that all the organics have been removed. The hydrochloric acid and the potassium chlorate was washed out of the samples in the centrifuge (1700 rpm) again for 10 minutes until the water turned clear.

The phytoliths were separated from the rest of the sediment using a heavy liquid solution. This heavy liquid was prepared by adding water to zinc bromide powder until the solution reached a density of approximately 2.30 g/cm^3 (*ca*. 2.28–2.32 g/cm^3). This zinc bromide solution was added to the sediment and, after centrifugation (1700 rpm) for five minutes, the phytoliths, which are lighter than the heavy liquid, had floated to the top. The phytoliths formed a ring and were syphoned off using pipettes, before being transferred to fresh test tubes. In the final stage of the treatment, phytoliths were dried with added acetone. Entellan was used to mount the phytolith onto microscope slides for analysis. While still fresh, Entellan enables the phytoliths to be rotated, leading to easier, more accurate identifications.

Quantification

Phytoliths were analysed under a light microscope and photographs were taken using Carl Zeiss Axiovision 4.2 software. The silt (A fraction) slides were analysed at 500x magnification and a minimum of 200 phytoliths were counted per sample, as this is the minimum number beyond which the diversity of encountered morphotypes declines significantly (Pearsall, 2000). Sand (C fraction) phytoliths were studied at 200x magnification. These phytoliths are usually less common, therefore only samples with a minimum of 200 phytoliths that were of C-fraction size were kept for further analysis to ensure sample comparability.

Phytolith identification

The following section describes the morphological characteristics and taxonomical association and significance of the phytoliths encountered in this study. A summary is also provided in Table 3.4.

Phytolith identification was conducted using published material and tested against the Archaeobotany and Palaeoecology Laboratory tropical plant phytolith reference collection housed in the University of Exeter's Department of Archaeology. This reference collection consists of more than 500 modern neotropical plant specimens from herbaria in London, Brazil, Uruguay, French Guiana, and Bolivia. Wherever possible, names and descriptions follows the International Code for Phytolith Nomenclature (ICPN) descriptors defined by Madella et al. (2005). The description starts with the grass phytoliths, followed by the non-grass monocots, then finishes with the eudicot phytoliths.

The phylogenetic classification of Poaceae phytoliths was carried out according to Judziewicz et al. (2000) and Soreng et al. (2015). Initially, Twiss et al., (1969) proposed a morphological classification of Poaceae family phytoliths, distinguishing , Panicoideae, Chloridoideae, and Pooideae grasses by the production diagnostic short-cell phytoliths in the grass leaf epidermis, as well as in lobate forms, saddles, and rondels/trapezoids (Fig. 3.11: G, H), respectively. This initial classification was later refined by Fredlund and Tieszen (1997), Alexandre et al. (1997), Piperno and Pearsall (1998b), Pearsall (2000), Lu and Liu (2003), Iriarte (2003), and finally Fernández Honaine et al. (2006).

However, in some cases, phytoliths morphotypes overlap amongst Poaceae species (Lu et al., 2006; Piperno, 2006). Non-diagnostic Poaceae morphotypes identified during this thesis' analyses included cross-shaped bodies (Fig. 3.11: C, D). These are produced in the leaf of most known grasses (Piperno, 2006), and they are classified as lobate forms with three or more lobes. Poaceae also produce smooth-edged cuneiform bulliform cells in their leaves and stems (Fig. 3.11: I), parallepiped bulliform cells and elongated silicified epidermal cells in their leaves (Fig. 3.11: J), but these types are of little taxonomic value. Among the Panicoideae lobate morphotypes, this study identified

Table 3.4: Phytoliths encountered in the study, their taxonomic associations, anatomical origins, occurrence after sample fractionation, and references.

Taxonomic level	Phytolith morphotype	Origin	Soil fraction	References
Panicoideae (Poaceae)	Bilobate	Leaf	silt	Alexandre et al. (1997), Fredlund and Tieszen (1997), Fernández Honaine et al. (2006), Lu and Liu (2003), Pearsall (2015), Piperno (2006), Piperno and Pearsall (1998b), Sase and Hosono (2001), Twiss et al. (1969), Madella et al. (2005).
Panicoideae (Poaceae)	Polylobate	Leaf	Silt	
Panicoideae (Poaceae)	Crosses	Leaf	Silt	
Chloridoideae (Poaceae)	Short saddle	Leaf	Silt	
Bambusoideae (Poaceae)	Collapsed saddle	Leaf	Silt	
Bambusoideae (Poaceae)	Spiky rondel	Leaf	Silt	
Bambusoideae (Poaceae)	Blocky cross,	Leaf	Silt	
Bambusoideae (Poaceae)	Bulliform with flared decoration	Leaf	Sand	
Olyreae (Poaceae)	Irregular, complex bodies	Leaf	Silt	
Chusqueinae (Poaceae)	Chusquoid bodies	Leaf	silt	
Poaceae (non-diagnostic)	Rondell/Tall Rondel	Leaf	Silt	
Poaceae (non-diagnostic)	Cuneiform bulliform cell	leaf/stem	Sand	
Poaceae (non-diagnostic)	Parallepiped bulliform cells	Leaf	silt/sand	
Cucurbita sp. (Cucurbitaceae)	Scalloped spheres	Rind	sand	Bozarth (1987), Piperno et al. (2000)
Cyprerus/Kyllinga sp. (Cyperaceae)	Stippled polygonal body	Seed	silt	Fernández Honaine et al. (2009), Piperno (1989), Schuyler (1971), Ollendor (1992).
Marantaceae	Globular, nodular	leaf/stem	silt/sand	Piperno (2006).
Marantaceae	Globular with hairs	Rhizome	silt	Piperno (2006).
Marantaceae	Conical bodies	Rhizome	sand	Piperno (1989).
Calathea sp. (Marantaceae)	Irregular or flat cylinder	Rhizome	sand	Chandler-Ezell et al. (2006), Piperno and Pearsall, (1998a).
Heliconia sp. (Heliconiaceae)	Smooth bodies with troughs	Rhizome	silt	Prychid et al. (2003), Tomlinson (1969).
Asteraceae	Opaque, perforated platelets	Seed	sand	Bozarth (1993).
Mendoncia sp. (Acanthaceae)	Globular with rugulose hemispheres	Seed	sand	Piperno (2006), Dickau et al. (2013).
Arecaceae	Globular echinates	all parts	silt	Piperno (2006), Tomlinson (1961), Dickau et al. (2013), Watling and Iriarte (2013), Watling et al. (2015).
Arecaceae	Large globular echinates with small spines	all parts	sand	Morcote-Ríos et al. (2016), Madella et al. (2005).

Arecaceae	Hat-shaped	all parts	silt	Piperno (1989), Tomlinson (1961).
cf. P. guianense (Burseraceae)	Elongated cylindrical bodies with psilate surfaces and verrucate/nodular decorations	Leaf	sand	Watling and Iriarte (2013), Madella et al. (2005).
Celtis sp. (Cannabaceae)	Stippled plates	Seed	silt	Bozarth (1993).
Annonaceae	Spherical, faceted bodies	Leaf	sand	Piperno (2006), Runge (1999), Madella et al. (2005).
Arboreal	Globular granulate	Wood	silt	Geis (1973, Madella et al. (2005).
Arboreal	Large globular granulate	Wood	sand	
Arboreal	Sclereids and tracheids	leaf/bark	silt/sand	Piperno (2006).
Arboreal	Faceted bodies	Leaf	silt/sand	Piperno (1985), Madella et al. (2005).
Arboreal	Vesicular infillings	Leaf	silt	Geis (1973), Strömberg (2003, 2004).
Arboreal	UID1 elongate sinuate	leaf/bark	silt/sand	Piperno (2006).
Arboreal	UID2 tabular		silt	Piperno (2006).
Arboreal?	UID4 hair cell		sand	Piperno (2006).
Trichomanes sp. (Pteridophytes)	Bowl-shaped	all parts	silt	Piperno (2006), Watling and Iriarte (2013).

bilobates (known in earlier studies as dumbbell-types) (Fig. 3.11: A) and polylobates, which have elongated bodies with more than four lobes (Fig. 3.11: B) which are generally diagnostic to the subfamily and sometimes even the genus level. In this family, Aristida is the only plant that produces phytoliths that can be identified to the genus level. An Aristida phytolith is a specific type of bilobate that has a long, narrow shaft and flared, convex lobes (Mulholland, 1989; Piperno and Pearsall, 1998b).

Panicoideae grasses—mostly following C_4 carbon fixation pathways—are widely distributed across the hot and humid tropics, and they are found in a variety of savanna environments, as well as forest understories, preferring disturbed habitats (Lu et al., 2006; Piperno and Pearsall, 1998b). The Chloridoideae subfamily is predominantly C_4 and consists of grasses adapted to hot, dry environments. These produce short saddle phytoliths (Fig. 3.11: E), exhibiting axes that are symmetrical in side view (Piperno and Pearsall, 1998b; Twiss, 1992). Domesticated maize can be identified by the wavy-top rondels that are produced in the cob of the plant (Bozarth, 1993; Pearsall, 1978; Piperno

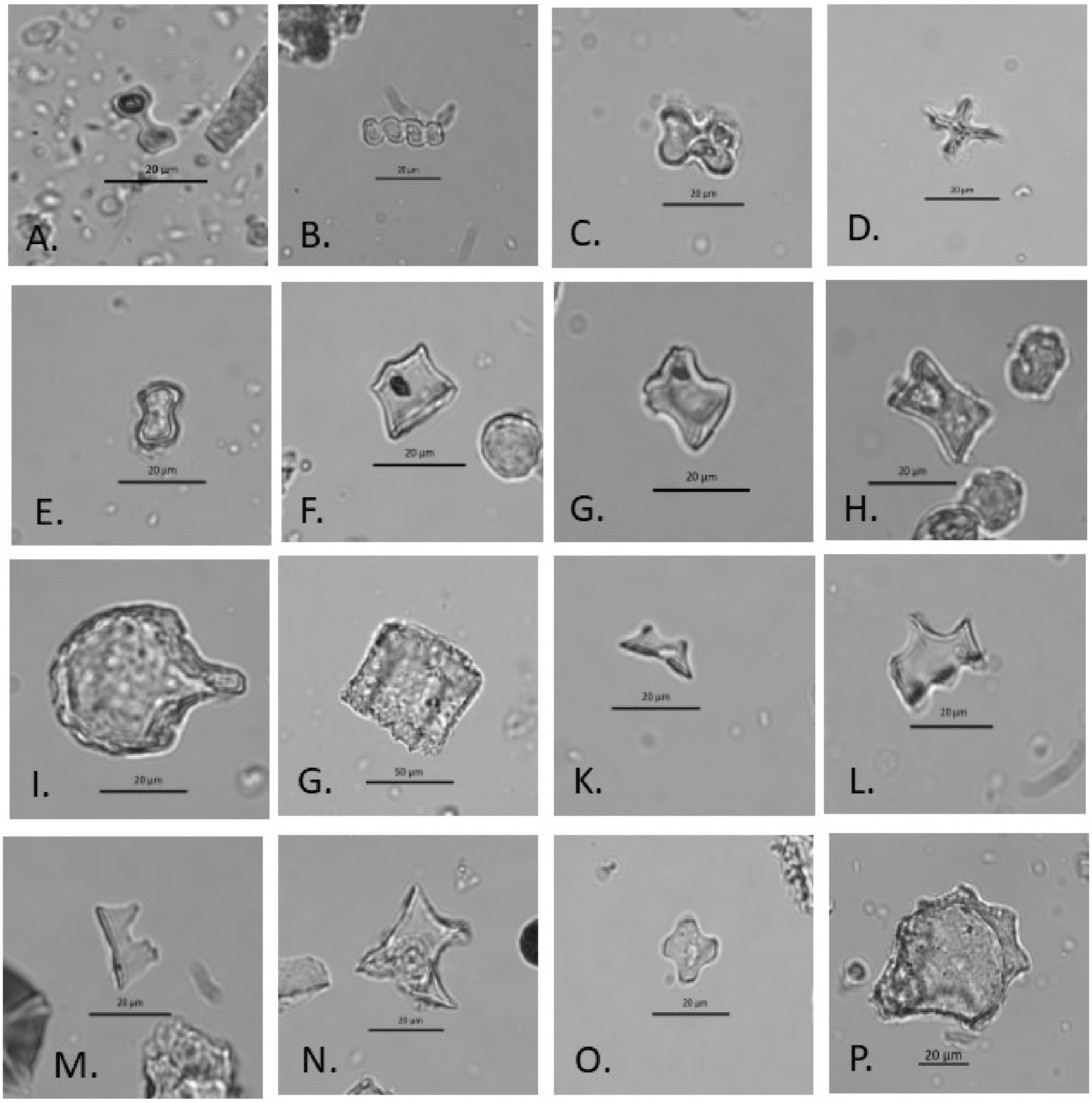


Figure 3.11: Microphotographs of Poaceae phytoliths identified in this study and their taxonomic and anatomical associations: (A) Panicoideae leaf bilobate; (B) Panicoideae leaf polylobate; (C) Poaceae, leaf, cross-shaped variant 1; (D) Poaceae, leaf, cross-shaped other variants; (E) Chloridoideae, leaf, short saddle; (F) Z. mays, cob, wavy top rondel; (G) Panicoideae, floral bract, rondel; (H) Panicoideae, floral bract, tall rondel; (I) Poaceae, leaf/stem, cuneiform bulliform cell; (J) Poaceae, leaf, parallepiped bulliform cells; (K) Chusquea sp., leaf, chusquoid body; (L) Olyreae, leaf, trapezoid irregular body; (M) Bambusoideae, collapsed saddle; (N) Bambusoideae, leaf, spiked rondel; (O) Bambusoideae, leaf, cross-shaped variant 10; (P) Bambusoideae, leaf/stem, cuneiform flared bulliform cell.

and Pearsall, 1993) and is characterised by concave sides and a flat oval or circular base that is longer than the height of the rondel. The characteristic top consists of a single complete wave that is equal to or shorter than the length of the rondel without sharp or spiny edges (Fig. 3.11: F) (Iriarte, 2003). Additionally, general rondel phytoliths characterised by at least one circular face (Fig. 3.11: G, H) occur in all Poaceae subfamilies (Piperno, 2006).

In this thesis, phytoliths from two tribes of the Bambusoideae subfamily were encountered: tropical woody bamboos (Bambuseae) and herbaceous bamboos (Olyreae), which are common components of forest understories (Kelchner and Bamboo Phylogenic Group, 2013). The Bambusoideae subfamily contributes to a significant number of diagnostic phytolith morphotypes (Behling and Hooghiemstra, 2000; Iriarte 2003; Kondo, 1994; Piperno and Pearsall, 1998b; Sase and Hosono, 2001). Bamboos produce robust, blocky crosses (Fig. 3.11: O) (Iriarte 2003; Piperno, 2006), saddles with collapsed sides (Fig. 3.11: M), cuneiform bulliforms with flared protrusions along the fan edge (Sase and Hosono, 2001) (Fig. 3.11: P), chusquoid bodies (Fig. 3.11: K), and rondels with spikes (Fig. 3.11: N). The Olyreae subfamily produces trapezoid-shaped irregular/complex bodies (Fig. 3.11: L) (Piperno and Pearsall, 1998b).

Non-Poaceae monocots also produce various phytoliths of distinctive taxonomies. The sedge (Cyperaceae) family produces polygonal phytoliths with densely stippled surfaces and large central protuberances found in the seeds which are often genus-specific (Fig. 3.12: F) (Piperno 1989; Schuyler, 1971) and were encountered in this study. Another phytolith morphotype produced by sedges are the conical leaf bodies (Fernández Honaine et al., 2009; Ollendorf, 1992; Piperno, 1989).

The Marantaceae family produce a large variety of phytolith morphotypes in different parts of the plant. Globular phytoliths, either with nodular surface decoration comprising small prominences or irregularly angled "hairs", are produced in the leaves and stems (Fig. 3.12: A, B) (Piperno, 1989). The seeds produce conical bodies with nodular projections that have either pointed or rounded apexes (Fig. 3.12: C) (Piperno, 1989). *Calathea* is an important genus in the Marantaceae family, as it includes economically important species. *Calathea* sp. rhizomes produce very distinctive, decorative conical bodies with more elongated shapes (Fig. 3.12: D.).

The phytolith from the fire-loving, early successional plant *Heliconia* of the Heliconiaceae family is characterised by a smooth or decorated surface with a deep trough in the centre of the phytolith (Fig. 3.12: E) (Piperno, 2006; Prychid et al,. 2003).

The palm (Arecaceae) family is an abundant producer of two phytolith morphotypes: (1) globular echinates, which have spiny projections distributed over the surfaces (Fig. 3.12: G–J); and (2) conical to hat-shaped bodies (Fig. 3.12: K) (Morcote-Ríos et al., 2016; Tomlinson, 1961, 2011). With very few exceptions, these morphotypes

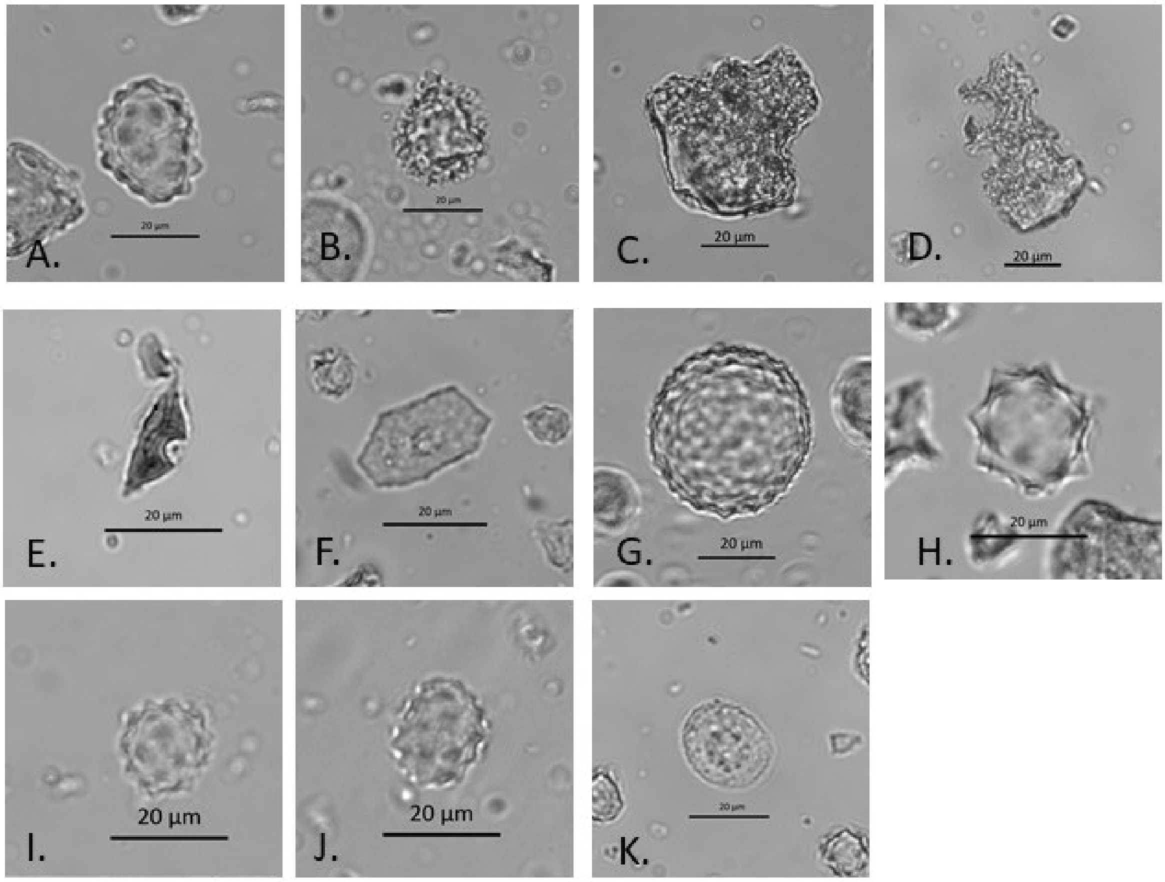


Figure 3.12: Microphotographs of phytoliths from non-Poaceae monocots identified in this study and their taxonomic and anatomical associations: (A) Marantaceae, leaf/stem, nodular sphere; (B) Marantaceae, rhizome, globular with hairs; (C) Marantaceae, rhizome, conical body; (D) cf. Calathea sp., rhizome, cylindrical flat cylinder; (E) Heliconiaceae, rhizome, smooth body with trough (burned); (F) Cyperaceae, seed, stippled polygonal body; (G) Arecaceae, all parts, large globular echinates; (H) Arecaceae, all parts, large globular echinates with small spines; (I–K) Arecaceae, all plant parts, globular echinate; (L) Arecaceae, all plant, parts conical body.

are never produced together in the same species (Piperno, 2006). Palms produce phytoliths in every part of their body but mainly in their leaves (Morcote-Ríos et al., 2016). Recently, scientists have focused more on identifying diagnostic morphotypes below the family level in the Arecaceae family (Bowdery, 2014; Morcote-Ríos et al., 2016; Tomlinson et al., 2011).

Using 92 species of Amazonian palms representing 29 genera across four subfamilies, Morcote-Ríos et al. (2016) classify the globular and conical phytoliths into eight subtypes that can help to identify Amazonian palms at the levels of subfamily, tribe, genus, and sometimes species. The classification is based on the size of the phytolith body and the number, length, and degree of symmetry of the projections. The following morphotypes were distinguished: (1) globular echinate symmetric; (2) globular echinate with numerous long, acute projections at the periphery; (3) globular echinate elongate; (4) large globular echinate with dense, short projections; (5) reniform echinate; (6) globular echinate with long, acute projections; (7) conical; and (8) conical with acute basal projections.

Eudicot plants consist of *ca*. 75% of all angiosperms (Piperno, 2006); however, in contrast to monocots, they rarely produce phytoliths diagnostic to the family or genus levels. In this thesis, several phytolith morphotypes from eudicots were identified.

The *Annona* genus (Annonaceae) produces edible fruits and, therefore, is very important to Amazonian archaeobotanical studies. It is distinguished by faceted phytoliths that have a shape that is spherical to aspherical overall (Fig. 3.13: C.) (Piperno, 1988; Runge, 1999).

The *Celtis* genus (Cannabaceae) comprises important fruit-bearing trees commonly known as hackberries, which produce stippled plate phytoliths in the fruits and seeds (Fig. 3.13: D) (Bozarth, 1992; Iriarte and Paz, 2009).

The major cultivar that was identified in this thesis' analyses is squash (*Cucurbita* sp.), which belongs to the Cucurbitaceae family. Squash produce a very distinctive phytolith morphotype in the rind of the fruit that express as spheres with deeply-scalloped surfaces of continuous concavities (Fig. 3.13: P) (Bozarth, 1987; Piperno et al., 2000).

The so-called "boney bodies" first isolated by Watling and Iriarte (2013) from the leaves of *Protium guianense* (Burseraceae) are described as, "elongated cylindrical bodies with psilate surface and verrucate/nodular decoration" (Fig. 3.11: E). *Protium* species are traditionally used for their fruits, or as firewood medicine, or other cultural applications. *P. guianense* is commonly known as the Incense tree, and it is mainly burned for its fragrant smoke. This boney phytolith morphotype has not been found in other members of the *Protium* genus (e.g. Piperno, 1989) indicating that it is diagnostic at the species level (Watling and Iriarte, 2013). It was, however, only found in this thesis' soil samples.

Lianas (*Mendoncia* sp.) are a genus of climbing plants in the family Acanthaceae. These were identified in this thesis by the presence of large spherical phytoliths with one wrinkled hemisphere and one granulate to psilate hemisphere (Fig. 3.13: O) (Piperno, 2006; Dickau et al., 2013). The Asteraceae family contains herbs or shrubs, woody vines,

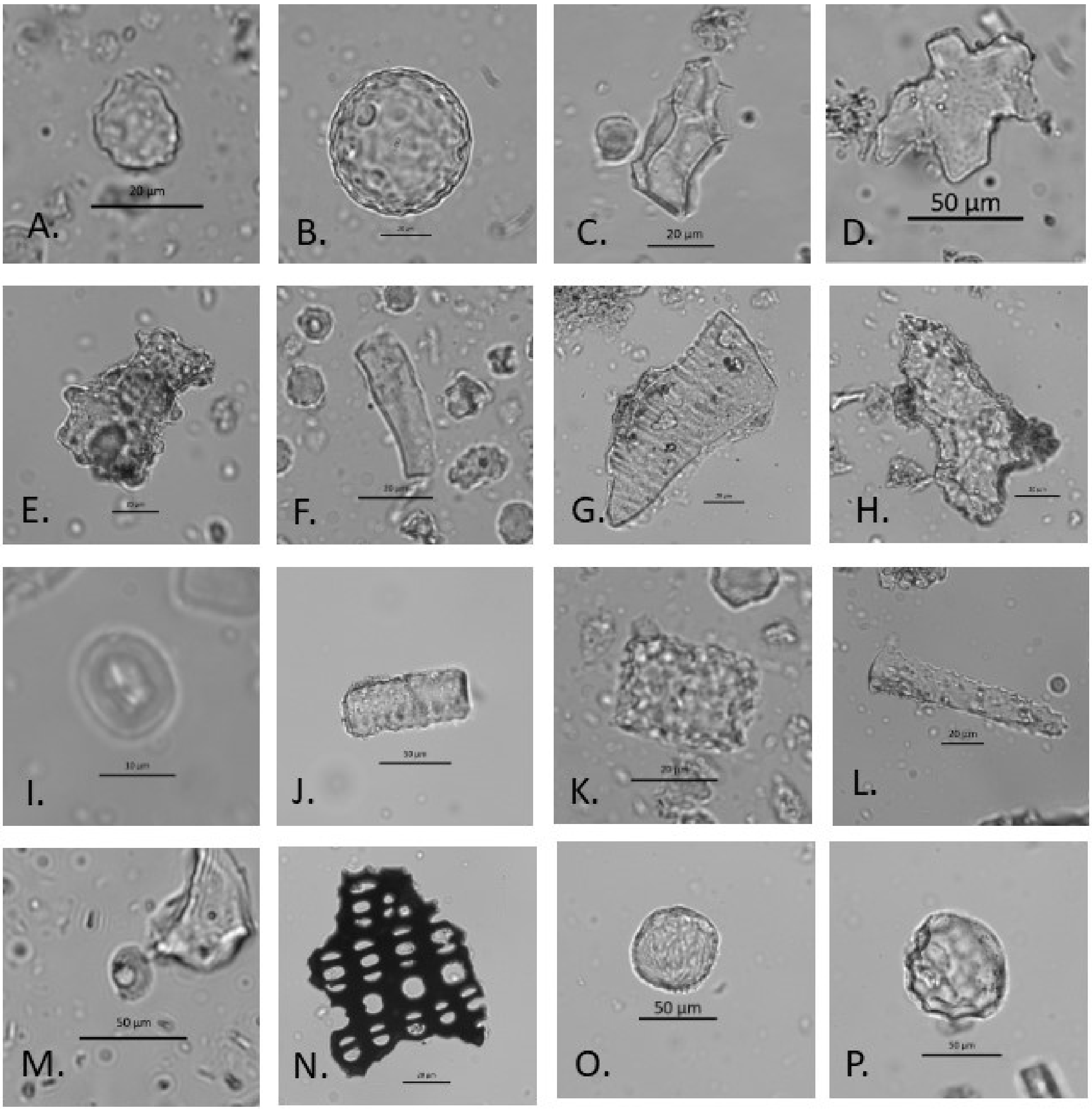


Figure 3.13: Microphotographs of phytoliths from eudicots identified in this study and their taxonomic and anatomical associations: (A) Arboreal all plant parts globular granulate; (B) Arboreal, all plant parts, large globular granulate; (C) cf. Annonaceae, leaf, irregular facetate; (D) Celtis sp., seed/fruit, stippled platelet; (E) cf. P. guianense, leaf, elongated cylindrical bodies with psilate surface and verrucate/nodular decoration; (F) Arboreal leaf/bark, sclereids; (G) Arboreal leaf/bark, tracheid; (H) Arboreal leaf/bark, facetate body; (I) Arboreal leaf, vesicular infilling; (J) Arboreal UID1, elongate sinuate; (K) Arboreal UID2, tabular body; (L) Arboreal UID4, hair cell; (M) Trichomanes sp., all plant parts, roughly bowl-shaped phytolith; (N) Asteraceae, inflorescence, opaque perforated platelet; (O) Mendoncia sp., seed, globular with rugulose hemisphere; (P) Cucurbita sp., rind, scalloped sphere.

lianas, and small trees, and produces large opaque platelet phytoliths with perforations in its seeds (Fig. 3.13: N) (Bozarth, 1992).

Apart from these diagnostic morphotypes, the vast majority of eudicot plants produce non-diagnostic phytoliths with wide taxonomic distributions (Piperno, 2006). These phytoliths, when present in this study, were classified as non-diagnostic arboreal. The most common type in this study was the globular granulate morphotype (Fig. 3.13: A, B) that can be described as a spherical body with rugulose decoration, which is produced in the sub-epidermis of many woody plants (Kondo et al., 1994).

Silicified conducting elements (sclereids, tracheids) were also abundant in the samples. The tracheids are usually cylindrical in shape and show regular protrusions, which are infillings of border pits in the cell walls (Fig. 3.13: G). Sclereids are silicified support structures of the xylem; these are typically elongated phytoliths with branched ends and psilate surfaces (Fig. 3.13: F) (Piperno, 2006).

Another commonly-produced arboreal phytolith is the type with an irregularly-shaped, elongated, multifaceted body with well-defined facets (Fig. 3.13: H) (Piperno and Pearsall, 1998b). Other non-diagnostic arboreal morphotypes were categorised as: elongate sinuates (UID1), which have elongated bodies with wavy edges and are probably also silicified conducting elements (Fig. 3.13: J); tabular morphotypes (UID2), which are rectangular in shape from the front and are thin from the side view (Fig. 3.13: K); and a final unidentifiable phytolith (UID4) is probably an arboreal hair cell with stippled decoration (Fig. 3.13: L). These latter types appeared mainly in the anthropogenic soil samples.

Vesicular infillings are bodies consisting of concentric laminations of silica (Fig. 3.13: I.) (Geis, 1973; Stromberg, 2004). They have been only recorded in arboreal taxa. However, their diagnostic significance is still not well understood (Watling and Iriarte, 2013). Finally, ferns (*Trichomanes* sp.) produce bowl-shaped phytoliths in all parts of the plant (Fig. 3.13: M) (Piperno, 2006; Watling and Iriarte, 2013).

3.2.2 Soil geochemical analysis

Soil geochemical methods

The analysis of the chemical characteristics of soils and sediments is a fairly widespread geoarchaeological technique (James, 1999, and references therein), as soil properties at archaeological sites can provide important information about past activities at the site. Such properities include soil pH, magnetic susceptibility, and high concentrations of phosphorous, lead, zinc, manganese, calcium, magnesium, potassium, arsenic, and organic carbon (McManamon, 1984). This thesis focuses on total and available phospherous content, total carbon, and total nitrogen, as well as C:N ratios.

The process by which soils are enriched with micro and macro elements at anthropogenic sites (habitation sites, ritual sites, cultivation sites, etc.) broadly involves residues from a range of organic and inorganic materials that are brought to the site accumulating in the soil. Such materials may include items used as food, clothing, building, household utensils, agricultural and industrial implements, as well as human and animal waste (James, 1999). Advances in methods for detecting the enrichment of soils have made it possible to investigate broader aspects of soil chemistry and employ it to distinguish different activity areas in a site (James, 1999). This has been used to determine horizontal and vertical boundaries of known sites, as well as features within sites, or to characterise given types of past land use (Eidt, 1984).

For example, Rapp and Hill (2006) suggest that elevated phosphate, barium, and manganese levels indicate areas of organic refuse disposal, whereas areas of craft production can be distinguished by high mercury and lead concentrations. Substantial amounts of nitrogen, phosphorus, and calcium, meanwhile, are added to the soil from food, human waste, and animal waste. Wood burning also raises the amount of magnesium in the soil, and a high pH may be related to fire. The changes to soil properties caused by human activities may be measured in terms of effect and amount, and, if these changes are beneficial, they are referred to as "soil enrichment", otherwise, "soil contamination" (Eidt, 1984).

Once organic and inorganic materials arrive at the site, their decomposition starts. This process depends on both the nature of the materials and the environment, including factors like temperature, redox status, and the movement of water through the soil. The introduced elements may be fixed by clays, organic matter, oxides of iron, aluminium, and manganese, or carbonates (Rapp and Hill, 2006). These fixed elements may then be redistributed either by natural (e.g. clay translocation, eluviation, bioturbation) or anthropogenic (e.g. tilling, ploughing, soil removal) processes. The chemical and physical signs of past human activities may even be buried by sediment deposition or removed through erosion (James, 1999).

In archaeological research, the most popular form of chemical analysis is measuring phosphate levels (Eidt, 1984; James, 1999). Especially in the humid tropics where evidence of pre-Columbian habitation is often invisible, phosphorous-enriched soils can be a good indication of past human presence (Dietz, 1957). Phosphorous is an essential element for living cells, and deficiencies hinder plant and animal growth, making them more prone to illnesses and limiting their reproduction (Brady and Weil, 1996). In natural conditions, the amount of available phosphorous in the soil is usually low. However, in areas where subsistence-related huma n activities (e.g. organic fertilization of gardens and disposal of household and human waste) took place in the past, higher concentrations of phosphorus can be detected (Lehmann et al., 2004). The only exception where agriculture has been conducted without the use of fertilizers, because it tends to deplete the available phosphorus (Terry et al., 2000).

Soil phosphates (the fully-oxidised acid salts of the element phosphorous) may be used as guides to the functions carried out in different parts of an archaeological site and to the intensity of occupation (Provan, 1971). Because phosphorous concentrations in bone and blood are extremely high, phosphorous also accumulates in settings associated with burials and blood rituals (Terry et al., 2000). Phosphorous in the soil becomes insoluble rapidly, therefore the accretion of phosphorous is measurable centuries later, meaning there is a permanent signature, unless the soil itself is removed (Eidt, 1984). Soil phosphorous can be found in many different forms, including: fixed inorganic phosphorous absorbed to aluminium, calcium, or iron compounds; soluble and labile inorganic phosphorous; and organic phosphorous (Terry et al., 2000).

Geochemical signal at ADE sites

Apart from the abundance of organic matter, the presence of archaeological artefacts, and the differences in textures, ADE soils differ from natural Amazonian soils in their chemical signals that can be related to anthropogenic activities (da Costa and Kern, 1999). This distinctive chemical signal can be characterised by high levels of phosphorous, magnesium, calcium, strontium, barium, chlorine, manganese, zinc and copper levels (e.g. Arroyo-Kalin, 2010; da Costa and Kern, 1999; Glaser et al., 2001; Kämpf at al., 2003; Kern, 2009; Schmidt and Heckenberger, 2009; Smith, 1980; Sombroek, 1966; Woods and McCann, 1999), but the chemical composition of ADE soils can vary widely between and within archaeological sites (Kern et al., 2004).

Although there have been only a few studies investigating the chemical differences between brown and black ADEs, it is already known that brown ADEs have fewer cultural remains, lighter soil colours, and lower levels of nutrients than black ADEs (Schmidt and Heckenberger, 2009). For example, Woods and McCann (1999) report that, around the Santarém region in central Amazonia, there are significant differences between the calcium, phosphorous, potassium, magnesium, zinc, and copper concentrations of black and brown ADE soils. Moreover, the phosphorous and calcium levels in brown ADEs are almost as low as those in the natural soil surrounding the site. The organic carbon content of brown ADEs was, however, higher than that of the black ADEs.

In research carried out in the Caxiuana region, Kern et al. (2004) reconstructed a hypothetical layout for the prehistoric settlement Manduquinha based on the geochemical signal of the soil. The indigenous group that inhabited the site discarded material in specific, differentiated places. For example, they discarded food waste—mainly of animal origin, such as bones that are high in phosphorous, calcium, and magnesium—on the western side of the site. Based on ethnographic data, this area would thus have likely

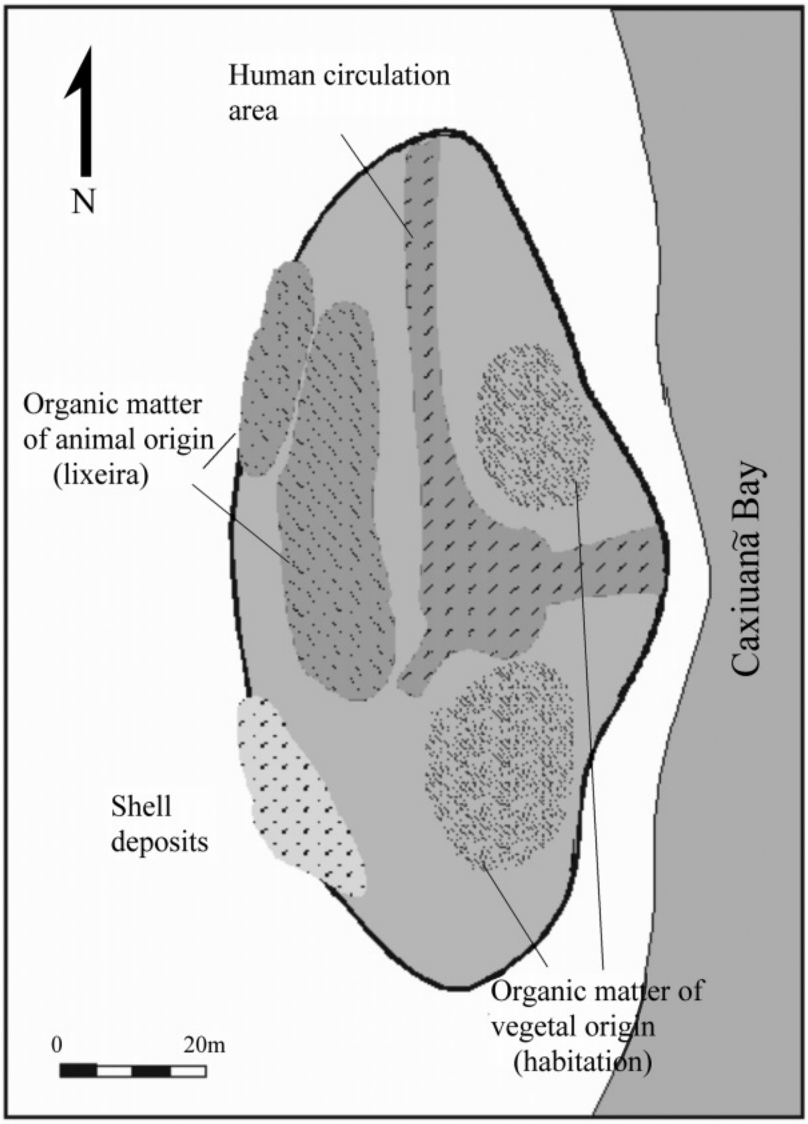


Figure 3.14: Hypothetical reconstruction of activity areas at Manduquinha site, based on the interpretation of the geochemical data (based on Kern 1996, reproduced in Kern et al., 2004).

been the kitchen area. Meanwhile, high concentrations of zing, magnesium, and copper—probably from vegetal organic matter used for construction—had accumulated in other areas of the site. Areas with low levels of ADE-typical elements will probably have been Manduquinha's central area (*plaza*) and the access to Caxiuanã Bay, the main source of water and fish for the site (Kern et al., 2004) (Fig. 3.14).

In this thesis, the total and available phosphorous content, total carbon, total nitrogen, and the C:N ratio of soil samples from profiles both in the PPBio forest modules and at the Couro Velho site were analysed, with the assistance of Dr Umberto Lombardo. Phosphorous levels contain information about the enrichment of soils with human, animal, and plant waste, indicating human soil modification. Since C:N ratios are naturally low in natural soils, high values indicate the addition of extra carbon from plant material and charcoal.

Laboratory procedures

NRM laboratories—a soil-testing facility located in the UK—conducted tests on the soil samples to measure particle size distribution, total available phosphorous, plant-available phosphorous, total nitrogen, and total carbon. Particle size distribuiton was determined using the pipette sedimentation method, then the textural class was assigned following the United States Department of Agriculture Classification. Total phosphorous was extracted by digesting the samples in an open vessel with aqua regia (concentrated hydrochloric and nitric acid) on a hot block. The elements dissolved in the acid were analysed by inductively coupled plasma optical emission spectrometry and inductively coupled plasma mass spectrometry. Plant-available phosphorous was determined using the Mehlich-1 method. Total carbon and total nitrogen levels were measured using the Dumas method.

3.2.3 Macro charcoal analysis

Justification

In this thesis, charcoals that measured >125 µm were quantified in four profiles: the control profile (M05 P1), one brown ADE from the Brazil nut stand (CAST1 P2), and two black ADE profiles from Couro Velho (TP1 P5, TP1 P7).

Studying charcoals as a proxy for fire frequency is common in palaeoecological studies (Whitlock and Larsen, 2001), but it is also a valuable proxy for archaeological investigations. Fire management has been especially important in creating anthropogenic forests and ADEs in pre-Columbian Amazonia (Arroyo-Kalin, 2012; Falcão et al., 2009; Piperno and Pearsall, 1998a; Urrego et al., 2013).Therefore, this thesis also uses soil macro charcoal counts as an indicator of the frequency and intensity of past fire events at Couro Velho to better understand the development of black and brown ADEs.

Charcoal is produced when plant matter is burned at a temperature between 280 and 500 °C (Chandler, 1983: 116). Lower-temperature fires may scorch plant matter but only produce char, while higher temperatures convert the material to soot and black carbon (Schmidt and Noack, 2000). Charcoal is recognised as black, opaque, angular, and usually planar fragments in soil sediments, and it is easily distinguished from minerals by its tendency to fracture under physical pressure(Schmidt and Noack, 2000). Charcoal emissions from fires vary depending on the size and intensity of the fire and the fuel conditions–. Fires of higher intensities produce fewer large particles, whereas low-intensity fires produce more particles due to low combustion efficiency. Charcoal can travel long distances by wind, but the distance travelled has been shown to be highly dependent on particle size. Studies indicate that charcoals of sizes <125 μm can travel longer distances and may not represent local fire events (Whitlock and Larsen, 2001).

Extraction and counting

Subsamples were taken using a 5 cm^3 syringe and sorted into 50 ml test tubes. To disaggregate the charcoal particles from the sediment, the samples were placed in a hot water bath (80 °C) with 45 ml of potassium hydroxide for 30 minutes . Occasionally, they were stirred with a wooden stick. Then, the samples were sieved in a 125 μm sieve under a low-pressure water stream until clean. Since the charcoal pieces can break easily, extra care was taken during the sieving to avoid breakage and damage to the charcoals. Petri dishes were scored with 1x1cm gridlines on their under sides, and the samples were transferred to them for counting under an Olympus 5761 magnifier. The samples were kept submerged in water during analysis to limit particle movement during systematic scanning of the petri dish. All charcoal was counted in the petri dish and the number of pieces was recorded.

3.2.4 Stable carbon isotope method

There are three main photosynthetic pathways applied by plants: the C_3, C_4, and Crassulacean Acid Metabolism (CAM) photosynthetic pathways. This thesis focuses on the C_3 and C_4 pathways. These pathways reflect distinct environmental conditions and result in different ecological pattern of growth and distribution (Forseth, 2010; Hodson, 2016). The variations of ^{13}C values derived from the carbonates of decayed plants trapped within SOM can be a valuable indicator of the type of vegetation that was present in the past. Plants that use a C_3 photosynthetic pathway, which includes trees and cold-adapted grasses, are more depleted of ^{13}C than plants that use a C_4 pathway, mainly grasses that prefer warm, sunny, relatively dry environments (Waller and Lewis, 1979). These ^{13}C values are preserved in the soils after the vegetation decomposes (Pessenda et al., 2001). Savanna ecosystems typically have values ranging between -19.5 and -16, and forested areas between -30 and -22.5. Intermediate values, in contrastm signify a mixture of C_3 and C_4 vegetation (Pessenda et al., 1998).

The stable carbon isotope analysis was conducted on selected samples from each of the four PPBio forest modules along the BR-319 highway to assess if there has been a change in the vegetation composition (C_3:C_4 ratio) since the middle of the late Holocene. Numerous studies have used the method alongside phytolith analysis to similar ends (Coe et al., 2014; de Freitas et al., 2001; Fredlund and Tieszen, 1997; Iriarte et al., 2010; Pessenda et al., 2001).

The depositional and post-depositional processes that influence phytolith distribution and movement in the soil profile can also have important consequences for this type of analysis. Like phytoliths, soil carbonates can be translocated by colluvium, which can lead to sediments with different ^{13}C values being mixed (Pessenda et al., 2001). As with phytolith deposition, this factor is negligible in the present thesis due to the position of the sampling locations away from natural slopes and depressions in the landscape.

Similar to the case of phytoliths, vertical movement of SOM in the soil profile can also occur by processes such as bioturbation, percolation, and deep deposition by roots, which can lead to the eventual mixing of new organic matter from the surface with older matter below (McClaran and Umlauf, 2000). These processes can result in several different dates for SOM in a single horizon. For instance, Coe et al. (2014), in their study of stable carbon isotopes from a soil profile in Rio de Janeiro, found age disparities betweem SOM samples up to 4000 years within one horizon of 5 cm. This problem can be overcome by dating the humin fraction rather than total SOM, which is more stable and less prone to contamination by new organic matter. Pessenda et al. (2001) have shown that humin fraction dates are much more comparable to charcoal dates from the same level, although the degree of correspondence changes with depth. The problem remains, however, that ^{13}C measurements still derive from total SOM.

In relation to phytoliths, studies have shown that size differences between SOM and phytoliths result in different translocation rates in soil profiles: the bigger and heavier phytoliths are less mobile than the SOM, therefore they can produce older dates than SOM from the same soil depth (e.g. McClaran and Umlauf, 2000), a factor that is pertinent to this thesis' analyses. Studies suggest that the problem of age differences can be resolved by the direct dating of organic matter trapped in the phytoliths (Kelly et al., 1998; Lu et al., 2000; Piperno, 2016; Smith and White, 2004). This method, however, has its own shortcomings: some scholars question the original source of the organic matter in the phytoliths and argue that, instead of deriving it from the atmosphere through photosensitisation, plants also take older organic matter from the soil through their root systems (see discussions in Hart, 2016; Hodson, 2012). Though this phenomenon has not been identified in the Neotropics (Piperno, 2016), Alexandre et al. (2014) have proposed that phytolith dating should no longer be considered a reliable technique.

Another issue that can directly affect the isotopic signature is the over- and underrepresentation of plant taxa in the phytolith record . This can also lead to false isotopic signatures from a given environment (McClaran and Umlauf, 2000). Furthermore, differences in the isotopic mass scale of phytoliths compared to SOM and modern plant tissue has sparked debate regarding its ability to help distinguish C_3 or C_4 photosynthetic pathways (Kelly, 1991; Smith and Anderson, 2001; Webb and Longstaffe, 2010).

Finally, another important consideration in the interpretation of carbon isotopic data is that enriched values can sometimes be caused by more open arboreal environments rather than changes in vegetation (de Freitas et al., 2001). Applying phytolith analysis alongside stable carbon isotope analysis will help to eliminate this uncertainty in this thesis' sample. There is also an effect whereby decomposition of the organic matter itself causes ^{13}C enrichment. This will be overcome by treating enrichments ≥3% as significant (Pessenda et al., 2004).

The stable carbon analysis was conducted by the Cornell University Isotope Laboratory (COIL), New York, during September 2016. A total of 56 samples were analysed from four soil profiles, one from each of the studied PPBio forest modules, using a Thermo Delta V isotope ratio mass spectrometer (IRMS) interfaced to a NC2500 elemental analyser. The samples were first dried and ground. The grinding ensured that the entire sample matrix had a uniform structure and composition. Around 10 mg of samples were then measured out, rolled, and shaped into balls. This was necessary, because the IRMS utilises pneumatic-type autosamplers that can only hold samples of a certain size.

The analysis was performed using primary reference scales—the standard is calcium carbonate from a belemnite taken from the Peedee formation, South Carolina—in-house standard soil samples, and two quality control standards. The first standard is a pure chemical that is used to test the instrument's linearity and define the instrument's response for the determination of elemental composition. The second standard is used to show measurement stability over the length of the run. These standards are run once every 10 samples to identify measurement variability or long-term drift. The isotope corrections were performed using this two-point normalisation (linear regression). Further information on the process is hosted on the COIL website (www.cobsil.com).

3.2.5 Radiocarbon dating

Four rounds of AMS dating were performed on wood charcoal from soil profiles at Couro Velho to refine the site's chronology. The aim was to isolate the onset of the ADE soil's development and the time of most intensive usage of the site. Additionally, one bulk soil samle from the M11 P2 profile was dated, in order to determine when a large-scale shift occurred in the vegetal composition of the M11 study area.

The samples were taken from the soil profiles with a clean knife and contained in aluminium foil to protect them from contamination. Their exact location in the profile was photographed and marked on the drawings. The analyses and calibration were conducted by Beta Analytic. The conventional radiocarbon ages were corrected for total fractionation effects, and calibration was performed using the IntCal13 northern hemisphere calibration curve (Reimer et al., 2013). The IntCal13 was chosen because, although the location of the study site is slightly south of the equator, the southern calibration curve is based on tree ring data from high-latitude, oceanic locations (e.g. New Zealand). Furthermore, the study area also falls within the Inter Tropical Convergence Zone's seasonal migration, which introduces northern hemispheric ^{14}C signals to these lower latitudes (McCormac et al. 2004), therefore IntCal13 gives more accurate results in this case.

3.2.6 Statistical approaches

For the statistical data analysis, nonmetric multidimensional scaling (NMDS) based on the Bray-Curtis dissimilarity and a Procrustes rotation was applied. Before any statistical transformation, all data were standardised by square root transformation to emphasise differences in smaller values and de-emphasise small differences in larger values. This is an important step before performing ordination using dissimilarity or distance measurements, because the amount of information that a species contributes to numerical analysis, like an ordination, increases with its variance; however, higher variance does not necessarily mean more important biological meaning. Therefore, species that are extremely abundant at some sites and poorly represented at others will dominate the NMDS ordination of the sites. In those circumstances, it would be difficult to detect the effect of other species which might also be of ecological interest (Legendre and Legendre, 2012).

Bray-Curtis dissimilarity

The Bray-Curtis dissimilarity is a normalisation method commonly used in botany, ecology, and environmental sciences. It is mainly used to quantify the similarities or differences in species populations between different sites (Bray and Curtis, 1957). The Bray-Curtis dissimilarity is popular in community ecological research, because it is a non-Euclidean distance measure similar to the Jaccard index,or Manhattan distance), meaning that it can violate the triangle inequality axiom. Specifically, if there are three objects, the distance between two of these objects cannot be larger than the sum of the two other distances, therefore zero values in the abundance data can be processed. This is useful to ecological data, as not all the samples have the same species compositions. Due to this property, some authors prefer to call the method a dissimilarity measure rather than a distance measure (e.g. McCune and Grace, 2002). The Bray-Curtis dissimilarity can be applied to abundance data, not only on presence/absence data.

Nonmetric multidimensional scaling

To demonstrate the similarity or dissimilarity in the vegetal composition of the study areas, NMDS ordination was chosen. The NMDS was performed on the vegetation inventories and phytoliths from surface soil samples for modern data, as well as on the phytolith assemblages of soil profiles at 60 cm b.s. to obtain pre-Columbian data. These latter assemblages served as baselines so that it was possible to compare the changes in the phytolith composition through time at the study sites. The objective of the NMDS was to plot soil profiles with dissimilar phytolith compositions far apart in the ordination space and soil profiles with similar phytolith compositions close to one another (Kruskal, 1964; Shepard, 1962).

NMDS is an ordination technique based on a distance or dissimilarity matrix (e.g. Bray-Curtis dissimilarity or Euclidean distance) for graphically representing relationships between objects (e.g. plots or samples) in a reduced multidimensional space (usually two or three). The Bray-Curtis dissimilarity is more useful in comparisons of community compositions, since it considers both the differences and similarities between samples, therefore it was calculated for this thesis' analysis before the NMDS was plotted. When an NMDS is plotted, a small number of axes (usually two or three) are chosen prior to the analysis and the data are fitted to those dimensions. In short, the analysis starts with a matrix of distances between all the datapoints in a multidimensional space. The algorithm then places the datapoints in a lesser number of dimensions (2D or 3D) and moves them around in this reduced space, so that the distances between points go in the same order (rank) as the distances between points in multidimensional space. The interpretation of the NMDS plots is straightforward: the closer the objects are to each other, the more alike they are.

The advantages of NMDS are that it:

- tolerates missing or zero pairwise distances to a certain extent, as long as there are enough measures left to position each object with respect to a few of the others. Too many missing values, however, can make the calculation of the distances between neighbouring samples impossible. Since, in this thesis' data, there were phytolith morphotypes not represented in all of the samples, it was important to choose an ordination technique that can handle missing or zero values, therefore sites can be compared to each other;
- uses quantitative, semi-quantitative, qualitative, or mixed variables;

- can be rotated, inverted, or centred to any desired configuration, since it is not an eigenvalue-eigenvector technique, like principal components analysis or correspondence analysis, that ordinates the data such that axis one explains the greatest amount of variance, while axis two explains the next greatest amount of variance.

The NMDS ordination is sensitive to the number of dimensions that are chosen; therefore a compromise must be made between the summary of the data and an accurate representation of the distances. An issue can be that, when too few dimensions are chosen, this forces multiple axes of variation to be expressed on a single ordination dimension. Alternatively, if too many dimensions are chosen, this can force a single source of variation to be expressed on more than one dimension (Holland, 2008).

The higher the number of dimensions, the lower the stress level of the ordination. In contrast, the number of samples and variables increases the stress value. The stress value expresses how well the ordination summarises the observed distances among the samples. However, a high number of dimensions can make the interpretation of the data difficult or even impossible. In order to find the right number of dimensions, the stress value should ideally be less than 0.2 or even 0.1 (Holland, 2008). Another way to investigate whether the data is suitable for NMDS is to perform a Shepard test, where ordination distances are plotted against community dissimilarities. A Shepard diagram compares how far apart the data points are before and after the transformation into the multidimensional scaling as a scatter plot—in essence, this is a representation of goodness of fit. The Shepard test gives two R^2 values between 0 and 1, a correlation based on stress (nonmetric fit) and a correlation between the fitted values and ordination distances (linear fit) (Oksanen, 2015). The value of R^2 is always between 0 and 1, and the closer the R^2 value to 1, the better the model explains all the variability of the response data around its mean (Draper and Smith, 1998).

Procrustes rotation

Finally, a Procrustes rotation (Peres-Neto and Jackson, 2001) of the NMDS data was applied to compare the phytolith composition of the forest profiles at 60 cm b.s. and 0 cm b.s. Since the orientation, scale, and location of the axes are not defined in NMDS, the Procrustes rotation makes the two ordinations comparable. The Procrustes analysis rotates, translates, and scales one matrix (fitted NMDS) to match the other (fixed NMDS), minimising the residual sum of squares between the NMDS ordinations (Oksanen, 2015). By applying the Procrustes rotation, it was possible to visualise the changes that the phytolith assemblages went through over time, which was due to increased human impact at some of the sites.

The NMDS ordination and Procrustes rotation were carried out using R software and the following packages: vegan, ggplot2, ggrepel, and grid.

CHAPTER 4

Results

This chapter outlines all field observations and laboratory analyses, followed by more detailed analyses of the phytolith and geochemical data. Finally, the statistical analyses are presented. For the rationale behind the selection of profiles and analyses, see Chapter 3.

4.1 Results of field and laboratory analyses of profiles at the PPBio forest modules

4.1.1 M05 P1 profile

The M05 P1 profile lies below a primary forest about 260 km from Manaus along the BR-319 road (see Fig. 3.1). In this thesis, the profile represents the control soil against which other profile's phytolith assemblages, geochemical and stable carbon isotope signals, and macro charcoal counts are compared.

Profile description

The texture of M05 P1 profile is clay loam, similar to the parent material of the ADE profiles, with a sandy silt-loam layer in the upper 10 cm b.s. The profile can be divided into five horizons (Fig. 4.1):

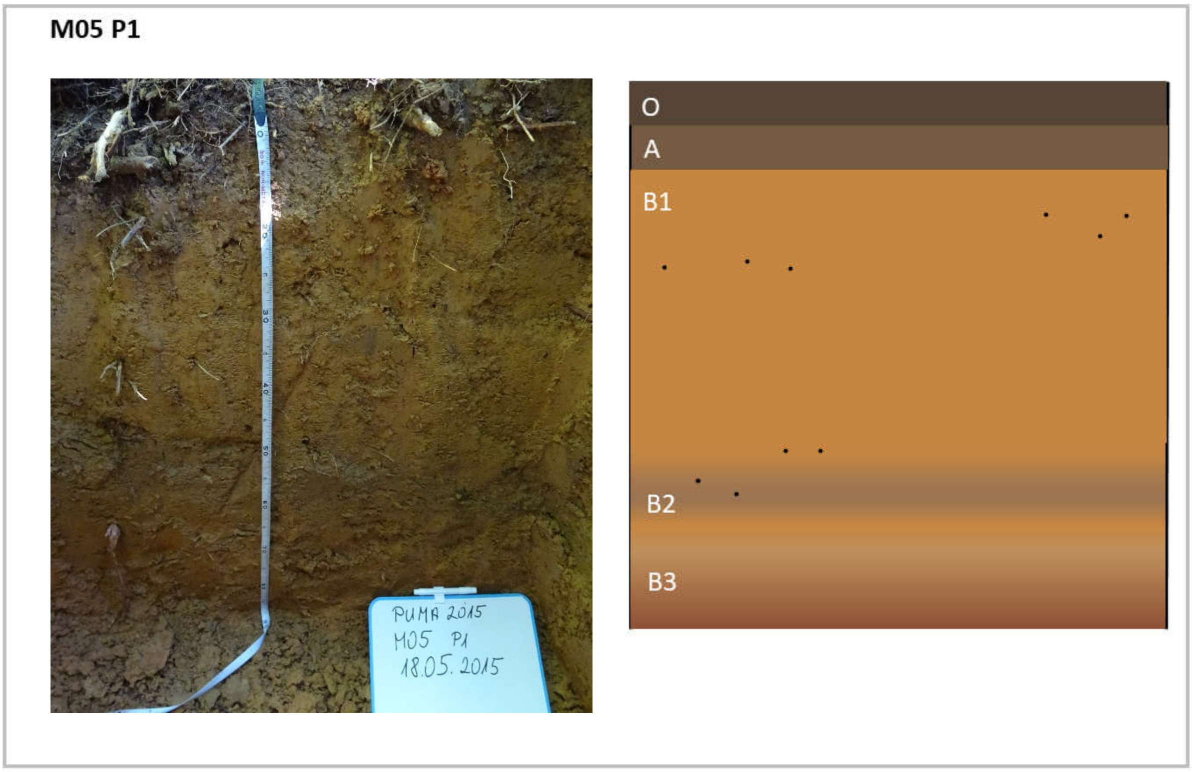


Figure 4.1: Photo and drawing of profile M05 P1. Black dots represent visible charcoal pieces.

- 0–5 cm b.s.: O horizon, exhibiting undecomposed or partly decomposed litter (10YR 2/3).
- 5–10 cm b.s.: Thin A horizon with greyish brown to brown colour, reddish yellow (7.5YR 4/2–4/3) colour.
- 15–50 cm b.s.: B1 horizon, orange colour (7.5YR 6/8) with a few layers of small charcoal.
- 50–60 cm b.s.: B2 horizon, slightly darker than B1 horizon (7.5YR 5/4).
- 60–75 cm b.s. B3 horizon (5YR 3.6).

Phytolith assemblage

The phytolith assemblage of profile M05 P1 comprises a very high percentage of arboreal phytoliths, an average of 95.9% (Fig. 4.2, Appendix II). The majority of arboreal phytoliths belong to the non-diagnostic arboreal category. Palm phytoliths constitute 4.6% of the assemblage. The percentage of palm phytoliths slightly increases towards the top—4.9% at 75 cm b.s. and 7.1% at 0 cm. Herbs constitute 1.3% of all phytoliths identified in this profile and exhibit a very slight increase towards the top of the profile. But, in general,

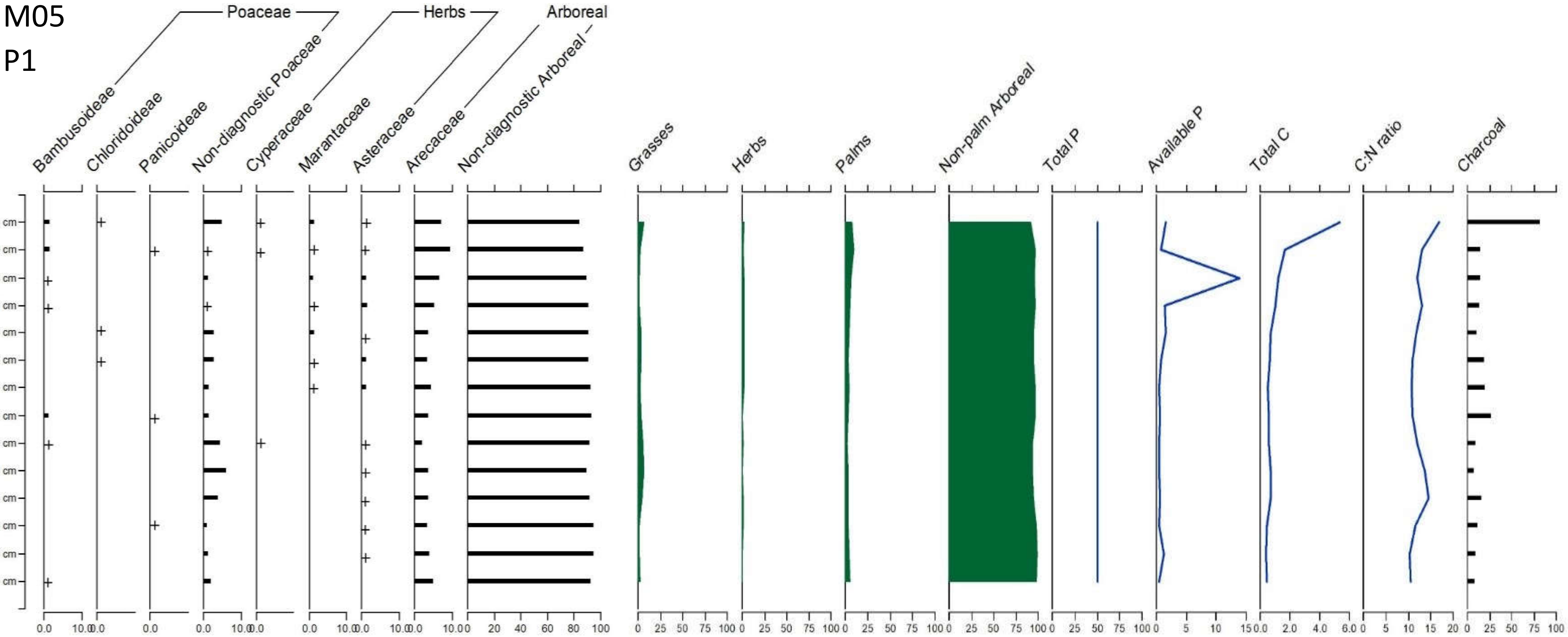


Figure 4.2: Relative frequencies of phytoliths recovered in profile M05 P1. Horizontal bars represent percentages; crosses denote the presence of plant taxa lower than 1% in abundance. Followed by a summary of the main phytolith taxa (relative percentage in green) in association with total phosphorous (mg/kg), available phosphorous (mg/kg), total carbon (mg/kg) the C:N ratio, macro charcoal counts, and stable carbon isotope ($\delta^{13}C$ (‰) values.

herbs are represented only in very low numbers at every depth. Asteraceae phytoliths are found in every layer, except 40 cm b.s. and 75 cm b.s. Marantaceae morphotypes are found rather in the top 35 cm b.s. and Cyperaceae phytoliths in the upper 10 cm b.s. Phytoliths produced by Poaceae species constitute 2.8% of the whole assemblage, and they also show a tendency to slightly increase towards the top of the profile. The greatest quantity of non-diagnostic morphotypes is 2.3%). Bambusoideae, Chloridoideae, and Panicoideae phytoliths were recovered only in trace amounts (<1% of identified phytoliths at a given depth).

The most important taxon in the whole phytolith assemblage is the non-palm arboreal (NPA). The palm and NPA phytoliths are separated from each other for two reasons: (1) palms played an important role in pre-Columbian subsistence practices, and they are direct evidence of past forest management (see section 2.4.1); (2) palm phytoliths are easy to distinguish from other arboreal phytoliths, whereas most trees produce the same type of phytoliths, therefore they cannot be distinguished in the assemblage (section 3.2.1).

The percentage of NPA phytoliths is always greater than 94%. The most is at 70 cm b.s., where 98.5% of the phytoliths were produced by NPAs. Between 55 cm b.s. and 40 cm b.s., there is a slight increase in grass phytoliths (6.1% at 50 cm b.s.). In general, more grass phytoliths were counted for the bottom part of the profile than the upper part. The amount of herb phytoliths begins to increase at 35 cm b.s. (3.4% at 25 cm b.s. and 6.7% in the subsoil), and, from this depth, the number of palm morphotypes increases as well (9.4% at 5 cm b.s.).

Macro charcoal analysis

The M05 P1 profile contains a very small quantities of charcoal throughout. The largest quantity was counted in the topsoil (82), and there is also a smaller peak at 40 cm b.s. (27). Apart from these peaks, charcoal counts are between seven and 21. The average charcoal count in this profile is 19.

Soil geochemical results

Total and available phosphorus

Total phosphorous values are constantly <50 mg/kg. The available phosphorous values, with some minor fluctuations, are also close to zero. The only notable exception is an extremely high value at 10 cm b.s. (13.9 mg/kg), but, based on the other values, this might be an anomaly.

Total carbon, total nitrogen, and the C:N ratio

The total carbon value in the topsoil is 5.36% w/w, but it drops rapidly, and, at 20 cm b.s., it is <1% w/w. It stays this low to the bottom of the profile.

The total nitrogen value is 0.32% w/w in the topsoil and drops to 0.04% w/w by the bottom of the profile. The C:N values in the topsoil are 16.8, which then slowly decreases, peaking again at 55 cm b.s. (14.6), after which it decreases again to 10.5 at 75 cm b.s.

Stable carbon isotopes

At 75 cm b.s., the stable carbon isotope value is -26.70, suggesting closed-canopy forest cover in this area. Towards the top of the profile, there is a slight depletion in the ^{13}C values. In the topsoil, the stable carbon isotope value is -30.40. These results clearly suggest that the forest cover at this site underwent only minor changes in the middle of the late Holocene.

Summary

The NPA phytoliths dominate the whole profile without major change. Similarly, the geochemical signal of the profile is stable, except for one odd peak in available phosphorus at 10 cm b.s. (13.9 mg/kg). The total phosphorous content is <50 mg/kg for the whole profile. The total carbon content is low, and the C:N ratio is low and stable as well. Although macro charcoal pieces are found at every depth, their number is typically <20, although the sample from the topsoil yielded 82 charcoal pieces. These values suggest that both the soil and the vegetation at this site have been stable, without major environmental or anthropogenic influences.

4.1.2 M02 P2 profile

The M02 forest module is located around 100 km from Manaus on the highway AM-354 that is accessible from the BR-319 road (Fig 3.1).

Profile description

Profile M02 P2 is also a plinthic acrisol (Fig. 4.3). Apart from the topsoil that is a sandy silt loam, the texture of the whole soil profile is clay loam.

- 0–3 cm b.s.: O horizon, containing partly undecomposed plant material (10YR 3/1)
- 3–10 cm b.s.: A horizon, dark greyish brown colour (10YR 4.2), sandy silt loam texture
- 10–75 cm b.s.: B horizon, pale brown (10YR 6/3) in the upper 10–35 cm b.s., exhibits a distinct layer of charcoal at around 10 cm b.s. Downwards, the colour changes to yellowish brown (10YR 5/6) from around 35 cm b.s., and then to mainly red, mixed with yellowish brown with light grey incisions around 55 b.s. (mix of 7.5R 4/8, 10YR 5/6, and 10YR 7/2).

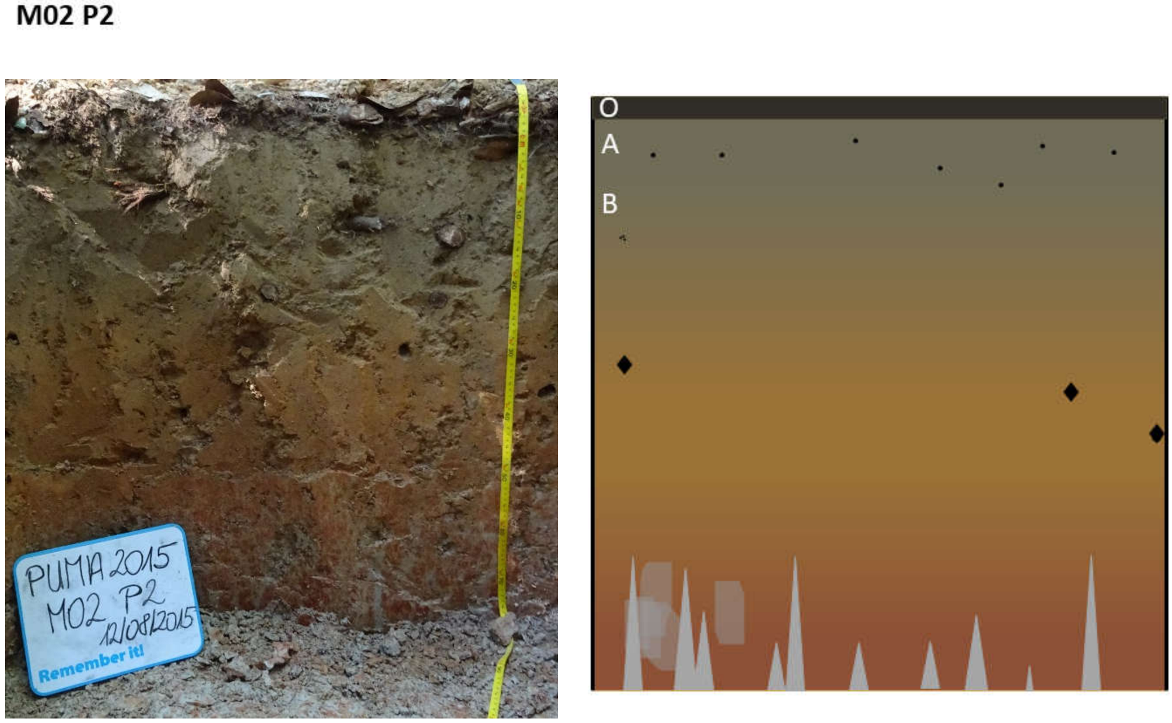


Figure 4.3: Photo and drawing of profile M02 P2. Black dots represent visible charcoal pieces, black diamonds represent burnt roots.

Phytolith assemblage

The majority of phytoliths in the M02 P2 profile are arboreal morphotypes, constituting on average 89.5% (Fig. 4.4, Appendix II). The quantity of non-Arecaceae arboreal phytoliths fluctuates throughout the profile, but in general it decreases towards the top. Annonaceae, the only diagnostic arboreal phytolith in this profile, was found in the topsoil. The number of palm morphotypes slightly increases towards the profile’s top (4.4% at 60 cm b.s., 8.9% at 0 cm b.s.) and averages at 5.1%. Herbs constitute 3% of the whole phytolith assemblage, and they mainly belong to the Marantaceae and Asteraceae morphotypes, which were encountered at every depth in the profile. The quantity of Asteraceae phytoliths is constant in the profile and averages 0.8%; however, the Marantaceae morphotypes show trend to increase towards the top of the profile (1.4% at 75 cm b.s., and 3.8% at 0 cm b.s.). Additionally, Heliconiaceae were identified mainly in the upper 20 cm b.s. in trace amounts, and Cyperaceae phytoliths were counted at 40 and 45 cm b.s. On average, Poaceae phytoliths total 2.5% of this profile’s whole phytolith assemblage. The number of Poaceae phytoliths is constant throughout the profile: on average, non-diagnostic Poaceae phytoliths constitute 1.9%, Panicoideae and Bambusoideae phytoliths 0.4%, and Chloridoideae phytoliths 0.3% of the total assemblage.

The fluctuations in the main phytolith taxa groups display larger fluctuations than in M05 P1. At the bottom of the profile, between 60 cm b.s. and 55 cm b.s. the number of grass and herb morphotypes increase (grasses 5.3%, herbs 4.4% at 55 cm b.s.). At 45 cm b.s., there is another peak where the grasses reach 6.1% and herbs 3.9% of the whole phytolith assemblage at this depth. Between 35 cm b.s. and 25 cm b.s., the quantity of NPA phytoliths increases and reaches more than 90% of the whole assemblage. From 20 cm b.s,. the quantity of palm morphotypes increases gradually to reach 10 % at 10 cm b.s.. This occurs at the expense of NPA morphotypes, wheras the percentage of herbs increases only slightly, and the percentage of grasses decreases slightly.

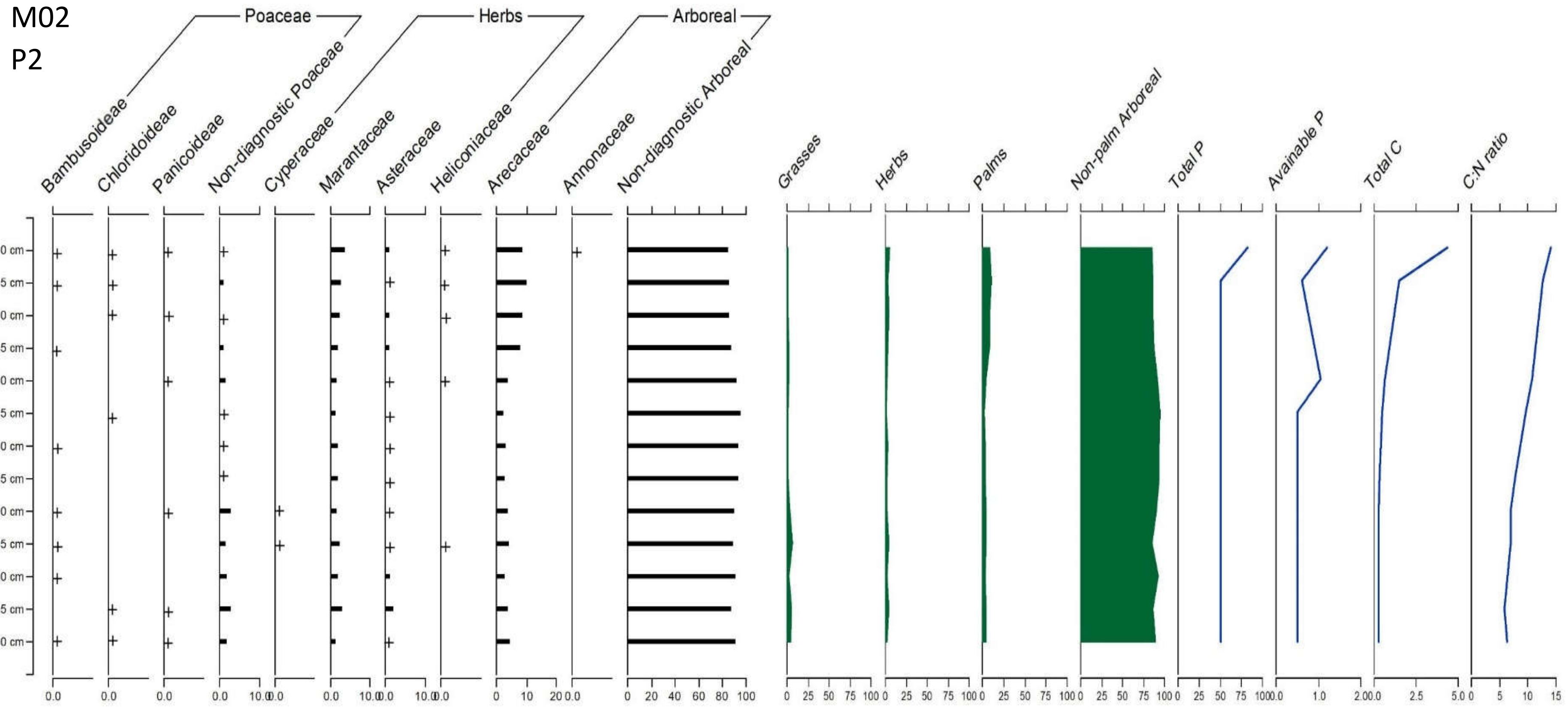


Figure 4.4: Relative frequencies of phytoliths recovered from profile M02 P2. Horizontal bars represent percentages; crosses denote the presence of plant taxa lower than 1% in abundance. Followed by a summary of main phytolith taxa (relative percentage in green) in association with total phosphorous (mg/kg), available phosphorous (mg/kg), total carbon (mg/kg), the C:N ratio, and stable carbon isotope (δ^{13}C (‰) values.

Soil geochemical results

Total and available phosphorous

The total P values are slightly elevated in the topsoil (82 mg/kg), however already at the first 5 cm b.s. the values drop back to <50 mg/kg and stay this low throughout the profile. Regarding the available P values, with some minor fluctuations (1.2 mg/kg at 0 cm and 1.05 mg/kg at 20 cm b.s.), the values are close to zero.

Total carbon, total nitrogen, and the C:N ratio

The total carbon value in the topsoil is 4.38% w/w, below which it drops to <1% w/w around 10 cm b.s. The total nitrogen value shows a similar trend: it is 0.31% w/w in the topsoil but decreases to 0.06% w/w at 20 cm b.s. The C:N ratio is 14:1 in the topsoil and slowly but steadily decreases to 4.8 by 75 cm b.s.

Stable carbon isotopes

At 75 cm b.s., the stable carbon isotope value is -27.20, suggesting closed-canopy forest cover in this area. In the middle of the profile, there is a slight increase in ^{13}C values, but they decrease again towards the top of the profile, reaching -29.88 in the topsoil. In the topsoil, the stable carbon isotope value is -30.40. These results clearly suggest that the forest cover at this site went through only minor changes in the middle of the late Holocene.

Summary

As the percentage of herb and palm phytoliths increases slightly in the upper part of M02 P2, the available phosphorous values grow slightly as well, although the total phosphorous values remain <50 mg/kg. The C:N ratio is less stable in this profileshowing a tendency to decrease towards the top of the profile. Although the forest above M02 P2 is considered oligarchic with some degree of human impact, only slight differences can be detected, which contrasts to profile M05 P1.

4.1.3 M02 P4 profile

Although this profile is only 2 km away from M02 P2, there are some notable differences between the two profiles.

Profile description

Profile M02 P4 is a plinthic acrisol (Fig. 4.5). Similar to M02 P2, the texture of the soil is clay loam, except for the O horizon, which is sandy silt loam:

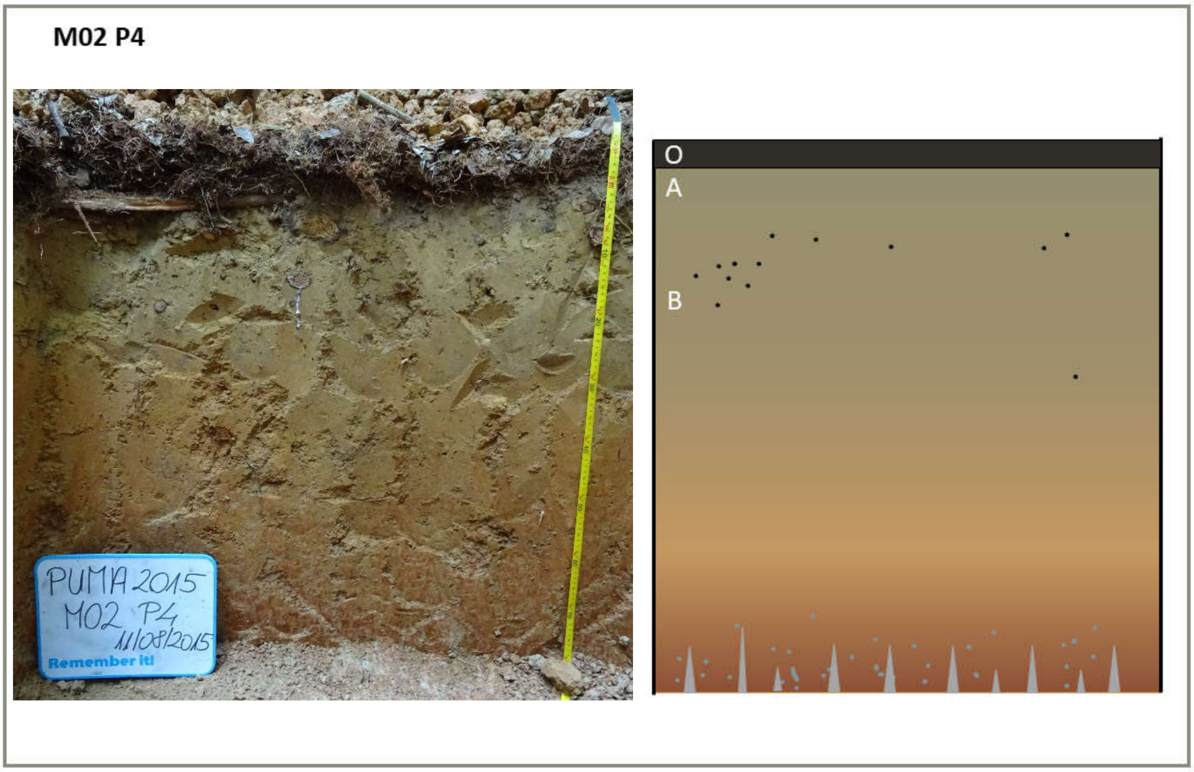


Figure 4.5: Photo and drawing of profile M02 P4. Black dots represent visible charcoal pieces.

- 0–5 cm b.s.: O horizon, comprising decomposed and partly-decomposed plant material (10YR 2/1).
- 5–8 cm b.s.: Thin A horizon, brownish black (10YR 3/2).
- 8 cm–75 cm b.s.: B horizon, light yellowish brown (10YR 6/4). The upper part (between around 8–20 cm b.s.) of this horizon contains many roots. The colour of the B horizon starts to change around 30–35 cm to a darker shade. Going downward, the profile has a more reddish tone and grey incisions (mix of 10YR 7/4 and 2.5YR 5/8).

Phytolith assemblage

In general, the phytolith assemblage of M02 P4 is mainly characterised by arboreal phytoliths (96.2%) (Fig. 4.6, Appendix II). However, the percentage of palm phytolithts

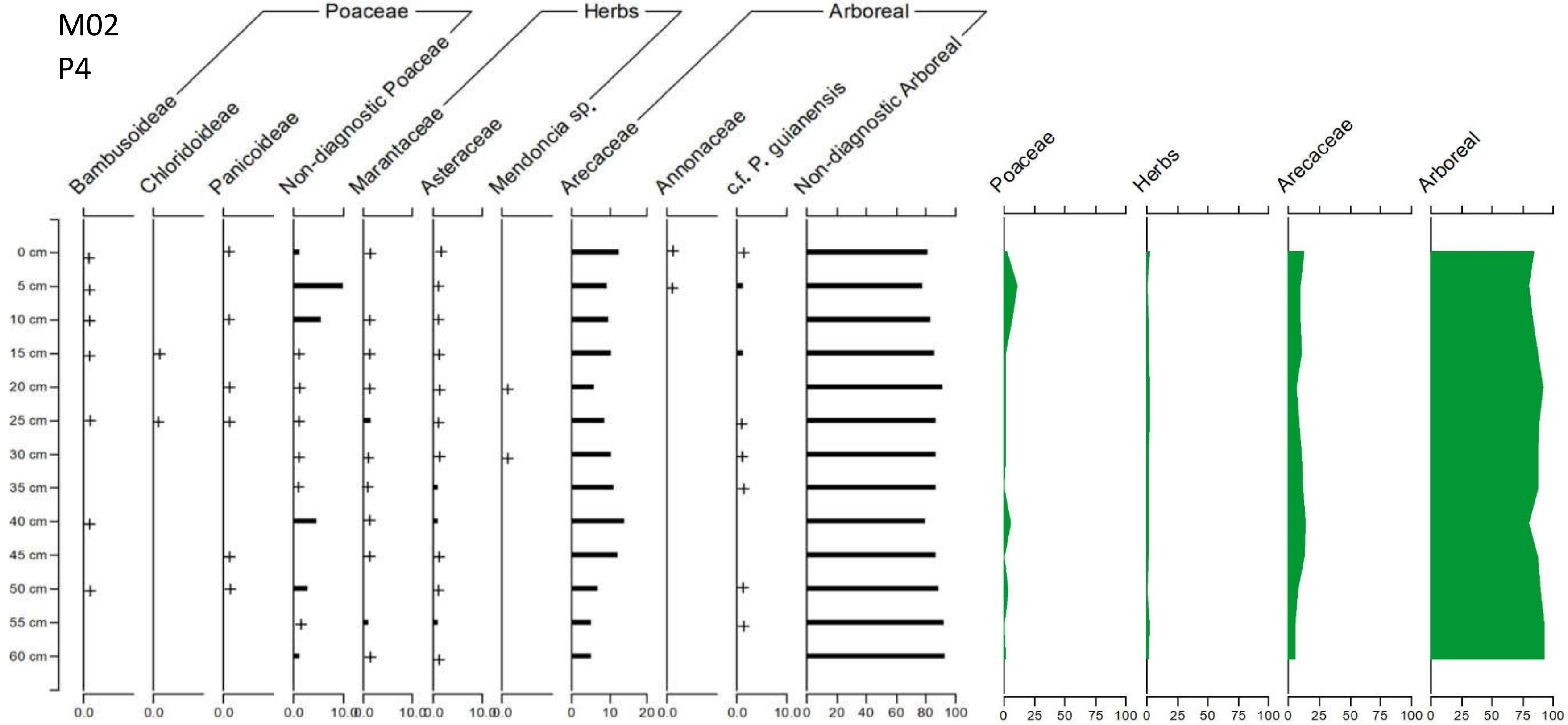


Figure 4.6: Relative frequencies of phytoliths recovered in M02 P2. Horizontal bars represent percentages; crosses denote the presence of plant taxa lower than 1% in abundance. Followed by a summary of the main phytolith taxa (relative percentage in green).

in this profile is 9.5%, which is 4.4% higher on average than M02 P2. The number of palm phytoliths fluctuates in the profile: there is a peak at 40 cm b.s. (14%) and another one at 0 cm b.s. (12.4%). A Burseraceae species, namely *cf. P. guianensis*, was identified at almost every depth but only in low amounts. Annonaceae were found at the top of the profile, at 0 and 5 cm b.s. All other non-diagnostic arboreal morphotypes show a slight decreasing trend towards the top of the profile and average 86.7%. The quantity of herb and Poaceae morphotypes is quite low: 1.2% and 2.6%, respectively. Asteraceae and Marantaceae show up in almost every sample in trace amounts. *Mendoncia* sp. was identified at 20 and 30 cm b.s. Although the number of non-diagnostic Poaceae morphotypes is generally low (2.4% on average), they peak at 5 cm b.s. with 9.9%. Diagnostic morphotypes in Poaceae subfamilies—Bambusoideae, Chloridoideae, and Panicoideae—constitute only trace amount of phytoliths.

4.1.4 M11 P2 profile

The M11 forest module is situated around 620 km from Manaus (Fig. 3.1) and is most easily accessed from Humaitá.

Profile description

Profile M11 P2 (Fig. 4.7) is a gleysol that is saturated with groundwater for long-enough periods to develop a characteristic gleyic colour pattern, according to the (WRB, 2015) These soils occur at low elevations in landscapes with high groundwater table, such as tidal areas, shallow lakes, and seashores:

- 0–3 cm b.s.: O horizon, exhibiting undecomposed or partly-decomposed litter (10YR 3/2).
- 3–5 cm b.s.: The A horizon is very thin, almost invisible in this profile. The colour is the same as that of the O horizon, a very dark greyish brown (10YR 3/2), the texture is sandy silt loam.
- 5–20 cm b.s.: B1 (or E?) horizon, the colour is dark yellowish brown (10YR 4/4), and the texture is clay loam.
- 20–75 cm b.s.: B2 horizon, slightly darker (10YR 5/2) than the B1 horizon, the texture is silty clay loam. Some charcoal pieces were found in this horizon and in the bottom of the profile at around 70 cm b.s. Red mottling was detected.

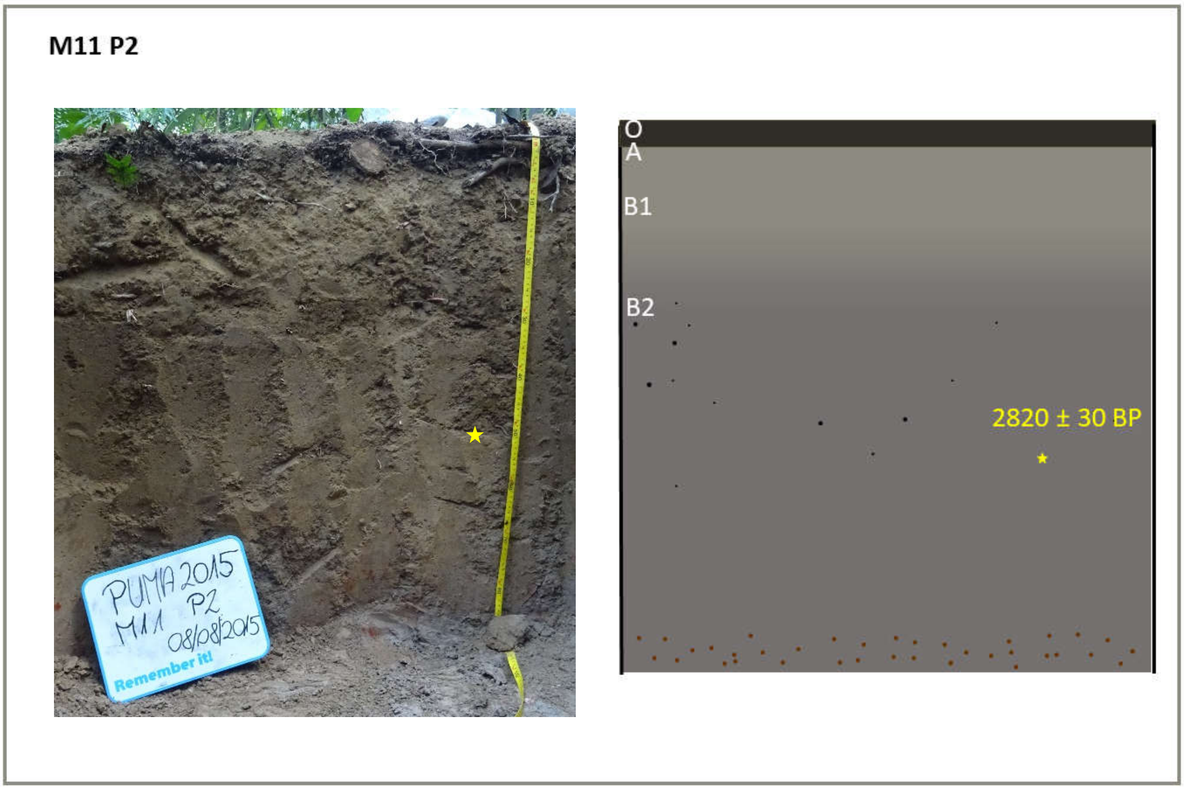


Figure 4.7: Photo and drawing of profile M11 P2. Black dots represent visible charcoal pieces, and the yellow star represents the spot where bulk soil was collected for radiocarbon dating.

Phytolith assemblage

Although non-diagnostic arboreal morphotypes constitute the majority of the phytolith assemblage, they only constitute 66.1% of all phytoliths identified (Fig. 4.8, Appendix II). There are well-visible trends for different plant types: NPA and Poaceae decrease in abundance towards the top of the profile. There is a difference of 14.1% in NPA between the profile bottom and top, while the difference for Poaceae is 9.6%. Conversely, palm phytoliths greatly increase towards the top (6.7% at 65 cm b.s., but 30.2% at 0 cm b.s.), replacing many of the other arboreal and Poaceae morphotypes in the assemblage. Non-diagnostic Poaceae constitute the majority of Poaceae morphotypes, therefore the decreasing trend is the most visible for this category. Other morphotypes were mainly encountered as trace amounts. Herbs are found as a very low percentage (0.7% on average). Asteraceae, Heliconiaceae, and Marantaceae phytoliths were identified at almost every depth. Cyperaceae is only found at 5 cm b.s. Additionally, a *Trichomanes* sp. phytolith was encountered at 0 cm b.s.

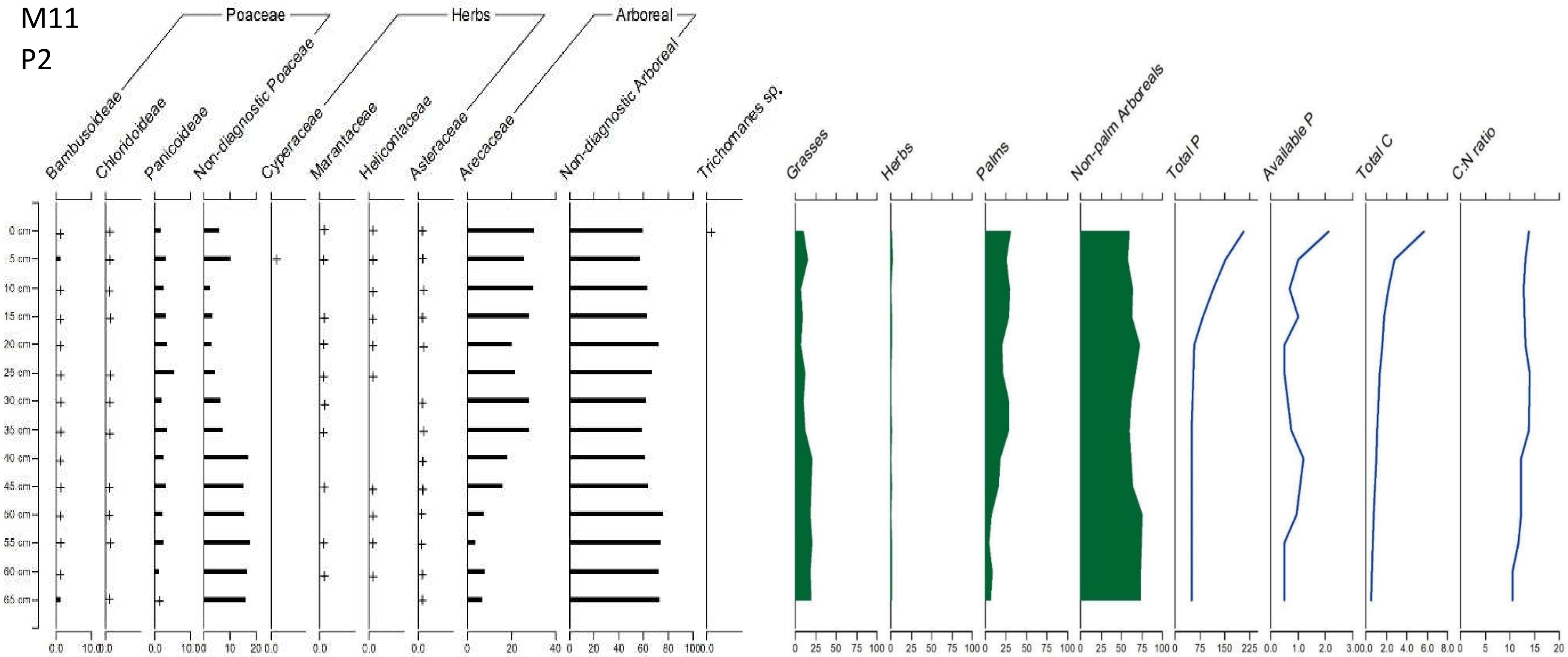


Figure 4.8: Relative frequencies of phytoliths recovered in M11 P2. Horizontal bars represent percentages; crosses denote the presence of plant taxa lower than 1% in abundance. Followed by a summary of the main phytolith taxa (relative percentage in green) in association with total phosphorous (mg/kg), available phosphorous (mg/kg), total carbon (mg/kg), the C:N ratio, and stable carbon isotope ($\delta^{13}C$ (‰) values.

.

Profile M11 P2 contains very few herb phytoliths and their percentage does not change largely throughout the profile, it is consistently <1%. The other three phytolith taxa groups—the grasses, palms, and NPA—however, go through notable fluctuations. Between 65 and 40 cm b.s., grass morphotypes account for more than 18% of the phytolith assemblages at each respective depth, while the number of palm morphotypes starts to drastically increase from 45 cm b.s. The quantity of palm phytoliths increases both at the expense of grass and NPA taxa. The palm phytoliths account for 20–30% of the whole assemblage between each depth from 45 cm b.s. and the topsoil. The lowest percentage of grasses (6.4%) and the lowest number of NPA morphotypes (57.5%) were counted at 10 cm b.s.

Soil geochemical results

Total and available phosphorous

On average, the total phosphorous values are substantially higher in this profile than in the other PPBio profiles. In the topsoil, it is 208 mg/kg, but then it sharply decreases as the profile reaches 25 cm b.s. From this depth downwards, the total phosphorous values are <50 mg/kg. The available phosphorous value is 2.1 mg/kg in the topsoil, and, as usual, it decreases to zero. However, there is a peak at around 40 cm b.s. where the value increases again to 1.2 mg/kg.

Total carbon, total nitrogen, and the C:N ratio

The total carbon value is 5.67% w/w in the topsoil, then it drops sharply to 2.78% w/w at 5 cm b.s. and remains >1% w/w until 40 cm b.s. Total nitrogen values are, again, slightly higher in M11 P2 than in the other PPBio profiles, but they follow the usual pattern: after a value of 0.41% w/w in the topsoil, the total nitrogen drops and decreases constantly to 0.05% w/w.

Stable carbon isotopes

The average of ^{13}C values in this profile is -21.64, which is in the lower range for average forest values, suggesting more open vegetation than in the other three forest modules (Pessenda et al., 1998). However, at the bottom of the profile, there is a significant enrichment of isotope values, which reach as high as -18.43 at 70 cm b.s. This situation was likely caused by the presence of C_4 plants. Between 70 and 50 cm b.s., the ^{13}C values do not fall below -19. A radiocarbon date retrieved from bulk soil at 50 cm suggests that, until *ca.* 2959–2782 cal BP, this area was covered by savanna with trees (Desjardins et al., 1996;Dickau et al., 2013; Pessenda et al., 1998). From around 45–40 cm b.s. towards the top of the profile, however, the ^{13}C values steadily decrease— this indicates transitional vegetation comprising mixed C_3 and C_4 plants— until about 25 cm b.s., covering a range from -19.96 to -21.58). From 20 cm b.s. towards the top of the profile, the stable carbon isotope values suggest closed-canopy forest vegetation, reaching similar values to the other three profiles (-27.73 at 0 cm b.s.).

Summary

In profile M11 P2, more prominent changes were detected than in the other profiles. The constant increase of palms in the phytolith assemblage is associated with the constant increase of available phosphorous values. Referring back to Lehmann et al.'s (2004) experiment, the growth of available phosphorous values might be the result of an increasing number of palms. Even when there is a slight retreat of palms between 20 and 30 cm b.s., the available phosphorous shows the same slight decrease. As discussed in section 2.1.3, debate is ongoing concerning whether the presence of palms is a reliable sign of forest management or a natural phenomenon. Therefore, in the case of M11 P2, further studies are needed to reveal whether the naturally-growing palms are the reason for the increasing phosphorous value,s or whether this profile is an example of combined vegetation and soil management far from archaeological sites in a *terra firme* setting.

4.1.5 M11 P4 profile

Profile M11 P4 is 2 km away from M11 P2, and, although their physical appearances are similar, there are some notable differences in the phytolith assemblages of these profiles.

Profile description

Profile M11 P4 is also a gleysol (Fig. 4.9), similar to M11 P2.

- 0–3 cm b.s.: The O horizon, comprising undecomposed and partly-decomposed plant matter, very thin (10YR 3/1).
- 3–5 cm b.s.: A horizon, very thin in this profile, almost non-existent.

- 5–75 cm b.s.: B horizon. Down to about 60 cm b.s., the colour of the soil is pale brown (10YR 6/3). At the bottom of the profile, the colour turns an even paler, light yellowish brown with red mottling (mix of 10YR 6/4 and 2.5YR 4/6). Very few roots were found in the whole profile.

Figure 4.9: Photo and drawing of profile M11 P4. Black dots represent visible charcoal pieces.

Phytolith assemblage

The phytolith analysis revealed an overall decrease in NPAmorphotypes (from 90% to 74.4%, with an average of 83%), and an increase in Arecaceae (from 2.2% to 15.7%) phytoliths (Fig. 4.10, Appendix II). *Cf. P. guianensis* phytoliths appear in the top half of the profile between 0 cm and 55 cm b.s. An Annonaceae phytolith was also found at 10 cm b.s. The percentage of non-diagnostic Poaceae phytoliths fluctuates in the profile, there are two peaks at 40 cm b.s. (20.6%) and at 5 cm b.s. (18.8%). Other Poaceae morphotypes—Bambusoideae, Chloridoideae, and Panicoideae—appear at every depth, but only in trace amounts. Regarding herbs, they only constitute 1.1% to the whole phytolith assemblage on average, and, whereas Asteraceae is found at

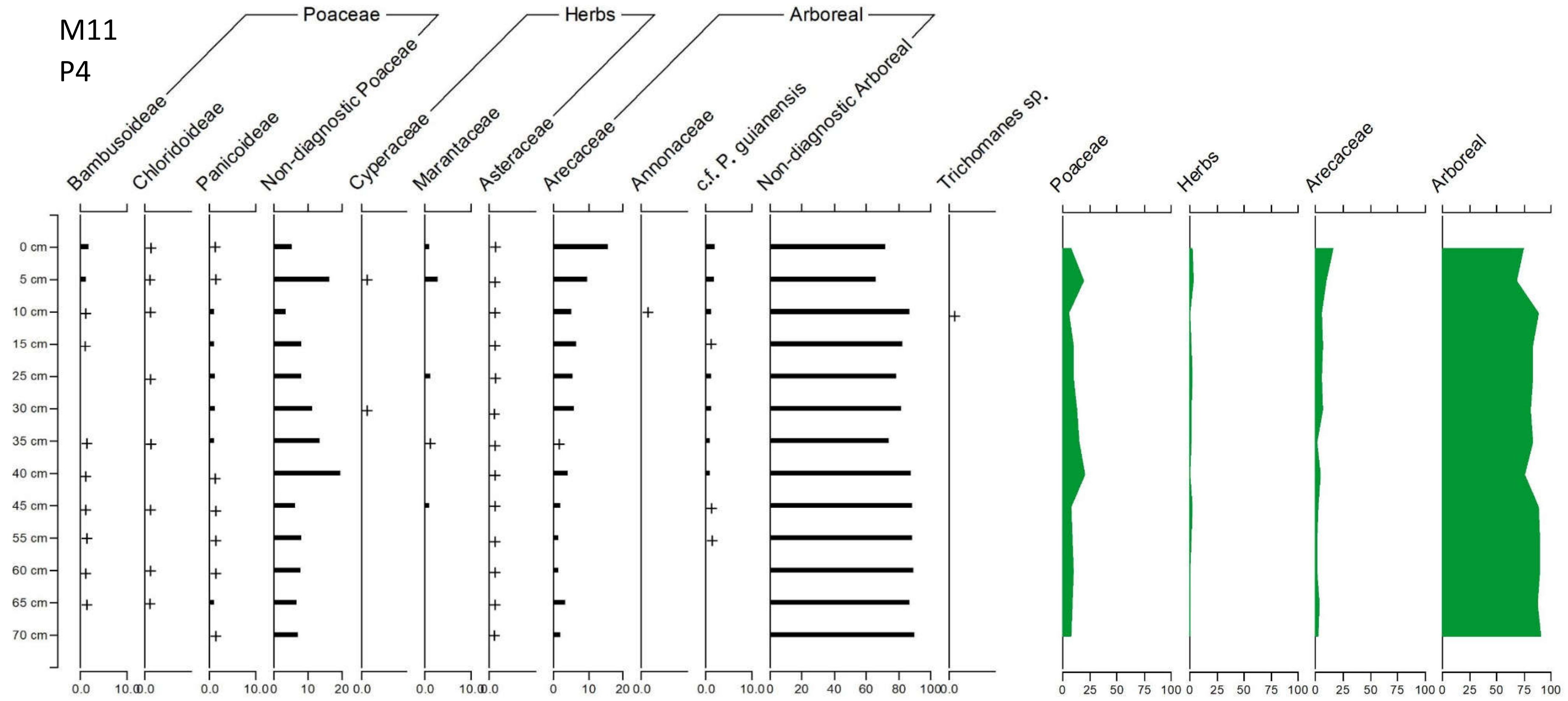


Figure 4.10: Relative frequencies of phytoliths recovered in M11 P4. Horizontal bars represent percentages; crosses denote the presence of plant taxa lower than 1% in abundance. Followed by a summary of the main phytolith taxa (relative percentage in green).

every depth, Marantaceae and Cyperaceae morphotypes are found only at a few depths in the upper half of the profile.

4.2 Results of field and laboratory analyses at the Brazil nut stand

4.2.1 CAST1 P2 profile

The Brazil nut stand is located next to Couro Velho along the Igapó-Açu River (04°38'44.0"S, 61°09'10.2"W) (see Fig. 3.1). A photo of the profile is shown in Fig. 4.11.

Profile description

- 0–20 cm b.s.: O horizon, exhibiting partly-decomposed and decomposed plant material. Signs of recent burning were detected in the topsoil and on the surface. On the border between the O and the lower Ac horizon, large pieces of orange burnt clay were found. Only a few pieces of charcoal were encountered. The colour of the horizon is dark greyish brown (10YR 4/2).
- 20–35 cm b.s.: Ac horizon (cultural layer), slightly darker greyish colour, denser in charcoals, especially between 20 and 30 cm b.s. A few burnt clay pieces were found in different colours from darker to lighter orange and yellow.
- 35–40 cm b.s.: initial E horizon (eluviation layer) (10YR 6/2). No artefacts were found, but a few charcoal pieces were encountered.
- 40–75 cm b.s.: B horizon. No artefacts or charcoal were found in this layer. The colour is a mix of red, yellow, and grey (10YR 7/6, 2.5YR 4/6, and 10YR 5/2).

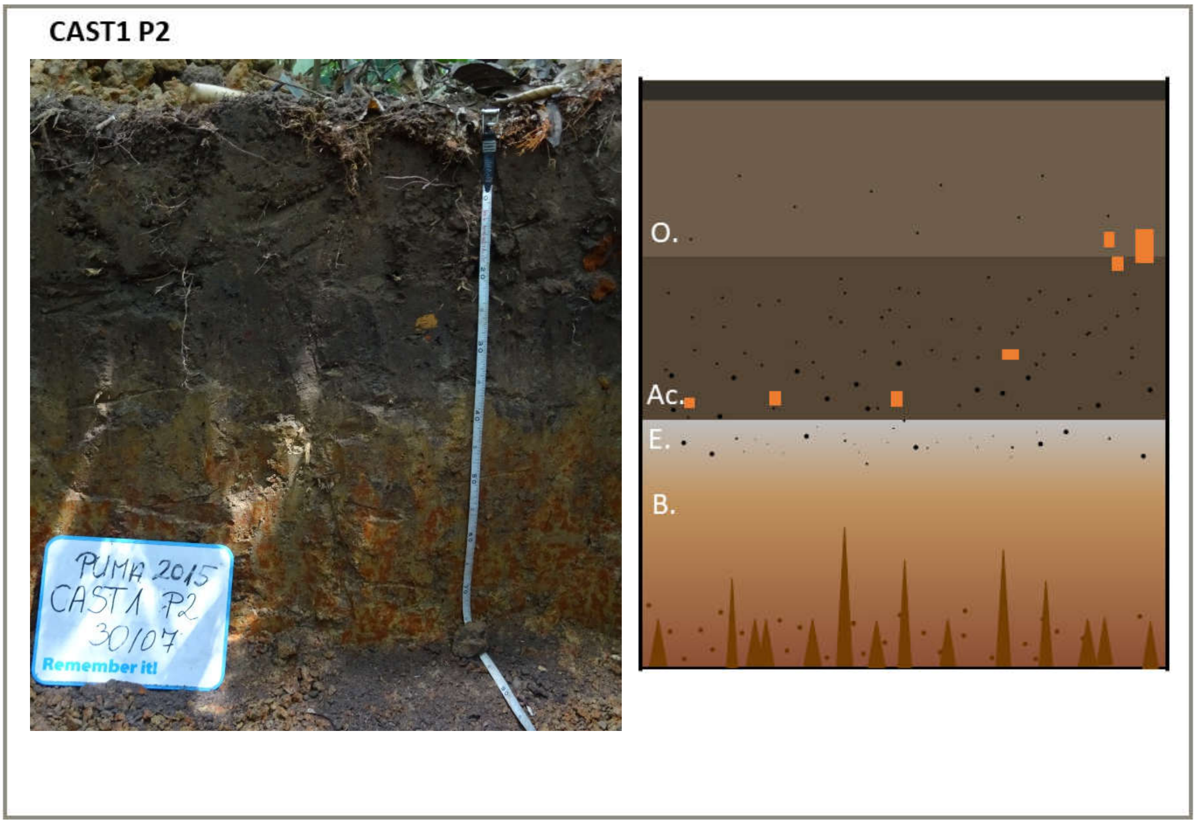


Figure 4.11: Photo and drawing of profile CAST1 P2. Black dots represent visible charcoal pieces, and orange rectangles represent burnt clay and pottery sherds.

Phytolith assemblage

The phytolith assemblage, and therefore the species richness, of anthropogenic soils is more diverse than that of natural soils in the PPBio forest modules. This may suggest that the species richness is higher in this forest than in the primary forests on natural soils.

In the CAST1 P2 profile, the NPA-type phytoliths constitute 80.1% of the whole assemblage (Fig. 4.12, Appendix II). In addition to the most common non-diagnostic arboreal morphotypes, a few diagnostic arboreal phytoliths were also encountered. Phytoliths produced by Annonaceae were found in some layers, between 5 and 55 cm b.s., and *cf. P. guianensis* was also detected in trace amounts. The percentage of NPA-type phytoliths decreases slightly towards the top of the profile; however, it does not drop below 64%, suggesting some opening in the landscape, but this is not explicit. The quantity of herb, palm, and Poaceae phytoliths increases towards the top of the profile, which also suggests the disturbance and opening of the landscape. Among herbaceous species, Marantaceae and Asteraceae phytoliths were encountered in every layer, and

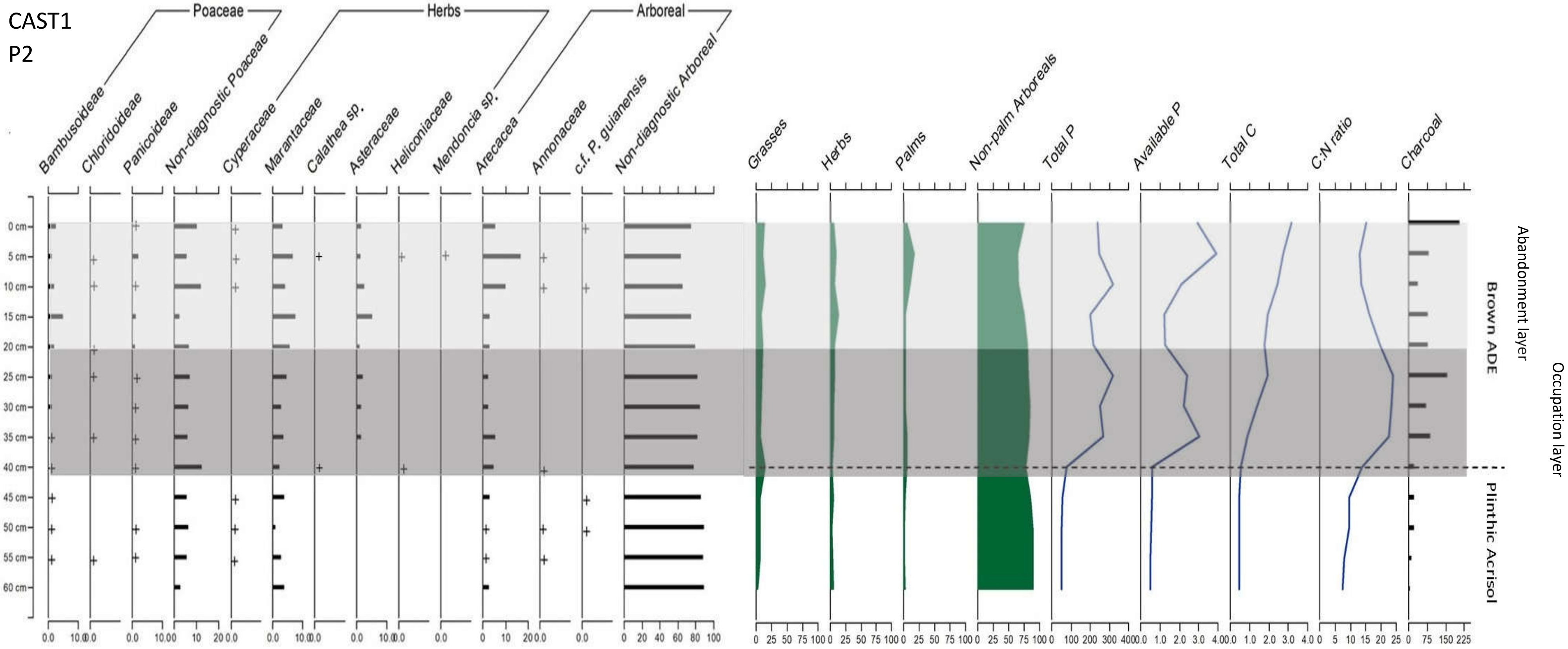


Figure 4.12: Relative frequencies of phytoliths recovered in the CAST1 P2 profile. Horizontal bars represent percentaes; crosses denote the presence of plant taxa lower than 1% in abundance. Followed by a summary of the main phytolith taxa (relative percentage in green) in association with total phosphorous (mg/kg), available phosphorous (mg/kg), total carbon (mg/kg), the C:N ratio, and macro charcoal counts.

which also suggests the disturbance and opening of the landscape. Among herbaceous species, Marantaceae and Asteraceae phytoliths were encountered in every layer, and their number increases towards the top of the profile. *Calathea* sp. phytoliths were found at 5 and 40 cm b.s. Additionally, *Mendoncia* sp. and Heliconiaceae phytoliths were found at 5 cm b.s. Poaceae morphotypes constitute 9.1% of the whole assemblage. The number of non-diagnostic Poaceae phytoliths increases notably towards the top of the profile from 3% to 13.4%, with some peaks at 40 cm b.s. (14%) and 10 cm b.s. (15%). The quantity of Bambusoideae phytoliths increases from 0.4% to 2.6%. Panicoideae phytoliths were found throughout the profile in trace amounts, and a few Chloridoideae phytoliths were identified sporadically throughout the profile.

Comparing the phytolith assemblage of the cultural layer with the natural layer, the percentage of non-Arecaceae arboreal phytoliths in the cultural soil is more than 10% lower than in the natural soil, at 76.6% and 88.4%, respectively. In contrast, palm phytoliths constitute 6% of the phytolith assemblage in the ADE layer (O and Ac horizons), but only 1.8% in the natural soil. Herb phytoliths are almost 3% higher in the ADE layer, while the percentage of Poaceae is twice as high at 5.7% in the natural soil and 10.6% in the cultural layer.

The number of phytolith morphotypes in the grass, herb, and palm taxa groups increases from the bottom to the top in the CAST1 P2 profile. At 40 cm b.s., at the border between the natural soil and the ADE soil, the number of grass morphotypes becomes suddenly very large, comprising 14% of the phytolith assemblage at this depth. This is probably the result of an initial clearing of the understorey that encouraged the growth of grasses and other early successional species. Herbs are represented in very low number at this depth, but herb taxa increase constantly in numbers, with some fluctuations, until 15 cm b.s., where they account for 12.8% of the whole phytolith assemblage. The quantity of palm phytoliths is lowest at 55 and 50 cm b.s. (<1%), and it reaches 16.8% at 10 cm b.s. with gradual growth. The NPA taxa group account for 75.5–89.6% of the phytolith assemblage between 60 and 15 cm b.s. Towards the top of the profile, the percentage of NPA phytoliths sharply decreases, and, at 5 cm b.s., they only account for 64% of the overall phytolith assemblage. In this profile, NPA morphotypes are only abundant in the topsoil, suggesting that, after the Couro Velho was abandoned by the occupants, the vegetation did not change drastically up to modern times.

Soil geochemical results

Total and available phosphorous

CAST1 P2 is *ca.* 300 m from the core of the Couro Velho site The total phosphorous level is highest at the top of the profile (240 mg/kg at 0 cm b.s.), after which it steadily decreases. The available phosphorous values follow a very similar pattern, being highest in the topsoil (5 mg/kg) and constantly decreasing save for a minor peak at 20 cm b.s. (1.3 mg/kg).

Total carbon, total nitrogen, and the C:N ratio

The total carbon values are 3.7% w/w in the topsoil. From here, values rapidly decrease below 0.5% w/w towards the bottom of the profile, although there is a small peak at 25 cm b.s. (1.92% w/w). The total nitrogen is highest in the topsoil and at 5 cm b.s. (0.21% w/w), and it decreases to 0.04% w/w around 35–40 cm b.s.. From this depth, it increases slightly and reaches 0.07% w/w at 75 cm b.s. The C:N ratio follows a similar pattern: it is 15.1 in the topsoil and peaks at 24 around 25 cm b.s., from where it gradually decreases until 6.6 at 75 cm b.s.

Macro charcoal analysis

The average charcoal count is 57 in the CAST1 P2 profile. The largest quantity of charcoal was counted in the topsoil (208), and the second highest at 25 cm b.s. (157). This depth represents the occupation layer (Ac) and contains artefacts, suggesting intensive use of the landscape. From this depth downwards, the quantity of charcoals consistently decreases in the profile. There is a significant difference in the quantity in the pre-ADE soil (40–75 cm b.s.), where the average charcoal count is 14, while in the brown ADE (0–35 cm b.s.), the count is 101.

Summary

In the CAST1 P2 profile, changes in the charcoal count show similar trends to the C:N ratio. There is also a small peak in the total carbon values at 25 cm b.s. Around the same depth between 35 and 25 cm b.s., a peak in total and available phosphorous also occurs. This peak correponds with the zone where the most artefacts have been found, therefore, although the phytolith assemblages do not show large-scale changes, this peak probably represents the formation of ADE soil and intensive use on it. Another peak in the total and available phosphorous values is around 15–10 cm b.s., which is accompanied by an increase in the charcoal count and total carbon values, as well as a slight increase in the percentage of palm phytoliths. This peak is probably associated with the modern usage of the area.

There is a distinct difference between the natural soil and the brown ADE in this profile. Where the colour changes in the profile to indicate the onset of ADE formation at 40 cm b.s., there is a small change in the composition of the phytolith assemblage: the slight increase in grass morphotypes and the decrease in arboreal phytoliths indicates small-scale clearing of the area, probably the removal of the shrubby understorey. The largest changes in the total and available phosphorous values, the C:N ratio, and the charcoal count between 35 and25 cm b.s. do not correlate with changes in the phytolith assemblage.

Conversely, during this time the vegetation seems to be stable, though there is a slight increase in the percentage of tree phytoliths. Given the fact that the area where the CAST profiles were excavated is an anthropogenic or managed Brazil nut forest (Clement, 1999), Couro Velho's inhabitantsprobably did not intend to completely clear the area; they likely only changed the forest's composition and enriched it with edible, economically useful species. However, the soil was most probably subjected to amelioration techniques, such as enrichment of the topsoil with ash, charcoal, and plant residues, as evidenced by the large peak in phosphorus content, C:N ratio and charcoal counts.

4.2.2 CAST2 P1 profile

The stratigraphy of the CAST2 P1 profile is shown in Fig. 4.13, as well as a drawing of the layers.

Profile description

- 0–20 cm b.s.: O horizon, exhibiting partly-decomposed and decomposed plant material. Signs of recent burning were seen on the surface. A few charcoal fragments but no artefacts were encountered in this horizon. The colour is yellowish brown (10YR 4/4) (Fig 4.13).

- 20–40 cm b.s.: Ac horizon (cultural layer). The charcoal density is much higher than in the O horizon. Occasionally, small burnt pieces of clay were encountered.
- 40–75 cm b.s.: B horizon. The colour is more reddish (mix of 2.5YR 4/6, 10YR 7/6, and 10YR 5/2) than in the CAST1 P2 profile, suggesting that this profile has been less saturated with water during the rainy season due to its higher position.

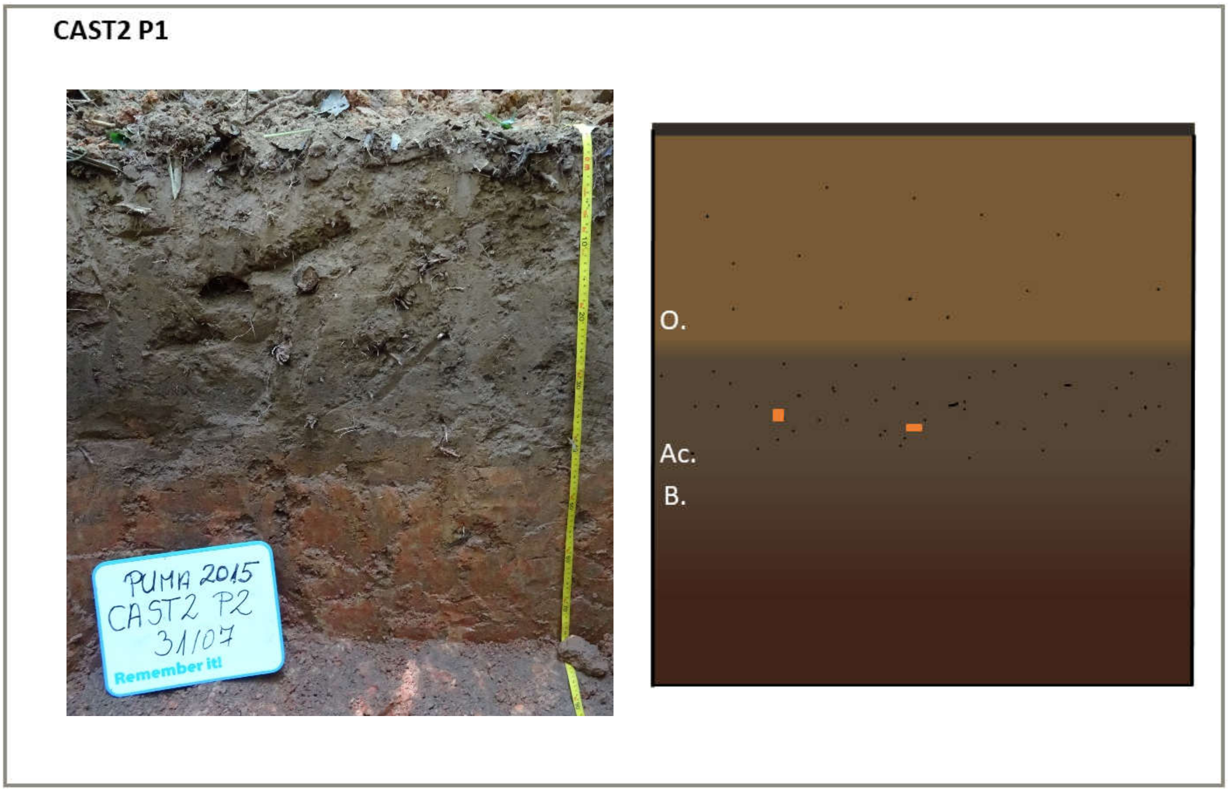


Figure 4.13: Photo and drawing of the CAST2 P1 profile. Black dots represent visible charcoal pieces, and orange rectangles represent burnt clay and pottery sherds.

Phytolith assemblage

Similar to the other profiles, the phytolith assemblage of the CAST2 P1 profile is also dominated by NPAtype phytoliths (81.4%) (Fig. 4.14, Appendix II). Also, similar to the other profiles, the percentage of NPA phytoliths decreases towards the top by around 11% from 90.8% to 80.1%. The opposite pattern is seen for Poaceae phytoliths, especially Bambuseae and non-diagnostic Poaceae morphotypes, which increase in frequency in the upper middle section of the profile between 45 and 5 cm b.s. Interestingly, there is a peak in non-diagnostic Poaceae phytoliths at 40 cm b.s. (20.4%).

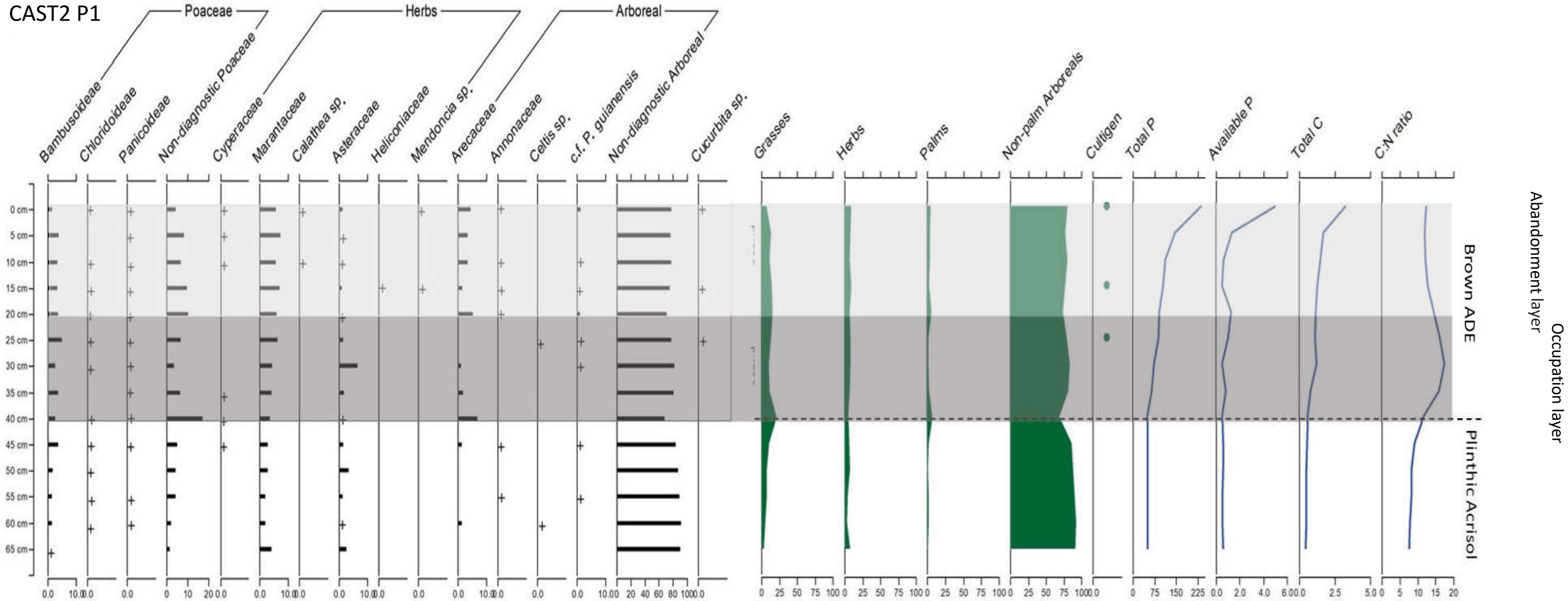


Figure 4.14: Relative frequencies of phytoliths recovered in the CAST2 P1 profile. Horizontal bars represent percentages; crosses denote the presence of plant taxa lower than 1% in abundance. Followed by a summary of the main phytolith taxa (relative percentage in green) in association with total phosphorous (mg/kg), available phosphorous (mg/kg), total carbon (mg/kg), and the C:N ratio.

Chloridoideae and Panicoideae morphotypes were identified throughout the profile in trace amounts. The ratio of herbaceous phytoliths in the whole assemblage is 6.3%. Amongst these types of plants, Marantaceae phytoliths were encountered in the highest number, and their number slightly increases towards the top of the profile (7.3% at 5 cm b.s.), but Asteraceae phytoliths were also found in every layer of the profile. Cyperaceae, *Calathea* sp., Heliconiaceae, and *Mendoncia* sp. morphotypes were found in trace amounts. *Cucurbita* sp. phytoliths were identified at 0 cm b.s., 15 cm b.s., and 25 cm b.s.

When comparing the cultural layer with the natural soil, the phytolith assemblages show a similar pattern than in the CAST1 P2 profile. The ratio of the NPA phytoliths is 11.8% higher in the natural soil than in the ADE (O and Ac horizons). Other than the NPA phytoliths, only Asteraceae phytoliths were found in a higher number in the natural soil (1.9%) than in the cultural layer (1.6%). All other phytolith types were identified in a higher ratio in the ADE soil than in the natural soil: Poaceae morphotypes are below 6.4%, and herbs are below 2.9%. Also, there are 2.5% more palm phytoliths in the ADE soil than in the natural soil.

In the CAST2 P1 profile, since the number of herb and palm morphotypes is almost constant, the amount of grass morphotypes drives the changes to the percentages of NPA phytoliths. The herb taxa account for 2.5–8.5% of the phytolith assemblages, showing only a slight increase towards the top of the profile. Palms account for 0.2–6.8% of the assemblages. In general, the graph exhibits the increasing trend of grass taxa up to 20 cm b.s., where the quantity peaks at 13.5%, then decreases towards the topsoil.

There is one depth that is an exception, which is 40 cm b.s. This depth marks the border between the natural soil and the ADE, and, similar to CAST1 P2, the quantity of grass taxa drastically increases (20.4%) here, probably as a result of clearing the area and early successional growth. The general trend is that, as the number of grass phytoliths increases, the number of NPA morphotypes decreases. The lowest quantity was encountered at 20 cm b.s. (73.1%), although NPA morphotypes only account for 68.2% of the whole assemblage at 40 cm b.s., where there is the sudden peak in grass phytoliths.

Soil geochemical results

Total and available phosphorous

The total phosphorous values are higher in CAST2 P1, which lies in the middle in the transect, 150 m away from the core of the Couro Velho site. However, the total phosphorous values show large variations throughout the profile. The highest value is found at 10 cm b.s. that reaches 320 mg/kg. Total phosphorous values from the border between the anthropogenic and natural soil (40–45 cm b.s.) are constantly below 50 mg/kg. The available phosphorous values of the CAST2 P1 profile are slightly higher than those in the other CAST profile. They peak at three depths, 5 cm b.s. (3.9 mg/kg), 25 cm b.s.(2.4 mg/kg), and 35 cm b.s. (3.05 mg/kg).

Total carbon, total nitrogen, and the C:N ratio

The total carbon value is 3.26% w/w in CAST2 P1's topsoil, and values rapidly decrease from here, though there is a small peak at 30 cm b.s. (1.92% w/w). The total nitrogen values in CAST2 P1 follow the same pattern as the control soil: they are highest in the topsoil (0.26% w/w), from whence the values sharply decrease. The C:N ratio increases until about 30 cm b.s., peaking at 17:4, and then consistently decrease.

Summary

Although the two CAST profiles are located *ca*.150 m apart from each other in the same Brazil nut stand next to the Couro Velho site, their geochemical signals are very different. This shows inter-site variability, probably due to different degrees of human impact. The same initial clearing of the vegetation seem in CAST1 P2 can also be detected in the phytolith record of the CAST2 P1 profile at 40 cm b.s. However, excluding the C:N ratio, there are only slight changes in the geochemical signal in the brown ADE layer. This suggests that, although squash was cultivated in this area and the soil is darker in colour, amelioration did not take place to the same degree as at the site of the CAST1 P2 profile.

4.3 Results of field and laboratory analyses at Couro Velho

4.3.1 TP1 P5 profile

The Couro Velho archaeological site is situated along the Igapó-Açu River (04°38'47.0"S, 61°09'05.1"W) (see Fig. 3.1). TP1 P5 is one of the black earth profiles in the core area of the ADE site (Fig. 4.15). Apart from the colour, the main differences between the CAST and TP profiles are slight changes in texture in the anthropogenic layers and the appearance of more artefacts—including burnt clay and pottery—in the TP profiles. The layers in the TP profiles look less unified in colour and thickness than the CAST profiles, despite the fact that they were opened in a much smaller area.

Profile description

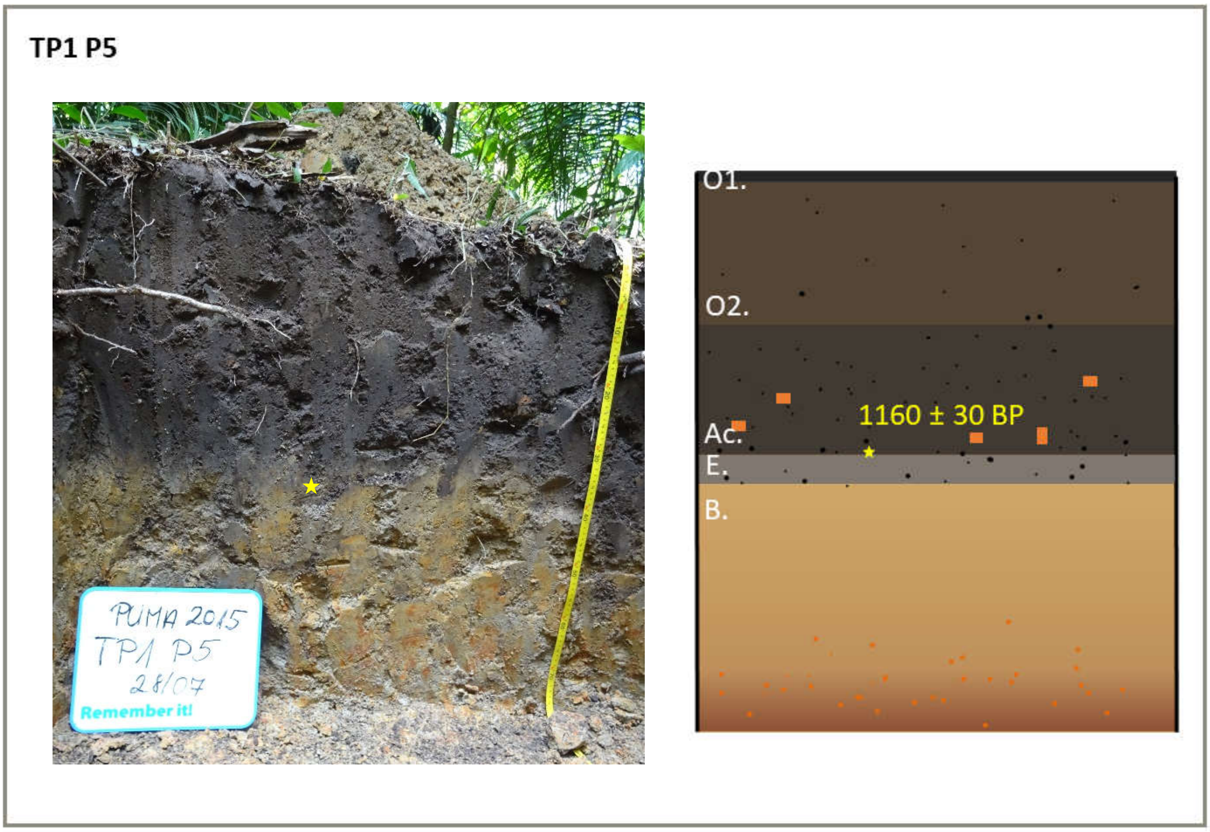


Figure 4.15: Photo and drawing of the TP1 P5 profile. Black dots represent visible charcoal pieces, orange rectangles represent burnt clay and pottery sherds, and the yellow star represents the charcoal selected for radiocarbon dating.

- 0–3 cm b.s. O1 horizon. The thin layer on the surface shows signs of recent burning. Charcoal is highly abundant in this layer; the colour was determined as black (10YR 2/1) and the texture as sandy silt loam, which has an oily feeling when rubbed between the fingers.
- 3–20 cm b.s. O2 horizon, typically has a lighter colour (10YR 4/2) than the O1 horizon above and the Ac (cultural horizon) below. This horizon has a clay-loam texture and, in general, contains much less charcoal and very few artefacts.

- 20–35 cm b.s.: Ac horizon (cultural horizon). It is abundant in charcoal, and the colour is very dark greyish brown (10YR 3/2). Artefacts, mainly burnt clay and ceramic sherds, were recovered. No other artefacts were found. The texture is sandy silt loam that has a slightly oily feeling when rubbed between the fingers.
- 35–40 cm b.s.: initial E horizon (eluviation layer) is currently forming in this layer, represented as a pale grey colour. This layer has probably developed due to constant burning of the ground vegetation (Schulz, 1960). It contains an abundance of different-sized charcoals. The border between the Ac and E horizons is very uneven, and it seems that the upper Ac layer has been partially worked into the natural soil below. A charcoal fragment was selected from the border of the Ac and E horizons to date the start of the formation of the ADE layer. This produced a date around 1160±30 cal BP.
- 45–75 cm b.s.: C horizon. This is natural soil, mainly dark yellowish brown mixed with grey and red in different amounts (10YR 4/6, 10YR 7/2, and 2.5YR 5/6), with stronger red mottling at the bottom of the profile.

Phytolith assemblage

The NPAtype phytoliths constitute 79.5% of the whole assemblage. This suggests that this area was covered by trees throughout the time of occupation (Fig. 4.16, Appendix II). The percentage of NPA phytoliths decreases towards the top of the profile by 12.6%, from 88.8% at the bottom to 76.2% at the top. Arecaceae phytoliths add 6.8% to the whole assemblage with notable fluctuations. There are peaks at 5 cm b.s. (12%), 15 cm b.s. (13.3%), 25 cm b.s. (11.4%), and 40 cm b.s. (13%). Herbaceous morphotypes constitute 4.8% of the whole assemblage. Marantaceae is the dominant species (3.6% on average), but Asteraceae was also found at every depth, constituting 1% overall. Cyperaceae, *Calathea* sp., and Heliconiaceae were found in trace amounts. All Poaceae morphotypes constitute 8.7% of the whole assemblage, with a notable increase from the bottom to top from 3.1% to 13.4%. Interestingly, both palm phytoliths and non-diagnostic Poaceae phytoliths fluctuate from 13.6% at 5 cm b.s. to 12.3% at 20 cm b.s. and 15.4% at 40 cm b.s. Conversely, Bambusoideae morphotypes increase in number from the bottom to the top of the profile from 0.5% at 75 cm b.s. to 3.3% at 0 cm b.s. Panicoideae and Chloridoideae were mainly found in the upper half of the profile.

TP1 P5

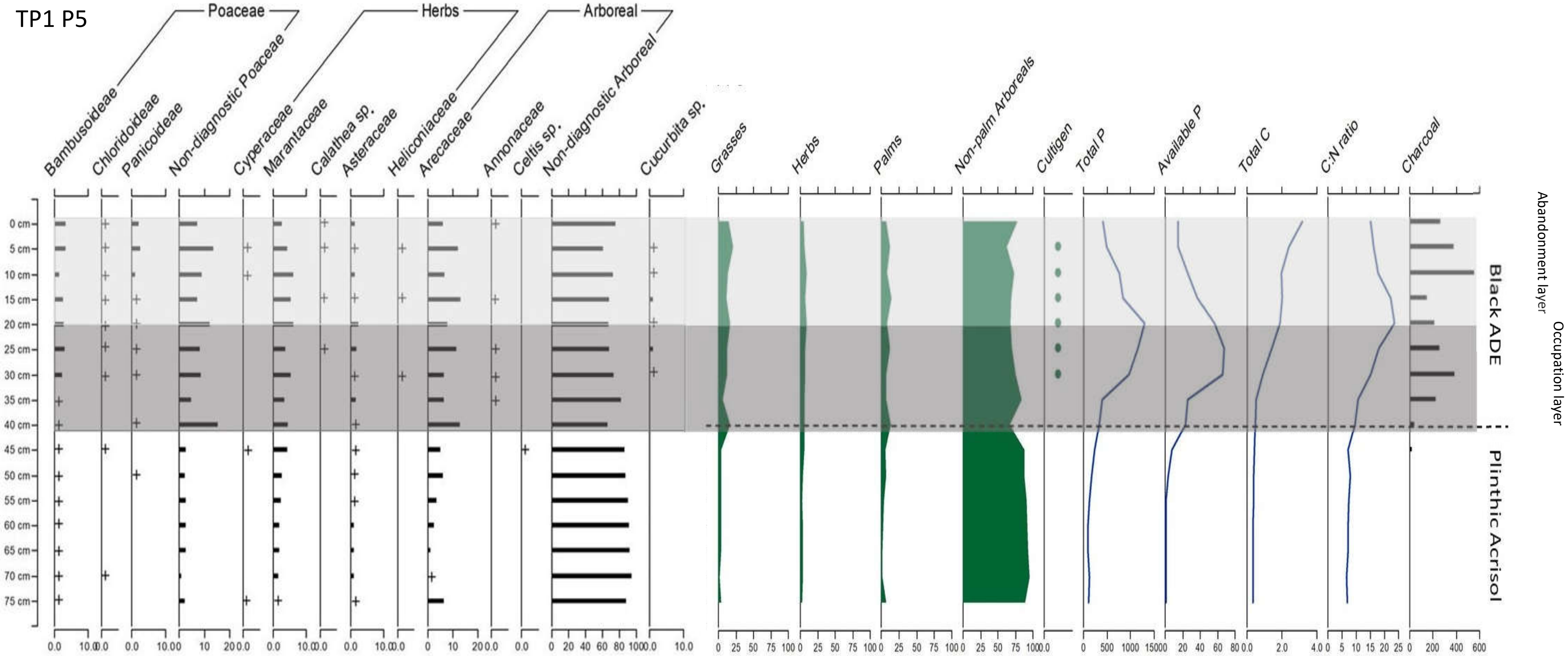


Figure 4.16: Relative frequencies of phytoliths recovered in the TP1 P5 profile. Horizontal bars represent percentages; crosses denote the presence of plant taxa lower than 1% in abundance. Followed by a summary of the main phytolith taxa (relative percentage in green) in association with total phosphorous (mg/kg), available phosphorous (mg/kg), total carbon (mg/kg), the C:N ratio, and raw charcoal counts.

The phytolith assemblage of the profile shows a clear distinction between the cultural (0–40 cm b.s.) and natural (40–75 cm b.s.) layers. On average, the number of NPA phytoliths is 20% higher in the natural soil (90.4%) than it is in the cultural layer (70.9%).

Regarding fruit trees, Annonaceae phytoliths were only recovered from the cultural layer, and *Celtis* sp. phytoliths were found at the top of the natural soil at 45 cm b.s. On average, the percentage of Arecaceae phytoliths is three times higher in the cultural layer (9.2%) than in the natural soil (3.6%). However, there are large fluctuations in the number of palm phytoliths in the cultural layer. The quantity of Poaceae morphotypes is over 10% higher in the cultural layer (13.2%) than in the natural soil (2.9%). The percentage of herb phytoliths also doubles in the cultural layer (6.2%) compared to the natural soil (3.0%). The difference is particularly explicit in the case of the Marantaceae phytoliths: their number more than doubles to 4.7% in the cultural layer from 2.2% in the natural layer. Cyperaceae was found in both the natural and cultural layers, but *Calathea* sp.and Heliconiaceae were only recovered from the cultural layer. *Cucurbita* sp. phytoliths were encountered at every depth between 5 and 30 cm b.s. from the cultural layer.

As in the case of the other profiles with anthropogenic soils, the general trend shows that the number of grass, herb, and palm taxa group phytoliths constantly increases towards the top of the profile. The lowest quantities from these taxa groups were counted at 70 cm b.s., where grasses constitute only 3.1%, herbs 2.7%, and palms 0.7%. The largest quantity for the grass morphotypes, was counted at 5 cm b.s. (19.9%). Again, similar to the other ADE profiles, the layer at 40 cm b.s. has a distinct phytolith composition. At this depth, grasses account for 16.3%, herbs account for 4.9%, and palm phytoliths account for 13% of the total phytolith assemblage, while the NPA taxa group comprises 65.8% of the assemblage.

Soil geochemical results

Total and available phosphorous

The total phosphorous value is 416 mg/kg in the topsoil, and it rapidly increases in the ADE layer (O2 and Ac horizons), reaching 1289 mg/kg at 20 cm b.s. Below the ADE layer, the total phosphorous value decreases sharply to 97 mg/kg. At the bottom of the profile, the value increases to 121 mg/kg. The available phosphorous values exhibit similar a pattern to that for the total phosphorous values. The highest value was measured in the ADE layer at 25 cm b.s. (67 mg/kg).

Total carbon, total nitrogen, and the C:N ratio

The total carbon value is 3.13 mg/kg, but this decreases from the top to the bottom of the profile. The rate of the decrease is slower in the ADE layer and faster in the natural soil below the ADE. The total nitrogen value consistently decreases from 0.21 mg/kg in the topsoil to 0.05 mg/kg by the bottom of the profile. The C:N ratio follows a bell curve, and it is highest (23.5) in the ADE layer at 20 cm b.s.

Macro charcoal analysis

The largest number of charcoal was counted at 10 cm b.s. (555). At 15 cm b.s., the charcoal count drops drastically, then peaks again at 30 cm b.s. with 383 counts. Interestingly, in the pre-ADE phase (40a–75 cm b.s.), there was even less charcoal counted than for the control profile. The charcoal count starts to grow slightly before the ADE formation starts. This may be the result of initial landscape clearing using fire and less intensive forest management. In TP1 P5, the average charcoal count in pre-ADE soil is 9, while the it is 301 in the black ADE.

Summary

The two black ADE profiles exhibit similar patterns in their geochemical signals, although these changes probably occurred at slightly different times, as the peaks are at different depths. In both profiles, where phytoliths of cultigens were found, the total and available phosphorous values and the C:N ratio peaked. In TP1 P5, the same small peak in grass phytolith morphotypes occurs at the border between the natural soil and the ADE; this was also seen in the CAST profiles.

However, the modification of the landscape probably started earlier than the onset of ADE development, because both the number of palm phytoliths and the values of total and available phosphorous had already started to increase in the acrisol at 45 cm b.s. Another explanation for the enrichment of the upper part of the natural soil with phosphorous would be leaching from the ADE; however, Cook & Heizer, (1965) propose that leaching through soil profiles is not rapid in terms of archaeological time scales, because phosphorous can easily be fixed by iron around pH 7.0 and 6.0, as well as by iron and aluminium below pH 5.0. Therefore, in tropical soils that usually have extremely high aluminium and iron contents, the increase in pH due to the high concentration of organic matter will allow more fixation of phosphorous. In the case of the profile, this means that the early enrichment of phosphorous was probably due to initial landscape management, e.g. burning of the understorey. During the same period, the studied chemical elements peak in the ADE soil, mainly between 35 and 10 cm b.s., and there is a slight decrease in NPA phytoliths but an increase in grasses, palms, and cultigens, namely squash. The low percentage of herbs may be the reason for weeding in the area, i.e. to keep the understorey clear for the cultigens. The charcoal count does not follow a similar pattern to the phosphours values and the C:N ratio. In the charcoal count, two big peaks occur: one at 35 cm b.s. (early ADE development) and one at 10 cm b.s.

4.3.2 TP1 P7 profile

The stratigraphy of the TP1 P7 profile is shown in Fig. 4.17, as well as a drawing of the layers.

Profile description

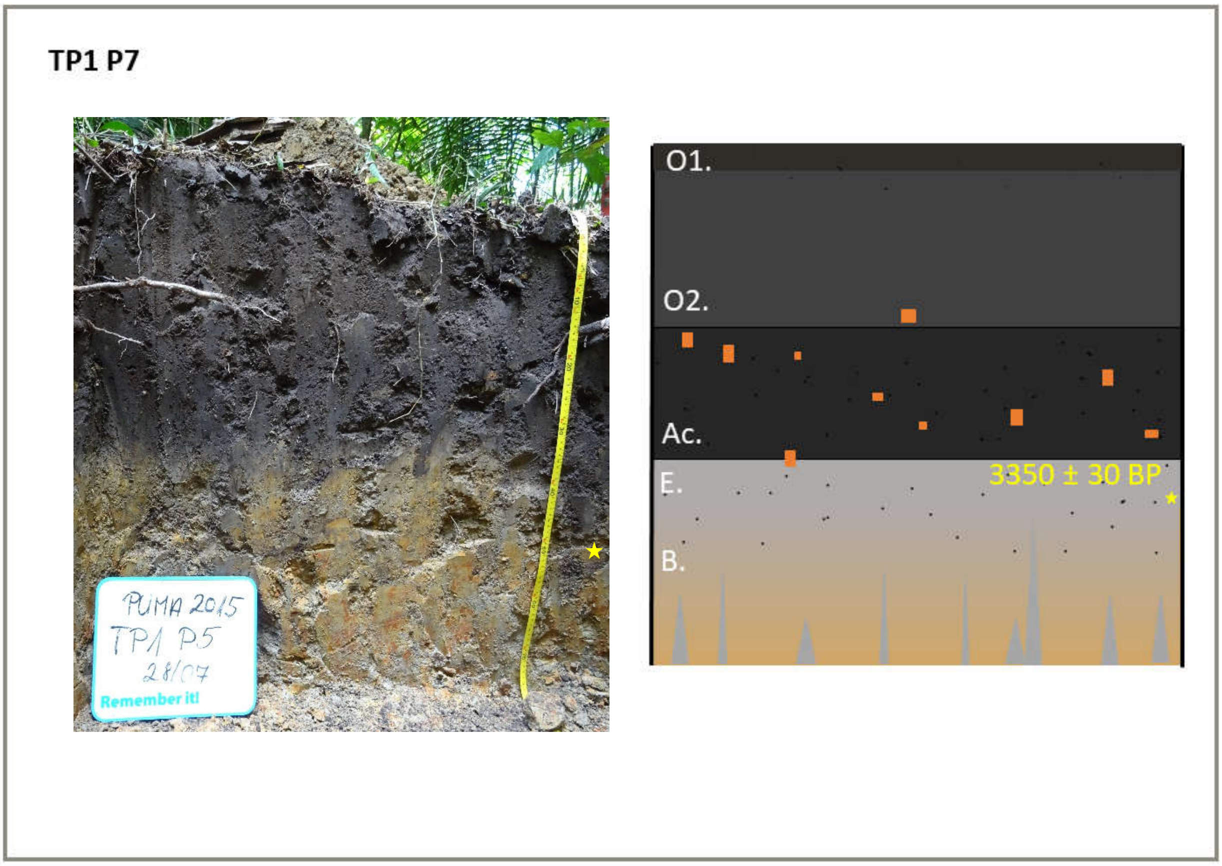


Figure 4.17: Photo and drawing of the TP1 P7 profile. Black dots represent visible charcoal pieces, orange rectangles represent burnt clay and pottery sherds, and the yellow star represents the charcoal selected for radiocarbon dating.

- 0–3 cm b.s.: O1 horizon. A thin layer on the surface showing signs of recent burning. Charcoal is highly abundant in this layer. The colour was determined to be black (10YR 2/1) and the texture sandy silt loam, which has an oily feeling when rubbed between the fingers.
- 3-20 cm b.s.: O2 horizon, which has a lighter (10YR 4/2) colour than the O1 horizon and the Ac horizon below. This horizon has a clay-loam texture and contains little charcoal and artefacts.
- 20–45 cm b.s.: The Ac horizon (cultural layer) is abundant in charcoal with the colour of very dark brown (10YR 2/2). Artefacts, mainly burnt clay and occasionally ceramic shards were recovered scattered around the whole layer. Texture is sandy silt loam with a slightly oily feeling when rubbed between the thumb and fingers.

- 45–55 cm b.s.: E horizon (eluviation layer). This is very distinctive and has a pale grey colour, which probably developed due to constant burning of ground vegetation (Schulz, 1960). This layer also contains an abundance of charcoals of different sizes. The border between the Ac and E horizons is sharp and even. However, the border between the E and C horizons is not even, and it seems that the above layer has been partially worked into the natural soil below.
- *ca*. 55–75 cm b.s.: C horizon. This is natural soil, mainly dark yellowish brown mixed with grey and red in different amounts (10YR 4/6, 10YR 7/2, and 2.5YR 5/6). In some profiles, strong red mottling at the bottom was found.

Phytolith assemblage

As in the other CAST and TP profiles, the overall phytolith assemblage is dominated by NPA morphotypes (72.9%), but the number decreases towards the top, from 86.9% to 52.5% (Fig 4.18, Appendix II). Useful tree species, Annonaceae, *Celtis* sp. and *cf. P. guianensis* were found in trace amounts. Palms, Poaceae, and some herbaceous species (mainly Marantaceae) morphotypes display the opposite trend. The number of palm phytoliths increases from the bottom to top (5.8% to 16%). The increase in Poaceae morphotypes is even more pronounced: 6.4% at the bottom and 23.3% at the top. The number of non-diagnostic Poaceae morphotypes fluctuates throughout the profile; the highest percentage (30.2%) is at 10 cm b.s. and lowest percentage (3.0%) is at 55 cm

TP1 P7

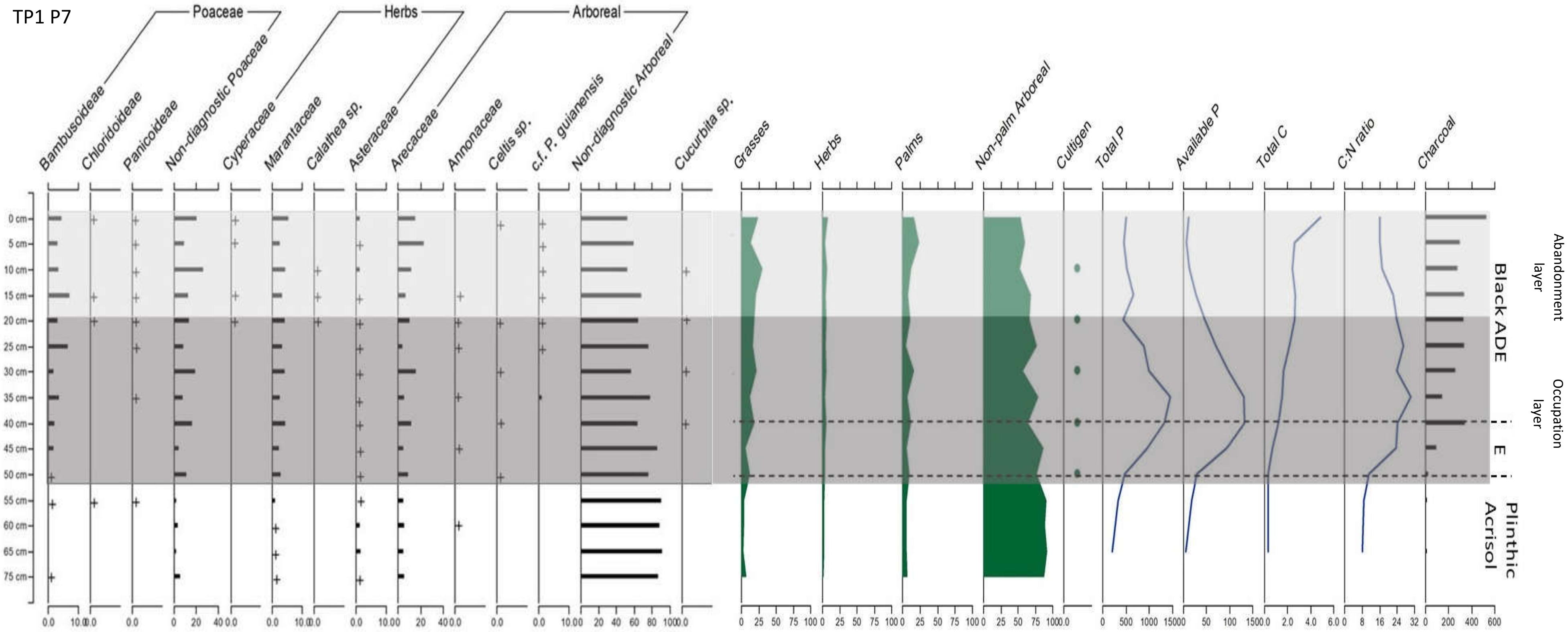


Figure 4.18. Relative frequencies of phytoliths recovered in the TP1 P7 profile. Horizontal bars represent percentages; crosses denote the presence of plant taxa lower than 1% in abundance. Followed by a summary of the main phytolith taxa (relative percentage in green) in association with total phosphorous (mg/kg), available phosphorous (mg/kg), total carbon (mg/kg), the C:N ratio, and raw charcoal counts.

.

b.s. Bambusoideae morphotypes were also recovered in larger numbers towards the top of the profile, with 0.9% at 75 cm b.s. and 4.4% at 0 cm b.s., with two peaks at 15 cm b.s. (7%) and 25 cm b.s. 6.5%). Chloridoideae and Panicoideae were mainly found in the upper part of the profile. Herb phytoliths constitute 3.8% of the whole assemblage, with Marantaceae making up 2.9%, while Asteraceae, Cyperaceae, and *Calathea* sp. were only identified in trace amounts.

When comparing the phytolith assemblages of the ADE layer (0–50 cm b.s.) and the natural soil (55–75 cm b.s.), notable changes are evident. There is *ca.* 20% difference in the percentage of NPA phytoliths between the natural soil (89.1%) and the ADE (68.6%). Useful (edible) trees with diagnostic phytoliths were encountered in the forms of Annonaceae and *Celtis* sp*.* in the cultural layers, and one Annonaceae phytolith was found in the natural soil at 60 cm b.s. The number of palm phytoliths doubles in the ADE layer (10.8%) compared to the natural soil (5.3%). The number of herb phytoliths is twice as high in the ADE layer (4.6%) compared to the natural soil (1.8%). As in the case of TP1 P5, Asteraceae and Marantaceae phytoliths were found throughout the profile (0.7% on average), although the ratio of Marantaceae phytoliths is much higher in the cultural layer (3.6%). Other herb phytoliths identified in this profile, such as Cyperaceae and *Calathea* sp., were only found in the ADE. The biggest difference between the natural and cultural layers is seen in the quantity of Poaceae phytoliths. Four times as much non-diagnostic Poaceae phytoliths were counted in the cultural layer (13.6%) than in the natural layer (3.3%). There is also a big difference in the amount of bamboo morphotypes: 3.3% in the cultural layer and 0.7% in the natural soil.

Although the relative distribution of main phytolith taxa in TP1 P7 follows the trend seen in the other profiles where Poaceae and palm taxa increase at the expense of NPA morphotypes, this profile displays the largest fluctuations among all the profiles examined. The peaks grow increasingly larger from the bottom to top of the profile, with the first peak occuring at 50 cm b.s. at the border between the natural soil and eluviation layer. At this depth, grass morphotypes account for 11.6%, herbs account for 3.3%, and palm phytoliths account for 9% of the whole assemblage.

The next peak is at 40 cm b.s., the border between the eluviation layer and the black ADE. Here, the largest increase is seen in the grass taxa group, which increase by 18.3% compared to the peak at 50 cm, although the percentages of herbs and palms also increase. At 30 cm b.s., the occupation layer, the percentage of grass taxa rises to 21.5%, and palms account for 16% of the phytolith assemblage.

The highest percentage of grass phytoliths occurs at 10 cm b.s. (30.2%). The percentage of palms also fluctuates, with the highest quantity in the whole assemblage encountered at 40 cm b.s., 20 cm b.s., and 10 cm b.s. The number of herb morphotypes is relatively low when compared to the other phytolith taxa groups, but it also increases slightly toward the top of the profile and peaks in the topsoil at 7.3%. This increase in grasses from the bottom to the top of the profile with occasional peaks suggests that human pressure on the area, such as clearing vegetation, was constant.

Soil geochemical analysis

Total and available phosphorous

The total phosphorous value is 501 mg/kg in the topsoil, and it slightly increases in the upper part of the ADE layer to 670 mg/kg at `5 cm b.s. At 25 cm b.s., it decreases to 445 mg/kg, after which it rapidly increases again to peak at 1459 mg/kg at 35 cm b.s. From this depth, the total phosphorous values sharply decrease again towards the bottom of the profile. The available phosphorous values peak in 35–40 cm b.s. with the highest value of 133 mg/kg.

Total carbon, total nitrogen, and the C:N ratio

The total carbon value sharply decreases from 4.87 mg/kg at the top of the profile until 10 cm b.s., then it increases slightly between 15 and 20 cm b.s. (2.62 mg/kg). Below this point, the values consistently decrease again. The total nitrogen value follows a consistently decreasing pattern: it is 0.3 mg/kg in the topsoil and decreases to 0.04 mg/kg by the bottom of the profile. The C:N ratio isfollows a bell curve, with some fluctuations. The ratio is highest in the ADE layer at 35 cm b.s. (30.4). This is the highest value measured of all the profiles.

Macro charcoal analysis

Among all the profiles, TP1 P7 contains the largest amount of charcoal. The maximum charcoal count is 529 in the topsoil, and the mean is 231. The fluctuation in the charcoal count in the ADE phase is lesser than that seen in the black ADE of other profile; however, a slightly higher count (*ca.* 330–340) than in the rest of the ADE layer is still visible between 15 and 25 cm b.s. The amount of charcoal increases sharply before the development of the ADE, suggesting a pre-ADE layer that already signals extensive land use in the area.

Summary

The changes in both natural vegetation and soil properties have an earlier onset in the TP1 P7 profile than in TP1 P5. The graph shown in Fig. 4.18 shows the first peak in grass and palm phytoliths at 50 cm b.s. correspondent to a retreat in NPA morphotypes. At the same depth, the first phytolith of a cultigen, maize, was found, and the enrichment of the soil with phosphorous also started at this depth. Moving upwards in the profile, the second peak in grass and palm phytoliths is at 40 cm b.s., which correlates well with the largest peak in total phosphorous (1323 mg/kg) and available phosphorous (133 mg/kg). This depth is also much richer in charcoal than the layers below and above, suggesting that fire was used to clear the understorey vegetation. The third peak in grasses and palms occurs at 30 cm b.s. and is accompanied by the appearnace of squash phytoliths. However, an increase in phosphorous was not detected at this depth. From around 40 cm b.s., the amount of total and available phosphorous consistently and rapidly decreases, alongside the less-rapid but consistent decrease in the C:N ratio—probably due to nitrogen enrichment—while the total carbon values increases with the charcoal count . Again, the very low number of herbaceous phytoliths throughout the profile despite the addition of organic fertilizers may be the result of weeding and clearing the understorey.

4.4 Modern botanical survey at the PPBio sites and Couro Velho

Vegetation inventories were taken at all the PPBio forest modules studied, as well as at the Brazil nut stand and Couro Velho. Section 3.1.2 outlines the methodology for performing plant inventories. The results are shown in Table 4.1, and in the Appendix I.

The taxonomical classification (family and genus/species) of each tree, as well as their CBH, DBH, and height were determined by Izaias Brazil.

The species richness and species diversity were also calculated. Species richness refers to the number of trees counted at each study site. Species diversity refers to the number of the different species in the communities and is expressed with the Shannon-Wiener diversity index (Spellerberg and Fedor, 2003):

$$H' = -\Sigma\left[\left(\frac{n_1}{N}\right)\ln\left(\frac{n_1}{N}\right)\right]$$

where H' is the Shannon-Wiener diversity index, n1 (or n2, n3…) is the number of species in the community, and N equals the total sum of all individual trees counted. The Shannon-Wiener index has no units, only a value that allows the comparison between two communities: the higher the value, the greater the diversity.

During interpretation, the number of inventories taken at each site has to be considered. As Table 4.1 shows, four vegetation inventories were taken at each of the PPBio profiles, two inventories were taken at the Brazil nut stand, and one was performed at the Couro Velho site. The differences in sample sizes may have an impact on the results. Additionall, the average height of trees at the four PPBio study sites ranges from 15.3 m (M02) to 17.4 m (M05). The average height is lowest on the black ADE soil at Couro Velho (8.68 m), and the second lowest occurs on the brown ADE in the Brazil nut stand (14.56 m).

Additionally, both the species richness and species diversity are the lowest on the black ADE at Couro Velho: species richness = 19 and species diversity = 2.8. The second lowest species richness and diversity were found in the Brazil nut stand on brown ADE: species richness = 45 and species diversity = 3.15. Compared to the PPBio forest modules, these anthropogenic forests have around 50% lower species richnesses.

In contrast, the two study sites with primary forests (M05, M06) have the highest values for species richness and diversity. At M05, species richness = 148 and species diversity = 3.97, while at M06 species richness is 118 and species diversity is 3.82. The oligarchic forest sites (M02, M11) have lower species richness. M02 has species richness = 99 and species diversity = 3.64, while M11 has species richness = 96 and species diversity = 3.69. These results support findings by Palace et al. (2017) and Junqueira et al. (2010) that forest cover on ADE soils differs from that on natural soils, specifically the lower the height of the canopy, the lower the species richness and diversity.

Table 4.1: Summary of the modern plant inventories performed during this thesis: (1) CBH, (2) DBH, (3) species diversity, (4) species diversity (H').

	No. of inventory plots	CBH[(1)] (cm)	DBH[(2)] (cm)	Height (m)	No. of plant families	Species richness[(3)]	H'[(4)]
M02	4				23	99	3.64
Mean		66.11	21.05	15.3			
SD		38.7	12.3	2.9			
Minimum		31.4	10	7			
Median		49.7	15.8	15			
Maximum		224	71.3	27			
M05	4				24	148	3.97
Mean		54.82	17.46	17.4			
SD		23	7.3	4.9			
Minimum		31.4	10	4			
Median		48.4	15.4	18			
Maximum		166.8	53.1	28			
M06	4				22	118	3.82
Mean		65.05	20.72	16			
SD		37.7	12	3.4			
Minimum		27	8.6	10			
Median		53.6	17.1	16			
Maximum		226	72	26			
M11	4				18	96	3.69
Mean		63.73	20.29	17.2			
SD		35.1	11.2	13.2			
Minimum		31.6	10.1	10			
Median		54.8	17.5	15			
Maximum		271.4	86.4	143			
CAST	2				14	45	3.15
Mean		65.09	20.73	14.56			
SD		53.8	17.1	5.2			
Minimum		31.4	10	5			
Median		44	14	14			
Maximum		330.4	105.2	26			
Couro Velho	1				7	19	2.08
Mean		55.34	17.62	8.68			
SD		19.7	6.3	2.6			
Minimum		31.4	10	5			
Median		51	16.2	8			
Maximum		89	28.3	14			

Anthropological studies have shown that local farmers recognise secondary forests on ADE through indicator plant species, even when the vegetation is dense (German, 2003). Farmers also recognise structural characteristics of vegetation associated with ADE, such as lower canopies and denser understories (Woods and McCann, 1999), smaller average diameter of adult trees, and a greater abundance of vines and plants with spines (German, 2003). Some species from secondary forests on ADE are recognised as ADE indicators, including some domesticated and/or useful species (Junqueira et al., 2010).

During the field survey along the Igapó-Açu River, Brazil nuts and babaçu palms (*Attalea speciosa)* that are indicators of ADE sites were found in abundance all along the river. On the Couro Velho site, ADE indicators, such as açai, coffee or cará do Índio (Clement 1999). The largest brazil nut three in the grove is 455 cm at DBH, and although there are many uncertainties around aging Brazil nut trees based on the diameter of their trunk, this individual can be *ca.* 1000 years old (Shephard and Ramirez, 2011; Peres and Baider, 1997), therefore it may have been planted by the people who created the ADE site.

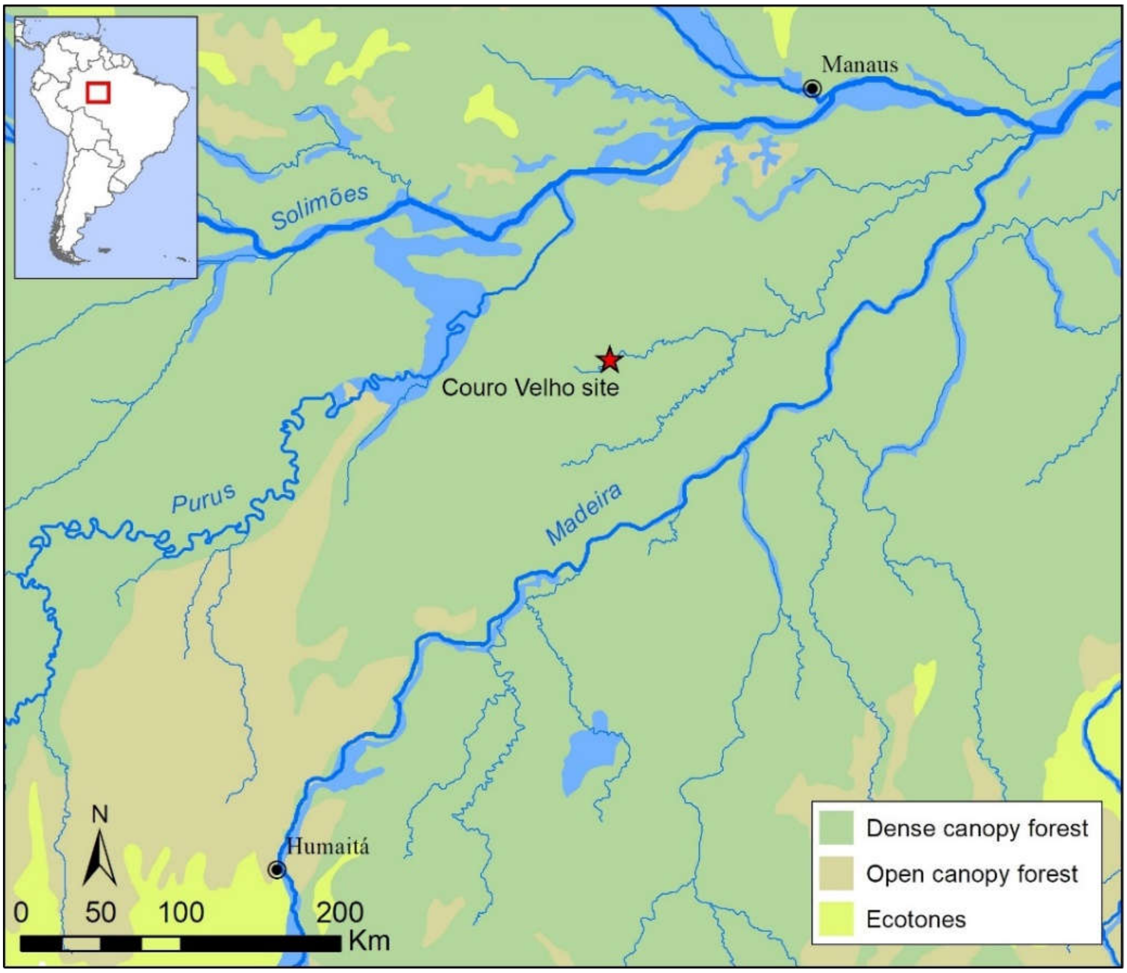


Figure 4.19: Location of the Couro Velho site along the Igapó-Açu River in the PMI. The vegetation classification is after IBGE (1992).

4.5 Archaeological finds at the Couro Velho site

The Couro Velho site is a black and brown ADE site (<1ha) along the Igapó-Açu River (Fig 4.19) that was possibly occupied around 1400–1100 cal BP (radiocarbon dates are outlined in section 4.7).

The artefacts consist mainly of burnt clay pieces of various sizes, consistencies, and colours, though a few pottery shards were encountered as well (Fig. 4.20). Although the thickness of the ADE layer is around 35–40 cm in every profile (O2 and Ac horizons), the majority of burnt clay and pottery was found in the Ac horizon *ca*. 20–30 cm b.s. (Fig. 4.21).

In some profiles, artefacts were found randomly (e.g. CAST1 P2), whereas in others (e.g. TP1 P3, TP1 P5) they exhibited distinct layers that signalled the approximate time of the ADEs formation (Fig. 4.21: B, C). Most of the pottery sherds that were found in the test pits were small, *ca*. 2–5 cm long and 0.5 cm thick (Fig. 4.20). Only one large pottery sherd was found, which probably came from the bottom of a vessel.

In the brown ADE profiles under Brazil nuts, even fewer ceramics were found; however, the amount of burnt clay was generally the same. Pottery was not found in the CAST profiles under the Brazil nut stand, only burnt clay was found. At Couro Velho, the TP1 P3 test pit yielded the largest amount of pottery during the excavation of the ADE layer (13 pieces), and the smallest amount was found in the ADE layer of TP1 P6 (4 pieces). Pottery sherds and burnt clay were also found on the surface of the site in small amounts (Fig. 4.21. A) both in the core area of Couro Velho and in the Brazil nut stand. On the surface, ceramics were particularly visible on the edge of the

Figure 4.20: Ceramics found during the excavation of test pits at Couro Velho.

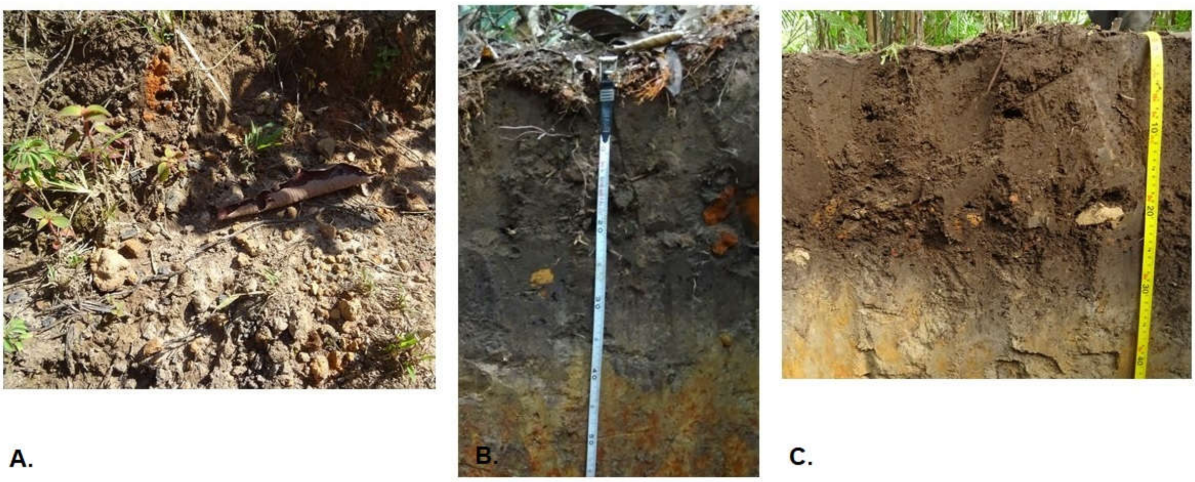


Figure 4.21: Burnt clay pieces at the Couro Velho site and the Brazil nut stand. (A) burnt clay on the soil surface, (B) large pieces of burnt clay in the CAST1 P2 profile in the Brazil nut stand, (C) layer of smaller burnt clay pieces in profile TP1 P3 n at Couro Velho.

river bluff where the soil has been eroded. No other artefacts were recovered from the site.

4.6 Measurements of *Cucurbita* sp. phytoliths

Apart from the one maize cob wavy top rondel found in TP1 P7 at 50 cm b.s., the *Cucurbita* sp. scalloped phytoliths represent domesticated species in the phytolith assemblages from Couro Velho and the Brazil nut stand.

Squash rind scalloped sphere phytoliths (Fig. 4.22) were recovered from one profile in the Brazil nut stand and two profiles at Couro Velho in the ADE horizons 0–40 cm b.s. (Table 4.2). In total, 32 scalloped spheres were identified and measured according to the method outlined by Piperno et al. (2000). Scalloped sphere phytoliths are produced by both wild and domesticated *Cucurbita* sp.*;* however, the domesticated species usually produce larger phytoliths. Piperno et al. (2000) compared the dimensions (length and thickness) of phytoliths from domesticated and wild *Cucurbita* fruits, and they found that only those from domesticated species exceed the length of 90 µm. Thus, none of the phytoliths identified in the present study are from domesticated squash. However, 16 of the 32 scalloped spheres identified fall into the category that Watling (2014:263) considers to represent a probable domesticate (>72 µm) in the lowland Amazon.

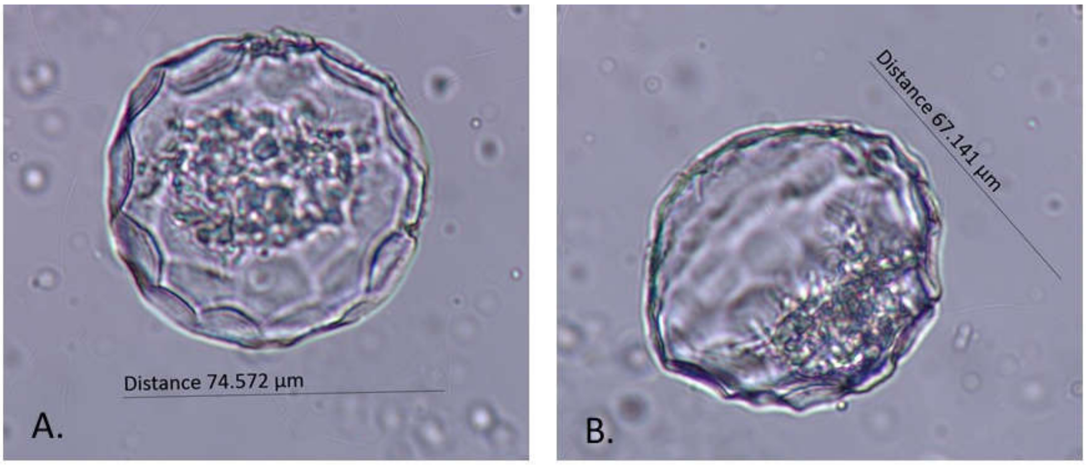


Figure 4.22: Microphotographs and measurements of a Cucurbita sp. scalloped sphere phytolith from TP1 P7 profile at 30 cm b.s.: (A) length, and (B) thickness.

Table 4.2: Length and thickness ranges, and average sizes of scalloped sphere phytoliths identified in soil profiles from the Brazil nut stand and Couro Velho.

Site	**Profile**	**Depth (cm b.s.)**	**No.**	**Thickness range (µm)**	**Mean thickness (µm)**	**Length range (µm)**	**Mean length (µm)**
Brazil nut stand	CAST2 P1	0	1	53	-	72	-
		15	2	55–61	58	68–69	69
		25	2	49–51	50	59	59
Couro Velho	TP1 P5	5	4	47–78	61	69–79	76
		10	1	67	-	73	-
		15	5	57–67	63	59–82	71
		20	1	61	-	67	-
		25	4	59–68	66	67–80	73
		30	2	51–64	57	70–81	75
	TP1 P7	10	1	59	-	78	-
		20	1	78	-	87	-
		25	1	45	-	65	-
		30	3	51–69	62	64–78	72
		40	4	58–74	65	43–74	54

4.7 Radiocarbon dates from Couro Velho and M11 P2

Four radiocarbon dates were obtained from wood charcoal at Couro Velho (Table 4.3). Three of them were taken from the cultural layer between 25 and 35 cm b.s from TP1 P2, TP1 P3 and TP1 P5. These dates fall 1360–1044 cal BP. One wood charcoal fragment was recovered from the border between the ADE and natural soil at 50 cm b.s. in TP1 P7 and was dated to 3632–3452 cal BP. All radiocarbon dates are for the core area of the site, but since all profiles at Couro Velho and the Brazil nut stand have a very similar structure, it is assumed that all soils developed around the same time. Therefore, since phytolith studies were not performed on TP1 P2 and TP1 P3 profiles and their geochemical signals show the same trends as that of TP1 P5, they are not discussed in more detail.

One radiocarbon date was retrieved from a bulk soil sample at 50 cm b.s. from M11 P2. Fifty centimetres marks the depth at which the a substantial increase in palm phytoliths occurs in the assemblage. All dates mentioned in the text from here onwards are calibrated, unless stated otherwise.

Table 4.3: Radiocarbon dates obtained from Couro Velho and M11 P2.

Laboratory no.	Profile	Depth (cm b.s.)	Context	Material	Conventional ^{14}C date	$\delta^{13}C$ ‰	Cal BP 2σ
Beta – 493370	TP1 P2	25 cm	Black ADE layer	charcoal	1210±30 BP	-26.6	1186–1059
Beta – 493371	TP1 P3	25 cm	Black ADE layer	charcoal	1410 ±30 BP	-26.9	1360–1285
Beta – 493369	TP1 P5	35 cm	Black ADE layer	charcoal	1160±30 BP	-26.2	1177–1044
Beta – 488810	TP1 P7	50 cm	Border of ADE and natural soil	charcoal	3350±30 BP	-27.2	3632–3452
Beta – 488813	M11 P2	50 cm	Natural soil under oligarchic forest	bulk soil	2820±30 BP	-18.6	2959–2782

4.8 Comparison of the distribution of main phytolith taxa groups in the soil profiles

Following the description of the main phytolith taxa groups in each profile (see sections 4.1–4.3), this section presents and discusses the distribution of the main taxa groups across the profiles. This comparison enables the assessment of the impact of different forest management practices on the vegetation composition.

4.8.1 Comparison of main phytolith taxa groups across all plots

The summary graph of the relative frequencies of the main phytolith taxa groups (Fig. 4.23) reveals a striking difference between the control site with primary forests (M05) and the other sites that have experienced different degrees of anthropogenic impact. The main difference corresponds to the amount of grass type phytoliths: as human impact grows, the number of grass phytoliths grows as well. The phytolith composition of the M05 P1 profile comprises *ca.* 3.5% grass taxa, *ca.* 2% herb taxa, *ca.* 4.5% palm taxa, and *ca.* 90% NPA taxa. In contrast, the phytolith composition of the black ADE profile, TP1 P7, contains *ca.* 17.5% grass, *ca.* 4.5% herb, *ca.* 11% palm, and *ca.* 66% NPA phytoliths.

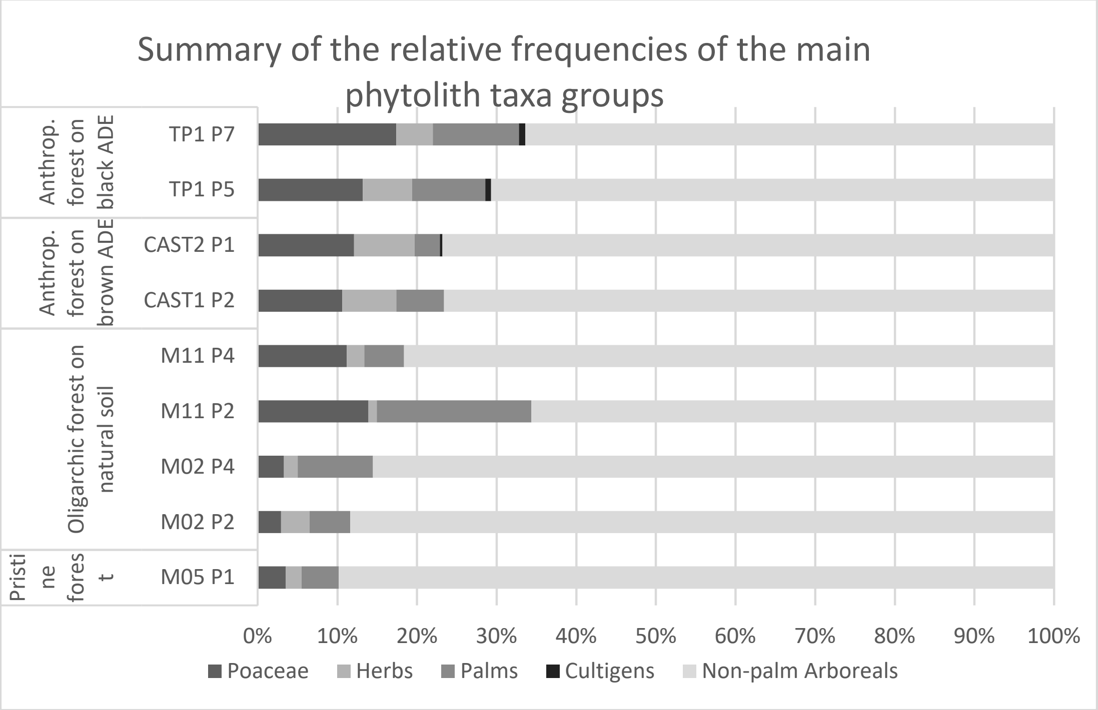


Figure 4.23: Summary of the distribution of the main phytolith taxa groups in each profile.

The only exception is the M11 P2 profile that contains many more grasses than the other profiles in the same oligarchic forest category. It is important to note that the difference in the percentage of grass phytoliths in the profiles under oligarchic forests relates both to anthropogenic and environmental processes. While the M02 study site is situated in central Amazonia, the M11 study site is situated next to Humaitá, close to the southern ecotone region between the rainforest and savanna. The approximately 600 km difference in location means the sites are subjected to different rainfall regimes. The two sites also have different natural vegetation: M02 has dense lowland forests, while M11 has open lowland forests (see section 3.2.1).

Numerous studies have suggested that open and drier forests are more sensitive to both climatic and anthropogenic influences than the dense forests, and natural or human-induced fires can more easily affect their vegetation compositions (e.g. Oliveras and Malhi, 2016; Silvério et al., 2013). The M11 P2 profile is an exception based on the high number of palm phytoliths, which may also relate to growing anthropogenic pressure (see section 4.1.5). In contrast, the other profile at the M11 study site (M11 P4) is 2 km away from M11 P2, and it does not exhibit equivalent differences to the other profiles under oligarchic forests, suggesting intra-site variability in the vegetation composition of site M11, which could have been caused by either a change in the local environment or less-intense human activity.

The quantity of herb phytoliths also increases with the increasing human impact, though this relationship is not as explicit as the relationship between grasses and human activity.

4.8.2 Comparison of the ADE profiles main phytolith taxa groups in the pre-ADE and ADE phases

The comparison of the distribution of the main phytolith taxa assemblages in the anthropogenic soil profiles before ADE formation (pre-ADE) and in the ADE itself (Fig. 4.24) exhibits an interesting pattern. Since, in all the profiles, the upper *ca*. 40 cm b.s. consists of ADE layers, this depth can be consdiered to differentiate the pre-ADE and ADE phases. In general, all pre-ADE phases consist of higher percentages of NPA morphotypes than in the ADE phases, as well as a lower amount of other phytolith taxa, suggesting that the vegetation was more closed before the ADE started to form.

However, it is also important to note that, even in the ADE phase, the NPA morphotypes dominate the phytolith assemblages, which implies that the area was never without tree cover. In the brown ADE profiles, the increase of grass phytoliths is 4.9% (CAST1 P2) and 6.4% (CAST2 P1), while the percentage of palms increases by 4.2% (CAST1 P2) and 2.4% (CAST2 P1), and the herb phytoliths increase by 2.8% (CAST1 P2) and 2.9% (CAST2 P1) compared to the natural soil below.

In the black ADE profiles, the difference between the phytolith assemblages of the pre-ADE and ADE phases is even more prominent. Compared to the pre-ADE phases, the percentage of grass phytoliths increases by 10.3% (TP1 P5) and 13.6% (TP1 P7), the number of herb phytoliths increases by 3.2 % (TP1 P5) and 2.8% (TP1 P7), and the number of palm morphotypes grows by 5.6% (TP1 P5) and 5.5% (TP1 P7). In summary, the number of herb phytoliths increases at the same rate in both the brown and black ADEs; however, the palms increase slightly more in the black ADEs. The increase of the grass taxa is twice as high in the black ADE soils than in the brown ADE soils when compared to their parent materials.

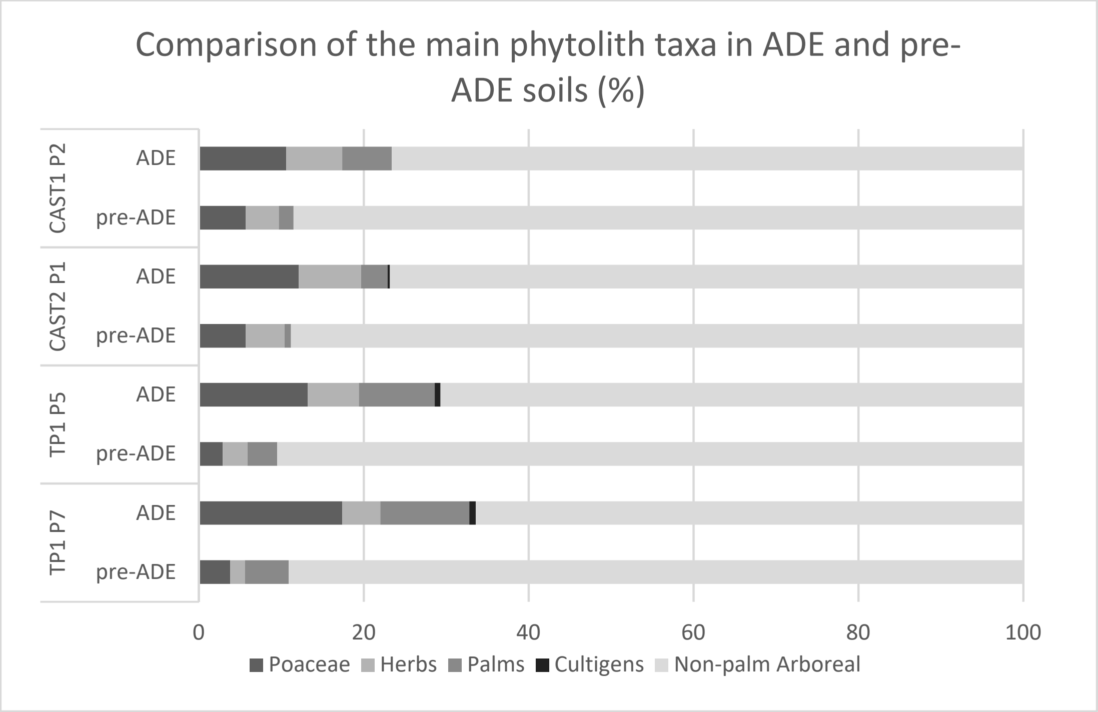


Figure 4.24: Distribution of main phytolith taxa in the anthropogenic profiles for the pre-ADE and ADE phase.

4.9 Variability in the soil geochemical and charcoal data based on linear regression analysis

Table 4.4. presents the results from calculating the coefficient of determination (R^2) with linear regression models between the total and available phosphorous, total carbon, total nitrogen, and charcoal count. R^2 is used to represent the degree of linear correlation between two variables, i.e. it explains how much the variability of one factor can be caused by its relationship to another factor. The correlation is also known as a goodness of fit, and R^2 is represented as a value between 0 and 1. The closer the value is to 1, the better the fit, i.e. the relationship, between the two factors.

Table 4.4: R^2 values representing correlations between soil geochemical data and charcoal data.

total phosphorous–available phosphorous (R^2)							
M05 P1	0	M02 P2	0.58	CAST1 P2	0.71	TP1 P5	0.55
M06 P4	0	M11 P2	0.60	CAST2 P1	0.75	TP1 P7	0.90
total phosphorous–total carbon (R^2)							
M05 P1	0	M02 P2	0.91	CAST1 P2	0.43	TP1 P5	0.31
M06 P4	0.98	M11 P2	0.92	CAST2 P1	0.97	TP1 P7	0
total phosphorous–total nitrogen (R^2)							
M05 P1	0	M02 P2	0.92	CAST1 P2	0.95	TP1 P5	0.07
M06 P4	0.92	M11 P2	0.93	CAST2 P1	0.20	TP1 P7	-0.03
total carbon–total nitrogen (R^2)							
M05 P1	0.99	M02 P2	0.99	CAST1 P2	0.91	TP1 P5	0.86
M06 P4	0.99	M11 P2	0.99	CAST2 P1	0.91	TP1 P7	0.88
charcoal–total phosphorous (R^2)							
M05 P1	0	CAST1 P2	0.61	TP1 P5	0.45	TP1 P7	0.03
charcoal–available phosphorous (R^2)							
M05 P1	0	CAST1 P2	0.20	TP1 P5	0.35	TP1 P7	0
charcoal–total carbon (R^2)							
M05 P1	0.86	CAST1 P2	0.56	TP1 P5	0.48	TP1 P7	0.83
charcoal–total nitrogen (R^2)							
M05 P1	0.83	CAST1 P2	0.53	TP1 P5	0.33	TP1 P7	0.63

The correlations between the total phosphorous and plant available phosphorous values are in general stronger in profiles with ADE soils than the profiles with natural soils. The exception is TP1 P5, where the correlation is only moderate (0.55). The available phosphorous is taken up by the roots of the plants, meaning a transportation of the available phosphorous from the subsoil to the topsoil and then the plant litter stays on the surface depositing phosphorous.

Available total phosphorous and total carbon correlate strongly in profiles with the least-modified soils—(M06 P4, M02 P2, and M11 P2. The only exception is CAST2 P1 with brown ADE. This correlation is weak in the two profiles with black ADE or there is even no correlation. Total phosphorous in the soil is relatively stable (Eidt, 1984); however, the stability of total carbon deepends on its composition. Organic carbon is subject to oxidation and migration in the profile; however, the total carbonalso includes charcoal that is stable. In the profiles where the macro charcoal counts are high, the amount of microcharcoal must be high as well, which makes the total carbonmore stable and less prone to leaching into the subsoil.

The correlation between charcoal counts and the total carbonvalues are the strongest in the control profile, M05 P1 (0.86), and in TP1 P7 (0.83). However, this strong correlation exists for different reasons. In the M05 P1 profile, the correlation is high, because both the amount of charcoal and the total carbonvalues are very low, whereas both are very high in the TP1 P7 profile. Total carbonand macro charcoal counts, however, do not necessarily correlate when the macro charcoal counts are lower, as in the case of TP1 P5 (0.48) and CAST1 P2 (0.56). Therefore, since total phosphorous is stable but total carbon is not necessarily stable in the soil, these variables will not always correlate, even when both elements are being added through anthropogenic input.

As Lehmann et al. (2003) suggested, the quantity of total nitrogen is usually higher in anthrosols than in natural soils, therefore its correlation with total carbon is expected to be stronger in ADE profiles than in natural soils. However, in this thesis' results, the total nitrogen content is not higher in the ADE soils than in the natural soils, consequently, due to the much higher total carbon content in the anthropogenic soils, the total carbon–total nitrogen correlation is very strong in the natural soils and slightly weaker in the profiles with ADE soils.

4.10 NMDS of modern vegetation inventories and phytolith assemblages at the studied forest plots

In this section the results of the NMDS of the modern vegetation inventories, the soil surface phytolith data, and the phytolith assemblages of the soil profiles at 60 cm b.s. are presented and discussed. In this thesis, the NMDS ordination proved to be useful to visualising similarities and dissimilarities between the study sites based on their modern vegetation compositions and phytolith data. The NMDS also allowed this complex, multidimensional data to be summarised in a 2D graph. The NMDS ordinations were performed based on Bray-Curtis dissimilarities.

4.10.1 NMDS of modern vegetation inventories

The similarities and dissimilarities between the modern vegetation data from the inventoried forest plots are shown in Fig. 4.26. Before interpreting the data, however, it is important to examine whether the data collected is suitable for this kind of transformation. The Shepard stress plot (Fig. 4.25) represents the differences between distance in reduced dimensional space (the NMDS plot) compared to complete multidimensional space (the data before the transformation), showing how much the data may need to be manipulated during the process to be fit into the 2D space.

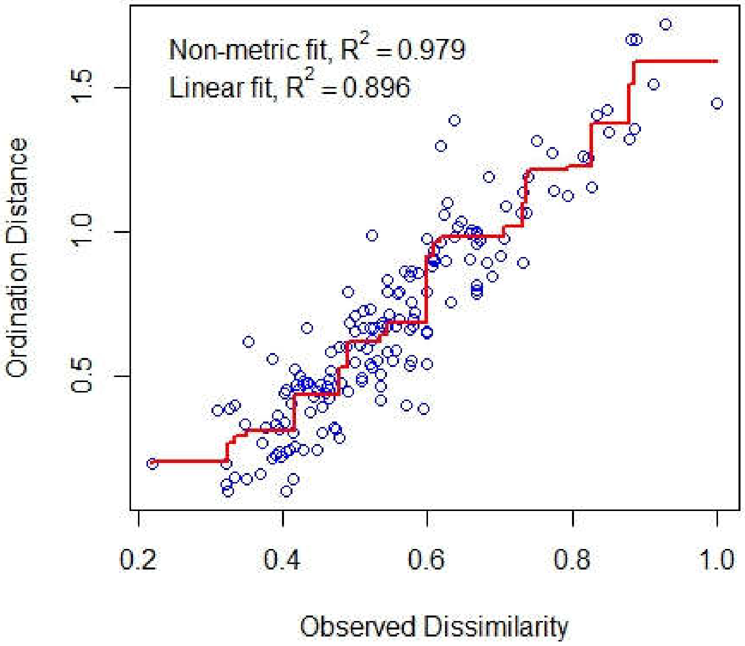


Figure 4.25: Shepard stress plot of the NMDS conducted on modern vegetation inventories representing the difference between distance in the reduced dimension compared to complete multidimensional space.

The very strong R^2 values on the Shepard stress plot imply that the data was not majorly manipulated in order to plot it for the 2D NMDS. Another way to review the NMDS ordination is to check the stress value, which gives an indication of how well the ordination summarises the distances betwenn the samples. If the stress value is

>0.1, the representation of the data in the reduced dimensions is great, if the value is >0.2, the representation is good (see section 3.2.6).

Visually, simlarity is expressed by how close the points representing vegetation inventories appear to each other on the plot. forest plots . In Fig. 4.26, forests are sorted by type, including inventories with primary vegetation (four plots at M05 and four at M06) are represented with purple crosses, oligarchic forests (four plots at M02 and four at M11) are represented with blue triangles, the Brazil nut stand (two CAST plots) is represented with green diamonds, and the plot at Couro Velho is also incuded.

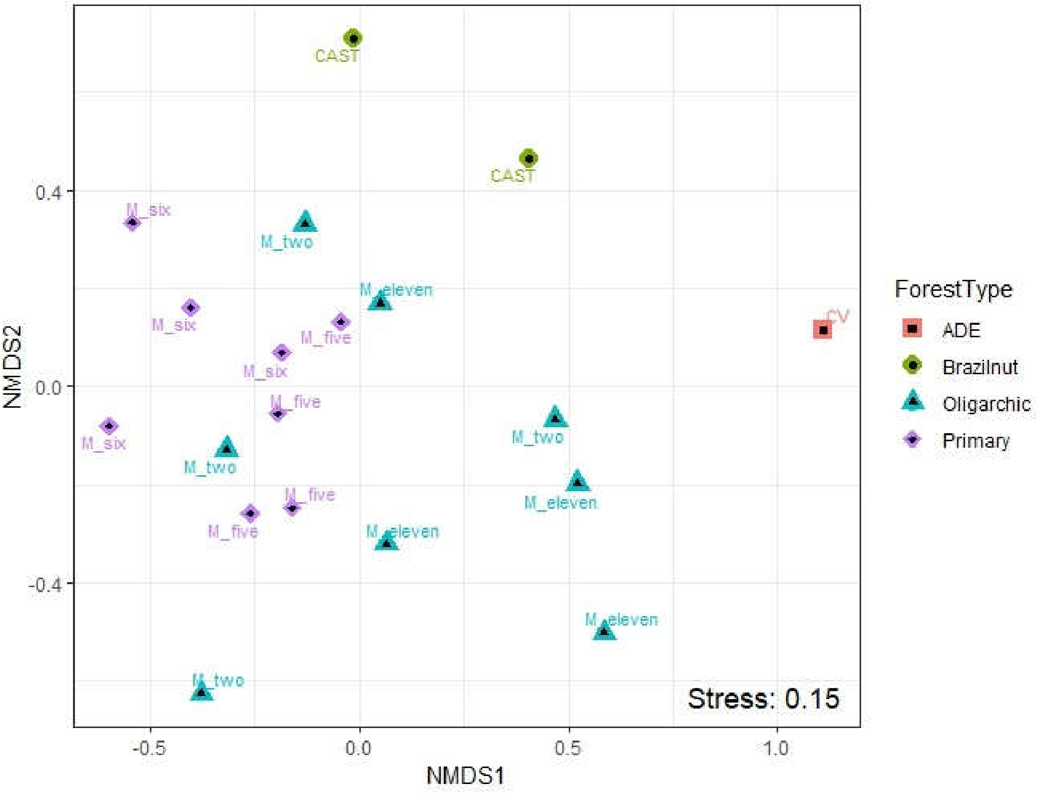


Figure 4.26: NMDS plot of modern vegetation inventories (trees with >10 cm DBH) on a family level based on Bray-Curtis dissimilarities. Stress value = 0.15.

The forest plots with primary vegetation (M05, M06) show great similarity to each other, as they appear in a cluster on the left side of Fig. 4.26. This means that, based on the vegetation inventories, their vegetation composition is very similar. However, slight differences within this forest type are still observable, as the M06 plots are situated in the upper left of the cluster, whereasM05's plots are situated further to the right.

On the other hand, the oligarchic forest plots (M02, M11), although still situated in the bottom left of the figure, are more scattered, which implies that their vegetation compositions are less similar than those in the primary forest group. Greater difference was anticipated for the oligarchic forest plots, because there is a large geographic distance between sites M02 and M11; however, the NMDS ordination also does not show clear clustering between the four M02 and the four M11 forest plots.

Other interesting information that can be seen is that the two plots from the Brazil nut stand (CAST) next to Couro Velho are far apart from each other on the figure. These two plots are located 150 m apart, and the differences in phytolith assemblages and geochemical signals between the two has already been noted (section 4.2.2). Despite these differences, the CAST plots represent a distinct cluster at the top of Fig. 4.26.

As expected, the vegetation inventory carried out on the ADE soil at Couro Velho (CV) represents vegetation that is very distinct from the other plots. It stands completely alone on the right side of the figure.

4.10.2 NMDS ordination of each profile’s phytolith assemblage at 60 cm b.s. and the surface

The NMDS ordination was applied to visualise the similarities and dissimilarities between the phytolith composition of each of the soil profiles. The phytolith assemblages of soil samples at 60 cm b.s. and at the surface were analysed from the control profile (M05 1), four profiles from forest modules representing oligarchic forests (M02 P2, M02 P4, M11 P2, M11 P4), two brown ADE profiles from the brazil nut stand (CAST1 P2, CAST2 P1), and two black ADE profiles from Couro Velho were analysed. The depth at 60 cm b.s. represents the time that most likely corresponds to minor or no human impact, and the surface soils represent the modern state of the study areas. The same methodology used in section 4.10.1 was applied. The names of the profiles and their code names for the NMDS are shown in Table 4.5.

The NMDS of the phytolith assemblage of all profiles at 60 cm b.s. (Fig. 4.27: A) reveals the inter-site variability of the vegetation. The phytolith composition of the primary forest (M05 P1) is most similar to one of the oligarchic forest plots (M02 P4) and one of the plots in the Brazil nut grove (CAST1 P2). They are all situated at the left side of the ordination, i.e. the part of the NMDS1 acis with negative values.

Table 4.5: Soil profiles that were included in the NMDS ordination with their assigned code names.

Forest type	Soil type	Soil profiles with phytolith data	Assigned code names	Assigned colour
Primary	Natural	M05 P1	M_five_one	purple
Oligarchic	Natural?	M02 P2	M_two_two	blue
		M02 P4	M_two_four	blue
		M11 2	M_eleven_two	blue
		M11 P4	M_eleven_four	blue
Brazil nut stand	Brown ADE	CAST1 P2	CAST_one	green
		CAST2 P1	CAST_two	green
Couro Velho site	Black ADE	TP1 P5	CV_five	red
		TP1 P7	CV_seven	red

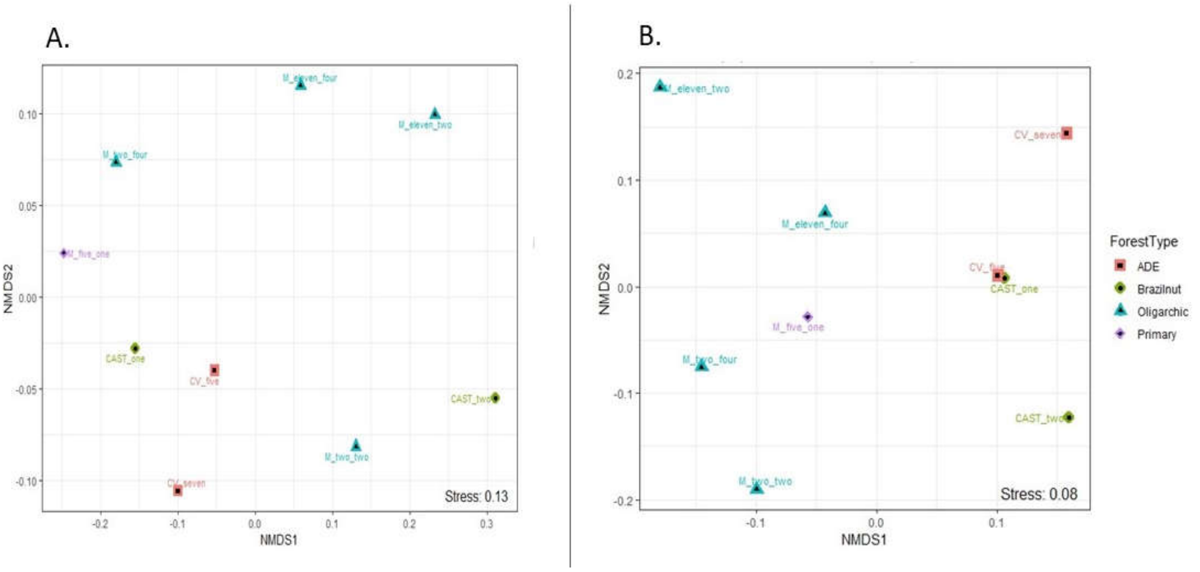


Figure 4.27: NMDS plot of the Bray-Curtis dissimilarity on phytolith assemblages at: (A) 60 cm b.s.; and (B) the topsoil.

However, plots from the same study sites (M02 P4, CAST2) are situated in the positive end of the NMDS1 axis, representing notable differences in the phytolith compositions of M02 and the Brazil nut stand. The phytolith assemblages of the profiles at M11 site are, however, more similar to each other, as they are both situated on the positive end of both the NMDS1 and NMDS2 axes. The distance of these sites from the other study sites might show an inherent difference in their vegetation compositions, as M11 is situated in a drier forest close to the southern border of the Amazon rainforest. The two black ADE profiles at Couro Velho are in the left bottom corner the negative side of both axes.

The NMDS of the surface soil phytoliths (Fig. 4.27: B) reveals how the phytolith composition of the forest plots changes through time with increasing human impact atf some sites. NMDS1 is likely the axis that represents the degree of human impact from low impact on the left side towards higher impact on the right. The NMDS ordination shows a very clear separation of phytolith assemblages in natural soils under primary or oligarchic forests (left side) and ADE soils (right side). Additionally, the phytolith assemblages of M02 (left side, bottom) and M11 (left side, top) are also clearly different from each other. This can either be explained by the ecological differences between the sites—M11 is a more open, dry forest with more abundant palms located close to Humaitá, whereas M02 is a closed-canopy forest with fewer palms in central Amazonia—or by the differing degrees of past human impacts.

The surface soils from the brown and black ADEs are also clearly separated in the plot, the black ADE plots are on the right at the top, while the brown ADE profiles on the right at the bottom. I interestingly, however, it is worth noting that one black and one brown soil profile have very similar phytolith assemblage in their surface soils.

4.10.3 Procrustes rotation of each profile's phytolith assemblage at 60 cm b.s. and the surface

Procrustes rotation was performed on the two NMDS ordinations to visualise the magnitude of changes each forest plot experienced through time based on the changes in their phytolith composition at 60 cm b.s. and in the topsoil (Fig. 4.28). The length of the arrows demonstrates the extent of the change evident in the phytolith assemblages from the bottom to the top of the profile. The direction of the arrows represents whether each assemblage is becoming more or less similar to other assemblages.

Many of the forest plots (TP1 P5, TP1 P7, CAST1 P2, M05 P1, and M02 P4) are located at the bottom left of Fig. 4.28 and move closer to each other over time. This part of the graph correponds to the minus values for both axes (dimension1 and dimension2). This suggests that the plots become more similar to each other through time. This is interesting, because M05 P1 is used in this thesis as a control profile, representing the most minimal human impact among all the study areas, but it is situated close to the forest plots with the largest anthropogenic impact. However, it is important to note that study of this profile’s phytoliths found a slight increase in the number of palms towards the surface (see section 4.1.1), and, since this is a trend common to all the profiles, this might be why these particular profiles cluster in the Procrustes rotation.

Alternatively, M11 P4 moves away from the negative cluster of forest plots but moves closer to the other profile from site M11, M11 P2. Based on the length of the arrows, the phytolith compositions of M02 P2 and CAST2 P1 appear to have undergone the biggest changes over time, becoming more similar to each other.

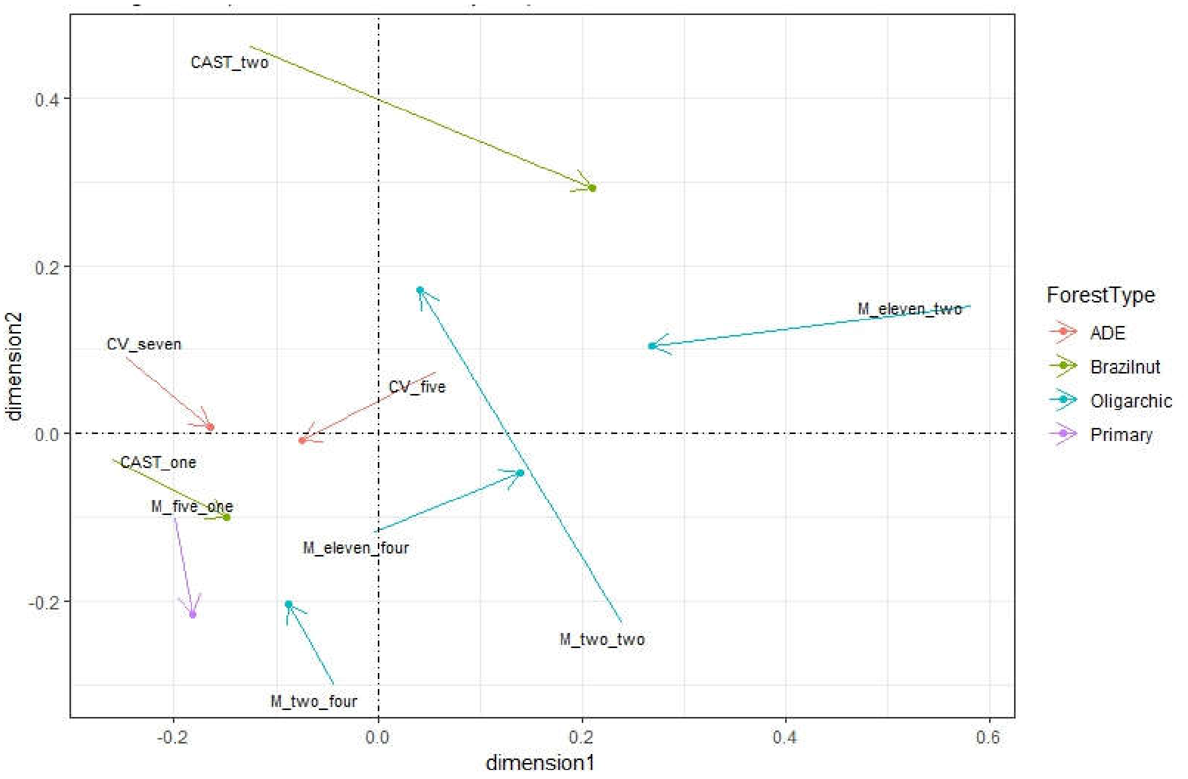


Figure 4.28: Procrustes rotation of the NMDS ordination on the phytolith assemblages at 60 cm b.s. and the surface.

CHAPTER 5

Discussion

The main objective of this chapter is to discuss the data presented in Chapter 4,.beginning by presenting the methodological implications of the phytolith study. This is followed by an overall evaluation of the phytolith and geochemical data, statistical analysis, and multidisciplinary approach in understanding the long-term impact of pre-Columbian land use on modern vegetation and soil properties. This thesis' key findings concerning the northernmost evidence for mid-Holocene drought, land use on ADE sites in small riverine settings, and the development of brown ADE soils are also discussed.

5.1 Methodological considerations of the phytolith analysis and interpretation

The general advantages and shortcomings of the phytolith method have been discussed in section 3.2.1. Here, some issues that arose during the fieldwork and the laboratory analyses are expounded upon, as examining these will produce a more reliable method.

5.1.1 The impact of bioturbation on phytolith deposition

During the excavation, cleaning, and description of the soil profiles, as well as taking the sample collection, the profiles were carefully examined to avoid visible disturbances, e.g. bioturbation by animals or plant roots, which are highly common in tropical forest soils (see section 3.1.2).

When Grave and Kealhofer (1999) examined the impact of bioturbation on phytolith deposition in soil profiles in tropical Vietnam, they found more than 50% of the sediment column had been disturbed by insect activity. This was evident at the scale 200–5000 µm. However, this thesis used a scale of 5–50 µm for the phytolith analysis, at which scale the sediments did not seem to be significantly mixed, therefore bioturbation did not affected the interpretation. Shillito (2013) argues that stratigraphic mixing and moving is a salient concern when trying to associate a phytolith deposit with radiocarbon dates; however, she cites a study that was conducted on loess soils in the Pampas by Osterrieth et al. (2009). Therefore, for this thesis, when large scale bioturbation was not visible, it was assumed that the phytoliths had remained stable in the profile. Larger scale and explicit bioturbation caused by roots was, however, considered. In TP1 P7 profile, for example, roots of a tree had disturbed the sampling column, therefore a new column was selected.

5.1.2 Post-deposition processes

Post-depositional processes, such as the erosion or dilution of phytoliths, were also considered during the analysis. The paucity of C-fraction phytoliths at lower levels in some of the profiles suggests that larger phytoliths might be more commonly dissolved or eroded than smaller phytoliths. Some studies have already addressed this phenomenon. For example, Cabanes and Shahack-Gross (2015) found that the stability of various morphotypes differs, mainly depending upon their surface area to bulk ratios. Calegari et al. (2013), while testing the effectiveness of different phytolith extraction methods, found that the number of phytoliths extracted decreased with depth, regardless of the method. They argue that taphonomic processes and vertical or lateral translocation by water can have a profound impact on phytolith assemblages.

In this thesis, C-fraction phytoliths were absent or only present in very low numbers at the depths of 65 cm b.s., 70 cm b.s., and 75 cm b.s. in most of the profiles, therefore only the A-fraction phytoliths were considered in the further analysis for these depths. The three exceptions were the control profile M05 P1 and the two black earth profiles at Couro Velho. In the M05 P1 profile, an insufficient number of C-fraction phytoliths was found at 30 and 60 cm b.s., but both the diversity and number of C-fraction phytoliths were satisfactory for further analysis below 60 cm b.s.

The field observations and geochemical analyses detected no visible bioturbation during sample collection, and neither the pH nor the texture of the soil differed at these depths from the rest of the profile. Therefore, the reason behind the suddenly low amount of C-fraction phytoliths at two points in the middle of the profile is unknown and requires further study. In the cases of the TP1 P5 and TP1 P7 profiles, they contained sufficient numbers and diversities of phytoliths throughout, therefore all depths were thoroughly examined.

5.1.3 Phytolith interpretation

Phytoliths can provide researchers with significant information, especially in tropical regions, where most macro plant remains are absent or poorly preserved (Piperno, 2006). However, the current low resolution for taxonomies in phytolith studies can be limiting for the use of phytoliths as proxies for environment reconstruction. For example, in tropical forests, closely-related taxa (e.g. palms or eudicots) produce similarly-shaped phytolith morphotypes, leading to difficulties in refining the identification to lower taxonomic levels, such as genus or species (Ball et al., 2016).

Phytolith studies of ADE sites in lowland Amazonia have mainly concentrated on identifying domesticates and useful wild resources (e.g. (Bozarth, Prince, Woods, & Rebellato, 2009); Morcote-Ríos et al., 2013; Macedo, 2014); however, species of domesticates, semi-domesticates, and exploited wild plants are either exceedingly limited, absent, or unidentifiable in the phytolith record. For example, peanuts (*Arachis hypogaea*) and hot peppers (*Capsicum* sp.) that were domesticated in the Upper Madeira region (Clement et al., 2016) do not produce diagnostic phytoliths (Piperno and Pearsall, 1998a).

Manioc is one of the most important domesticates besides maize and squash, but it only rarely produces diagnostic phytoliths (so called “heart-shaped” phytoliths) and only in its secretory bodies (Chandler-Ezell et al. 2006). Therefore, even if manioc has been cultivated, its presence in the archaeological record can be limited. Additionally, the study that identified the diagnostic phytoliths from manioc by Chandler-Ezell et al. (2006) was only performed on domesticated species; wild species were not included. Therefore, there is currently no scientific agreement that only domesticated manioc species produce these rare, diagnostic phytoliths.

Palms are probably one of the most common wild resources used by pre-Columbian people (Morcote-Rios & Bernal, 2001), or they are at least the most common wild resource in the phytolith record. In this thesis’ soil profiles, palms were more common in anthropogenic soils than in non-anthropogenic ones, with only one exception: M11 P2, which is from an oligarchic forest. Thanks to recent efforts in providing diagnostic information at the levels of subfamily, tribe, genus, and, in some cases, species (e.g. Morcote-Ríos et al., 2016), more morphotypes can be distinguished and better assumptions made about pre-Columbian diets.

Morcote-Ríos et al. (2016) found that the two main phytolith morphotypes in palms, conical bodies (hat-shaped), and globular echinates are usually not produced by the same plant, therefore the presence of one or the other type narrows down the plant families that were utilised by Amerindians on a particular site. For example, large globular echinates with short, dense projections were isolated in the *Euterpee* and *Oenocarpus* genera. Therefore, their presence in the phytolith record could indicate the consumption of açaí fruits. Conical bodies are produced by the *Bactris* and *Astrocaryum* genera, while symmetrical echinates occur only in the *Mauritia*, *Mauritiella*, *Euterpe*, *Oenocarpus*, *Ammandra*, and *Attalea* taxa (Morcote-Ríos et al., 2016: 356). Further studies are still needed, however, for palm phytoliths to be usable as solid tools for reconstructing pre-Columbian diet and land use.

In addition to the study of palm phytoliths, another way to look beyond the over-representation of arboreal-type phytoliths has been the measurement of human impact based on the proportion of disturbance and early successional species (e.g. *Heliconia* sp*.,* grasses, and sedges) in the phytolith record. This approach has been applied in a number of studies in different regions of Amazonia to suggest a range of human impact (McMichael et al., 2012b, 2014; Piperno et al., 2015); however, an issue is that extensive agroforestry practices—here opposed to the intensive farming of cultigens—remain difficult to detect in the phytolith record, as they do not leave strong visible signals (Clement et al., 2015; Stahl, 2015). For example, in this thesis, grass phytoliths constitute *ca.* 10–17% and herbs (early successional taxa) only *ca.* 5–8% of phytolith assemblages in the anthropogenic soil profiles at Couro Velho and the Brazil nut stand (see section 4.8.1). Thus, if the presence or absence of herbaceous taxa had been used as a proxy for human activity in this thesis, these explicitly anthropogenic sites would have overlooked.

5.2 Overall summary of the phytolith and geochemical data and their implications

5.2.1 Phytolith data

As outlined in the review of previous research (2.2.3), this thesis built on the findings of two previous studies that have examined pre-Columbian human impact in the PMI. McMichael et al. (2012b) proposed that human impact was, if any, sparse and localised in the PMI, while Levis et al. (2012) were ambivalent about whether large, forested areas were managed to a lower or higher degree.

The phytolith record examined in this thesis showed minimal differences in the assemblages from the control site with primary forest (M05 P1) and the M02 forest site considered oligarchic by Levis et al. (2012). The likely importance of agroforestry to pre-Columbian land use strategies has long been assumed, but, as yet, little evidence has been accumulated to support this assumption in locations devoid of ADEs, as probably is the case for M02.

The other oligarchic forest site (M11) exhibited greater differences compared to the control site. Grass taxa constituted 11–14% of the phytolith assemblages at M11, which is comparable to that in the ADE soil profiles, although herbs only constituted 1–2% of the whole assemblage, which is the lowest among all the sites. Palm morphotypes, on the other hand, were recovered in the largest quantities at M11 P2. Since M11 is close to the ecotone region between the southern rim of the Amazon rainforest and savanna, where the vegetation is more sensitive to climatic and human pressures, smaller events can leave larger footprints than in the more resilient inner regions of the Amazon Basin (Oliveras and Malhi, 2016). Either due to natural or anthropogenic influences, the phytolith record shows more open forest here, shown by *Heliconia* sp. (a sun-loving, early successional plant), for example, which were recovered in the largest quantities from M11 P2.

The CAST1 P2 and CAST2 P1 profiles in the Brazil nut stand are good examples of a gradient of forest types from oligarchic (forests dominated by useful trees) to anthropogenic (forests dominated by useful trees on ADE soils). In the CAST profiles, although the number of palm phytoliths was relatively low, grass and herb taxa were represented in larger quantities than in the oligarchic forests.

In both the CAST and Couro Velho soiil profiles, other useful plants beside palms, like Asteraceae, Cyperaceae, Marantaceae, *Mendoncia* sp., Annonaceae, and *Celtis* sp., were encountered. The Annonaceae, which was probably domesticated to some extent (Clement, 1999), was recovered from the M02 study site as well as the ADE soils. *Celtis* sp. was only found in the profiles with ADE soils.

Among the herbs, the Marantaceae family includes important species that produce diagnostic phytoliths. This family's species are known to produce starch-rich, edible roots, such as arrowroot (*Maranta arundinacea*) and leren (*C. allouia*) (Chandler-Ezell et al., 2006). In this thesis' analyses, Marantaceae phytoliths were found in higher numbers in the ADE profiles than the natural soil profiles, and *Calathea* was only recovered from the ADE soils. Since the Marantaceae family comprises shade-adapted plants, their higher presence in the ADE profiles may indicate that the forests on the ADE soils at Couro Velho and the Brazil nut stand were not removed completely during occupation.

In addition, from the cultigen-producing phytoliths, squash was recovered from the two black ADE profiles and one brown ADE profile, in addition to one maize cob wavy-top rondel from the pre-ADE phase in the brazil nut stand profile. As the phytoliths from the cob are produced in small quantities by the plant organs (Piperno, 2006), the large number demonstrates that maize was regularly eaten at the site. Evidence for farming maize—the occurrence of phytoliths produced in the leaf of the maize—was not found.

5.2.2 Geochemical data

The geochemical analyses revealed large differences between the natural soils at M02, M05, M06, and M11 study sites (plinthic acrisol and gleysol) and the ADE soils at the Brazil nut stand and Couro Velho. These differences manifested in all the properties examined: total and available phosphorous, total carbon, total nitrogen, and the C:N ratio. For example, total phosphorous was <50 mg/kg in the natural soils, excluding the upper 5 cm b.s., where there was some biological activity. The only exception from this rule is the M11 P2 profile, where either the naturally higher number of palms or human impact has caused higher total phosphorous values in the upper 25 cm b.s. of the profile. Since the phytolith record from the other M11 study site (M11

P4) does not show a similar increase in the number of palms, however, it is likely that the forest patch and soil have been manipulated by humans in the past.

As discussed in sections 2.3, 2.5, and 3.2.2, ADEs are anthropogenic soils widespread in Amazonia that are associated with archaeological sites. They present high values for pH, organic carbon, nitrogen, calcium, phosphorous, potassium, zinc, magnesium, and manganese (Kern 2009). The activities and processes required for the formation of ADEs, however, remain a matter of debate among scholars of the Amazon across several fields.

Initially, brown and black ADEs were separated, and it was thought that they formed under different types of land use: black ADEs were considered the outcome of settlement activities—mainly household and construction waste disposal—while brown ADEs were the outcome of intensive cultivation practices or even the intentional creation of brown ADEs for agricultural purposes (Arroyo-Kalin, 2010, 2012, 2014; Woods and McCann, 1999). Others, however, have questioned this simplistic classification, arguing that there is much higher variability in the origin and properties of these anthropogenic soils. Suggestions have been made that the difference between brown and black ADEs is not limited to different land use but also intensities of land use. From this perspective, the brown ADEs are the results of less intensive practices, while the black ADEs have resulted from more intensive practices (Kämpf et al., 2003; Kern et al. 2009b).

In this thesis, the geochemical analyses revealed the possible different origins of the brown ADE soils at Couro Velho (TP1 P2, TP1 P2, TP1 P6) and the Brazil nut stand (CAST1 P2, CAST2 P1). Although all these profiles had a *ca*. 35–40 cm-thick brown layer with two distinct sublayers that containedlarge amounts of charcoal and some artefacts, there were differences in their geochemical signals. While the total carbon content and the C:N ratio of these soil profiles was very similar to each other, there were notable differences in their total and available phosphorous content.s Compared to the control profile (M05 P1), the total phosphorous content was clearly higher in the CAST profiles, as expected from an anthropogenic soil, but it was much lower than that in the brown and black earth profiles. This suggests a larger amount and/or different source of phosphorous for the brown ADE soils at Couro Velho than the Brazil nut grove.

In the case of available phosphorous, the CAST profiles contained very similar amounts to the control profile. The Couro Velho profiles, however, contained much larger amounts of available phosphorous than the CAST profiles. Based on these results, it seems that, although the brown ADE at the Brazil nut stand and brown ADE at Couro Velho look similar, they have different origins. The brown ADE at Couro Velho is probably a young black ADE which received phosphorous from sources such as household waste, food waste, human and animal excreta, hearth ash, river sediment, etc. In contrast, the brown ADE at the Brazil nut stand is the result of extensive farming, including burning the forest understorey and incorporating the charcoal and ash into the soil.

5.2.3 Statistical approaches

The statistical analysis revealed interesting things about the study sites, particularly the relationship between them. The NMDS analysis successfully detected differences in the vegetation compositions of the study areas clearly separating them on the plots. (section 4.10.1).

In earlier studies, other ordination methods, especially principal components analysis have been successfully applied to compare soil profile samples and distinguish vegetation formations in Amazonia (Dickau et al., 2013; Watling et al., 2016).

For this thesis, NMDS analysis of the sites' modern vegetation inventories was particularly useful for separating the pristine, oligarchic forests from the anthropogenic forest and ADE, which can be used to show the gradient of increasing human impact (Clement, 1999). The natural state of all profiles' vegetation compositions was represented in the NMDS analysis using the results at depth 60 cm b.s. This acted as a baseline for the later analysis, and revealed the variability between the sites, showing, for example, that two profiles at one site might have quite different phytolith signals (e.g. M02, both CAST profiles). The NMDS analysis of the surface soil phytoliths also showed a clear difference between the forest sites with no or minimal anthropogenic impact and those with higher anthropogenic impact.

Finally, the Procrustes rotation displayed the complex interaction between the natural inter- and intra-site variability and the different degrees of human impact on the sites.

5.2.4 Usefulness of the multidisciplinary approach for unentangling long-term human-environment interactions

In this section, the four land use/forest management types—primary forest on natural soil, oligarchic forest on natural soil, anthropogenic forest on brown ADE, archaeological site with black ADE—are examined, and the relationships between their phytolith assemblages, geochemical signals—total and available phosphorous, total carbon, total nitrogen, and the C:N ratio—and micro charcoal contents are discussed. The question raised here is whether the changes in the phytolith assemblages and, consequently, the vegetation composition in the past can be associated with changes in the geochemical signals and charcoal contents of the soil profiles? Alternatively, how have the anthropogenic and natural processes in the soils impacted the structure and composition of the vegetation?

At the regional scale, the phytolith assemblages and charcoal contents of forest soils that have experienced different degrees of human impact have been studied in *terra firme* forests in western and south-western Amazonia (e.g. McMichael et al., 2015; Watling et al., 2017), as well as at sites on river bluffs in central Amazonia (e.g. Maezumi et al., 2018); however, their results are controversial (see Introduction).

At the local scale, anthropological accounts of soil-ameliorating techniques in and around indigenous settlements are useful to understanding and interpreting geochemical and charcoal data, and may even help connect these with the phytolith data. As an example, Hecht (2003) detaiils contemporary Kayapó practices and describes how their everyday lifestyles can contribute to the development of ADE soils. The technique used by the group to improve soil properties on agricultural fields is to prepare a midden of food residue, ashes, old baskets, large animal bones and hides, old roofs, other construction materials, and palm leaves. The midden is then set alight so it burns at a “cool” temperature that causes the incomplete combustion of the organic material. The ashes and black charcoal waste are then scattered on the Kayapó’s fields to enhance fertility by increasing levels of phosphorous, carbon, and potassium. A similar process is described in van Hofwegen (2009) who created a conceptual model of nutrient flows that contribute to ADE formation (Fig. 5.1).

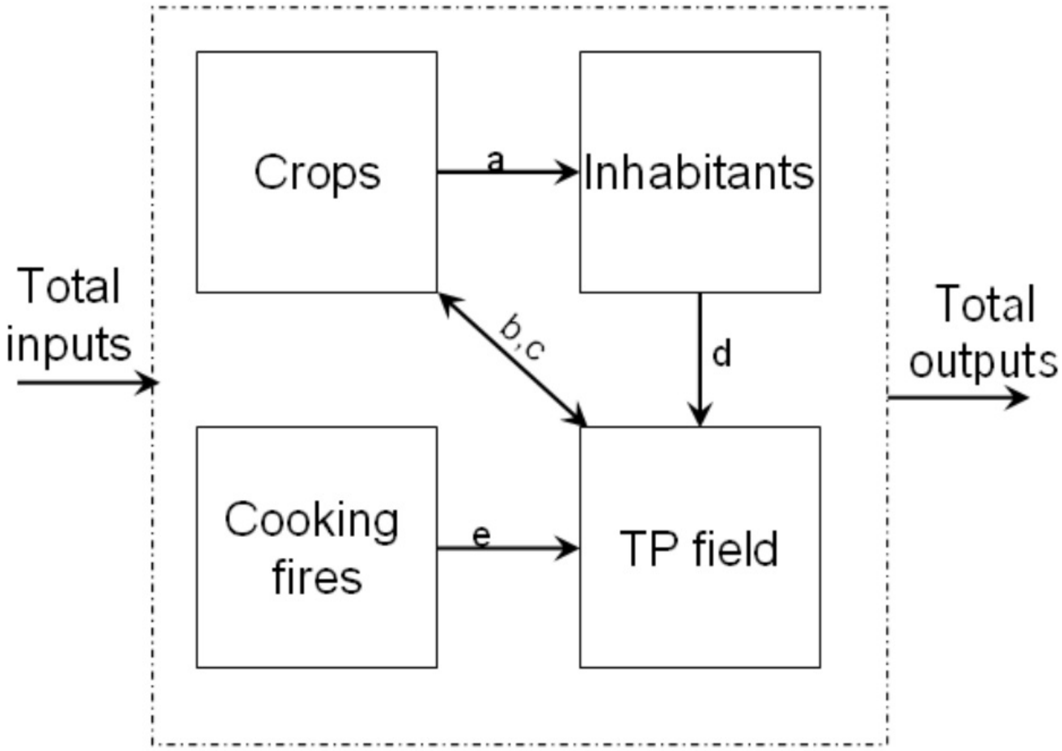


Figure 5.1: Conceptual model of internal nutrient flows that contribute to ADE formation. All arrows represent flows of carbon, nitrogen, and phosphorous. The letters represent: (A) harvested products, (B) uptake of nutrients by crops, and (C) nutrients from crop residue.

High-organic matter content is one of the main features of ADE soils (see section 2.3). Stabilisation of the organic matter, as well as macronutrients and micronutrients, is associated with the incomplete combustion of organic material, called black carbon (charcoal) (Glaser et al., 2001). Since the major components of organic matter are carbon and nitrogen, this suggests that elevated concentration of carbon in the soils can be directly associated with vegetation management, the use of fire, and the production of charcoal.

In this thesis, both the macro charcoal content and the concentration of carbon were extremely high in the ADE soils compared to the control soil. Bones, urine, human and animal excreta, and food preparation activities could have added phosphorous to this soil composition (Woods, 2003; Birk et al., 2011). Additionally, transfer of phosphorous from biomass to soil following slash-and-burn activities could initially increase phosphorous availability to plants (Palm et al., 1996). The anthropogenic soils examined in this thesis, especially the black ADE profiles at the core of Couro Velho, were characterised by elevated levels of phosphorous. The large concentrations of total phosphorous, carbon, and nitrogen resulted in a stabilised soil where the C:N ratio is *ca*. 17.6. This stabilisation could aid the further enrichment of soil (van Hofwegen et al., 2009). Although

Lehmann et al. (2003) suggest that, even though the quantity of nitrogen is usually higher in anthrosols than in natural soils, it can be immobilised (unavailable for plants) if the C:N ratio is too high. In this thesis, the C:N ratios of the PPBio soil profiles do not reach the 17.6 level. The highest was found in the M11 P2 profile, which reached 13:8 at 35 cm b.s. In the case of the anthropogenic profiles, especially in the ADE layers (upper 40 cm b.s.), the C:N ratio fluctuates markedly between 9.6 (40 cm b.s.) at TP1 P5 and 30.4 (35 cm b.s.) at TP1 P7, but it is 16.7 on average, which is close to the ideal 17.6.

Finally, Lehmann et al. (2001) conducted experiments on the impact of inorganic and organic phosphorous fertilizers on Amazonian agroforestry systems. They found that tree species with rapid aboveground nutrient cycling and high-quality litter are important contributors to the enrichment of infertile soils with phosphorous. Such species include peach palm, a domesticated species and, therefore, an indicator of human presence in the landscape. The M11 P2 profile is very interesting from this point of view, as both the number of palm phytoliths and the concentration of phosphorous increase towards the top of the profile. The low accuracy of palm phytolith studies, however, currently means that it is not possible to identify the exact species of palms that were increasingly present in this profile.

Based on Morcote-Ríos et al. (2016), it is assumed that peach palms produce conical body-type phytoliths, therefore the number should be high in the phytolith assemblage in the upper part of the soil profile. However, only a few conical bodies were encountered during the analysis, and most of the palm phytoliths were globular echinates. This may either suggest that other species also contributed to the increase of the phosphorous concentration, or that there was an alternative human or environmental source for this extra phosphorous.

5.3 Multidisciplinary study on the impact of pre-Columbian land use in the PMI along a 600 km transect

The present study is the first to have investigated an approximately 600 km-long transect in the PMI by applying a multidisciplinary approach combining archaeobotany, soil geochemistry, macro charcoal analysis, and stable carbon isotope analysis, as well as modern vegetation inventories. This thesis concludes that the human impact in the PMI was higher, both in terms of geographical extent and degree of intensity, than previously suggested (McMichael et al., 2012b).

Earlier, archaeological research has concentrated mainly on settlement sites along the main rivers in central Amazonia, at the confluence of the Rio Negro and the Rio Solimões, along the Tapajós and Madeira rivers. Later, the discovery of massive earthworks in south-west Amazonia directed archaeological interest towards the vast *terra firme* regions at the southern rim, where numerous sites were discovered with or without ADE soils. The *terra firme* areas in central Amazonia have, however, been neglected in archaeological research so far. The few studies conducted with the aim to detect signs of past human presence and impact concluded with controversial results, and their methodological approaches generated intense debate. While Levis et al. (2012) implied that large, forested areas were once managed by people and were turned into oligarchic forests, McMichael et al. (2012b) did not find evidence for large-scale forest management in the PMI (see Introduction and section 2.2).

In this thesis, the combination of phytolith, geochemical, and stable carbon isotope analyses revealed that the PPBio forest sites in *terra firme* forests across the PMI experienced enrichment, with palms present at sites M05, M02, and M11. In the case of M05 and M02, the enrichment was visible in the upper 15 cm b.s. Interestingly, although Levis et al. (2012) classified the M05 forest module as a primary forest and the M02 forest module as oligarchic forest, this difference was barely visible in the phytolith records (see section 4.1.1–4.1.3). However, at site M11, the phytolith record showed a much earlier and larger scale change in the forest structure (*cf.* profile M11 P2, see section 4.1.4).

As discussed, the increasing number of palm phytoliths from around 50 cm b.s. (*ca.* 2300 years ago) together with increasing total phosphorous values from *ca.* 35 cm b.s. suggest changes in both the vegetation composition and the soil properties, which may be the result of long-term forest management. Additionally, although the presence of palms cannot always be associated with intentional forest management (Forline, 2008), several studies have shown that the enrichment of forests with palms and other useful species may be an important sign of non-agricultural cultivation and agroforestry in the past. This practice, as part of a mixed model, could have sustained larger sedentary groups before agriculture started to dominate (e.g. Balée 1994; Denevan 2001; Killion, 2013).

5.4 The northernmost evidence for the mid-Holocene drought

For the M11 P2 profile, situated in this thesis' southernmost forest module, both the stable carbon isotope values and the phytolith analysis suggest a large-scale vegetation transformation since the middle of the late Holocene. At the bottom of the profile, the vegetation type indicated a savanna (probably with some trees or shrubs), which gradually evolved into a dry, closed-canopy palm forest. A radiocarbon date from 50 cm b.s. indicates that this transition started around 2959–2782 cal BP.

Other studies on the southern border between the Amazon rainforest and the savanna have also found evidence for savanna expansion during the early to mid-Holocene, then forest expansion due to wetter climate conditions around 3000 BP (Burbridge et al., 2004; Carson et al., 2014; de Freitas et al., 2001; Mayle et al., 2000; Pessenda et al., 2001a). However, the M11 P2 profile currently represents the most northern border of this transition (Fig. 5.2). De Freitas et al. (2001) and Pessenda et

Figure 5.2: Location of sites outlined by other studies in relation to M11 P2.

al. (2001) report the transition from savanna-type vegetation to closed-canopy forest between Humaitá in Amazonas and Porto Velho in Rondônia just south of the M11 forest module. Based on pollen analysis from two lagoons in the NKMNP in eastern Bolivia, Mayle et al. (2000) and Burbridge et al. (2004) found evidence that Amazonian rainforest communities only expanded into the NKMNP within the past three millennia to their current geographical limit at 15°S. Pollen analysis suggests that savanna vegetation dominated here prior to 3000 BP. Another Bolivian pollen study by Carson et al. (2014) revealed that the geoglyph builders of Iténez Province exploited a naturally open savanna landscape when they started to create the geoglyphs, and the area was kept clear during the climate-driven expansion of the rainforest across the region that began *ca*. 2000 years ago.

5.5 Land use on ADE soils

Another important discussion point is land use on ADE soils. Studies by Maezumi et al. (2018) and Alves (2017) on central Amazonian ADE sites have suggested that a land use technique existed that brings previous assumptions about food production in lowland Amazonia into question. The phytolith, pollen, geochemical, and charcoal records in these studies show that closed-canopy forest existed throughout the occupation of these sites, but the vegetation composition and structure were manipulated through different management techniques: forests were enriched with palms and other edible species at different stages of domestication, and small areas were opened for crop cultivation. The shade of the forest cover and minor fires were used to control the understorey.

The phytolith, geochemical, and charcoal records at Couro Velho and the Brazil nut stand show a very similar picture. Although the amount of NPA) phytoliths decreased in the profiles' ADE phases compared to the pre-ADE phases, suggesting the slight opening of the landscape, it is consistently >50% throughout the whole phytolith assemblage. In the ADE phase, the NPA phytoliths are mainly replaced by palm and grass phytoliths. The CAST1 P2 and CAST2 P1 profiles in the Brazil nut stand are an excellent example for displaying the increasing gradient of anthropogenic impact from oligarchic forest (forests dominated by useful trees) (M02, M11) to anthropogenic forest (forest dominated by useful trees on ADE soils) with brazil nut trees.

In the CAST profiles, although the number of palm phytoliths was relatively low, the grass and herb taxa were represented in more considerable amounts than in the profiles in oligarchic forests. In both the CAST and Couro Velho profiles, other useful plants beside palms, like Asteraceae, Cyperaceae, Marantaceae, *Calathea* sp., *Mendoncia* sp., Annonaceae, and *Celtis* sp. were encountered. The *Annona* sp. that was probably domesticated to some extent (Clement, 1999), was recovered from the M02 study site next to the ADE soils. *Celtis* sp. was only found in the profiles with ADE soils. Among the herbs, Marantaceae phytoliths were found in a higher number in the ADE profiles than in the natural soil profiles, and *Calathea* was only recovered from the ADE soils at Couro Velho and in the Brazil nut stand. Since the Marantaceae family comprises of shade-adapted plants, their greater presence in the ADE profiles also suggests that the forests on the ADE soils at Couro Velho and the Brazil nut stand were closed-canopy forests during the period of occupation.

Also, for cultigens that produce phytoliths, squash was recovered from the ADE deposits in the two black ADE and in one brown ADE profile. One maize cob wavy-top rondel from the pre-ADE phase in TP1 P7 was encountered. As the phytoliths from the cob are produced in small quantities by the plant organs (Piperno, 2006), we can be confident that maize was regularly consumed at the site. Evidence for farming maize—phytoliths produced in the leaf—was not found. The amount of macro charcoal and the values of the studied geochemical elements (total and available phosphorous, total carbon, and the C:N ratio) were strikingly high in almost all of the ADE soils compared to soils in other studies, suggesting a large amount of extra organic input into these soils through waste deposal, burning of vegetation, and either intentional or unintentional fertilization of the soils at Couro Velho and the Brazil nut stand. These soil-amelioration techniques and the exploitation of a wide range of wild, semi-domesticated and domesticated food sources mean that it is possible that the habitants of Couro Velho were sedentary, even without large-scale forest clearing and fields of cultigens.

The results of this study provide novel evidence for pre-Columbian settlements in small riverine settings. Most notably, they attest to the existence of a mixed economy combining the gathering of wild resources (probably both plant and animal), management of anthropogenic forests high in edible species, the cultivation of domesticated species, and the creation of ADE soils. These findings reveal the extreme capability of ancient Amerindian groups to recognise and manipulate plant and soil resources to different degrees to meet their needs in environmental settings that are typically not considered suitable for permanent settlement.

5.6 Contribution to the understanding of ADE sites in small riverine settings

Couro Velho is a unique archaeological site in Amazonia, as it is situated in a small riverine setting. These habitats have been neglected in terms of archaeological research, probably because of two factors: (1) based on earlier assumptions, these areas were not considered suitable for permanent settlement; and (2) these regions are sometimes very remote, and the logistics for surveying them can be complicated (Levis et al., 2013). Although predictive models by McMichael et al. (2014) and Palace et al. (2017) suggested the existence of ADE sites along tributaries to major rivers in western and central Amazonia, this thesis is the first to confirm these predictions in the PMI.

The known ADE sites in the central, eastern, and southern portions of Amazonia were formed over a borad time span. ADE sites situated at the confluence of the Rio Negro and Rio Solimões were created during late pre-Columbian times, around 1500–2500 BP. ADE sites in the lower and middle portions of the Madeira River associated with the Curralinho phase were dated to *ca*. 3500–2800 BP (Simões and Lopes, 1987). The earliest ADE site reported from the Upper Madeira region is Teotonio near Porto Velho, where black earth started to form around 6000 BP, though the site itself was already occupied roughly 9500 BP (Watling et al., 2018). Fortified villages with ADE soils were dated to *ca.* 3400 BP in the Upper Tapajós Basin, and de Souza et al. (2018) suggest that the peak of occupation in the entire southern rim of Amazonia was between *ca*. 3250–3500 BP. In the Upper Xingu region, ADE sites date to 1500 BP (Heckenberger et al., 2008).

Couro Velho is an ADE site situated on a bluff along the Igapó-Açu River, a tributary of the Madeira River flowing across the PMI. The site contains black and brown ADE soils to a depth of *ca.* 40 cm. The ADE soils are rich in burnt clay, and few pottery sherds were also encountered. Radiocarbon dates from the occupation zone associated with the artefacts between 25–35 cm b.s. suggest that the site was occupied and used intensively around 1400–1200 cal BP, although a charcoal piece from 50 cm b.s. (pre-ADE) that was associated with a phytolith produced by a cultigen (maize), was dated to *ca*. 3350 cal BP.

5.7 Advances in the understanding of the development of brown ADEs

As discussed in sections 2.3 and 2.5, ADEs are anthropogenic soils widespread in Amazonia. While the activities and processes involved in the formation of ADEs continue to be debated, this thesis' analyses have gone some way to resolving theories of the types of land use necessary to create brown and black ADEs. Moving on from initial hypotheses that brown ADEs were either the result of intensive cultivation or deliberate manipulation for agricultural purposes (*cf.* Arroyo-Kalin, 2010, 2012, 2014; Denevan, 2009; Woods and McCann, 1999), researchers questioned whether anthropogenic soils might have more diverse properties. The suggestion put forward was that varying intensities of land use could led to the difference between brown and black ADEs, in addition to general differences in land use strategies. Such reasoning stipulated that brown ADEs must stem from less intense practices, whereas black ADEs were caused by more intensive activities (Kampf et al., 2003; Kern et al., 2009b).

The geochemical analysis in the present study revealed the different processes that led to the formation of brown ADE soils at Couro Velho (TP1 P2, TP1 P2, TP1 P6) and the Brazil nut stand (CAST1 P2, CAST2 P1) (see section 5.5). Although all profiles from the two sites exhibited a 35–40 cm-thick brown anthropogenic layer wcomprising distinctive sublayers, charcoal, and several artefacts, differences in their geochemical signals are notable. While the total carbon contents of these profiles are very similar to each other, the total phosphorous contents are clearly higher in the brown ADE profiles at Couro Velho than the Brazil nut stand.

This difference in total phosphorous contents suggests that the brown ADE soils at Couro Velho received more or a different source of phosphorous than the Brazil nut grove. In the case of available phosphorous, the brown ADE at Couro Velho contained much higher quantities than the brown ADE of the Brazil nut stand. Based on these results, it seems likely that these brown ADEs having different origins, despite looking similar.

It seems likely that the brown ADE at Couro Velho would have become a ADE if it had received more amelioration and experienced a longer period of occupation. The phosphorous in this ADE likely came from organic matter that also contributed to the creation of the black ADE at the core of the site, namely household waste, food waste, human and animal excreta, ash from hearths, and sediment from the Igapó-Açu River. The soil is brown and not black, because it did not receive as much input as the black ADE in the core area. The brown ADE at the Brazil nut stand, however, is a product of forest management. Most probably, this management involved burning the forest's understorey and incorporating the plant material, charcoal, and ash into the soil.

CHAPTER 6

Conclusions

This thesis aimed to assess the pre-Columbian human impact on the *terra firme* forests of the PMI. Surveying the landscape along the Igapó-Açu River revealed a much more complex picture of interlinked human-environment relations in the PMI than it was thought existed. The multiproxy approach implemented in this thesis has provided promising results for answering questions on the geographical extent, intensity, and long-term legacy of pre-Columbian land use in the PMI. The results of this study have revealed a full gradient of forest management strategies from minimal/no impact on primary forests to high impact on anthropogenic forests on ADE soils.

Returning to the questions that oriented this research, the data presented in the previous chapters is summarised to provide answers:

1. Were the forests and soils of the PMI modified by humans in late pre-Columbian times?

This study has identified a wide range of evidence for past anthropogenic impact in the PMI. Low impact (oligarchic forest) modification was detected in the M11 P2 profile. At the M02 forest module, evidence for similar impact was anticipated, but the data collected was not entirely convincing. At Couro Velho and the Brazil nut stand, the anthropogenic impact was high. People have used this landscape for millennia, which has left profound changes detectable in the vegetation and soils. Anthropogenic forests enriched with palms, domesticated, semi-domesticated, and other useful plants were created using fire, understorey clearing, and the deliberate selection of certain plants. The soils were also deeply modified. By incorporating organic matter, charcoal, broken pottery, and other household waste into the natural soil, pre-Columbian people created ADE soils, one of the most fertile soils on earth.

2. If yes, what kind of subsistence strategies were applied, and what was the nature and geographic scale of their impact?

The results of the multidisciplinary approach suggest that there was no large-scale deforestation in the PMI during the late Holocene. Instead, the compositions of forests and the properties of soils were modified in some areas. The data obtained imply that the enrichment of vegetation with palms in oligarchic forests was the most important development. In the study areas with anthropogenic soils, more intensive landscape modification was detected. It is assumed that the indigenous people who occupied the Couro Velho site and created the Brazil nut stand utilised a mixed-economy subsistence strategy. They gathered wild resources (probably both plant and animal), managed anthropogenic forests high in edible species, created ADE soils, and cultivated crops and semi-domesticated plants .

3. Did pre-Columbian land use have a lasting effect on forest composition and soil properties in the PMI?

In many areas of the PMI, pre-Columbian land use hadlasting changes on the landscapes to the degree that they are still visible today. The M11 forest module was probably enriched with palms by pre-Columbian societies. However, the most prominent change was seen along the Igapó-Açu River and at Couro Velho. Local people today have taken advantage of the excellent properties of the ADE soil and use it as an abacaba palm plantation. Besides abacaba, other useful species are also grown on ADE soil, such as açai, coffee, yam. The Brazil nut stand is also regularly visited by local people, and they collect the nuts and other useful plants, as well as hunting for animals that also visit the orchard. By continuously using these areas in a sustainable way for millennia, local indigenous people have created a highly-resilient landscape that still provides food and other resources today.

This study has demonstrated the potential of multiproxy research for investigating past subsistence practices and their modern legacies. It has also highlighted the probability that even larger areas were once occupied and modified by pre-Columbian societies than previously thought. The previously-unexplored PMI had the capacity to sustain sedentary communities along its tributaries, and this finding raises the question of, given the vast geographical extent and variety of environmental settings, how much do we still not know about long-term human-environment interactions in Amazonia?

Although this PhD thesis has presented valuable data for resolving the debate about the long-term environmental impact of pre-Columbian communities in the PMI, it has only scratched the surface of what can be learnt about the human history of these landscapes. This enduring natural and cultural heritage is worth studying and protecting, because it will undoubtedly serve as a valuable example for sustainable land use in other regions of the Amazon Basin in future.

APPENDIX I.

Modern vegetation inventories of all study sites

Family	Species	M02	M05	M06	M11	Brazil nut s.	Couro Velho
Anacardiaceae	*Anacardium giganteum*	0	0	0	1	0	0
Anonnaceae	*Duguetia odorata*	1	2	0	4	0	0
Anonnaceae	*Xylopia sp1*	0	0	0	0	0	1
Anonnaceae	*Xylopia sp2*	2	0	1	0	0	0
Anonnaceae	*Xylopia sp3*	0	1	0	0	0	2
Anonnaceae	*Xylopia sp4*	3	0	0	0	0	0
Anonnaceae	*Mezilaurus sp2*	0	1	0	0	0	0
Anonnaceae	*Rollinia sp1*	0	1	0	1	0	0
Apocynaceae	*Aspidosperma sp1*	0	0	0	1	0	0
Apocynaceae	*Tabernaemonta sp1*	1	2	1	0	1	0
Apocynaceae	*Himatanthus sucuuba*	1	1	0	0	0	0
Arecaceae	*Oenocarpus bataua*	6	6	1	7	0	0
Arecaceae	*Euterpe precatoria*	1	0	0	2	0	0
Arecaceae	*Oenocarpus mapora*	0	2	0	0	0	0
Arecaceae	*Attalea maripa*	1	1	0	0	0	0
Arecaceae	*Orbignya phalerata*	0	0	0	2	0	0
Bignoniaceae	*Jacaranda sp1*	0	1	0	1	0	0
Bignoniaceae	*Jacaranda sp2*	1	0	1	2	0	0
Burseraceae	*Protium sp1*	1	7	2	0	1	1
Burseraceae	*Protium sp2*	0	0	1	1	0	0
Burseraceae	*Protium sp3*	0	0	0	1	1	0
Burseraceae	*Protium sp4*	0	0	1	0	0	0
Burseraceae	*Protium sp5*	0	0	1	1	0	0
Burseraceae	*Protium sp6*	0	0	0	0	1	0
Burseraceae	*Protium sp7*	1	0	1	2	3	0
Caryocaraceae	*Caryocar sp1*	0	1	0	0	0	0
Chrysobalanaceae	*Hirtella sp1*	5	1	5	2	1	0
Chrysobalanaceae	*Hirtella sp2*	1	5	4	1	0	0
Chrysobalanaceae	*Hirtella sp3*	0	3	0	0	0	0
Chrysobalanaceae	*Hirtella sp4*	0	0	0	1	0	0

Chrysobalanaceae	*Licania sp1*	6	14	5	11	3	0
Chrysobalanaceae	*Licania sp2*	0	3	1	1	0	0
Chrysobalanaceae	*Licania sp3*	0	0	2	0	0	0
Chrysobalanaceae	*Licania sp4*	0	0	2	0	0	0
Chrysobalanaceae	*Licania sp5*	0	0	0	1	0	0
Combretaceae	*Combretum sp1*	0	1	0	0	0	0
Euphobiaceae	*Euphobiaceae sp1*	0	1	0	0	0	0
Euphorbiaceae	*Hevea sp1*	0	1	0	0	0	0
Euphorbiaceae	*Hevea brasiliensis*	0	2	2	0	0	0
Fabaceae	*Hymenaea parvifolia*	1	0	0	0	0	0
Fabaceae	*Bowdichia sp1*	1	0	0	0	0	0
Fabaceae	*Bowdichia sp2*	0	0	0	3	1	0
Fabaceae	*Bowdichia sp3*	0	0	0	2	0	0
Fabaceae	*Senna Silvestris*	0	0	0	0	1	2
Fabaceae	*Pterocarpus sp1*	1	3	0	0	0	0
Fabaceae	*Parkia sp1*	0	0	0	1	0	0
Fabaceae	*Copaifera sp1*	0	0	0	1	0	0
Fabaceae	*Tachigali sp1*	1	0	0	0	0	0
Fabaceae	*Tachigali sp2*	0	2	1	1	3	0
Fabaceae	*Taralea sp1*	0	0	0	1	0	0
Fabaceae	*Tabernaemonta sp1*	1	0	0	0	0	0
Fabaceae	*Fabaceae sp1*	1	0	0	0	0	0
Fabaceae	*Fabaceae sp2*	0	1	0	0	0	0
Fabaceae	*Dinizia sp1*	0	0	1	0	0	0
Fabaceae	*Inga sp1*	0	1	0	1	0	0
Fabaceae	*Inga sp2*	0	0	0	0	0	4
Fabaceae	*Inga sp3*	0	0	1	0	0	0
Fabaceae	*Inga sp4*	0	0	0	0	0	1
Lauraceae	*Nectandra sp1*	2	0	0	0	1	0
Lauraceae	*Nectandra sp2*	2	0	3	2	1	0
Lauraceae	*Ocotea sp1*	0	0	0	1	0	0
Lauraceae	*Ocotea sp2*	0	2	0	0	0	0
Lauraceae	*Mezilaurus itauba*	0	1	1	0	0	0
Lauraceae	*Mezilaurus sp2*	0	1	1	0	0	0
Lecythidaceae	*Eschweilera sp1*	0	0	1	0	0	0
Lecythidaceae	*Eschweilera sp2*	0	0	1	0	0	0
Lecythidaceae	*Eschweilera sp3*	0	0	1	0	0	0
Lecythidaceae	*Eschweilera sp5*	0	2	0	0	0	0
Lecythidaceae	*Eschweilera sp6*	6	9	12	1	2	0
Lecythidaceae	*Eschweilera sp7*	2	2	0	0	1	0
Lecythidaceae	*Eschweilera sp8*	0	1	0	0	0	0
Lecythidaceae	*Bertholletia excelsa*	0	0	0	0	1	0
Lecythidaceae	*Lecytis sp1*	0	0	1	0	0	0
Lecythidaceae	*Cariniana sp1*	0	0	2	0	0	0
Lecythidaceae	*Couratari sp1*	0	0	0	2	0	0
Malvaceae	*Cavanillesia sp1*	0	1	0	0	0	0
Malvaceae	*Ceiba sp1*	0	1	2	0	0	0
Malvaceae	*Sterculia sp1*	1	0	0	1	1	0

Malvaceae	*Tabernaemonta sp1*	1	0	1	0	3	0
Malvaceae	*Theobroma microcarpum*	0	0	0	0	0	1
Malvaceae	*Quaribea sp1*	0	0	1	0	1	0
Meliaceae	*Guarea sp1*	2	1	4	0	0	0
Meliaceae	*Guarea sp2*	0	0	1	0	0	0
Meslastomataceae	*Miconia sp1*	0	0	1	1	0	0
Moraceae	*Brosimum sp1*	1	1	0	0	0	0
Moraceae	*Brosimum sp2*	0	0	1	0	0	0
Moraceae	*Pseudolmedia sp1*	0	1	1	3	0	0
Moraceae	*Pseudolmedia sp2*	4	2	0	0	0	0
Moraceae	*Pseudolmedia sp3*	1	0	0	0	0	0
Moraceae	*Perebea sp1*	7	1	2	2	0	0
Moraceae	*Perebea sp2*	0	1	0	0	0	0
Moraceae	*Perebea sp3*	0	1	0	0	0	0
Moraceae	*Nalcleopis sp1*	0	0	1	0	0	0
Moraceae	*Ficus sp1*	0	0	1	0	0	0
Myristicaceae	*Iryanthera sp1*	1	0	0	0	4	0
Myristicaceae	*Iryanthera sp2*	4	3	1	2	0	0
Myristicaceae	*Virola sp1*	3	1	1	6	1	0
Myristicaceae	*Virola sp2*	2	1	0	0	0	0
Myristicaceae	*Virola sp3*	0	0	0	1	0	0
Myristicaceae	*Virola sp4*	0	2	0	0	1	0
Myristicaceae	*Virola sp5*	0	2	0	0	0	0
Myristicaceae	*Virola sp6*	0	1	0	1	0	0
Myristicaceae	*Virola sp7*	0	2	2	2	0	0
Myristicaceae	*Virola sp8*	1	0	0	0	0	0
Myristicaceae	*Virola sp9*	0	0	0	1	0	0
Myrtaceae	*Myrcia sp1*	0	1	0	0	0	0
Myrtaceae	*Eugenea sp1*	1	0	0	0	1	0
Nyctaginaceae	*Neea sp1*	0	1	0	0	0	0
Olacaceae	*Minquartia sp1*	2	2	2	0	0	0
Olacaceae	*Minquartia sp2*	3	2	3	0	0	0
Olacaceae	*Heisteriasp1*	0	1	0	0	0	0
Rubiaceae	*Rubiaceae sp1*	1	0	0	0	0	0
Rubiaceae	*Coussarea sp1*	0	1	1	0	0	0
Rubiaceae	*Alseis sp1*	0	0	0	0	1	1
Salicaceae	*Casearia sp1*	1	3	6	0	0	0
Salicaceae	*Casearia sp2*	0	1	0	0	0	0
Salicaceae	*Casearia sp3*	0	1	0	0	0	0
Sapindaceae	*Talisia sp1*	1	2	2	0	5	0
Sapindaceae	*Talisia sp2*	0	1	0	0	0	0
Sapotaceae	*Pouteria sp1*	6	0	2	1	0	0
Sapotaceae	*Pouteria sp2*	0	3	1	0	0	0
Sapotaceae	*Pouteria sp3*	0	1	3	2	0	0
Sapotaceae	*Pouteria sp4*	0	1	0	0	0	0
Sapotaceae	*Pouteria sp5*	0	3	0	0	0	0
Sapotaceae	*Pouteria sp6*	0	1	0	0	0	0
Sapotaceae	*Pouteria sp7*	0	0	5	0	0	0

Sapotaceae	*Pouteria sp8*	0	2	0	0	0	0
Sapotaceae	*Pouteria sp9*	0	4	0	0	1	0
Sapotaceae	*Pouteria sp10*	0	0	3	0	0	0
Sapotaceae	*Pouteria sp11*	0	0	1	0	0	0
Sapotaceae	*Pouteria sp12*	2	5	3	1	0	0
Sapotaceae	*Pouteria sp13*	0	3	2	0	1	0
Sapotaceae	*Pouteria sp14*	1	0	1	3	1	0
Sapotaceae	*Pouteria sp15*	0	0	1	0	0	0
Sapotaceae	*Manilkara huberi*	0	2	0	0	0	0
Siparunaceae	*Siparuna sp1*	1	0	0	0	0	0
Urticaceae	*Cecropia sciadophylla*	0	0	1	0	0	1
Urticaceae	*Pourama sp1*	1	0	2	1	2	0
Urticaceae	*Pourama sp2*	1	0	0	1	0	0
Urticaceae	*Pourama sp3*	0	0	0	1	0	0
Verbenaceae	*Vitex sp1*	0	0	0	0	0	1
Vochysiaceae	*Vochysia sp1*	1	1	0	0	0	0
Vochysiaceae	*Vochysia sp2*	0	0	0	2	0	0
Vochysiaceae	*Vochysia sp3*	1	2	1	3	0	0
Vochysiaceae	*Erisma sp1*	0	1	0	1	0	0
Vochysiaceae	*Qualea spq*	0	0	0	1	0	0

APPENDIX II.

Summary of the phytolith-stratigraphic data in all soil profiles

Rows in grey represents depths with insufficient amount of phytoliths in the C fraction (Materials and Methods, section 3.2.1) and therefore were excluded from further discussion.

M05 P1

Depth (cm)	Phytolith assemblage	Summary of phytolith taxa
0	Arboreal – Arecaceae	non-diagnostic Arboreal (84.1%), Arecaceae (7.1%), non-diagnostic Poaceae (5%), Bambusoideae (1.5%), Marantaceae (1.3%), Asteraceae (0.6%), Chloridoideae (0.2%), Cyperaceae (0.2%)
5	Arboreal – Arecaceae	non-diagnostic Arboreal (87.2%), Arecaceae (9.4%), Bambusoideae (1.5%), Cyperaceae (0.7%), non-diagnostic Poaceae (0.4%), Marantaceae (0.4%), Asteraceae (0.2%), Panicoideae (0.2%)
10	Arboreal – Arecaceae	non-diagnostic Arboreal (89.7%), Arecaceae (6.5%), non-diagnostic Poaceae (1.2%), Marantaceae (1.2%), Asteraceae (1.2%), Bambusoideae (0.2%)
15	Arboreal – Arecaceae	non-diagnostic Arboreal (91.2%), Arecaceae (5.2%), Asteraceae (1.6%), non-diagnostic Poaceae (0.9%), Marantaceae (0.9%), Bambusoideae (0.2%)
20	Arboreal – Arecaceae	non-diagnostic Arboreal (91.1%), Arecaceae (3.7%), non-diagnostic Poaceae (3%), Marantaceae (1.4%), Asteraceae (0.5%), Chloridoideae (0.2%)
25	Arboreal – Arecaceae	non-diagnostic Arboreal (91.2%), Arecaceae (3.3%), non-diagnostic Poaceae (2.9%), Asteraceae (1.4%), Marantaceae (0.7%), Chloridoideae (0.5%)
30	Arboreal – Arecaceae	non-diagnostic Arboreal (93.5%), Arecaceae (3.7%), Asteraceae (1.2%), Marantaceae (0.6%), non-diagnostic Poaceae (0.3%), Panicoideae (0.3%), Bambusoideae (0.3%)
35	Arboreal – Arecaceae	non-diagnostic Arboreal (92.2%), Arecaceae (4.4%), non-diagnostic Poaceae (1.7%), Asteraceae (1.3%), Marantaceae (0.4%)
40	Arboreal – Arecaceae	non-diagnostic Arboreal (93.3%), Arecaceae (3.6%), non-diagnostic Poaceae (1.7%), Bambusoideae (1.2%), Panicoideae (0.2%)
45	Arboreal – Poaceae	non-diagnostic Arboreal (92.0%), non-diagnostic Poaceae (4.6%), Arecaceae (2.1%), Asteraceae (0.9%), Bambusoideae (0.2%), Cyperaceae (0.2%)
50	Arboreal – Poaceae	non-diagnostic Arboreal (89.8%), non-diagnostic Poaceae (6.1%), Arecaceae (3.6%), Asteraceae (0.5%)
55	Arboreal – Arecaceae	non-diagnostic Arboreal (91.6%), Arecaceae (3.6%), non-diagnostic Poaceae (3.9%), Marantaceae (0.5%), Asteraceae (0.5%)
60	Arboreal – Arecaceae	non-diagnostic Arboreal (91.7%), Arecaceae (5.9%), Asteraceae (1.5%), non-diagnostic Poaceae (0.9%)
65	Arboreal – Arecaceae	non-diagnostic Arboreal (95.0%), Arecaceae (3.3%), non-diagnostic Poaceae (1%), Marantaceae (0.5%), Asteraceae (0.2%), Panicoideae (0.2%)
70	Arboreal – Arecaceae	non-diagnostic Arboreal (94.5%), Arecaceae (4.0%), non-diagnostic Poaceae (1.2%), Asteraceae (0.2%)
75	Arboreal – Arecaceae	non-diagnostic Arboreal (92.5%), Arecaceae (4.9%), non-diagnostic Poaceae (2.1%), Bambusoideae (0.5%)

M02 P2

Depth (cm)	Phytolith assemblage	Summary of phytolith taxa
0	Arboreal – Arecaceae	non-diagnostic Arboreal (84.6%), Arecaceae (8.9%), Marantaceae (3.8%), Asteraceae (1.1%), non-diagnostic Poaceae (0.4%), Panicoideae (0.4%), Heliconiaceae (0.4%), Bambusoideae (0.2%), Chloridoideae (0.2%), Annonaceae (0.2%)
5	Arboreal – Arecaceae	non-diagnostic Arboreal (85.9%), Arecaceae (10.0%), Marantaceae (2.7%), non-diagnostic Poaceae (1.1%), Asteraceae (0.5%) Bambusoideae (0.2%), Chloridoideae (0.2%), Heliconiaceae (0.2%)
10	Arboreal – Arecaceae	non-diagnostic Arboreal (86.2%), Arecaceae (8.6%), Marantaceae (2.3%), Asteraceae (1.1%), non-diagnostic Poaceae (0.7%), Chloridoideae (0.5%), Heliconiaceae (0.5%), Panicoideae (0.2%)
15	Arboreal – Arecaceae	non-diagnostic Arboreal (87.5%), Arecaceae (7.9%), Marantaceae (1.8%), non-diagnostic Poaceae (1.1%), Asteraceae (1.1%), Bambusoideae (0.7%)
20	Arboreal – Arecaceae	non-diagnostic Arboreal (91.8%), Arecaceae (3.7%), non-diagnostic Poaceae (1.7%), Marantaceae (1.5%), Asteraceae (0.6%), Heliconiaceae (0.4%), Panicoideae (0.2%)
25	Arboreal – Arecaceae	non-diagnostic Arboreal (95.2%), Arecaceae (2.4%), Marantaceae (1.3%), non-diagnostic Poaceae (0.7%), Asteraceae (0.2%), Chloridoideae (0.2%)
30	Arboreal – Arecaceae	non-diagnostic Arboreal (94.1%), Arecaceae (3.0%), Marantaceae (2.0%), Asteraceae (0.7%), non-diagnostic Poaceae (0.5%), Bambusoideae (0.2)
35	Arboreal – Arecaceae	non-diagnostic Arboreal (93.9%), Arecaceae (2.8%), Marantaceae (1.9%), non-diagnostic Poaceae (0.9%), Asteraceae (0.2%)
40	Arboreal – Arecaceae	non-diagnostic Arboreal (90.3%), Arecaceae (3.7%), non-diagnostic Poaceae (2.8%), Marantaceae (1.6%), Panicoideae (0.5%), Cyperaceae (0.5), Asteraceae (0.5), Bambusoideae (0.2%),
45	Arboreal – Poaceae	non-diagnostic Arboreal (85.5%), non-diagnostic Poaceae (5.4%), Arecaceae (4.2%), Marantaceae (2.3%), Asteraceae (0.9%), Bambusoideae (0.7%), Heliconiaceae (0.5%), Cyperaceae (0.2%)
50	Arboreal – Arecaceae	non-diagnostic Arboreal (92.3%), Arecaceae (2.8%), non-diagnostic Poaceae (1.9%), Asteraceae (1.4%), Marantaceae (0.9), Bambusoideae (0.7%)
55	Arboreal – Poaceae	non-diagnostic Arboreal (86.6%), non-diagnostic Poaceae (4.6%), Arecaceae (3.8%), Marantaceae (2.2%), Asteraceae (2.2%), Panicoideae (0.5%), Chloridoideae (0.2%)
60	Arboreal – Arecaceae	non-diagnostic Arboreal (89.5%), Arecaceae (4.4%), non-diagnostic Poaceae (3.3%), Marantaceae (1.4%), Asteraceae (0.5%), Panicoideae (0.5%), Bambusoideae (0.2%), Chloridoideae (0.2%)
65	Arboreal – Arecaceae	non-diagnostic Arboreal (95.3%), Arecaceae (2.0%), Marantaceae (1.4%), non-diagnostic Poaceae (0.9%), Bambusoideae (0.2%)
70	Arboreal – Arecaceae	non-diagnostic Arboreal (95.0%), Arecaceae (2.7%), non-diagnostic Poaceae (0.9%), Marantaceae (0.9%), Panicoideae (0.5%)
75	Arboreal – Arecaceae	non-diagnostic Arboreal (85.0%), Arecaceae (7.0%), non-diagnostic Poaceae (5.1%), Marantaceae (1.9%), Bambusoideae (0.5%), Asteraceae (0.5%)

M02 P4

Depth (cm)	Phytolith assemblage	Summary of phytolith taxa
0	Arboreal – Arecaceae	non-diagnostic Arboreal (81.8%), Arecaceae (12.4%), non-diagnostic Poaceae (1.2%), Asteraceae (0.9%), Bambusoideae (0.8%), Marantaceae (0.7%), *c.f. P. guianensis* (0.4%), Panicoideae (0.2%)
5	Arboreal – Poaceae	non-diagnostic Arboreal (78.1%), non-diagnostic Poaceae (9.9%), Arecaceae (9.4%), *c.f. P. guianensis* (1.4%), Bambusoideae (0.7%), Asteraceae (0.2%), Annonaceae (0.2%)
10	Arboreal – Arecaceae	non-diagnostic Arboreal (87.6%), Arecaceae (9.7%), Asteraceae (0.9%), non-diagnostic Poaceae (0.7%), Panicoideae (0.5%) Marantaceae (0.2%), Bambusoideae (0.4%),
15	Arboreal – Arecaceae	non-diagnostic Arboreal (87.5%), Arecaceae (7.9%), Marantaceae (1.8%), non-diagnostic Poaceae (1.1%), Asteraceae (1.1%), Bambusoideae (0.7%)
20	Arboreal – Arecaceae	non-diagnostic Arboreal (91.0%), Arecaceae (6.1%), Panicoideae (0.9), Asteraceae (0.9%), Marantaceae (0.7%), non-diagnostic Poaceae (0.2%), Mendoncia (0.2%)
25	Arboreal – Arecaceae	non-diagnostic Arboreal (87.8%), Arecaceae (8.9%), Marantaceae (1.6%), non-diagnostic Poaceae (0.9%), Asteraceae (0.2%), Chloridoideae (0.2%), Panicoideae (0.2%), Bambusoideae (0.2%)
30	Arboreal – Arecaceae	non-diagnostic Arboreal (87.4%), Arecaceae (10.5%), Asteraceae (0.9%), non-diagnostic Poaceae (0.7%), Marantaceae (0.5%)
35	Arboreal – Arecaceae	non-diagnostic Arboreal (87.0%), Arecaceae (11.3%), Asteraceae (1.0%), Marantaceae (0.5%), non-diagnostic Poaceae (0.2%)
40	Arboreal – Arecaceae	non-diagnostic Arboreal (78,4%), Arecaceae (20.9%), Asteraceae (0.7%)
45	Arboreal – Arecaceae	non-diagnostic Arboreal (86.8%), Arecaceae (12.3%), Asteraceae (0.5%), Marantaceae (0.2%), Panicoideae (0.2%)
50	Arboreal – Arecaceae	non-diagnostic Arboreal (91.3%), Arecaceae (7.1%%), non-diagnostic Poaceae (0.7%), Asteraceae (0.5%), Panicoideae (0.2%), Bambusoideae (0.2%)
55	Arboreal – Arecaceae	non-diagnostic Arboreal (95.0%), Arecaceae (3.9%), non-diagnostic Poaceae (0.4%), Marantaceae (0.4%), Asteraceae (0.4%)
60	Arboreal – Arecaceae	non-diagnostic Arboreal (94.8%), Arecaceae (3.8%), Asteraceae (0.7%), non-diagnostic Poaceae (0.3%), Marantaceae (0.3%)
65	Arboreal – Arecaceae	non-diagnostic Arboreal (82.9%), Arecaceae (13.4%), Asteraceae (3.7%)
70	Arboreal – Arecaceae	non-diagnostic Arboreal (79.5%), Arecaceae (14.5%), Asteraceae (2.6%), non-diagnostic Poaceae (1.7%), Panicoideae (1.7%)
75	Arboreal – Arecaceae	non-diagnostic Arboreal (87.4%), Arecaceae (12.6%),

M11 P2

Depth (cm)	Phytolith assemblage	Summary of phytolith taxa
0	Arboreal – Arecaceae	non-diagnostic Arboreal (59.8%), Arecaceae (32.0%), non-diagnostic Poaceae (4.0%), Panicoideae (1.8%), Chloridoideae (0.7%), Marantaceae (0.5%), Bambusoideae (0.4%), Asteraceae (0.2%), Heliconiaceae (0.2%), *Trichomanes sp.* (0.4%)
5	Arboreal – Arecaceae	non-diagnostic Arboreal (63.7%), Arecaceae (28.0%), Panicoideae (3.1%), Bambusoideae (1.4%), Marantaceae (0.7%), Asteraceae (0.4%), Cyperaceae (0.2%), Chloridoideae (0.2%)
10	Arboreal – Arecaceae	non-diagnostic Arboreal (63.3%), Arecaceae (29.9%), Panicoideae (2.6%), non-diagnostic Poaceae (2.4%), Bambusoideae (0.9%), Chloridoideae (0.5%), Heliconiaceae (0.2%), Asteraceae (0.2%)
15	Arboreal – Arecaceae	non-diagnostic Arboreal (63.8%), Arecaceae (28.3%), Panicoideae (3.2%), non-diagnostic Poaceae (2.3%), Chloridoideae (0.9%), Asteraceae (0.5%), Bambusoideae (0.5%), Marantaceae (0.2%), Heliconiaceae (0.2%)
20	Arboreal – Arecaceae	non-diagnostic Arboreal (73.2%), Arecaceae (20.0%), Panicoideae (3.8%), non-diagnostic Poaceae (2.1%), Asteraceae (0.9%), Marantaceae (0.7%), Bambusoideae (0.2%) Heliconiaceae (0.2%)
25	Arboreal – Arecaceae	non-diagnostic Arboreal (66.8%), Arecaceae (21.3%), Panicoideae (5.5%), non-diagnostic Poaceae (4.3%), Chloridoideae (0.9%), Bambusoideae (0.7%), Marantaceae (0.2%), Heliconiaceae (0.2%)
30	Arboreal – Arecaceae	non-diagnostic Arboreal (65.8%), Arecaceae (28.6%), non-diagnostic Poaceae (2.2%), Panicoideae (2.0%), Bambusoideae (0.4%), Chloridoideae (0.4%), Asteraceae (0.9%), Marantaceae (0.5%)
35	Arboreal – Arecaceae	non-diagnostic Arboreal (63.6%), Arecaceae (28.7%), Panicoideae (3.6%), non-diagnostic Poaceae (2.5%), Bambusoideae (0.7%), Asteraceae (0.5%), Marantaceae (0.5%), Chloridoideae (0.2%)
40	Arboreal – Arecaceae	non-diagnostic Arboreal (75.9%), Arecaceae (18.3%), Panicoideae (2.7%), non-diagnostic Poaceae (2.2%), Bambusoideae (0.6%), Asteraceae (0.2%)
45	Arboreal – Arecaceae	non-diagnostic Arboreal (76.6%), Arecaceae (15.9%), non-diagnostic Poaceae (4.2%), Panicoideae (1.5%) Chloridoideae (0.4%), Heliconiaceae (0.4%), Asteraceae (0.4%), Marantaceae (0.2%), Bambusoideae (0.2%)
50	Arboreal – Arecaceae	non-diagnostic Arboreal (82.6%), Arecaceae (9.3%%), Panicoideae (3.9%), non-diagnostic Poaceae (2.7%), Asteraceae (0.4%), Heliconiaceae (0.4%), Bambusoideae (0.4%), Chloridoideae (0.4%)
55	Arboreal – Arecaceae	non-diagnostic Arboreal (89.7%), Arecaceae (3.9%), non-diagnostic Poaceae (2.5%), Panicoideae (2.5%), Asteraceae (0.5%), Marantaceae (0.2%), Heliconiaceae (0.2%), Chloridoideae (0.2%), Bambusoideae (0.2%)
60	Arboreal – Arecaceae	non-diagnostic Arboreal (88.8%), Arecaceae (8.0%), non-diagnostic Poaceae (1.3%), Panicoideae (0.6%), Asteraceae (0.4%), Heliconiaceae (0.4%), Marantaceae (0.2%)
65	Arboreal – Arecaceae	non-diagnostic Arboreal (89.7%), Arecaceae (6.8%), Panicoideae (0.9%), Asteraceae (0.7%), Bambusoideae (0.7%), non-diagnostic Poaceae (0.7%), Chloridoideae (0.2%), Heliconiaceae (0.2%)
70	Arboreal – Poaceae	non-diagnostic Arboreal (92.8%), non-diagnostic Poaceae (3.6%) Arecaceae (2.4%), Panicoideae (0.8%), Asteraceae (0.4%)
75	Arboreal – Poaceae	non-diagnostic Arboreal (61%%), non-diagnostic Poaceae (30.8%), Asteraceae (0.3%)

M11 P4

Depth (cm)	Phytolith assemblage	Summary of phytolith taxa
0	Arboreal – Arecaceae	non-diagnostic Arboreal (72.2%), Arecaceae (15.7%), non-diagnostic Poaceae (45.4%), *c.f. P. guianensis* (2.2%), Bambusoideae (1.8%), Marantaceae (1.1%), Asteraceae (0.9%), Chloridoideae (0.4%), Panicoideae (0.2%)
5	Arboreal – Poaceae	non-diagnostic Arboreal (66.1%), non-diagnostic Poaceae (16.3%), Arecaceae (9.9%%), Marantaceae (2.8%), *c.f. P. guianensis (1.8%)*, Bambusoideae (1.4%), Panicoideae (0.9%), Asteraceae (0.5%), Cyperaceae (0.2%), Chloridoideae (0.2%)
10	Arboreal – Arecaceae	non-diagnostic Arboreal (87.1%), Arecaceae (5.2%), non-diagnostic Poaceae (3.4%), *c.f. P. guianensis* (1.8%), Bambusoideae (1.4%), Panicoideae (0.9%), Asteraceae (0.5%), Chloridoideae (0.2%), Cyperaceae (0.2%)
15	Arboreal – Poaceae	non-diagnostic Arboreal (82.3%), non-diagnostic Poaceae (8.1%), Arecaceae (6.7%%), Panicoideae (1.1%), *c.f. P. guianensis* (0.9%), Asteraceae (0.7%), Bambusoideae (0.6%)
25	Arboreal – Poaceae	non-diagnostic Arboreal (81.3%), non-diagnostic Poaceae (8.3%), Arecaceae (5.6%%), *c.f. P. guianensis* (1.4%), Panicoideae (1.2%), Asteraceae (0.9%), Chloridoideae (0.2%)
30	Arboreal – Poaceae	non-diagnostic Arboreal (79.0%), non-diagnostic Poaceae (11.3%), Arecaceae (5.8%), *c.f. P. guianensis* (1.4%), Panicoideae (1.2%), Asteraceae (0.9%), Cyperaceae (0.5%)
35	Arboreal – Poaceae	non-diagnostic Arboreal (81.9%), non-diagnostic Poaceae (13.4%), Panicoideae (1.1%), *c.f. P. guianensis* (1.1%), Arecaceae (0.9%), Asteraceae (0.7%), Marantaceae (0.5%), Bambusoideae (0.2%), Chloridoideae (0.2%)
40	Arboreal – Poaceae	non-diagnostic Arboreal (73.9%), non-diagnostic Poaceae (19.7%), Arecaceae (4.1%), *c.f. P. guianensis* (1.1%), Bambusoideae (0.7%), Panicoideae (0.2%), Asteraceae (0.2%)
45	Arboreal – Poaceae	non-diagnostic Arboreal (87.9%), non-diagnostic Poaceae (6.4%), Arecaceae (2.1%), Marantaceae (1.1%), *c.f. P. guianensis* (0.9%), Asteraceae (0.7%), Chloridoideae (0.4%), Heliconiaceae (0.4%), Bambusoideae (0.2%)
55	Arboreal – Poaceae	non-diagnostic Arboreal (88.8%), non-diagnostic Poaceae (8.3%), Arecaceae (1.5%%), Asteraceae (0.7%), Panicoideae (0.2%), Bambusoideae (0.2%), *c.f. P. guianensis* (0.2)
60	Arboreal – Poaceae	non-diagnostic Arboreal (89.1%), non-diagnostic Poaceae (7.8%), Arecaceae (1.5%), Chloridoideae (0.7%), Panicoideae (0.5%), Bambusoideae (0.2%), Asteraceae (0.2%)
65	Arboreal – Poaceae	non-diagnostic Arboreal (87.4%), non-diagnostic Poaceae (6.9%), Arecaceae (3.6%), Panicoideae (1%), Bambusoideae (0.5%), Chloridoideae (0.5%), Asteraceae (0.2%)
70	Arboreal – Poaceae	non-diagnostic Arboreal (90%), non-diagnostic Poaceae (7.2%), Arecaceae (2.2%), Panicoideae (0.4%), Asteraceae (0.2%)
75	Arboreal – Poaceae	non-diagnostic Arboreal (79.1%), non-diagnostic Poaceae (14.1%), Arecaceae (4.2%), Bambusoideae (1.1%), Marantaceae (1.1%), Asteraceae (0.4%)

CAST1 P2

Depth (cm)	Phytolith assemblage	Summary of phytolith taxa
0	Arboreal – Poaceae	non-diagnostic Arboreal (75.1%), non-diagnostic Poaceae (10.4%), Arecaceae (5.6%), Marantaceae (3.5%), Bambusoideae (2.6%), Asteraceae (1.5%), Panicoideae (0.4%), *c.f. P. guianensis* (0.4%), Cyperaceae (0.2%)
5	Arboreal – Arecaceae	non-diagnostic Arboreal (63.5%), Arecaceae (16.8%), Marantaceae (6.8%), non-diagnostic Poaceae (5.8%), Panicoideae (2.1%), Bambusoideae (1.4%), Asteraceae (1.2%), Chloridoideae (0.9%), Cyperaceae (0.2%), *Calathea sp.* (0.2%), Heliconiaceae (0.2%), *Mendoncia sp.*(0.2%)
10	Arboreal – Poaceae	non-diagnostic Arboreal (65.3%), non-diagnostic Poaceae (12.0%), Arecaceae (10.1%), Marantaceae (4.3%), Asteraceae (2.6%), Bambusoideae (2.0%), Annonaceae (0.8%), Panicoideae (0.8%), Cyperaceae (0,4%), Chloridoideae (0.2%), *c.f. P. guianensis* (0.2%),
15	Arboreal – Marantaceae	non-diagnostic Arboreal (75.5%), Marantaceae (7.6%), Asteraceae (5.2%), Bambusoideae (4.9%), Arecaceae (3.1%), non-diagnostic Poaceae (2.4%), Panicoideae (1.2%),
20	Arboreal – Poaceae	non-diagnostic Arboreal (79.8%), non-diagnostic Poaceae (6.8%), Marantaceae (5.7%), Arecaceae (3.0%), Bambusoideae (2.0%), Panicoideae (1.1%), Asteraceae (1.1%), Chloridoideae (0.5%)
25	Arboreal – Poaceae	non-diagnostic Arboreal (81.9%), non-diagnostic Poaceae (7.0%), Marantaceae (4.8%), Arecaceae (2.4%), Asteraceae (2.0%), Bambusoideae (1.2%), Panicoideae (0.4%), Chloridoideae (0.2%)
30	Arboreal – Poaceae	non-diagnostic Arboreal (84.8%), non-diagnostic Poaceae (6.3%), Marantaceae (3.0%) Arecaceae (2.4%), Asteraceae (1.7%), Bambusoideae (1.3%), Panicoideae (0.4%)
35	Arboreal – Poaceae	non-diagnostic Arboreal (82.4%), non-diagnostic Poaceae (5.9%), Arecaceae (4.8%), Marantaceae (3.7%), Asteraceae (1.5%), Panicoideae (0.4%), Bambusoideae (0.2%), Chloridoideae (0.2%)
40	Arboreal – Poaceae	non-diagnostic Arboreal (77.8%), non-diagnostic Poaceae (12.5%), Arecaceae (4.8%), Marantaceae (2.4%), Panicoideae (0.9%), Bambusoideae (0.6%), *Calathea sp.*(0.4%), Annonaceae (0.2%)
45	Arboreal – Poaceae	non-diagnostic Arboreal (85.6%), non-diagnostic Poaceae (5.8%), Marantaceae (4.0%), Arecaceae (3.0%), Asteraceae (0.5%), Cyperaceae (0.5%), Bambusoideae (0.5%), *c.f. P. guianensis* (0.2%)
50	Arboreal – Poaceae	non-diagnostic Arboreal (89.2%), non-diagnostic Poaceae (6.4%), Marantaceae (1.1%), Asteraceae (0.9%), Arecaceae (0.7%), Cyperaceae (0.5%), Bambusoideae (0.4%), Panicoideae (0.2%), Annonaceae (0.2%), *c.f. P. guianensis* (0.2%)
55	Arboreal – Poaceae	non-diagnostic Arboreal (88.8%), non-diagnostic Poaceae (5.7%), Marantaceae (2.9%), Arecaceae (0.7%), Asteraceae (0.5%), Bambusoideae (0.4%), Panicoideae (0.2%), Chloridoideae (0.2), Cyperaceae (0.2%), Annonaceae (0.2%)
60	Arboreal – Marantaceae	non-diagnostic Arboreal (89.3%), Marantaceae (4.0%), non-diagnostic Poaceae (3.0%), Arecaceae (2.8%), Asteraceae (0.9%)
65	Arboreal – Marantaceae	non-diagnostic Arboreal (91.2%), Marantaceae (4.4%), Asteraceae (1.6%), non-diagnostic Poaceae (1.2%), Arecaceae (0.8%), Bambusoideae (0.2%), Panicoideae (0.2%)
70	Arboreal – Marantaceae	non-diagnostic Arboreal (96.2%), Marantaceae (2.9%), Asteraceae (1.0%)
75	Arboreal – Marantaceae	non-diagnostic Arboreal (94.2%), Marantaceae (3.4%), Panicoideae (1.5%), non-diagnostic Poaceae (0.5%), Arecaceae (0.5%)

CAST2 P1

Depth (cm)	Phytolith assemblage	Summary of phytolith taxa
0	Arboreal – Marantaceae	non-diagnostic Arboreal (78%), Marantaceae (5.8%), Arecaceae (4.6%), non-diagnostic Poaceae (4.4%), Bambusoideae (1.6%), Asteraceae (1.4%), *c.f. P. guianensis* (1.2%), *Calathea sp.* (0.9%), Annonaceae (0.9%) Panicoideae (0.5%), Chloridoideae (0.2%), Cyperaceae (0.2%), *Mendoncia sp.* (0.2%), *Cucurbita sp.* (0.2%)
5	Arboreal – Poaceae	non-diagnostic Arboreal (76.3%), non-diagnostic Poaceae (8.2%), Marantaceae (7.3%), Bambusoideae (4.0%), Arecaceae (3.5%), Panicoideae (0.2%), Asteraceae (0.2%), Cyperaceae (0.2%)
10	Arboreal – Poaceae	non-diagnostic Arboreal (78.1%), non-diagnostic Poaceae (6.9%), Marantaceae (5.9%), Bambusoideae (3.3%), Arecaceae (3.3%), *c.f. P. guianensis* (0.7%), Asteraceae (0.5%), Annonaceae (0.5%), Panicoideae (0.2%), Chloridoideae (0.2%), Cyperaceae (0,4%), *Calathea sp.* (0.2%)
15	Arboreal – Poaceae	non-diagnostic Arboreal (75.2%), non-diagnostic Poaceae (9.7%), Marantaceae (7.1%), Bambusoideae (3.4%), Arecaceae (1.6%), Asteraceae (1.1%), Annonaceae (0.7%), Panicoideae (0.2%), Chloridoideae (0.2%), Heliconiaceae (0.2%), *Mendoncia sp.* (0.2%), *c.f. P. guianensis* (0.2%)
20	Arboreal – Poaceae	non-diagnostic Arboreal (71.1%), non-diagnostic Poaceae (10.2%), Marantaceae (6.0%), Arecaceae (5.3%), Bambusoideae (3.6%), Annonaceae (1%), *c.f. P. guianensis* (1%), Panicoideae (0.7%), Asteraceae (0.7%), Chloridoideae (0.5%)
25	Arboreal – Poaceae	non-diagnostic Arboreal (78%), non-diagnostic Poaceae (6.7%), Marantaceae (6.2%), Bambusoideae (5.0%), Asteraceae (1.6%), Arecaceae (0.9%), Panicoideae (0.5%), *Cucurbita sp.* (0.5%), Chloridoideae (0.2%), *Celtis sp.* (0.2%), *c.f. P. guianensis* (0.2%)
30	Arboreal – Poaceae	non-diagnostic Arboreal (81.9%), non-diagnostic Poaceae (5.7%), Asteraceae (4.2%), Marantaceae (3%), Bambusoideae (2.7%), Arecaceae (1.1%), *c.f. P. guianensis* (0.7%), Chloridoideae (0.5%), Panicoideae (0.2%)
35	Arboreal – Poaceae	non-diagnostic Arboreal (81.0%), non-diagnostic Poaceae (6.4%), Marantaceae (4.3%), Bambusoideae (3.6%), Arecaceae (1.9%), Asteraceae (1.9%), Panicoideae (0.7%), Cyperaceae (0.2%)
40	Arboreal – Poaceae	non-diagnostic Arboreal (68.2%), non-diagnostic Poaceae (17.1%), Arecaceae (6.8%), Marantaceae (3.7%), Bambusoideae (2.7%), Asteraceae (0.6%), Panicoideae (0.4%), Cyperaceae (0.4%), Chloridoideae (0.2%)
45	Arboreal – Poaceae	non-diagnostic Arboreal (83.8%), non-diagnostic Poaceae (5.2%), Bambusoideae (3.6%), Marantaceae (2.9%), Asteraceae (1.7%), Arecaceae (1.2%), Annonaceae (0.7%), Chloridoideae (0.2%), Panicoideae (0.2%), Cyperaceae (0.2%), *c.f. P. guianensis* (0.2%)
50	Arboreal – Poaceae	non-diagnostic Arboreal (87.2%), non-diagnostic Poaceae (4.2%), Asteraceae (3.3%), Marantaceae (2.8%), Bambusoideae (1.9%), Arecaceae (0.5%), Chloridoideae (0.2%), *c.f. P. guianensis* (0.2%)
55	Arboreal – Poaceae	non-diagnostic Arboreal (89.0%), non-diagnostic Poaceae (4.2%), Marantaceae (2.2%), Bambusoideae (1.5%), Asteraceae (1.2%), Arecaceae (0.7%), Panicoideae (0.5%), Chloridoideae (0.2), Annonaceae (0.2%)
60	Arboreal – Poaceae	non-diagnostic Arboreal (91.6%), non-diagnostic Poaceae (2.2%), Marantaceae (2.0%), Bambusoideae (1.5%), Arecaceae (1.2%), Asteraceae (0.5%), Panicoideae (0.5%), Chloridoideae (0.2),
65	Arboreal – Marantaceae	non-diagnostic Arboreal (90.8%), Marantaceae (4.2%), Asteraceae (2.6%), non-diagnostic Poaceae (1.4%), Bambusoideae (0.7%), Arecaceae (0.2%)
70	Arboreal – Marantaceae	non-diagnostic Arboreal (90.1%), Marantaceae (2.8%), non-diagnostic Poaceae (2.8%), Arecaceae (1.7%), Bambusoideae (1.4%), Panicoideae (0.6%), Asteraceae (0.3%), *Celtis sp.* (0.3%)
75	Arboreal – Arecaceae	non-diagnostic Arboreal (91.3%), Arecaceae (5.7%), Marantaceae (1.6%), non-diagnostic Poaceae (0.5%), Panicoideae (0.5%)

TP1 P5

Depth (cm)	Phytolith assemblage	Summary of phytolith taxa
0	Arboreal – Poaceae	non-diagnostic Arboreal (76.2%), non-diagnostic Poaceae (7.4%), Arecaceae (5.9%), Bambusoideae (3.3%), Marantaceae (2.6%), Panicoideae (2.0%), Asteraceae (1.3%), Chloridoideae (0.7%), *Calathea sp.* (0.4%), Annonaceae (0.2%)
5	Arboreal – Poaceae	non-diagnostic Arboreal (61.5%), non-diagnostic Poaceae (13.6%), Arecaceae (12.0%), Marantaceae (4.2%), Bambusoideae (3.5%), Panicoideae (2.6%), *Cucurbita sp.* (0.9%), *Calathea sp.* (0.5%), Chloridoideae (0.5%), Cyperaceae (0.2%), Heliconiaceae (0.2)
10	Arboreal – Poaceae	non-diagnostic Arboreal (72.2%), non-diagnostic Poaceae (9.2%), Arecaceae (6.9%), Marantaceae (6.2%), Bambusoideae (1.6%), Asteraceae (1.4%), Panicoideae (1.1%), Chloridoideae (0.7%), Cyperaceae (0.5%), *Cucurbita sp.* (0.2%)
15	Arboreal – Arecaceae	non-diagnostic Arboreal (67.9%), Arecaceae (13.3%), non-diagnostic Poaceae (7.4%), Marantaceae (5.5%), Bambusoideae (2.5%), *Cucurbita sp.* (1.1%), Panicoideae (0.6%), *Calathea sp.* (0.6%), Chloridoideae (0.2%), Heliconiaceae (0.2%)
20	Arboreal – Arecaceae	non-diagnostic Arboreal (67.4%), non-diagnostic Poaceae (12.3%), Arecaceae (7.7%), Marantaceae (6.3%), Bambusoideae (2.8%), Asteraceae (2.3%), Panicoideae (0.7%), Chloridoideae (0.5%), *Cucurbita sp.* (0.2%)
25	Arboreal – Arecaceae	non-diagnostic Arboreal (68.9%), Arecaceae (11.4%), non-diagnostic Poaceae (8.5%), Marantaceae (3.9%), Bambusoideae (3.2%), Asteraceae (1.9%), *Cucurbita sp.* (1.0%), Annonaceae (0.5%), Panicoideae (0.2%), Chloridoideae (0.2%), *Calathea sp.* (0.2%)
30	Arboreal – Poaceae	non-diagnostic Arboreal (74.0%), non-diagnostic Poaceae (8.9%), Arecaceae (6.3%), Marantaceae (5.4%), Bambusoideae (2.3%), Asteraceae (0.9%), Annonaceae (0.7%), *Cucurbita sp.* (0.5%), Panicoideae (0.5%), Chloridoideae (0.2%), Heliconiaceae (0.2%)
35	Arboreal – Arecaceae	non-diagnostic Arboreal (82.6%), Arecaceae (6.5%), non-diagnostic Poaceae (4.8%), Marantaceae (3.6%), Asteraceae (1.5%), Bambusoideae (0.7%), Annonaceae (0.2%)
40	Arboreal – Poaceae	non-diagnostic Arboreal (65.8%), non-diagnostic Poaceae (15.4%), Arecaceae (13.0%), Marantaceae (4.7%), Bambusoideae (0.6%), Asteraceae (0.2%), Panicoideae (0.2%)
45	Arboreal – Arecaceae	non-diagnostic Arboreal (86.7%), Arecaceae (4.9%), Marantaceae (4.2%), non-diagnostic Poaceae (2.7%), Bambusoideae (0.4%), Asteraceae (0.4%), Chloridoideae (0.2%), Cyperaceae (0.2%), *Celtis sp.* (0.2%)
50	Arboreal – Arecaceae	non-diagnostic Arboreal (87.6%), Arecaceae (5.9%), Marantaceae (2.7%), non-diagnostic Poaceae (2.4%), Bambusoideae (0.5%), Asteraceae (0.5%), Panicoideae (0.2%)
55	Arboreal – Arecaceae	non-diagnostic Arboreal (90.6%), Arecaceae (3.6%), non-diagnostic Poaceae (2.7%), Marantaceae (2.4%), Bambusoideae (0.5%), Asteraceae (0.2%)
60	Arboreal – Poaceae	non-diagnostic Arboreal (91.3%), non-diagnostic Poaceae (2.9%), Arecaceae (2.4%), Marantaceae (1.9%), Asteraceae (1.0%), Bambusoideae (0.5%)
65	Arboreal – Poaceae	non-diagnostic Arboreal (92.7%), non-diagnostic Poaceae (2.8%), Marantaceae (1.9%), Asteraceae (1.2%), Arecaceae (1.2%), Bambusoideae (0.2%)
70	Arboreal – Marantaceae	non-diagnostic Arboreal (95.0%), Marantaceae (1.6%), non-diagnostic Poaceae (1.1%), Asteraceae (1.1%), Arecaceae (0.7%), Bambusoideae (0.2%), Chloridoideae (0.2%)
75	Arboreal – Arecaceae	non-diagnostic Arboreal (88.8%), Arecaceae (6.4%), non-diagnostic Poaceae (2.6%), Marantaceae (0.8%), Asteraceae (0.8%), Bambusoideae (0.5%), Cyperaceae (0.2%)

TP1 P7

Depth (cm)	Phytolith assemblage	Summary of phytolith taxa
0	Arboreal – Poaceae	non-diagnostic Arboreal (52.5%), non-diagnostic Poaceae (20.5%), Arecaceae (15.3%), Marantaceae (5.5%), Bambusoideae (4.4%), Asteraceae (1.3%), Panicoideae (0.7%), *c.f. P. guianensis* (0.7%), Chloridoideae (0.2%), Cyperaceae. (0.2%), *Celtis sp.* (0.2%)
5	Arboreal – Arecaceae	non-diagnostic Arboreal (59.6%), Arecaceae (23.0%), non-diagnostic Poaceae (9.4%), Bambusoideae (3.1%), Marantaceae (2.6%), Asteraceae (0.9%), Panicoideae (0.7%), *c.f. P. guianensis* (0.4%),
10	Arboreal – Poaceae	non-diagnostic Arboreal (51.8%), non-diagnostic Poaceae (26.4%), Arecaceae (11.6%), Marantaceae (4.4%), Bambusoideae (2.8%), Asteraceae (1.3%), Panicoideae (0.7%), *Calathea sp.* (0.2%), *c.f. P. guianensis* (0.2%), *Cucurbita sp.* (0.2%)
15	Arboreal – Poaceae	non-diagnostic Arboreal (67.8%), non-diagnostic Poaceae (12.5%), Bambusoideae (7.0%), Arecaceae (6.8%), Marantaceae (3.3%), Asteraceae (0.6%), Chloridoideae (0.4%), Panicoideae (0.4%), Cyperaceae (0.2%), *Calathea sp.* (0.6%), Annonaceae (0.2%), *c.f. P. guianensis* (0.2%)
20	Arboreal – Poaceae	non-diagnostic Arboreal (64.9%), non-diagnostic Poaceae (13.7%), Arecaceae (10.4%), Marantaceae (4.3%), Bambusoideae (3.2%), Panicoideae (0.9%), *c.f. P. guianensis* (0.7%), Cyperaceae (0.5%), Chloridoideae (0.2%), *Calathea sp.* (0.2%), *Cucurbita sp.* (0.2%), Annonaceae (0.2%), *Celtis sp.* (0.2%)
25	Arboreal – Poaceae	non-diagnostic Arboreal (75.7%), non-diagnostic Poaceae (8.6%), Bambusoideae (6.5%), Arecaceae (4.3%), Marantaceae (3.4%), Asteraceae (0.7%), Panicoideae (0.5%), Annonaceae (0.2%), *c.f. P. guianensis* (0.2%)
30	Arboreal – Poaceae	non-diagnostic Arboreal (56.2%), non-diagnostic Poaceae (19.6%), Arecaceae (16.0%), Marantaceae (4.1%), Bambusoideae (1.9%), Asteraceae (0.9%), *Cucurbita sp.* (0.9%), *Celtis sp.* (0.2%)
35	Arboreal – Poaceae	non-diagnostic Arboreal (77.5%), non-diagnostic Poaceae (7.7%), Arecaceae (5.6%), Bambusoideae (3.7%), Marantaceae (2.5%), *c.f. P. guianensis* (1%), Asteraceae (0.8%), Panicoideae (0.4%), Annonaceae (0.2%)
40	Arboreal – Poaceae	non-diagnostic Arboreal (63.3%), non-diagnostic Poaceae (16.2%), Arecaceae (11.7%), Marantaceae (4.6%), Bambusoideae (2.1%), *Cucurbita sp.* (1.2%), Asteraceae (0.8%), *Celtis sp.* (0.2%)
45	Arboreal – Arecaceae	non-diagnostic Arboreal (86.0%), Arecaceae (5.1%), non-diagnostic Poaceae (4.0%), Marantaceae (2.4%), Bambusoideae (1.8%), Asteraceae (0.4%), Annonaceae (0.2%)
50	Arboreal – Arecaceae	non-diagnostic Arboreal (75.8%), non-diagnostic Poaceae (11.3%), Arecaceae (9.0%), Marantaceae (2.8%), Asteraceae (0.5%), Bambusoideae (0.3%), *Celtis sp.* (0.2%)
55	Arboreal – Arecaceae	non-diagnostic Arboreal (89.9%), Arecaceae (5.1%), non-diagnostic Poaceae (2.2%), Marantaceae (1.1%), Asteraceae (0.9%), Bambusoideae (0.4%), Chloridoideae (0.2%), Panicoideae (0.2%)
60	Arboreal – Arecaceae	non-diagnostic Arboreal (88.5%), Arecaceae (5.5%), non-diagnostic Poaceae (3.7%), Asteraceae (1.4%), Marantaceae (0.7%), Annonaceae (0.2%)
65	Arboreal – Arecaceae	non-diagnostic Arboreal (91.0%), Asteraceae (4.9%), non-diagnostic Poaceae (1.9%), Arecaceae (1.5%), Marantaceae (0.6%)
75	Arboreal – Arecaceae	non-diagnostic Arboreal (86.9%), Arecaceae (5.8%), non-diagnostic Poaceae (5.5%), Bambusoideae (0.9%), Marantaceae (0.5%), Asteraceae (0.4%)

BIBLIOGRAPHY

Absy, M. L., Cleef, A., Fournier, M., Martin, L., Servant, M., Sifeddine, A., … van der Hammen, T. (1991). Occurrence of four episodes of rain forest regression in southeastem Amazonia during the last 60,000 yrs. First comparison with other tropical regions. *C. R. Acad. Sci. Paris, Ser. II 312*, *3*, 673–678.

Alexandre, A, Meunier, J.-D., Lkzine, A.-M., Vincens ’, A., & Scliwartz, /. (1997). Phytoliths : indicators of grassland dynamics during the late Holocene in intertropical Africa. *Palaeogeography, Palaeoclimatology. Palaeoecology*, *136*(2), 13–229.

Alexandre, A, Santos, G. M., Harutyunyan, A., Reyerson, P., Gallagher, K., Basile-Doelsch, I., & Borschneck, D. (2014). The next chapter of direct phytolith 14C dating: debunking the myth of occluded photosynthetic carbon exclusivity. In *9th International Meeting for Phytolith Research*. Brussels, Belgium.

Alexandre, A., Meunier, J.-D., & Mariotti, A. (1999). *Late Holocene phytolith and carbon-isotope record from a latosol at Salitre, South-Central Brazil*. *Quaternary Research* (Vol. 51).

Almeida, F. O., & Kater, T. (2017). As cachoeiras como bolsões de historias dos grupos indigenas das terras baixas sul-americanas. *Rev Bras Histo´ria*, *37*(75), 39–67.

Alves, D. T. (2017). *Dark Earth Plant Management in the Lower Tapajos*. PhD thesis, University of Exeter.

Governo do Estado Amazonas. (2014). *Plano de gestão reserva de desenvolvimento sustentável Igapó-Açu*. Manaus.

Anderson, D. G., Maasch, K. A., Sandweiss, D. H., & Mayewski, P. A. (2007). Climate and culture change: exploring Holocene transitions. In D. G. Anderson, K. A. Maarsch, & D. H. Sandweiss (Eds.), *Climate Change and Cultural Dynamics: A Global Perspective on Mid-Holocene Transitions* (1st editio, p. 602). Academic Press.

Arroyo-Kalin, M. (2009). Steps Towards an Ecology of Landscape: The Pedo-Stratigraphy of Anthropogenic Dark Earth. In *Amazonian Dark Earths: Wim Sombroek’s Vision* (pp. 33–83). Dochrecht: Kluver.

Arroyo-Kalin, M. (2010). The Amazonian formative: Crop domestication and anthropogenic soils. *Diversity*, *2*(4), 473–504. https://doi.org/10.3390/d2040473

Arroyo-Kalin, Ma. (2012). Slash-burn-and-churn: Landscape history and crop cultivation in pre-Columbian Amazonia. *Quaternary International*, *249*, 4–18. https://doi.org/10.1016/j.quaint.2011.08.004

Arroyo-Kalin, M. (2014). Anthropogenic sediments and soils: Geoarchaeology. In *Encyclopaedia of Global Archaeology* (pp. 279–284). New York: Springer. https://doi.org/10.1097/00010694-200503000-00009

Balée, W, & Campbell, D. G. (1990). Evidence for the Successional Status of Liana Forest (Xingu River Basin, Amazonian Brazil). *Biotropica*, *22*(1), 36–47.

https://doi.org/10.2307/2388717

Balée, W. (1989). The culture of Amazonian forests. In Darrell Addison Posey & W. Balee (Eds.), *Resource Management in Amazonia: Indigenous Folk Strategies* (pp. 1–21). New York: Advances in Economic Botany 7.

Balée, W. (1993). Indigenous Transformation of Amazonian Forests : An Example from Maranhão, Brazil. *L'Homme*, *33*(La remontée de l'Amazone), 231–254. https://doi.org/10.3406/hom.1993.369639

Balée, W. (1994). *Footprints of the forest: Ka'apor ethnobotany—the historical ecology of plant utilization by an Amazonian people*. New York: Columbia University Press.

Balée, W. (2006). The Research Program of Historical Ecology. *Annual Review of Anthropology*, *35*(1), 75–98. https://doi.org/10.1146/annurev.anthro.35.081705.123231

Balée, W. (2010). Contingent diversity on anthropic landscapes. *Diversity*, *2*(2), 163–181. https://doi.org/10.3390/d2020163

Balée, W. (2013). *Cultural Forests of the Amazon: A Historical Ecology of People and Their Landscapes*. https://doi.org/10.1111/aman.12194

Balée, W., & Gély, A. (1989). Managed forest succession in Amazonia: the Ka'apor case. In Darrell Addison Posey & W. Balée (Eds.), *Resource Management in Amazonia: Indigenous and Folk Strategies. Advances in Economic Botany 7* (pp. 129–158). New York: New York Botanical Garden.

Ball, T. B., Davis, A., Evett, R. R., Ladwig, J. L., Tromp, M., Out, W. A., & Portillo, M. (2016). Morphometric analysis of phytoliths : recommendations towards standardization from the International Committee for Phytolith Morphometrics. *Journal of Archaeological Science*, *68*(September 2011), 106–111. https://doi.org/10.1016/j.jas.2015.03.023

Barlow, J., Parry, L., Gardner, T. a., Lees, A. C., & Peres, C. a. (2012a). Developing evidence-based arguments to assess the pristine nature of Amazonian forests. *Biological Conservation*, *152*, 293–294. https://doi.org/10.1016/j.biocon.2012.03.024

Barlow, J., Gardner, T. a., Lees, A. C., Parry, L., & Peres, C. a. (2012b). How pristine are tropical forests? An ecological perspective on the pre-Columbian human footprint in Amazonia and implications for contemporary conservation. *Biological Conservation*, *151*(1), 45–49. https://doi.org/10.1016/j.biocon.2011.10.013

Beckerman, S. (1979). The Abundance of Protein in Amazonia: A Reply to Gross. *American Anthropologist*, *81*(3), 533–560. https://doi.org/10.1525/aa.1979.81.3.02a00020

Beckerman, S., & Lizarralde, R. (2013). Conclusions. In *The Ecology of the Barí: Rainforest Horticulturalists of Latin America* (pp. 212–236). University of Texas.

Behling, H. (1998). Late Quaternary vegetational and climatic changes in Brazil. *Review of Palaeobotany and Palynology*, *99*(2), 143–156. https://doi.org/10.1016/S0034-6667(97)00044-4

Behling, H., & Hooghiemstra, H. (2000). Holocene Amazon rainforest-savanna dynamics and climatic implications: High-resolution pollen record from Laguna Loma Linda in eastern Colombia. *Journal of Quaternary Science*, *15*(7), 687–695. https://doi.org/10.1002/1099-1417(200010)15:7<687::AID-JQS551>3.0.CO;2-6

Bezerra Caldarelli, S., & Kipnis, R. (2017). *A ocupação pré-colonial da Bacia do Rio Madeira: novos dados e problemáticas associadas* (Vol. 30).

Bezerra, J. (2015). Terra Preta de Índio and Amazonian History. In *The Brazilian Amazon: Politics, Science and International Relations in the History of the Forest* (pp. 15–58).

Switzerland: Springer International Publishing.

Birk, J. J., Teixeira, W. G., Neves, E. G., & Glaser, B. (2011). Faeces deposition on Amazonian Anthrosols as assessed from 5b-stanols. *Journal of Archaeological Science*, *38*, 1209–1220. https://doi.org/10.1016/j.jas.2010.12.015

Bowdery, D. (2014). An enigma revisited: identification of palm phytoliths extracted from the 1983 Rapa Nui, Rano Kao2 core. *Vegetation History and Archaeobotany*. https://doi.org/10.1007/s00334-014-0503-x

Bozarth, S. R. (1987). Diagnostic opal phytoliths from rinds of selected Cucurbita species. *American Antiquity*, *52*(3), 607–615.

Bozarth, S. R. (1992). Classification of opal phytoliths formed in selected dicotyledons native to the Great Plains. In S. C. Mulholland & G. J. Rapp (Eds.), *Phytolith Systematics: Emerging Issues* (pp. 193–214). New York: Plenum Press.

Bozarth, S. R. (1993). Maize (Zea mays) cob phytoliths from a Central Kansas Great Bend aspect archaeological site. *Plains Anthropologist*, *38*, 279–286.

Bozarth, S. R., Prince, K., Woods, W. I., & Rebellato, L. (2009). Phytoliths and Terra Preta: the Hatahara site Example. In W. I. Woods, W. G. Teixeira, J. Lehmann, C. Steiner, & L. Rebellato (Eds.), *Amazonian Dark Earths: Wim Sombroek's Vision* (pp. 85-98). New York: Springer Science. https://doi.org/10.1007/978-1-4020-9031-8

Brady, N. C., & Weil, R. R. (1996). *Nature and Properties of Soils* (11th ed). Upper Sadle River, New Jersey: Prentice Hall.

Bray, J. R., & Curtis, J. T. (1957). An Ordination of the Upland Forest Communities of Southern Wisconsin. *Ecological Monographs*, *27*(4), 325–349.

Burbridge, R. E., Mayle, F. E., & Killeen, T. J. (2004). Fifty-thousand-year vegetation and climate history of Noel Kempff Mercado National Park, Bolivian Amazon. *Quaternary Research*, *61*(2), 215–230. https://doi.org/10.1016/j.yqres.2003.12.004

Bush, M. B., Miller, M. C., Oliveira, P. E. De, & Colinvaux, P. A. (2000). Two histories of environmental change and human disturbance in eastern lowland Amazonia. *The Holocene*, *5*, 543–553.

Bush, M. B., De Oliveira, P. E., Colinvaux, P. a., Miller, M. C., & Moreno, J. E. (2004). Amazonian paleoecological histories: One hill, three watersheds. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *214*(4), 359–393. https://doi.org/10.1016/j.palaeo.2004.07.031

Bush, M. B., McMichael, C. H., Piperno, D. R., Silman, M. R., Barlow, J., Peres, C. A., … Palace, M. W. (2015). Anthropogenic influence on Amazonian forests in pre-history: An ecological perspective. *Journal of Biogeography*, *42*, 2277–2288. https://doi.org/10.1111/jbi.12638

Bush, M. B., & Silman, M. R. (2004). Observations on Late Pleistocene cooling and precipitation in the lowland Neotropics. *Journal of Quaternary Science*, *19*(7), 677–684. https://doi.org/10.1002/jqs.883

Bush, M/ B., & Silman, M. R. (2007). Amazonian exploitation revisited: ecological asymmetry and the policy pendulum. *Frontiers in Ecology and the Environment*, *5*(9), 457–465. https://doi.org/10.1890/070018

Cabanes, D., & Shahack-Gross, R. (2015). Understanding Fossil Phytolith Preservation : The Role of Partial Dissolution in Paleoecology and Archaeology. *PLoS ONE*, *10*(5), 1–16. https://doi.org/10.1371/journal.pone.0125532

Calegari, M. R., Madella, M., Vidal-torrado, P., Luis, X., Macias, F., & Osterrieth, M. (2013). Opal phytolith extraction in oxisols. *Quaternary International*, *287*, 56–62. https://doi.org/10.1016/j.quaint.2011.11.005

Camargo, F. (1941). *Estudo de Alguns Perfils do Solos Coletados em Diversas Regiões da Hiléia*. Belém.

Carneiro, R. L. (1970). A Theory of the Origin of the State. *Science*, *168*(3947), 733–738.

Carneiro, R. L. (1983). The cultivation of manioc among the Kuikuru of the upper Xingu. In R. B. Hames & W. T. Vickers (Eds.), *Adaptive Responses of Native Amazonians* (pp. 65–112). New York: Academic Press.

Carson, J. F., Whitney, B. S., Mayle, F. E., Iriarte, J., Prümers, H., Soto, J. D., & Watling, J. (2014). Environmental impact of geometric earthwork construction in pre-Columbian Amazonia. *PNAS*, *111*(29), 10497–10502. https://doi.org/10.1073/pnas.1321770111

Chandler-Ezell, K., Pearsall, D. M., & Zeidler, J. A. (2006). Root and Tuber Phytoliths and Starch Grains Document Manioc (Manihot esculenta), Arrowroot (Maranta arundinacea), and Llerén (Calathea sp.) at the Real Alto Site, Ecuador. *Economic Botany*, *60*(2), 103–120.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L., & Williams, D. (1983). *Fire in Forestry: Volume 1*. New York: John Wiley & Sons.

Cleary, D. (2001). Towards an Environmental History of the Amazon: From Prehistory to the Nineteenth Century. *Latin American Research Review*, *36*(2), 65–96.

Clement, C. R. (1999). 1492 and the loss of Amazonian crop genetic resources I. The relation between domestication and human population decline. *Economic Botany*, *53*(2), 188–202.

Clement, C. R. (2014). Landscape domestication and archaeology. In C. Smith (Ed.), *Encyclopedia of Global Archaeology* (2014 editi, pp. 4388–4394). Springer.

Clement, C. R., de Cristo-Araújo, M., D'Eeckenbrugge, G. C., Alves Pereira, A., & Picanço-Rodrigues, D. (2010). Origin and Domestication of Native Amazonian Crops. *Diversity*, *2*(1), 72–106. https://doi.org/10.3390/d2010072

Clement, C. I., Picanço Rodrigues, D. I., Alves-Pereira III, A., Santos Mühlen, G. I., de Cristo-Araújo, M. I., Ambrósio Moreira, P. I., … Maciel Reis, V. I. (2016). Crop domestication in the upper Madeira River basin Domesticação de plantas cultivadas na bacia do alto rio Madeira. *Bol. Mus. Para. Emílio Goeldi. Cienc. Hum*, (11), 193–205. https://doi.org/10.1590/1981.812

Clement, C. R., Mccann, J. M., & Smith, N. J. H. (2003). Agrobiodiversity in Amazonia and its relationship with Dark Earths. In J. Lehmann, D. C. Kern, B. Glaser, & W. I. Woods (Eds.), *Amazonian Dark Earths – Origin, Properties, and Management* (pp. 159–178). The Netherlands: Kluwer Academic Publishers.

Clement, C. R., Cristo-Araújo, M. de, Coppens d'Eeckenbrugge, G., Reis, V. M. dos, Lehnebach, R., & Picanço-Rodrigues, D. (2017). Origin and Dispersal of Domesticated Peach Palm. *Frontiers in Ecology and Evolution*, *5*(November). https://doi.org/10.3389/fevo.2017.00148

Clement, C. R., Denevan, W. M., Heckenberger, M. J., Junqueira, A. B., Neves, E. G., Teixeira, W. G., & Woods, W. I. (2015). The domestication of Amazonia before European conquest. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1812), 20150813. https://doi.org/10.1098/rspb.2015.0813

Cochrane, T. T., & Sánchez, P. A. (1982). Land resources, soils and their management in the Amazon region: A state of knowledge report. In S. Hecht, G. A. Nores, P. A. Sánches, J. M. Spain, & G. Toenniessen (Eds.), *Amazonia: Agriculture and land use research: Proceedings* (pp. 137–209). Cali, Colombia: Centro Internacional de Agricultura Tropical (CIAT).

Coe, H. H. G., Macario, K., Gomes, J. G., Chueng, K. F., Oliveira, F., Gomes, P. R. S., … Santos, G. M. (2014). Understanding Holocene variations in the vegetation of Sao Joao River basin, southeastern coast of Brazil, using phytolith and carbon isotopic analyses. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *415*, 59–68. https://doi.org/10.1016/j.palaeo.2014.01.009

Colinvaux, P. a., De Oliveira, P. E., Moreno, J. E., Miller, M. C., & Bush, M. B. (1996). A Long Pollen Record from Lowland Amazonia: Forest and Cooling in Glacial Times. *Science*, *274*(5284), 85–88. https://doi.org/10.1126/science.274.5284.85

Colinvaux, Paul a., & De Oliveira, P. E. (2000). Palaeoecology and climate of the amazon basin during the last glacial cycle. *Journal of Quaternary Science*, *15*(4), 347–356. https://doi.org/10.1002/1099-1417(200005)15:4<347::AID-JQS537>3.0.CO;2-A

Cook, S. F., & Heizer, R. F. (1965). *Studies on the chemical analysis of archaeological sites*. Los Angeles: Univeristy of California Press.

Costa, L. (2009). Worthless Movement: Agricultural Regression and Mobility. *Luiz Tipití: Journal of the Society for the Anthropology of Lowland South America*, *7*(2).

Cunha Franco, E. (1962). As ‘terras pretas’ do planalto de Santarém. *Revista Da Sociedade Agronômica e Veterinária Do Pará.*, *8*, 17–21.

da Costa, M. L., & Kern, D. C. (1999). Geochemical signatures of tropical soils with archaeological black earth in the Amazon, Brazil. *Journal of Geochemical Exploration*, *66*, 369–385.

de Freitas, H. A., Pessenda, L. C. R., Aravena, R., Gouveia, S. E. M., de Souza Ribeiro, A., & Boulet, R. (2001). Late Quaternary Vegetation Dynamics in the Southern Amazon Basin Inferred from Carbon Isotopes in Soil Organic Matter. *Quaternary Research*, *55*(1), 39–46. https://doi.org/10.1006/qres.2000.2192

de Souza, J. G., Pahl Schaan, D., Robinson, M., Damasceno Barbosa, A., O C Aragão, L. E., Hur Marimon Jr, B., … Iriarte, J. (2018). Pre-Columbian earth-builders settled along the entire southern rim of the Amazon. *Nature Communications*, *9*, 1–10. https://doi.org/10.1038/s41467-018-03510-7

Denevan, W. M. (2003). The Native Populations of Amazonia in 1492 Reconsidered. *Revista de Indias*, *LXIII*(227), 175–187.

Denevan, W. M. (1996). A bluff model of riverine settlement in prehistoric Amazonia. *Annals of the Association of American Geographers*, *86*(4), 654–681.

Denevan, W. M. (1982). Hydraulic agriculture in the American tropics: Forms, measures, and recent research. In K. V. Flannery (Ed.), *Maya subsistence: Studies in memory of Dennis E. Puleston* (pp. 181–203). New York: Academic Press.

Denevan, W. M. (1992). The Pristine Myth: The Landscape of the Americas in 1492. *Annals of the Association of American Geographers*, *82*(3), 369–385. https://doi.org/10.1111/j.1467-8306.1992.tb01965.x

Denevan, W. M. (1998). Comments on Prehistoric Agriculture in Amazonia. *Culture & Agriculture*, *20*(2–3), 54–59. https://doi.org/10.1525/cag.1998.20.2-3.54

Denevan, W. M. (2001). *Cultivated Landscapes of Native Amazonia and the Andes*. Oxford: Oxford University Press.

Denevan, W. M. (2012a). Rewriting the Late Pre-European History of Amazonia. *Journal of Latin American Geography*, *11*(1), 9–24. https://doi.org/10.1353/lag.2012.0001

Denevan, W. M. (2012b). The “Pristine Myth” revisited. *The Geographical Review*, *101*(4), 576–591. https://doi.org/10.1126/science.15.370.195

Desjardins, T., Filho, a. C., Mariotti, a., Girardin, C., & Chauvel, a. (1996). Changes of the forest-savanna boundary in Brazilian Amazonia during the Holocene revealed by stable isotope ratios of soil organic carbon. *Oecologia*, *108*(4), 749–756. https://doi.org/10.1007/BF00329051

Dickau, R., Whitney, B. S., Iriarte, J., Mayle, F. E., Soto, J. D., Metcalfe, P., … Killeen, T. J. (2013). Differentiation of neotropical ecosystems by modern soil phytolith assemblages and its implications for palaeoenvironmental and archaeological reconstructions. *Review of Palaeobotany and Palynology*, *193*, 15–37. https://doi.org/10.1016/j.revpalbo.2013.01.004

Dietz, E. F. (1957). Phosphorus accumulation in soil of an Indian habitation site. *American Antiquity*, *22*(4), 405–409.

Dobyns, H. F. (1966). An Appraisal of Techniques with a New Hemispheric Estimate a New Hemispheric Estimate. *Current Anthropology*, *7*(4), 395. https://doi.org/10.1086/200749

Draper, N. R., & Smith, H. (1998). *Applied Regression Analysis* (3rd Editio). Wiley-Blackwell.

Eidt, R. C. (1984). *Advances in Abandoned Settlement Analysis: Application to Prehistoric Anthrosols in Columbia, South America*. Milaukee, WI: University Of Wisconsin, Center for Latin America.

Erickson, C. (2003). Historical ecology and future explorations. In Johannes Lehmann, K. Dirse, B. Glaser, & W. I. Woods (Eds.), *Amazonian Dark Earths: Origin, Properties, and Management* (pp. 455–500). The Netherlands: Kluwer Academic Publishers.

Erickson, C. L. (1995). Archaeological Methods for the Study of Ancient Landscapes of the Llanos de Mojos in the Bolivian Amazon, 66–95.

Erickson, C. L. (2006). The Domesticated Landscapes of the Bolivian Amazon. In W Balée & C. Erickson (Eds.), *Time and Complexity in Historical Ecolog y: Studies in the Neotropical Lowlands* (pp. 235–278). New York: Columbia University Press.

Erickson, C. L., & Balée, W. (2006). The Historical Ecology of a Complex Landscape in Bolivia. In William Balée & C. L. Erickson (Eds.), *Time and Complexity in Historical Ecolog y: Studies in the Neotropical Lowlands* (pp. 187–234). New York: Columbia University Press.

Falcão, N. P. S., Clement, C. R., Tsai, S. M., & Comerford, N. B. (2009). Pedology, fertility, and biology of central amazonian dark earths. In W. I. Woods, W. G. Teixeira, J. Lehmann, C. Steiner, A. M. G. A. Winklerprins, & L. Rebellato (Eds.), *Amazonian Dark Earths: Wim Sombroek’s Vision* (pp. 213–228). Berlin Heidelberg. https://doi.org/10.1007/978-1-4020-9031-8_11

Falesi, I. (1974). Soils of Brazilian Amazon. In C. H. Wagley (Ed.), *Man in the Amazon* (pp. 201–229). Gainesville: Center for Latin America Study, Univ. of Florida.

Feiss, T., El Ene Horen, H., Brasseur, B., Er ^ Ome Buridant, J., Gallet-Moron, E., & Decocq, G. (2017). Historical ecology of lowland forests: Does pedoanthracology support historical and archaeological data? *Quaternary International*, *457*, 99–112.

https://doi.org/10.1016/j.quaint.2016.10.029

Fernández H., M. A., Zucol B, A. F., & Osterrieth A, M. L. (2009). Phytolith analysis of Cyperaceae from the Pampean region, Argentina. *Australian Journal of Botany*, *57*, 512–523. https://doi.org/10.1071/BT09041

Fernández H., M., Zucol, A. F., & Osterrieth, M. L. (2006). Phytolith Assemblages and Systematic Associations in Grassland Species of the South-Eastern Pampean Plains, Argentina. *Annals of Botany*, *98*, 1155–1165. https://doi.org/10.1093/aob/mcl207

Fisher, R. F., Bourn, C. N., & Fisher, W. F. (1995). Opal phytoliths as an indicator of the floristics of prehistoric grasslands. *Geoderma*, *68*(4), 243–255. https://doi.org/10.1016/0016-7061(95)00044-9

Fishkis, O., Ingwersen, J., Lamers, M., Denysenko, D., & Streck, T. (2010). Phytolith transport in soil: A laboratory study on intact soil cores. *European Journal of Soil Science*, *61*(4), 445–455. https://doi.org/10.1111/j.1365-2389.2010.01257.x

Forline, L. C. (2008). Putting History Back into Historical Ecology: Some Perspectives on the Recent Human Ecology of the Amazon Basin. *Journal of Ecological Anthropology*, *12*(1), 69–74.

Forseth, I. N. (2010). The Ecology of Photosynthetic Pathways. *Nature Education Knowledge*, *3*(10), 4.

Fraser, J. A., & Charles, R. C. (2008). Dark Earths and manioc cultivation in Central Amazonia: a window on pre-Columbian agricultural systems: *Bol. Mus. Para. Emilio Goeldi. Ciencias Humanas, Belem*, *3*(2), 175–194. https://doi.org/10.1590/S1981-81222008000200004

Fraser, J. A., Junqueira, A. B., & Clement, C. R. (2011a). Homegardens on Amazonian Dark Earths, Non-anthropogenic Upland, and Floodplain Soils along the Brazilian Middle Madeira River Exhibit Diverging Agrobiodiversity. *Economic Botany*, *65*(1), 1–12. https://doi.org/10.1007/s12231-010-9143-y

Fraser, J. A., Teixeira, W., Falcão, N., Woods, W., Lehmann, J., Junqueiraf, A. B., … Falcao, N. (2011b). Anthropogenic soils in the Central Amazon : from categories to a continuum Linked references are available on JSTOR for this article : Anthropogenic soils in the Central Amaz categories to a continuum. *Area*, *43*(3), 264–273.

Fredlund, G. G., & Tieszen, L. L. (1997). Phytolith and Carbon Isotope Evidence for Late Quaternary Vegetation and Climate Change in the Southern Black Hills, South Dakota. *QUATERNARY RESEARCH*, *47*, 206–217.

Furley, P. A. (2006). Fragility and resilience of Amazonian soils: models from indigenous management. In Darrell Addison Posey & M. J. Balick (Eds.), *Human Impacts on Amazonia: The tole of traditional ecological knowledge in conservation and development* (pp. 122–145). New York: Columbia University Press.

Galluzzi, G., Dufour, D., Thomas, E., Van Zonneveld, M., Felipe, A., Salamanca, E., … Gonzalez Mejia, A. (2015). An Integrated Hypothesis on the Domestication of Bactris gasipaes. *PloS One*, *10*(12), 1–24. https://doi.org/10.1371/journal.pone.0144644

Ganopolski, A., Rahmstorf, S., Petoukhov, V., & Claussen, M. (1998). Simulation of modern and glacial climates with a coupled global model of intermediate complexity. *Nature*, *391*(6665), 351–356. https://doi.org/10.1038/34839

Geis, J. W. (1973). Biogenic silica in selected species of deciduous angiosperms. *Soil Science*, *116*, 113–130.

German, L. a. (2003). Historical contingencies in the coevolution of environment and livelihood: Contributions to the debate on Amazonian Black Earth. *Geoderma*, *111*(3–4), 307–331. https://doi.org/10.1016/S0016-7061(02)00270-7

Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). The “Terra Preta” phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften*, *88*(1), 37–41. https://doi.org/10.1007/s001140000193

Goulding, M., Barthem, R., & Ferreira, E. (2003). *The Smithonian Athlas of the Amazon*. Smithsonian Institution Press.

Grave, P., & Kealhofer, L. (1999). Assessing Bioturbation in Archaeological Sediments using Soil Morphology and Phytolith Analysis. *Journal of Archaeological Science*, *26*, 1239–1248.

Gross, Daniel R. (1975). Protein Capture and Cultural Development in the Amazon Basin. *American Anthropologist*, *77*(3), 526–549. https://doi.org/10.1525/aa.1975.77.3.02a00040

Haberle, S. G., & Maslin, M. A. (1999). Late Quaternary Vegetation and Climate Change in the Amazon Basin Based on a 50,000 Year Pollen Record from the Amazon Fan, ODP Site 932. *Quaternary Research*, *51*(1), 27–38. https://doi.org/10.1006/qres.1998.2020

Haffer, J. (1969). Specialization of Amazonian forest birds. *Science*, *165*(3889), 131–137.

Harris, D. R. (1989). An evolutionary continuum of people-plant interaction. In D. R. Harris & G. C. Hillmann (Eds.), *Foraging and farming: the evolutionof plant exploitation* (pp. 11–26). London: Routledge.

Hart, D. M., & Humphreys, G. S. (2003). Phytolith depth functions in surface regolith materials. In *Advances in regolith: Proc. CRC LEME Regional Regolith Symp.* (pp. 159–163). Adelaide, Canberra, and Perth.

Hart, T. C. (2016). Issues and directions in phytolith analysis. *Journal of Archaeological Science*, *68*, 24–31. https://doi.org/10.1016/j.jas.2016.03.001

Hecht, S. (2003). Indigenous soil management and the creation of Amazonian dark earths: implications of Kayapó practices. In Johannes Lehmann, D. C. Kern, W. I. Woods, & B. Glaser (Eds.), *Amazonian Dak Earth - Origin, properties, management* (pp. 355–372). Dordrecht, The Neatherlands: Kluwer Academic Publishers.

Hecht, S., & Posey, D. (1989). Preliminary Results on Soil Management Techniques of the Kayapó Indians. In D. A. Posey & W. Balée (Eds.), *Resource Management in Amazonia: Indigenous and Folk Strategies* (pp. 174–188). New York: The New York Botanical Garden.

Heckenberger, M. J., Petersen, J. B., & Neves, E. G. (1999). Village Size and Permanence in Amazonia: Two Archaeological Examples from Brazil. *Latin American Antiquity*, *10*(04), 353–376. https://doi.org/10.2307/971962

Heckenberger, M. J., Kuikuro, A., Kuikuro, U. T., Russell, J. C., Schmidt, M., Fausto, C., & Franchetto, B. (2003). Amazonia 1492: pristine forest or cultural parkland? *Science (New York, N.Y.)*, *301*(5640), 1710–1714. https://doi.org/10.1126/science.1086112

Heckenberger, M. J., Russell, J. C., Fausto, C., Toney, J. R., Schmidt, M. J., Pereira, E., … Kuikuro, A. (2008). Pre-Columbian urbanism, anthropogenic landscapes, and the future of the Amazon. *Science (New York, N.Y.)*, *321*(5893), 1214–1217. https://doi.org/10.1126/science.1159769

Heckenberger, M., & Neves, E. G. (2009). Amazonian Archaeology. *Annual Review of*

Anthropology, *38*(1), 251–266. https://doi.org/10.1146/annurev-anthro-091908-164310

Henderson, P. A., & Crampton, W. G. R. (1997). A Comparison of Fish Diversity and Abundance between Nutrient-Rich and Nutrient-Poor Lakes in the Upper Amazon Published by : Cambridge University Press Stable URL : http://www.jstor.org/stable/2560124. *Journal of Tropical Ecology*, *13*(2), 175–198.

Hilbert, M. L., Neves, E. G., Pugliese, F., Whitney, B. S., Shock, M., Veasey, E., … Iriarte, J. (2017). Evidence for mid-Holocene rice domestication in the Americas. *Nature Ecology and Evolution*, *1*(11), 1693–1698. https://doi.org/10.1038/s41559-017-0322-4

Hiraoka, M., Yamamoto, S., Matsumoto, E., Nakamura, S., Falesi, I., & Camacho Baena, A. R. (2003). Contemporary Use and Management of Amazonian Dark Earths. In Johannes Lehmann, D. C. Kern, B. Glaser, & W. I. Woods (Eds.), *Amazonian Dark Earths*. Dordrecht: Springer.

Hirshberg, R., & Hirshberg, J. (1957). Meggers' Law of Environmental Limitation on Culture. *American Anthropologist*.

Hodson, M. (2012). Interactive comment on "Comment on: 'Possible source of ancient carbon in phytolith concentrates from harvested grasses' by G. M. Santos et al. (2012)" by L. A. Sullivan and J. F. Parr. *Biogeosciences Discuss*, *9*, C5612–C5615.

Hodson, M. J. (2016). The development of phytoliths in plants and its influence on their chemistry and isotopic composition. Implications for palaeoecology and archaeology. *Journal of Archaeological Science*, *68*, 62–69. https://doi.org/10.1016/j.jas.2015.09.002

Holland, S. M. (2008). Non-Metric Multidimensional Scaling (MDS). Department of Geology, University of Georgia, Athens, GA.

Hostetler, S. W., & Mix, A. C. (1999). Reassessment of ice-age cooling of the tropical ocean and atmosphere. *Nature*, *399*(June), 673–676.

Hyland, E. G., Smith, S. Y., & Sheldon, N. D. (2013). Representational bias in phytoliths from modern soils of central North America: implications for palaeovegetation reconstructions. *Palaeogeography, Palaeoclimate, Palaeoecology*, *374*, 338–348.

Hynes, R. A., & Chase, A. K. (1982). Plants, Sites and Domiculture: Aboriginal Influence upon Plant Communities in Cape York Peninsula. *Archaeology in Oceania*, *17*(1), 38–50. https://doi.org/10.1002/j.1834-4453.1982.tb00037.x

IBGE. (1992). *Manual Técnico da Vegetação Brasileira*. Rio de Janeiro.

Ingrouille, M. (1995). *Historical Ecology of the British Flora* (1st ed.). Chapman and Hall.

Iriarte, J., Power, M. J., Rostain, S., Mayle, F. E., Jones, H., Watling, J., … McKey, D. B. (2012). Fire-free land use in pre-1492 Amazonian savannas. *Proceedings of the National Academy of Sciences*, *109*(17), 6473–6478. https://doi.org/10.1073/pnas.1201461109

Iriarte, J. (2003). Assessing the feasibility of identifying maize through the analysis of cross-shaped size and three-dimensional morphology of phytoliths in the grasslands of southeastern South America. *Journal of Archaeological Science*, *30*, 1085–1094. https://doi.org/10.1016/S0305-4403(02)00164-4

Iriarte, J., Glaser, B., Watling, J., Wainwright, A., Birk, J. J., Renard, D., … McKey, D. (2010). Late Holocene Neotropical agricultural landscapes: phytolith and stable carbon isotope analysis of raised fields from French Guianan coastal savannahs. *Journal of Archaeological Science*, *37*(12), 2984–2994. https://doi.org/10.1016/j.jas.2010.06.016

Iriarte, J., & Paz, E. A. (2009). Phytolith analysis of selected native plants and modern soils from southeastern Uruguay and its implications for paleoenvironmental and archeological reconstruction. *Quaternary International*, *193*(1–2), 99–123. https://doi.org/10.1016/j.quaint.2007.10.008

Iriarte, J., Smith, R. J., Gregorio de Souza, J., Mayle, F. E., Whitney, B. S., Cárdenas, M. L., … Valdes, P. (2017). Out of Amazonia: Late-Holocene climate change and the Tupi–Guarani trans-continental expansion. *Holocene*, *27*(7), 967–975. https://doi.org/10.1177/0959683616678461

Irion, G., Bush, M. B., Nunes de Mello, J. a., Stüben, D., Neumann, T., Müller, G., … Junk, J. W. (2006). A multiproxy palaeoecological record of Holocene lake sediments from the Rio Tapajós, eastern Amazonia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *240*(3–4), 523–535. https://doi.org/10.1016/j.palaeo.2006.03.005

IUSS Working Group. WRB (2015). *World Reference Base for Soil Resources 2014, update 2015, International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106.* FAO, Rome.

James, P. (1999). Soil Variability in the Area of an Archaeological Site near Sparta, Greece. *Journal of Archaeological Science*, *26*, 1273–1288.

Judziewicz, E. J., Soreng, R. J., Davidse, G., Peterson, P. M., Filgueiras, T. S., & Zuloaga, F. O. (2000). Catalogue of New World Grasses (Poaceae): I. Subfamilies Anomochlooideae, Bambusiodeae, Ehrhartoideae and Pharoideae. *Contributions from the United States National Herbarium*.

Junk, W. J., Teresa Fernandez Piedade, M., Schöngart, J., Cohn-Haft, M., Marion Adeney, J., & Wittmann, F. (2011). A Classification of Major Naturally-Occurring Amazonian Lowland Wetlands. *Wetlands*, *31*, 623–640. https://doi.org/10.1007/s13157-011-0190-7

Junqueira, A. B., Shepard, G. H., & Clement, C. R. (2010). Secondary Forests on Anthropogenic Soils of the Middle Madeira River: Valuation, Local Knowledge, and Landscape Domestication in Brazilian Amazonia. *Economic Botany*, *65*(1), 85–99. https://doi.org/10.1007/s12231-010-9138-8

Kämpf, N., Woods, W. I., Sombroek, W., Kern, D. C., & Cunha, T. J. F. (2003). Classification of Amazonian dark earths and other ancient anthropic soils. In Johannes Lehmann, D. C. Kern, B. Glaser, & W. I. Woods (Eds.), *Amazonian Dak Earth - Origin, properties, management* (pp. 77–102). New York: Kluwer Academic Publishers.

Kelchner, S. A., & Group, B. P. (2013). Higher level phylogenetic relationships within the bamboos (Poaceae: Bambusoideae) based on five plastid markers. *Molecular Phylogenetics and Evolution*, *67*, 404–413. https://doi.org/10.1016/j.ympev.2013.02.005

Kelly, E. F., Blecker, S. W., Yonker, C. M., Olson, C. G., Wohl, E. E., & Todd, L. C. (1998). Stable isotope composition of soil organic matter and phytoliths as paleoenvironmental indicators. *Geoderma*. https://doi.org/10.1016/S0016-7061(97)00097-9

Kelly, E. F, Amundson, R. G., Marino, B. D., & Deniro-P~, M. J. (1991). Stable Isotope Ratios of Carbon in Phytoliths as a Quantitative Method of Monitoring Vegetation and Climate Change. *QUATERNARY RESEARCH*, *35*, 222–233.

Kern, D. C. (2009). Análise e interpretação dos solos e, ou, sedimentos nas pesquisas arqueológicas. *Revista Do Museu de Arqueologia e Etnologia*, *8*, 21–35.

Kern, D. C., D’Aquino, G., Rodrigues, T. E., Frazao, L. F. J., Sombroek, W. G., Myers, T. P., & Neves, E. G. (2003). Distribution of Amazonian Dark Earthsin the Brazilian Amazon. In J. Lehmann, D. C. Kern, B. Glaser, & W. I. Woods (Eds.), *Amazonian Dark Earths: Origin, Properties, and Management* (pp. 51–75). The Netherlands: Kluwer Academic

Publisher.

Kern, D. C., Costa, M. L. Da, & Frazão, F. J. L. (2004). Evolution of the scientific knowledge regarding archaeological black earths of Amazonia. In Bruno Glaser & W. I. Woods (Eds.), *Amazonian Dark Earths: Explorations in Space and Time* (pp. 19–28). Springer. https://doi.org/10.1007/978-3-662-05683-7_3

Killion, T. W. (2013). Nonagricultural Cultivation and Social Complexity. *Current Anthroplogy*, *54*(5), 569–606.

Kondo, R., Childs, C., & Atkinson, L. (1994). *Opal Phytoliths of New Zealand*. Lincoln, NZ: Manaaki Whenua Press.

Kruskal, J. B. (1964). *Nonmetric multidimensional scaling: A numerical method*.

Lathrap, D. W. (1970). *The Upper Amazon*. London: Thames and Hudson.

Latinis, D. K. (2000). The development of subsistence system models for Island Southeast Asia and Near Oceania: the nature and role of arboriculture and arboreal-based economies. *World Archaeology*, *32*(1), 41–67. https://doi.org/10.1080/004382400409880

Ledru, M. P., Bertaux, J., Sifeddine, a, & Suguio, K. (1998). Absence of last glacial maximum records in lowland tropical forests. *Quaternary Research*, *49*(2), 233–237. https://doi.org/10.1006/qres.1997.1953

Legendre, P., & Legendre, L. (2012). *Numerical Ecology, Volume 24* (3 edition). Elsevier.

Lehmann, J. D., Campos, C. V., De Macêdo, J. L. V, & German, L. (2004). Sequential P Fractionation of Relict Anthropogenic Dark Earths of Amazonia. In B Glaser & W. I. Woods (Eds.), *Amazonian Dark Earths: Explorations in Space and Time* (pp. 113–123). Berlin, Heidelberg: Springer.

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

Lehmann, J, D., Da Mota, M. S., De Almeida, M. P., Zech, W., & Kaiser, K. (2001). *Inorganic and organic soil phosphorus and sulfur pools in an Amazonian multistrata agroforestry system*. *Agroforestry Systems* (Vol. 53).

Levis, C., Costa, F. R. C., Bongers, F., Peña-Claros, M., Clement, C. R., Junqueira, A. B., … ter Steege, H. (2017). Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. *Science*, *355*(6328).

Levis, C, de Souza, P. F., Schietti, J., Emilio, T., Pinto, J. L. P. D. V., Clement, C. R., & Costa, F. R. C. (2012). Historical human footprint on modern tree species composition in the Purus-Madeira interfluve, central Amazonia. *PloS One*, *7*(11), e48559. https://doi.org/10.1371/journal.pone.0048559

Levis, C., Flores, B. M., Moreira, P. A., Luize, B. G., Alves, R. P., Franco-Moraes, J., … Clement, C. R. (2018). How People Domesticated Amazonian Forests. *Front. Ecol. Evol*, *5*(171). https://doi.org/10.3389/fevo.2017.00171

Levis, C., Silva, M. D. S., Almeida, M., & Moraes, C. P. (2013). What do we know about the distribution of Amazonian Dark Earth along tributary rivers in Central AmazoniaNo Title. In *Poster Text – III Encuentro Internacional de Arqueología Amazónica (EIAA)*.

Lombardo, U., Szabo, K., Capriles, J. M., May, J. H., Amelung, W., Hutterer, R., … Veit, H. (2013). Early and Middle Holocene Hunter-Gatherer Occupations in Western

Amazonia: The Hidden Shell Middens. *PLoS ONE*, *8*(8). https://doi.org/10.1371/journal.pone.0072746

Lu, H.-Y., Wu, N.-Q., Liu, K.-B., Jiang, H., & Liu, T.-S. (2007). Phytoliths as quantitative indicators for the reconstruction of past environmental conditions in China II: palaeoenvironmental reconstruction in the Loess Plateau. *Quaternary Science Reviews*, *26*, 759–772. https://doi.org/10.1016/j.quascirev.2006.10.006

Lu, H.-Y., Wu, N.-Q., Yang, X.-D., Jiang, H., Liu, K.-B., & Liu, T.-S. (2006). Phytoliths as quantitative indicators for the reconstruction of past environmental conditions in China I: phytolith-based transfer functions. *Quaternary Science Reviews*, *25*, 945–959. https://doi.org/10.1016/j.quascirev.2005.07.014

Lu, H., & Liu, K.-B. (2003). Morphological Variations of Lobate Phytoliths from Grasses in China and the South-Eastern United States. *Diversity and Distributions*, *9*(1), 73–87.

Lü, H., Wang, Y., Wang, G., Yang, H., & Li, Z. (2000). Analysis of carbon isotope in phytoliths from C3 and C4 plants and modern soils. *Chinese Science Bulletin*, *45*(19), 1804–1808. https://doi.org/10.1007/BF02886272

Madari, B. E., Benites, V. de M., & Cunha, T. J. F. (2003). The Effect of Management on hte Fertility of Amazonian Dark Earth Soils. In Johannes Lehmann, D. C. Kern, B. Glaser, & W. I. Woods (Eds.), *Amazonian Dak Earth - Origin, properties, management* (pp. 407–426). Dordrecht: Springer.

Madella, M., Alexandre, A., & Ball, T. (2005). International Code for Phytolith Nomenclature 1.0. *Annals of Botany*, *96*, 253–260. https://doi.org/10.1093/aob/mci172

Madella, M., & Lancelotti, C. (2012). Taphonomy and phytoliths: A user manual. *Quaternary International*, *275*, 76–83. https://doi.org/10.1016/j.quaint.2011.09.008

Maezumi, S. Y., Alves, D., Robinson, M., Gregorio de Souza, J., Levis, C., Barnett, R. L., … Iriarte, J. (2018). The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon. *Nature Plants*, *In Press*(July). https://doi.org/10.1038/s41477-018-0205-y

Maia, C. M. B. F., Madari, B. E., & Novotny, E. H. (2011). Advances in Biochar Research in Brazil. *Dynamic Soil, Dynamic Plant*, *5*((Special Issue 1)), 53–58.

Major, J., Clement, C. R., & DiTommaso, A. (2005). Influence of Market Orientation on Food Plant Diversity of Farms Located on Amazonian Dark Earth in the Region of Manaus, Amazonas, Brazil. *Economic Botany*, *59*(1), 77–86. https://doi.org/10.1663/0013-0001(2005)059[0077:IOMOOF]2.0.CO;2

Major, J., Ditommaso, A., German, L. A., & Mccann, J. M. (2003). Weed population dynamics and management on Amazonian Dark Earth. In Johannes Lehmann, D. C. Kern, B. Glaser, & W. I. Woods (Eds.), *Amazonian Dark Earths: Origin, Properties, Management* (pp. 433–454). The Netherlands: Kluwer Academic Publishers.

Mann, C. C. (2002). “1491.” *The Atlantic*, *March*. Retrieved from https://www.theatlantic.com/magazine/archive/2002/03/1491/302445/

May, P. H., Anderson, A. B., Balick, M. J., Jos~, A., & Fraz~o, M. F. (1985). Subsistence Benefits from the Babassu Palm (Orbignya martiana) 1.

May, P. H., Anderson, A. B., Balick, M. J., Mario, J., & Fraz~o, F. (1985). *Subsistence Benefits from the Babassu Palm (Orbignya martiana) 1. Economic Botany* (Vol. 39).

Mayle, F. E., Beerling, D. J., Gosling, W. D., & Bush, M. B. (2004). Responses of Amazonian ecosystems to climatic and atmospheric carbon dioxide changes since the last glacial maximum. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *359*(1443), 499–514. https://doi.org/10.1098/rstb.2003.1434

Mayle, F. E., Burbridge, R., & Killeen, T. J. (2000). Millennial-scale dynamics of southern Amazonian rain forests. *Science*, *290*(December), 2291–2294. https://doi.org/10.1126/science.290.5500.2291

Mayle, F. E., & Iriarte, J. (2014). Integrated palaeoecology and archaeology - a powerful approach for understanding pre-Columbian Amazonia. *Journal of Archaeological Science*, *51*, 54–64. https://doi.org/10.1016/j.jas.2012.08.038

Mayorga, E., Logsdon, M. G., Ballester, M. V. R., & Richey, J. E. (2005). Estimating cell-to-cell land surface drainage paths from digital channel networks, with an application to the Amazon basin. *Journal of Hydrology*, *315*(1–4), 167–182. https://doi.org/10.1016/j.jhydrol.2005.03.023

McClaran, M. P., & Umlauf, M. (2000). Desert grassland dynamics estimated from carbon isotopes in grass phytoliths and soil organic matter. *Journal of Vegetation Science*, *11*, 71–76. https://doi.org/10.2307/3236777

McCormac, F. G., Hogg, A. G., Blackwell, P. G., Buck, C. E., Higham, T. F. G., & Reiner. P. J. (2004). SHCal04 Southern Hemisphere Calibration, 0-11.0 Cal Kyr Bp. *Radiocarbon*, *46*(3), 1087–1092.

McCune, B., & Grace, J. B. (2002). Distance Measures. In *Analysis of Ecological Communities* (p. 304). Gleneden Beach, Oregon, USA: Mjm Software Design. m

McKey, D., Rostain, S., Iriarte, J., Glaser, B., Birk, J. J., Holst, I., & Renard, D. (2010). Pre-Columbian agricultural landscapes, ecosystem engineers, and self-organized patchiness in Amazonia. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(17), 7823–7828. https://doi.org/10.1073/pnas.0908925107

McManamon, F. P. (1984). Discovering Sites Unseen. *Advances in Archaeological Method and Theory*, *7*, 223–292.

McMichael, C. H., Bush, M. B., Piperno, D. R., Silman, M. R., Zimmerman, a. R., & Anderson, C. (2011). Spatial and temporal scales of pre-Columbian disturbance associated with western Amazonian lakes. *The Holocene*, *22*(2), 131–141. https://doi.org/10.1177/0959683611414932

McMichael, C. H., Correa-Metrio, A., & Bush, M. B. (2012a). Pre-Columbian fire regimes in lowland tropical rainforests of southeastern Peru. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *342–343*, 73–83. https://doi.org/10.1016/j.palaeo.2012.05.004

McMichael, C. H., Piperno, D. R., Bush, M. B., Silman, M. R., Zimmerman, a. R., Raczka, M. F., & Lobato, L. C. (2012b). Sparse Pre-Columbian Human Habitation in Western Amazonia. *Science*, *336*(6087), 1429–1431. https://doi.org/10.1126/science.1219982

McMichael, C. N. H., Matthews-Bird, F., Farfan-Rios, W., & Feeley, K. J. (2017). Ancient human disturbances may be skewing our understanding of Amazonian forests. *Proceedings of the National Academy of Sciences*, *114*(3). https://doi.org/10.1073/pnas.1614577114

McMichael, C H, Palace, M. W., Bush, M. B., Braswell, B., Hagen, S., Neves, E. G., … Czarnecki, C. (2014). Predicting pre-Columbian anthropogenic soils in Amazonia. *Proceedings of the Royal Society*, *281*(January), 2–9. https://doi.org/10.1098/rspb.2013.2475

McMichael, Crystal H., Piperno, D. R., Neves, E. G., Bush, M. B., Almeida, F. O., Mongeló, G., & Eyjolfsdottir, M. B. (2015). Phytolith Assemblages Along a Gradient of Ancient

Human Disturbance in Western Amazonia. *Frontiers in Ecology and Evolution*, *3*, 1–15. https://doi.org/10.3389/fevo.2015.00141

Meggers, B. J. (1954). Meggers 1954 Environmental Limitation on the Development of Culture.pdf. *American Anthropologist*, *56*(5), 801–824.

Meggers, B.J. (2011). Handbook of South American Archaeology reviewed by Betty J. Meggers. *Revista de Antropología Chilena*, *43*(1), 147–157.

Meggers, B. J. (1971). *Amazonia: Man and culture in a counterfeit paradise*. Chicago: Aldine-Atherton.

Meggers, B. J. (1994). Archeological evidence for the impact of mega-Niño events on Amazonia during the past two millennia. *Climatic Change*, *28*, 321–338.

Meggers, B. J. (1993). Amazonia On the Eve Of European Contact: Ethnohistorical, Ecological, And Anthropological Perspectives. *Revista de Arqueología Americana*, (8), 91–115.

Meggers, B. J. (1996). *Amazonia: Man and Culture in a Counterfeit Paradise (Revised Edition)*. Smithsonian Institution Press.

Meggers, B. J., & Ewans, C. (1957). *Archeological Investigations at the Mouth of the Amazon*. Wasington, DC: Smithsonian Institution.

Michon, G., & de Foresta, H. (1997). Agroforests: pre-domestication of forest trees or true domestication of forest ecosystems? *Netherlands Journal of Agricultural Science*, *45*, 451–462.

Miller. (1992). Arqueologia nos empreendimentos hidrelectricos da Electronorte: Resultados preliminares. Brasilia: Electronorte.

Moran, E. F. (1993). Managing Amazonian variability with indigenous knowledge. *Tropical Forests, People and Food. Biocultural Interactions and Applications to Development*, *765*(93), 753–766.

Morcote-Rios, G., & Bernal, R. (2001). Remains of Palms (Palmae) at Archaeological Sites in the New World: A Review. *The Botanical Review*, *67*, 309–350.

Morcote-Ríos, G., Bernal, R., & Raz, L. (2016). Phytoliths as a tool for archaeobotanical, palaeobotanical and palaeoecological studies in Amazonian palms. *Botanical Journal of the Linnean Society*, *182*(2), 348–360. https://doi.org/10.1111/boj.12438

Mori, S. A., & Prance, G. T. (1990). Taxonomy, Ecology, and Economic Botany of the Brazil Nut (Bertholletia excelsa Humb. & Bonpl.: Lecythidaceae). *Advances in Economic Botany*, *8*, 130–150.

Mulholland, S. C. (1989). *Phytolith Shape Frequencies in North Dakota Grasses: A Comparison to General Patterns*. *Journal of Archaeological Science* (Vol. 16).

Myers, T/ P. (1988). El efecto de las pestes sobre las poblaciones de la Amazonia alta. *Amazonía Peruana*, *8*, 61–81.

Myers, T. P. (1992). Agricultural limitations of the Amazon in theory and practice. *World Archaeology*, *24*(1), 82–97. https://doi.org/10.1080/00438243.1992.9980195

Neves, E G. (1999). Changing perspectives in Amazonian archaeology. In G. G. Politis & B. Alberti (Eds.), *Archaeology in Latin America* (pp. 219–250). London and New York: Routledge.

Neves, E. G., Petersen, J. B., Bartone, R. N., & Da Silva, C. A. (2003). Historical and Socio-

Cultural Origins of Amazonian Dark Earths. In Johannes Lehmann (Ed.), *Amazonian Dark Earths: Origin, Properties, Management* (pp. 29–50). The Netherlands: Kluwer Academic Publishers.

Neves, E. G., Petersen, J. B., Bartone, R. N., & Heckenberger, M. J. (2004). The Timing of Terra Preta Formation in the Central Amazon: Archaeological Data from Three Sites. In Bruno Glaser & W. I. Woods (Eds.), *Amazonian Dark Earths: Explorations in Space and Time* (pp. 125–134). Berlin Heidelberg: Springer.

Oksanen, J. (2015). *Multivariate Analysis of Ecological Communities in R: vegan tutorial*.

Oliveras, I., & Malhi, Y. (2016). Many shades of green: the dynamic tropical forest - savanna transititon. *Philosophical Transactions*, *371*, 20150308. https://doi.org/10.1098/rstb.2015.0308

Ollendorf, A. L. (1992). Toward a Classification scheme of sedge (Cyperaceae) phytoliths. In G. J. Rapp & S. C. Mulholland (Eds.), *Phytolith Systematics. Advances in Archaeological and Museum Science* (pp. 91–111). Boston, MA: Springer.

Oslisly, R., & White, L. (2007). Human Impact and Environmental Exploitation In Gabon During The Holocene. In T. Denham, J. Iriarte, & L. Vrydaghs (Eds.), *Rethinking Agriculture: Archaeological and Ethnoarchaeological Perspectives* (pp. 347–360). Walnut Creek, CA, USA: Left Coast Press.

Osterrieth, M., Madella, M., Zurro, D., & Alvarez, M. F. (2009). Taphonomical aspects of silica phytoliths in the loess sediments of the Argentinean Pampas. *Quaternary International*, *193*(April 2018), 70–79. https://doi.org/10.1016/j.quaint.2007.09.002

Palace, M. W., McMichael, C. N. H., Braswell, B. H., Hagen, S. C., Bush, M. B., Neves, E., … Frolking, S. (2017). Ancient Amazonian populations left lasting impacts on forest structure. *Ecosphere*, *8*(12), e02035. https://doi.org/10.1002/ecs2.2035

Palm, C. A., Swift, M. J., & Woomer, P. L. (1996). Soil biological dynamics in slash-and-burn agriculture. *Agriculture, Ecosystems and Environment*, *58*(1), 61–74. https://doi.org/10.1016/0167-8809(95)00653-2

Parker, E. (1992). Forest Islands and Kayapo; Resource Management in Amazonia: A Reappraisal of the Apete. *American Anthropologist*, *94*(2), 406–428. https://doi.org/10.1525/aa.1992.94.2.02a00090

Pärssinen, M., Schaan, D., & Ranzi, A. (2009). Pre-Columbian geometric earthworks in the upper Purus: a complex society in western Amazonia. *Antiquity*, *83*(December 2008), 1084–1095. https://doi.org/10.1017/S0003598X00099373

Pearsall, D. M. (1978). Phytolith Analysis of Archeological Soils: evidence for maize cultivation in Formative Ecuador. *Science*, *199*, 177–178. https://doi.org/10.1126/science.199.4325.177

Pearsall, D. M. (2000). *Paleoethnobotany: A Handbook of Procedures* (2nd Editio). San Diego: Academic Press.

Pearsall, D. M., Chandler-Ezell, K., & Chandler-Ezell, A. (2003). Identifying maize in neotropical sediments and soils using cob phytoliths. *Journal of Archaeological Science*, *30*, 611–627. https://doi.org/10.1016/S0305-4403(02)00237-6

Peres-Neto, P. R., & Jackson, D. A. (2001). How well do multivariate data sets match? The advantages of a Procrustean superimposition approach over the Mantel test. *Oecologia* , *129*, 169–178. https://doi.org/10.1007/s004420100720

Peres, C. A., & Baider, C. (1997). Seed dispersal, spatial distribution and population structure of Brazilnut trees (Bertholletia ecxelsa) in southeastern Amazonia. *Journal of Tropical Ecology*, *13*(4), 595–616.

Pessenda, L, Gouveia, S., Gomes, B., Aravena, R., Riberio, A. S., & Boulet, R. (1998). The carbon isotope record in soils along a forest-cerrado ecosystem transect: implications for vegetation changes in the Rondonia state, southwestern Brazilian Amazon region. *The Holocene*, *8*(5), 599–603.

Pessenda, L, Gouveia, S., & Aravena, R. (2001). Radiocarbon Dating of Total Soil Organic Matter and Humin Fraction and Its Comparison With 14C Ages of Fossil Charcoal. *Radiocarbon*, *43*(2), 595–601. https://doi.org/10.2458/azu_js_rc.v.3890

Pessenda, L. C. R., Ribeiro, A. D. S., Gouveia, S. E. M., Aravena, R., Boulet, R., & Bendassolli, J. A. (2004). Vegetation dynamics during the late Pleistocene in the Barreirinhas region, Maranhão State, northeastern Brazil, based on carbon isotopes in soil organic matter. *Quaternary Research*, *62*(2), 183–193. https://doi.org/10.1016/j.yqres.2004.06.003

Peters, C. M. (2000). Precolumbian Silviculture and Indigenous Management of Neotropical Forests. *Imperfect Balance: Landscape Transformations in the Pre-Columbian Americas*, (October), 203–224.

Petersen, J. B., Neves, E., & Heckenberger, M. J. (2001). Gift from the past: Terra Preta and prehistoric Amerindian occupation in Amazonia. In C. McEwan, C. Barreto, & E. G. Neves (Eds.), *Unknown Amazon: culture in nature ancient Brazil* (pp. 86–105). London: British Museum Press.

Pezzini, F., Alves de Melo, P. H., Silva de Oliveira, D. M., Xavier de Amorim, R., Gouvêa de Figueiredo, F. O., Pignatari Drucker, D., … Pena Pimentel, T. (2012). The Brazilian Program for Biodiversity

Piperno, D. R., McMichael, C., & Bush, M. B. (2015). Amazonia and the Anthropocene: What was the spatial extent and intensity of human landscape modification in the Amazon Basin at the end of prehistory? *The Holocene*. https://doi.org/10.1177/0959683615588374

Piperno, D. R., & Pearsall, D. M. (1993). Phytoliths in the Reproductive structures of maize and teosinte: implications for the study of maize evolution. *Journal of Archaeological Science*, *20*, 337–362.

Piperno, D. R. (1988). *Phytolith Analysis: An Archaeological and Geological Perspective*. San Diego: Academic Press.

Piperno, D. R. (2006). *Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists*. Lanham, MD: Altamira Press.

Piperno, Do. R., Andres, T. C., & Stothert, K. E. (2000). Phytoliths in Cucurbita and other Neotropical Cucurbitaceae and their occurrence in early archaeological sites from the lowland American tropics. *Journal of Archaeological Science*, *27*(3), 193–208. https://doi.org/10.1006/jasc.1999.0443

Piperno, D. R., & Pearsall, D. M. (1998a). *The Origins of Agriculture in the Lowland Neotropics*. San Diego: Academic Press.

Piperno, D. R., & Pearsall, D. M. (1998b). The Silica Bodies of Tropical American Grasses: Morphology, Taxonomy, and Implications for Grass Systematics and Fossil Phytolith Identification. *Smithsonian Contributions to Botany*. https://doi.org/10.5479/si.0081024X.85

Piperno, D. R. (1989). The Occurrence of Phytoliths in the Reproductive Structures of

Selected Tropical Angiosperms and Their Significance in Tropical Paleoecology, Paleoethnobotany and Systematics. *Review of Palaeobotany and Palynology Elsevier Science Publishers B.V*, *61*, 147–173.

Piperno, D. R. (2016). Phytolith radiocarbon dating in archaeological and paleoecological research: a case study of phytoliths from modern Neotropical plants and a review of the previous dating evidence. *Journal of Archaeological Science*, *68*, 54–61. https://doi.org/10.1016/j.jas.2015.06.002

Piperno, D. R, Mcmichael, C., & Bush, M. B. (2017). Further evidence for localized, short-term anthropogenic forest alterations across pre-Columbian Amazonia. *PNAS*, *114*, E4118–E4119. https://doi.org/10.1073/pnas.1705585114

Posey, D. A., Frechione, J., & Eddins, J. (1984). Ethnoecology as Applied Anthropology in Amazonian Development. *Human Organization*, *43*(2), 95–107.

Posey, D. A.. (1985). Indigenous management of tropical forest ecosystems: the case of the Kayapo Indians of the Brazilian Amazon. *Agroforestry Systems*, *3*, 139–158. https://doi.org/10.1007/BF00122640

Posey, D. A., & Plenderleith, K. (2002). *Kayapo Ethnoecology and Culture*. New York: Routledge.

Prance, G. T. (1987). Vegetation. In T. C. Whitmore & G. T. Prance (Eds.), *Biogeography and Quaternary History in Tropical America* (pp. 28–45). Oxford: Oxford University Press.

Provan, D. M. J. (1971). Soil phosphate analysis as a tool in archaeology.pdf. *Norwegian Archaeological Review*, *4*(1), 37–50.

Prümers, H., & Jaimes Betancourt, C. (2014). 100 años de investigación arqueológica en los Llanos de Mojos. *Arqueoantropológicas*, *4*, 11–54.

Prychid, C. J., Rudall, P. J., & Gregory, M. (2003). Systematics and Biology of Silica Bodies in Monocotyledons. *The Botanical Review*, *69*(4), 377–440.

Rapp, G. J., & Hill, C. L. (2006). *Geoarchaeology: The earth-science approach to archaeological interpretation (2nd ed.)*. New Haven, CT: Yale University Press.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., … van der Plicht, J. (2013). IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. *Radiocarbon*, *55*(04), 1869–1887. https://doi.org/10.2458/azu_js_rc.55.16947

Roosevelt, A. C., Housley, R. A., Imazio, M., Silveira, D., Maranca, S., & Johnson, R. (1991). Eighth Millennium Pottery from a Prehistoric Shell Midden in the Brazilian Amazon. *Source: Science, New Series*, *254*(5038), 1621–1624.

Roosevelt, A. C., Lima Da Costa, M., Lopes Machado, C., Michab, M., Mercier, N., Valladas, H., … Schick, K. (1996). Paleoindian Cave Dwellers in the Amazon: The Peopling of the Americas. *Science*, *272*, 373–384.

Roosevelt, A. C. (1980). *Parmana: Prehistoric Maize and Manioc Susbistence along the Amazon and Orinoco*. New York: Academic Press.

Roosevelt, A. C. (2014). The Amazon and the Anthropocene: 13,000 Years of Human Influence in a Tropical Rainforest. *Anthropocene*, *4*(2013), 69–87. https://doi.org/10.1016/j.ancene.2014.05.001

Roosevelt, A. C. (1993). The Rise and Fall of the Amazon Chiefdoms. *L’Homme*, *33*(126), 255–283. https://doi.org/10.3406/hom.1993.369640

Roosevelt, A. C. (1999). Twelve thousand years of human environment interaction in the Amazon floodplain. In C. Padoch & A. Henderson (Eds.), *Diversity, Development, and Conservation in Amazonia's Floodplains* (Adv. Econ., pp. 371–392). New York: New York Botanical Garden.

Runge, F. (1999). The opal phytolith inventory of soils in central Africa —quantities, shapes, classification, and spectra. *Review of Palaeobotany and Palynology*, *107*, 23–53.

Sanchez, P. A. (1976). *Properties and Management of Soils in the Tropics* (1st Editio). New York: John Wiley & Sons.

Sase, T., & Hosono, M. (2001). *Phytolith record in soils interstratified with late Quaternary Tephras overlying the eastern region of Towada volcano, Japan*. *Phytoliths: Applications in Earth Sciences and Human History*.

Saunaluoma, S. (2010). Pre-Columbian Earthworks in the Riberalta Region of the Bolivian Amazon. *Amazônica*, *2*, 86–115.

Schaan, D. (2010). *Sacred Geographies of Ancient Amazonia. Historical Ecology of Social Complexity*. Walnut Creek, California: Left Coast Press.

Schaan, D., Pärssinen, M., Ranzi, A., & Piccoli, J. C. (2007). Geoglifos da Amazônia Ocidental: evidência de complexidade social entre povos da terra firme. *Revista de Arqueologia*, *20*, 67–82.

Schaan, D., Pärssinen, M., Saunaluoma, S., Ranzi, A., Bueno, M., & Barbosa, A. (2012). New radiometric dates for precolumbian (2000-700 b.p.) earthworks in western Amazonia, Brazil. *Journal of Field Archaeology*, *37*(2), 132–142. https://doi.org/10.1179/0093469012Z.00000000012

Schimmelmann, A., Lange, C. B., & Meggers, B. J. (2003). Palaeoclimatic and archaeological evidence for a 200-yr recurrence of floods and droughts linking California, Mesoamerica and South America over the past 2000 years. *The Holocene*, *135*, 763–778.

Schmidt, M. J., & Heckenberger, M. J. (2009). Amerindian Anthrosols : Amazonian Dark Earth Formation in the Upper Xingu. *Amazonian Dark Earths: Wim Sombroek's Vision*, *1*, 163–191. https://doi.org/10.1007/978-1-4020-9031-8_8

Schmidt, M. W. I., & Noack, A. G. (2000). Black Carbon in Soils and Sediments: Analysis, Distribution, Implications, and Current Challenges. *Global Biogeochem Cy*, *14*(3), 777–793.

Schulz, J. P. (1960). *Ecological Studies on Rain Forest in Northern Suriname*. Utrecht: Mededelingen van het Botanisch Museum en Herbarium van de Rijksuniversiteit te Utrecht.

Schuyler, A. E. (1971). Scanning Electron Microscopy of Achene Epidermis in Species of Scirpus (Cyperaceae) and Related Genera. *Proceedings of the Academy of Natural Sciences of Philadelphia*, *123*, 29–52.

Shepard Jr., G. H., & Ramirez, H. (2011). "Made in Brazil": Human Dispersal of the Brazil Nut (Bertholletia excelsa, Lecythidaceae) in Ancient Amazonia. *Economic Botany*, *65*(1), 44–65. https://doi.org/10.1007/s12231-011-9151-6

Shepard, R. N. (1962). The analysis of proximities: Multidimensional scaling with an unknown distance function. I. *Psychometrika*, *27*(2), 125–140. https://doi.org/10.1007/BF02289630

Shillito, L. M. (2013). Grains of truth or transparent blindfolds ? *Vegetation History and*

Archaeobotany, *22*(1), 71–82. https://doi.org/10.1007/s00334-011-0341-z

Shorter Oxford English Dictionary on Historical Principles, 5th ed. (2002). Oxford: OUP.

Silvério, D. V, Brando, P. M., Balch, J. K., Putz, F. E., Nepstad, D. C., Oliveira-Santos, C., & Bustamante, M. M. C. (2013). Testing the Amazon savannization hypothesis: fire effects on invasion of a neotropical forest by native cerrado and exotic pasture grasses. *Philosophical Transactions of the Royal Society*, *368*. https://doi.org/10.1098/rstb.2012.0427

Simões, M. F., & Lopes, D. F. (1987). *Pesquisas arqueológicas no ba¡xo / médio rio Madeira (AM)*. *Revista de Arqueologia* (Vol. 4).

Smith, F. A., & Anderson, K. B. (2001). Characterization of organic compounds in phytoliths: improving the resolving power of phytolith d13C as a tool for paleoecological reconstruction of C3 and C4 grasses. In J. D. Meunier & F. Colin (Eds.), *Phytoliths: Applications in Earth Sciences and Human History* (pp. 317–327). Lisse, Netherlands: A A Balkmea Publishers.

Smith, F. A., & White, J. W. C. (2004). Modern calibration of phytolith carbon isotope signatures for C 3 /C 4 paleograssland reconstruction. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *207*, 277–304. https://doi.org/10.1016/j.palaeo.2003.09.029

Smith, M., & Nelson, B. W. (2011). Fire favours expansion of bamboo-dominated forests in the south-west Amazon. *Journal of Tropical Ecology Journal of Tropical Ecology*, *27*, 59–64. https://doi.org/10.1017/S02

Smith, N. J. H. (1980). Anthrosols and Human Carrying Capacity in Amazonia. *Annals of the Association of American Geographers*, *70*(4).

Sombroek, W. (2000). Amazon Landforms and soils in relation to biological diversity. *Acta Amazonica*, *30*, 81–100.

Sombroek, W. G. (1966). *Amazon Soils: A reconnaissance of the soils of the Brazilian Amazon region*. Wageningen: Centre for Agricultural Publications and Documentation.

Sombroek, W., Kern, D., Rodrigues, T., Cravo, M. de S., Jarbas, T. C., Woods, W. I., & Glaser, B. (2002). Terra Preta and Terra Mulata : pre-Columbian Amazon kitchen middens and agricultural fields , their sustainability and their replication. In R. Dudal (Ed.), *Symposium 18, Anthropogenic Factors of Soil Formation, 17th World Congress of Soil Science* (pp. 1–9). Bangkok.

Sombroek, W., Ruivo, M., Fearnside, P. M., Glaser, B., & Lehmann, J. (2003). Anthropogenic Dark Earths as Carbon Stores and Sinks. In *Amazonian Dark Earths: Origin, Properties, Management*. Dordrecht, The Neatherlands: Springer., (pp. 125–139) https://doi.org/10.1007/1-4020-2597-1

Soreng, R. J., Peterson, P. M., Romaschenko, K., Davidse, G., Zuloaga, F. O., Judziewicz, E. J., … Bull, R. D. (2015). A worldwide phylogenetic classification of the Poaceae (Gramineae). *Journal of Systematics and Evolution*, *53*(2), 117–202. https://doi.org/10.1111/jse.12150

Spellerberg, I. A. N. F., & Fedor, P. J. (2003). A tribute to Claude Shannon (1916 – 2001) and a plea for more rigorous use of species richness , species diversity and the ‘ Shannon-Wiener ’ index. *Global Ecology and Biogeography*, *12*(3), 177–179. https://doi.org/10.1046/j.1466-822X.2003.00015.x

Stahl, P. W. (2002). Paradigms in paradise: revising standard Amazonian prehistory. *The Review of Archaeology*, *23*(2), 39–51.

Stahl, P. W. (2008). The contributions of zooarchaeology to historical ecology in the neotropics. *Quaternary International*, *180*, 5–16. https://doi.org/10.1016/j.quaint.2007.08.028

Stahl, P. W. (2015). Interpreting interfluvial landscape transformations in the pre-Columbian Amazon. *The Holocene*, 1–6. https://doi.org/10.1177/0959683615588372

Steward, J. H. (1940-1947). *Handbook of South American Indians*. (G. Editor, Ed.). Wasington, DC: Smithsonian Institution.

Steward, J. H. (1949). *The Tropical Forest Tribes*. (J. H. Steward, Ed.). Wasington, DC: Smithsonian Institution.

Stromberg, C. A. E. (2004). Using phytolith assemblages to reconstruct the origin and spread of grass-dominated habitats in the great plains of North America during the late Eocene to early Miocene. *Palaeogeography, Palaeoclimate, Palaeoecology*, *207*(3–4), 239–275.

Swetnam, T. W., Allen, C. D., & Betancourt, J. L. (1999). Applied Historical Ecology : Using the Past to Manage for the Future. *Ecological Applications*, *9*(4), 1189–1206.

ter Steege, H., Pitman, N. C. a, Sabatier, D., Baraloto, C., Salomão, R. P., Guevara, J. E., … Silman, M. R. (2013). Hyperdominance in the Amazonian tree flora. *Science (New York, N.Y.)*, *342*(6156), 1243092. https://doi.org/10.1126/science.1243092

Terrell, J. E., Hart, J. P., Barut, S., Cellinese, N., Curet, A., Denham, T., … Staller, J. E. (2003). Domesticated Landscapes: The Subsistence Ecology of Plant and Animal Domestication. *Journal of Archaeological Method and Theory*, *10*(4), 323–368.

Terry, R. E., Nelson, S. D., Carr, J., Parnell, J., Hardin, P. J., Jackson, M. W., & Houston, S. D. (2000). Quantitative phosphorus measurement: A field test procedure for archaeological site analysis at Piedras Negras, Guatemala. *Geoarchaeology*, *15*(2), 151–166. https://doi.org/10.1002/(SICI)1520-6548(200002)15:2<151::AID-GEA3>3.0.CO;2-T

Thomas, E., Alcázar Caicedo, C., Mcmichael, C. H., Corvera, R., & Loo, J. (2015). Uncovering spatial patterns in the natural and human history of Brazil nut (Bertholletia excelsa) across the Amazon Basin. *Journal of Biogeography*, *42*(8), 1367–1382. https://doi.org/10.1111/jbi.12540

Tollefson, J. (2013). Footprints in the Forest. *Nature*, *502*, 160–162.

Tomlinson, P. B. (1961). *Anatomy of the Monocotyledons II: Palmae*. London: Oxford University Press.

Tomlinson, P. B., Horn, J. W., & Fisher, J. B. (2011). *The Anatomy of Palms: Arecaceae - Palmae*. Oxford: Oxford University Press.

Troufflard, J. (2013). A Reflection on Archaeology and Sustainability in the Brazilian Amazon.

Twiss, P. C. (1992). Predicted World Distribution of C3 and C4 Grass Phytoliths. In G. Rapp & S. C. Mulholland (Eds.), *Phytolith Systematics. Advances in Archaeological and Museum Science*. Boston, MA: Springer.

Twiss, P. C., Suess, E., & Smith, R. M. (1969). Morphological Classification of Grass Phytoliths1. *Soil Science Society of America Journal*, *33*(1), 109. https://doi.org/10.2136/sssaj1969.03615995003300010030x

Urrego, D. H., Bush, M. B., Silman, M. R., Niccum, B. A., De, P., Rosa, L., … Palace, M. (2013). Holocene fires, forest stability and human occupation in south-western

Amazonia. *Journal of Biogeography*, *40*, 521–533. https://doi.org/10.1111/jbi.12016

Vacher, S., Jérémie, S., & Briand, J. (1998). *Amérindiens du Sinnamary (Guyane): Archéologie en forêt équatoriale*. *Éditions de la Maison des Sciences de l'Homme*.

van der Hammen, T., & Absy, M. L. (1994). Amazonia during the last glacial. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *109*(2–4), 247–261. https://doi.org/10.1016/0031-0182(94)90178-3

Van Hofwegen, G., Kuyper, T. W., & Becx, G. A. (2009). Opening the Black Box: Deciphering Carbon and Nutrient Flows in Terra Preta. In W. I. Woods, W. G. Teixeira, J. Lehmann, C. Steiner, & L. Rebellato (Eds.), *Amazonian Dark Earths: Wim Sombroek's Vision* (pp. 1–502). New York: Springer Science. https://doi.org/10.1007/978-1-4020-9031-8

Viveiros de Castro, E. (1996). Images of Nature and Society in Amazonian Ethnology. *Annual Review of Anthropology*, *25*(1), 179–200. https://doi.org/10.1146/annurev.anthro.25.1.179

Walker, J. H. (2008). The Llanos de Mojos. In H. Silverman & W. H. Isbell (Eds.), *Handbook of South American Archaeology* (pp. 927–939). New York: Springer. https://doi.org/10.1007/978-0-387-74907-5_46

Waller, S. S., & Lewis, J. K. (1979). Occurrence of C3 and C4 Photosynthetic Pathways in North American Grasses Linked references are available on JSTOR for this article : Occurrence of C3 and C4 Photosynthetic Pathways in North American Grasses. *Journal of Range Management*, *32*(1), 12–28.

Watling, J. (2014). *Environmental Impact of the Pre-Columbian Geoglyph Builders of Western Amazonia*. PhD thesis. University of Exeter.

Watling, J., Iriarte, J., Whitney, B. S., Consuelo, E., Mayle, F., Castro, W., … Feldpausch, T. R. (2016). Differentiation of neotropical ecosystems by modern soil phytolith assemblages and its implications for palaeoenvironmental and archaeological reconstructions II: Southwestern Amazonian forests. *Review of Palaeobotany and Palynology*, *226*. https://doi.org/10.1016/j.revpalbo.2015.12.002

Watling, J., & Iriarte, J. (2013). Phytoliths from the coastal savannas of French Guiana. *Quaternary International*, *287*, 162–180. https://doi.org/10.1016/j.quaint.2012.10.030

Watling, J., Iriarte, J., Mayle, F. E., Schaan, D., Pessenda, L. C. R., Loader, N. J., … O 'connell, J. (2017). Impact of pre-Columbian " geoglyph " builders on Amazonian forests. *PNAS*, *114*, 1868–1873. https://doi.org/10.1073/pnas.1614359114

Watling, J., Saunaluoma, S., Pärssinen, M., & Schaan, D. (2015). Subsistence practices among earthwork builders: Phytolith evidence from archaeological sites in the southwest Amazonian interfluves. *JASREP*, *4*, 541–551. https://doi.org/10.1016/j.jasrep.2015.10.014

Watling, J., Shock, M. P., Mongelo, G. Z., Almeida, F. O., Kater, T., Oliveira, P. E. De, & Neves, E. G. (2018). Direct archaeological evidence for Southwestern Amazonia as an early plant domestication and food production centre. *PLoS ONE*, *13*(7), 1–28.

Webb, E. A., & Longstaffe, F. J. (2010). Limitations on the climatic and ecological signals provided by the d C values of phytoliths from a C 4 North American prairie grass. *Geochimica et Cosmochimica Acta*, *74*, 3041–3050. https://doi.org/10.1016/j.gca.2010.03.006

Whitehead, N. L. (1998). Ecological history and historical ecology: diachronic modeling versus historical explanation. In W. Balée (Ed.), *Advances in historical ecology* (pp. 30–

41). New York: Columbia University Press.

Whitlock, C., & Larsen, C. (2001). Charcoal as a fire proxy. In J. P. Smol, H. J. B. Birks, & W. M. Last (Eds.), *Tracking Environental Change Using Lake Sediments*. Dordrecht, The Neatherlands: Kluwer Academic Publishers.

Whitney, B. S., Dickau, R., Mayle, F. E., Walker, J. H., Soto, J. D., & Iriarte, J. (2014). Pre-Columbian raised-field agriculture and land use in the Bolivian Amazon. *The Holocene*, *1*(1). https://doi.org/10.1016/j.yqres.2013.06.005

Wiersum, K. F. (1997). From natural forest to tree crops, co-domestication of forests and tree species, an overview. *Netherlands Journal of Agricultural Science*, *45*, 425–438.

Winklerprins, A. M. G. A., & Aldrich, S. P. (2010). Locating Amazonian Dark Earths: Creating an interactive GIS of known locations. *Journal of Latin American Geography*, *9*(93), 33–50.

Woods, W. I., & McCann, J. M. (1999). The Anthropogenic Origin and Persistence of Amazonian Dark Earths. *Yearbook, Conference of Latin American Geographers*, *25*, 7–14.