ANTHROPOGENIC SOILS IN CENTRAL AMAZONIA: FARMERS' PRACTICES, AGROBIODIVERSITY AND LAND-USE PATTERNS

TERRA PRETA PROGRAM

André Braga Junqueira

Anthropogenic soils in central Amazonia: farmers’ practices, agrobiodiversity and land-use patterns

André Braga Junqueira

Thesis committee

Promotor
Prof. Dr P.C. Struik
Professor of Crop Physiology
Wageningen University

Co-promotors
Dr T.J. Stomph
Assistant professor, Centre for Crop Systems Analysis
Wageningen University

Dr C.J.M. Almekinders
Assistant professor, Knowledge, Technology and Innovation Group
Wageningen University

Dr C.R. Clement
Researcher, Coordination of Technology and Innovation
National Institute of Amazonian Research, Manaus, Brazil

Other members
Prof. Dr F.J.J.M. Bongers, Wageningen University
Prof. Dr L. Brussaard, Wageningen University
Dr J.J. Neeteson, Wageningen University
Dr M. Arroyo-Kalin, University College London, United Kingdom

This research was conducted under the auspices of the C.T. De Wit Graduate School of Production Ecology and Resource Conservation.

Anthropogenic soils in central Amazonia: farmers' practices, agrobiodiversity and land-use patterns

André Braga Junqueira

Thesis
submitted in fulfillment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Wednesday 30 September 2015
at 1:30 p.m. in the Aula.

André Braga Junqueira
Anthropogenic soils in central Amazonia: farmers' practices, agrobiodiversity and land-use patterns
163 pages.

PhD thesis, Wageningen University, Wageningen, NL (2015)
With references, with summary in English

ISBN: 978-94-6257-447-2

Abstract

André Braga Junqueira (2015). Anthropogenic soils in central Amazonia: farmers' practices, agrobiodiversity and land-use patterns. PhD thesis, Wageningen University, The Netherlands, with summary in English, 163 pp.

Rural Amazonia is increasingly experiencing environmental and socio-economic changes that directly affect smallholder farmers, with potential negative effects for environmental quality, agrobiodiversity and livelihoods. In this dynamic context, there is an urgent need to support pathways for smallholder agriculture that guarantee farmers' economic and food security while maintaining and enhancing ecosystem functions. Amazonian Dark Earths (ADE, or *Terra Preta*) are anthropogenic soils created by pre-Columbian populations. Due to their high carbon content and enhanced fertility, ADE have been considered models for sustainable agriculture, based on the idea that transforming soils by mimicking some of the properties of ADE would benefit farmers, sequester carbon and reduce pressure on forests. Investigating the current use of ADE and surrounding soils by smallholder farmers allows us to evaluate the relevance of anthropogenic soils and of soil heterogeneity for smallholder farming in Amazonia, and to identify opportunities and constraints associated with the cultivation of fertile soils. The main objective of this thesis is to understand how ADE are understood and cultivated by smallholder farmers in Central Amazonia, and how these soils influence cultivation systems, agrobiodiversity and land-use patterns.

Ethnographic data indicated that farmers' understanding of ADE – and of soils in general – is based on their historical and shared knowledge about soil variation across the landscape, on physical attributes of the soil, and mainly on the recognition of different soil-vegetation interactions. A widespread perception about ADE is that these soils are suitable for the cultivation of 'almost everything' and always produce decent yields, but they require much more weeding during cultivation. Farmers' decision-making in shifting cultivation is grounded in this differential understanding of soil-vegetation relationships, and weighed against the labor demands. Soil and vegetation inventories in swiddens used for shifting cultivation showed that the soil fertility gradient between surrounding soils and ADE was associated with more intensive cultivation (shorter fallow periods, shorter and more frequent cultivation cycles, higher labor requirements) and with changes in the crop assemblages, but with similar or larger numbers of species cultivated. In homegardens, vegetation structure and crop diversity were mainly influenced by natural variation in soil texture (homegardens on sandier soils being denser and more diverse), while the soil fertility gradient between ADE and adjacent soils influenced mainly the crop assemblages. At the farm level, the relationship between farmers' use of ADE and the need to open areas for shifting cultivation was strongly dependent on the labor availability of the household. Instead of driving specific trends in land use, fertile soils are incorporated into local livelihoods as part of an extensive repertoire of resource management activities; most often, farmers with enough available labor manage multiple plots, combining more intensive cultivation on ADE with typical long-fallow shifting cultivation on poorer soils. Farmers' access to increased soil fertility, therefore, does not necessarily lead to reduced pressure on forests.

This thesis has shown that cultivation systems on ADE are associated with specific knowledge, practices and agrobiodiversity, providing increased opportunities for farmers to diversify their cultivation systems and grow a greater diversity of crops. Despite these advantages, ADE can also be associated with conventional intensification practices that can lead to environmental degradation and pose threats to local livelihoods. It cannot be assumed, therefore, that the use of more fertile soils will be associated with sustainable cultivation, neither that it will reduce pressure on forests. Initiatives aiming to promote sustainable pathways for agriculture in Amazonia should promote (and make use of) the heterogeneity of soils and of cultivation strategies, and should aim at increasing and not narrowing farmers' opportunities for resource use and management.

Keywords: Terra Preta; Amazonian Dark Earths; Shifting cultivation; Homegardens; Intensification; Diversification; Smallholder farming.

Table of contents

Chapter 1

General Introduction

André Braga Junqueira

Smallholder farming is the basis of the livelihoods of people in Amazonia. Large areas in Amazonia are experiencing, particularly in the last decades, the expansion of large-scale agriculture, of cattle ranching and infrastructure (roads, dams, etc.), rural-urban migration and increasing interaction of rural populations with cities and market economies (Padoch et al. 2008, Parry et al. 2010b, Davidson et al. 2012, Emperaire and Eloy 2015). In this dynamic context, smallholder farmers are constantly developing new cultivation and livelihood strategies, as they are active and informed actors of the changes in their socio-ecological environment (Cramb et al. 2009, Feintrenie et al. 2010). However, many of these changes convey inputs, practices and new socio-economic arrangements that are potentially detrimental for environmental quality, biodiversity, and livelihoods (Matson et al. 1997, Jackson et al. 2007). There is, therefore, an urgent need to study and support strategies for smallholder farming in Amazonia that guarantee farmers' economic and food security while maintaining and enhancing ecosystem functions.

Farmers' opportunities and constraints to develop their agricultural and other livelihood activities depend on how they interact with their environmental and socio-economic context. Especially in societies that depend heavily on agriculture, soils play a central role in local livelihoods, as different soils may favor or restrict certain crops and cultivation strategies and also co-evolve with knowledge, practice and the crops themselves. In Amazonian uplands, soils are usually poor and acidic, and farmers have developed crops and cultivation systems (e.g., shifting cultivation) well suited to these conditions (e.g., Denevan et al. 1984). However, in Amazonia patches of high-fertility anthropogenic soils are also found, called *terra preta* or Amazonian Dark Earths (ADE). These soils, which result from pre-Columbian activity, have changed our understanding of the degree and extent to which people transformed the Amazonian landscape in the past, and have inspired technologies of soil fertility management aiming to improve agriculture in the tropics [e.g., 'biochar'; Glaser et al. (2001), Glaser (2007)].

Today, ADE are used by smallholder farmers under different cultivation systems, and are associated with specific cultivation and agrobiodiversity patterns (e.g., German 2003b, 2004, Junqueira et al. 2010b, Fraser et al. 2011a, Fraser et al. 2011b, Junqueira et al. 2011, Kawa et al. 2015, Lins et al. 2015). This thesis focuses on the current use of ADE by smallholder farmers in Central Amazonia. Investigating the current use of ADE (1) allows us to evaluate the role of these anthropogenic soils in smallholder farming in Amazonia, (2) improves our understanding of the role of soil fertility and heterogeneity in cultivation systems in a wider sense, and (3) provides insights for evaluating and developing strategies aiming to improve the sustainability of smallholder farming.

Amazonian historical ecology and anthropogenic soils

Amazonia has been seen for many decades as a pristine forest, minimally impacted by native populations who inhabit the region for at least 12,000 years. This view, which has largely dominated the understanding of Amazonia by scholars and the general public until the late 20th century, was based on the idea that the poor soils that predominate in the region would limit agricultural production and therefore restrict the development of complex societies (Meggers 1954, Meggers 1971). In the last three decades, this view has been increasingly challenged by archaeological evidence showing that many areas in the Amazon were occupied in the past by relatively large and complex societies, which impacted in various ways and to different extents the landscapes they inhabited (e.g., Heckenberger et al. 2003, Balée and Erickson 2006, Heckenberger et al. 2007, Erickson 2008, Pärssinen et al. 2009, McKey et al. 2010, Rostain 2010, Schaan 2010). Fueled by these evidences, a new understanding of Amazonia emerged in the late 1990s under the name 'Historical Ecology' (Balée 2006), which postulates that humans are not 'constrained' by their natural environment, but instead they are able to *transform* the environments they inhabit over time and in ways that affect their overall physiognomy and properties (Balée 2006). From this perspective, the current configuration of the Amazonian landscapes, as well as the opportunities that these landscapes afford to people, result from long-term interactions between people and environment. Although the spatial scale at which pre-Columbian societies have transformed the Amazonian landscape is subject of an ongoing debate (e.g., Clement and Junqueira 2010, Barlow et al. 2011, Levis et al. 2012, McMichael et al. 2012), the impact of pre-Columbian populations on the Amazonian landscape has been increasingly recognized.

One of the most important, widespread and long-lasting changes promoted in the Amazonian landscapes by pre-Columbian Amerindians are the so-called Amazonian Dark Earths (ADE). These anthropogenic soils were created by the activities of pre-Columbian indigenous populations between 500 and 2,500 years ago (Neves et al. 2003, Glaser and Birk 2012). ADE patches are widely distributed in the Amazon Basin, mainly in Central Amazonia, occurring in patches that vary from <1 to more than 100 hectares (Kern et al. 2003, WinklerPrins 2010). Since these soils result from cultural activities, they are usually associated with concentrations of ceramic and lithic artifacts (Neves et al. 2003) and are also very heterogeneous, both between and within patches (Lehmann et al. 2003b). In general, ADE tend to be darker than surrounding soils, show higher organic matter content, higher pH, as well as higher concentrations of many macro- and micro-elements [e.g., Ca, P, Mg, Mn, Zn; Lehmann et al. (2003b), Glaser and Birk (2012)]. Patches of ADE started to be formed in the Amazon around 2,500-2000 years ago, coinciding with the period when indigenous populations started to become larger and more sedentary (Neves et al. 2003, Moraes and Neves 2012).

The current scientific understanding of the origin of these soils is that they result from the concentration of plant and animal residues, together with carbonized organic matter (pyrogenic organic matter, or charcoal), surrounding pre-Columbian habitation sites (Glaser and Birk 2012). The question whether the soil transformations that resulted in ADE were intentional or not (or both) is a controversial one. There are examples of ADE in areas where the 'natural' soils are already fertile [e.g., floodplains (Teixeira et al. 2006) and SE Amazonia (Quintero-Vallejo et al. 2015)], suggesting that these soils can be formed simply as a byproduct of human activity. It has been argued that soils with intermediate color, lacking ceramic fragments and with moderate nutrient enhancements [called *terra mulata*; Woods and McCann (1999), Sombroek et al. (2002), Arroyo-Kalin (2010)] could be the result of intentional soil fertility management. Regardless of ADE resulting from intentional or non-intentional activities (or both), their enhanced and long-lasting soil fertility (even under the weathering conditions in the tropics) arose great interest among scientists from different disciplines, and served as an inspiration for the development of technologies aiming to improve tropical soils and agriculture.

The use of anthropogenic soils for plant cultivation and management

ADE have likely been used by local people since they have existed, given that they were formed around pre-Columbian habitation sites, where plant cultivation and experimentation occurred intensively (Clement et al. 2003). Due to this close and long-term interaction with human activity, ADE might have played an important role in the domestication of several Amazonian species, which find favorable conditions for their development in homegardens and dump heaps (Clement et al. 2003, Arroyo-Kalin 2010). After European arrival, many ADE patches were abandoned, since a large part of the indigenous population in Amazonia was decimated in the first 200 years after contact (Denevan 1992). In some regions that were more or less continuously occupied (such as the upper Xingu River), local indigenous people have permanently inhabited existing ADE and created new ADE (Schmidt and Heckenberger 2009, Schmidt et al. 2014), but most ADE patches in Central Amazonia [where these soils occur more often than elsewhere in the basin; McMichael et al. (2014)] were only reoccupied after the late 19th century, during the rubber boom (Weinstein 1983). Both in pre-Columbian Amazonia and also during the rubber boom, patches of ADE were likely favored for reoccupation, given the strategic position of these soils in the landscape [usually located on river bluffs (Denevan 1996)] and because, being associated with former settlements, these areas likely concentrated useful and domesticated plants left from previous occupations.

The use of ADE for plant cultivation was reported among the first descriptions of these soils in the late 19th century:

"[...] [tobacco] is cultivated on the rich black lands along the edge of these [river] bluffs [...]" (Smith 1879, p. 238);

"[...] [guaraná is cultivated] on the rich black land, where it bears well in three or four years." (Smith 1879, p. 255);

"José's mandioca plantation is at one of these black-land localities [...]"(Smith 1879, p. 271);

"The black land in this vicinity gives excellent crops of mandioca and corn, and a little sugar-cane [...]"(Smith 1879, p. 272);

"[...] At the present day these localities [ADE] are highly prized as agricultural grounds, owing to their fertility; and they bear the name of 'Terras Pretas' (Brown and Lidstone 1878, p. 271).

Since these early reports, the use of ADE for cultivation (and particularly its high value for agriculture) have been reported anecdotally for several indigenous and peasant groups in different parts of the Amazon basin (e.g., Faria 1946, Gourou 1949, Hilbert 1955, Frikel 1959, 1968, Silva et al. 1970, Pereira 1974, Smith 1980), but more systematic investigations on the use of these soils by local people started only after the 2000s.

Today, ADE are used by smallholder farmers throughout the Amazon under many different cultivation systems, ranging from complex 'traditional' subsistence systems to market-oriented monocrop plantations in areas close to cities (Hiraoka et al. 2003). In rural areas, given the overlap between ADE and current villages, ADE are commonly found under homegardens or other agroforestry-like systems (Fraser et al. 2011a, Fraser et al. 2011b, Kawa et al. 2011, Lins et al. 2015), but these soils are also frequently used to produce annual/biannual crops in shifting cultivation systems (German 2003b, Major et al. 2005b, Fraser 2010b, Fraser et al. 2011b, Peña-Venegas et al. 2014). Recent studies on the use of ADE by smallholder farmers in central Amazonia have shown that, when compared with surrounding soils, cultivation systems on ADE are associated with different agrobiodiversity and cultivation patterns. Swiddens on ADE are usually opened from younger fallows, are cultivated for shorter fallow periods (German 2003b, Fraser et al. 2012), show strong weed proliferation (Major et al. 2005b) and, when abandoned, they result in secondary forests with distinct floristic composition and higher abundance of useful and domesticated species (Junqueira et al. 2010b, Junqueira et al. 2011). These swiddens are often cultivated with more exotics and/or more nutrient-demanding annual species (German 2003b, 2004, Kawa et al. 2011), but may also be used for the cultivation of bitter manioc; when that is the case, farmers cultivate on ADE a specific set of landraces, with similar ecological characteristics from those cultivated in floodplains [e.g., fast maturing, low starch content (Fraser et al. 2012); but see Peña-Venegas et al. (2014)]. It has also been shown that homegardens on ADE show a distinct floristic composition from that in surrounding soils and in floodplains (Fraser et al. 2011a). Taken together, these studies indicate that farmers in Central Amazonia have developed cultivation practices and crops suited to the ecological characteristics of ADE.

These studies, however, have considered ADE as a distinct soil category, although it is known that, being the product of human activity in the past, these soils are very heterogeneous (regarding color, density of cultural artefacts and nutrient concentration), both between and within patches (Lehmann et al. 2003b, Neves et al. 2003). Although it has been argued that ADE can be subdivided in two categories (‘*terra preta*’ and ‘*terra mulata*’) according to color and ceramics [*terra preta* being darker than *terra mulata* and with ceramic fragments; Woods and McCann (1999), Sombroek et al. (2002)], others have argued that these categories are only parts of a continuous variation in soil properties between surrounding soils and the ‘core’ of ADE patches (Fraser et al. 2011c). Nonetheless, archaeological and pedological evidence increasingly underlies the high diversity of soil properties in landscapes where ADE occur, indicating that categorizing anthropogenic soils (and cultivation systems associated with them) with such complex and heterogeneous origins is an oversimplification.

Therefore, despite our growing understanding of the current use of ADE by smallholder farmers, in order to obtain a thorough understanding of the role of these soils for local livelihoods and agrobiodiversity it is crucial to incorporate soil heterogeneity. Differently from all previous studies on the use of ADE, in this thesis I take into account the whole variation in soil physical and chemical properties (associated with ADE patches and their surroundings) that is accessed and used by farmers at the plot and farm levels, and I investigate how this heterogeneity relates to farmers' decision-making, to cultivation practices, as well as to agrobiodiversity and land-use patterns. Apart from providing a more realistic understanding of the role of ADE for smallholder farmers and Amazonian agrobiodiversity, this approach also allows to evaluate – in a wider sense – how soil fertility and heterogeneity influence and are incorporated into smallholder farming systems.

Amazonian Dark Earths as a model for sustainable agriculture

Besides their significant archaeological relevance, ADE have received increased attention (from both inside and outside academia) due to their enhanced and long-lasting soil fertility. Apart from challenging environmental determinism (by showing that poor soils that would 'constrain' the development of societies could also be improved), ADE also pointed towards the possibility of practices of soil/plant management that could lead to long-term soil improvement in the tropics. One of the most distinctive characteristics of ADE is its high concentration of charcoal ('pyrogenic organic matter'), which plays an important role in the chemical and biological processes that result in the high and resilient fertility of these soils (Glaser and Birk 2012). This has stimulated research and development efforts focused on the use of charcoal as a soil amendment, a technology known as 'biochar' (Rittl et al. 2015). ADE began to be considered a model for 'sustainable agriculture' (Glaser et al. 2001, Glaser 2007), based on the idea that, by recreating their properties, it would be possible to sequester carbon, improve soil properties and reduce pressure on forests through agricultural intensification [although there are also trade-offs between these potential benefits; Jeffery et al. (2015)]. Despite the growing interest in biochar, it is still unclear to what extent these assumptions hold in the context of smallholder farming systems, and how smallholders can benefit from this technology (Kawa and Oyuela-Caycedo 2008).

Investigating the current use of ADE by smallholder farmers improves our understanding of the role of soil fertility in cultivation systems and local livelihoods, and it also provides useful insights for evaluating potential benefits, opportunities and constraints of strategies aiming to improve soils by mimicking the properties of ADE. This thesis focuses on different aspects related to the current use of ADE that are important for assessing their social and ecological relevance in smallholder agriculture: the role that these soils play in farmers' rationales and decision-making regarding cultivation (Chapter 2), the relationships between these soils and farmers' opportunities and constraints to intensify and diversify their cultivation systems (and their associated agrobiodiversity; Chapters 3 and 4), and the relationships between ADE and land-use patterns (Chapter 5). Addressing these issues in the context of smallholder farmers provides a ground-based appraisal of the role of soil fertility and heterogeneity in local livelihoods, and can aid the evaluation and development of strategies aiming to support sustainable pathways for smallholder agriculture in Amazonia.

Objectives of this thesis

In relation to the above mentioned, the main objective of this thesis is to understand how anthropogenic soils are understood and cultivated by smallholder farmers, and how these soils influence cultivation systems, agrobiodiversity and land-use patterns. In order to achieve that, I used an interdisciplinary approach, combining qualitative and quantitative data obtained from farmers' interviews and from biophysical measurements taken on their cultivation systems. The specific objectives are:

1) To understand farmers' rationales and decision-making regarding the use of ADE and surrounding soils (Chapter 2);
2) To evaluate how ADE affect the cultivation strategies and crop assemblages in shifting cultivation systems (Chapter 3);
3) To evaluate the effect of ADE on the vegetation structure, diversity and floristic composition of homegardens (Chapter 4);
4) To examine the relationship between the use of ADE and the total area used by farmers for cultivation (Chapter 5).

Thesis outline

This thesis consists of six chapters: this general introduction (Chapter 1), four research chapters (Chapters 2 to 5) and a general discussion (Chapter 6).

In **Chapter 2** I focus on the local rationales concerning the use of ADE for shifting cultivation. Using an ethnographic approach based on interviews with farmers, I evaluate their rationales and decision-making in relation to the use of ADE (objective 1).

In **Chapter 3** I examine the relationship between soil fertility and cultivation strategies used by farmers in shifting cultivation systems (objective 2). Combining soil, vegetation and management data, I look at how cultivation practices (e.g., fallow period, weeding requirements, plot size) and crop assemblages change along soil gradients between ADE and adjacent soils.

In **Chapter 4** I focus on the effects of natural and anthropogenic (modern and pre-Columbian) soil variation in homegardens surrounding habitation sites. Using an approach similar to Chapter 3, I investigate how soil variation associated with ADE and surrounding soils relates to changes in structure, diversity and floristic composition of homegardens (objective 3).

In **Chapter 5** I study the relationship between ADE and land-use patterns. Combining biophysical data from Chapters 3 and 4 with socioeconomic data obtained at the household level, I investigate the relationship between the use of ADE and the area used by farmers for cultivation (objective 4). In order to focus on this particular relationship, I use a comprehensive framework, taking into account farmers' economic activities and their social and economic resources.

Finally, in **Chapter 6** I integrate data from Chapters 2, 3, 4 and 5 and discuss the implications of the results I found for our wider understanding of ADE, of smallholder farming in Amazonia and of the relationship between soil fertility and heterogeneity in smallholder agriculture.

Study setting and sampling design

Biophysical setting

The study area is located in central Amazonia, along the middle and lower Madeira River (Figure 1.1). The Madeira is one of the largest tributaries of the Amazon River (approximately 3,350 km long), with its headwaters in the Peruvian and Bolivian Andes, and its mouth in the middle Amazonas river, ≈140 km downstream from the city of Manaus. Similarly to other rivers in Amazonia with their headwaters in the Andes, the waters of the Madeira carry large amounts of sediments, although some of its tributaries drain geologically older areas and have black- or clear-waters (e.g., Rio Aripuanã). The annual flood pulse [which has an average amplitude of ≈10 meters; Junk et al. (1989)] inundates extensive areas along the Madeira (floodplains), home to nutrient-rich ecosystems, distinct from those in the uplands. Soils in uplands are mostly ferralsols, with patches of acrisols, podzols and lixisols, as well as fertile gleysols along the floodplains (IBGE 2010).

The regional climate is tropical rainforest climate [a transition between *Af* and *Am* in the Köppen classification system (Alvares et al. 2013)], with precipitation between 2,600-2,800 mm and annual temperatures between 27 and 28 °C. Rainfall is unevenly distributed throughout the year, with the rainiest months being January to April and a relatively short dry season between July and September [less than 100 mm/month (INMET 2015)]. The vegetation is composed predominantly of *Terra Firme* forests, small patches of savannas and flooded forests along the rivers. The southern and southwestern part of the Madeira Basin (i.e., the ‘upper’ Madeira, in the Brazilian states of Rondônia and Acre) overlap with the expanding agricultural frontier (the ‘deforestation arch’), therefore these regions have been heavily deforested especially since the 1970s (Fearnside 2005). In the middle and lower Madeira, however (where this study focuses), the landscape is predominantly covered by natural vegetation types, with relatively localized open areas and secondary forests concentrated in the vicinity of cities and small roads.

Past and current human occupation

The Madeira River has a long history of human occupation, with archaeological evidences dating as early as 7,500 years BP (Moraes and Neves 2012). There is increasing evidence showing that some regions within the Madeira River Basin (especially in the upper Madeira) were occupied in the past by relatively dense populations which caused significant transformations in the landscape [e.g., the raised fields in Bolivia (Erickson 2010, Lombardo and Prümers 2010) and the geoglyphs in Acre (Pärssinen et al. 2009)], domesticated important Amazonian crops [e.g., manioc (Olsen and Schaal 1999), peach palm (Cristo-Araújo et al. 2013)] and possibly created the earliest patches of anthropogenic soils (Moraes and Neves 2012). Patches of anthropogenic soils ranging from 2 to more than 50 ha in size are commonly found in the region (especially in the middle and lower Madeira), usually on bluffs along the main river, tributaries and lakes (Fraser et al. 2011b, Moraes and Neves 2012, Levis et al. 2014). Many of these patches are located under present villages or small cities.

As many other regions of Amazonia, the Madeira experienced a severe depopulation following European contact, and the population began to rise again only towards the end of the 19th century with the 'rubber boom' (Weinstein 1983). The contact between the remaining indigenous populations and colonists resulted in a heterogeneous mixed-blood population that today forms the majority of the population in the region: the *caboclos* or *ribeirinhos* (Adams et al. 2009). In some regions, especially in the upper Madeira, there was also a more recent (since the 1970s) influx of colonists, attracted by agrarian reform settlements created by the federal government (Fearnside 2005).

The current population in the middle and lower Madeira is largely concentrated along the major river and some of its tributaries, but the overall population density is very low (<2 inhabitants per km^2). Approximately half of the population lives in cities (~20-40k inhabitants) and the other half lives in rural areas (IBGE 2011), in villages that range from a few families to a few hundred inhabitants. Local livelihoods are strongly reliant on the use and management of natural resources, but similarly to other riverine populations in Amazonia (e.g., Brondízio 2004, Castro 2009, Futemma 2009), their subsistence and commercial activities are very heterogeneous, combining plant cultivation, extraction of forest products, animal husbandry, hunting, fishing and off-farm activities. Still, agriculture is the most important livelihood activity for people from the Madeira River, and it is widely practiced both on floodplains and on uplands. The most common form of agriculture on uplands is shifting cultivation, and it is particularly focused on the production of manioc (*Manihot esculenta* Crantz) flour (*farinha*), the main staple food and also an important cash product (Fraser 2010b).

Sampling design and data collection

The geographical area on which the thesis focuses is a stretch of approximately 400 km along the middle and lower Madeira River, in the municipalities of Manicoré, Novo Aripuanã and Borba, state of Amazonas (Figure 1.1). In an initial survey, aiming to obtain an overview of the variation in local perceptions and use of ADE, I visited 21 villages located on (or close to) ADE patches and interviewed ~200 farmers. Based on this general survey, I chose seven villages for in-depth research (Figure 1.1); villages were chosen so that (1) the areas used by farmers for cultivation within the village showed a large variation in soil properties and (2) they were relatively well spread across the focal area. Fieldwork for the general survey and in-depth research were done between 2011 and 2013, but the qualitative data presented here (particularly for Chapter 2) is also based on my previous experience in the region, where I have been working since 2006.

Data collection involved an interdisciplinary approach, combining ethnographic methods (participant observation, unstructured, semi-structured and structured interviews), botanical inventories and soil sampling. In each village, detailed interviews and the collection of biophysical data was done with 7 to 13 households; I selected households that used different soils along the gradient between ADE and surrounding soils, and that were willing to participate in the study. Interviews were focused on local perceptions and rationales about ADE and its use (Chapter 2), as well as on households' socioeconomic characteristics and livelihood activities (Chapter 5). For each of the households interviewed, I obtained biophysical and management data in their most important agroecosystems used for food production: homegardens (Chapter 4) and swiddens used for shifting cultivation (Chapter 3; Figure 1.2). Together with at least one of the household heads, I located and measured their homegardens and swiddens (using GPS), conducted detailed botanical inventories of the crop species and landraces that they cultivated in these agroecosystems (including also spontaneous plants in homegardens), collected soil samples and obtained information on the history and land-use dynamics of the plot (e.g., previous land use, planting and harvesting dates, labor invested, etc.). In order to obtain an estimation of the total area used by a household for plant cultivation (Chapter 5), I took into account all their active swiddens and those that had been used in the 12 months before to the interview, but given time constraints it was not always possible to obtain data *in situ* in all their swiddens; in those cases, I obtained secondary information on the location and size of these swiddens from farmers' interviews, and soil data were inferred from the nearest sample. In total, I conducted detailed interviews with 90 farmers, I collected *in situ* biophysical and management data on 73 homegardens and 114 swiddens, and I obtained secondary information for 95 plots.

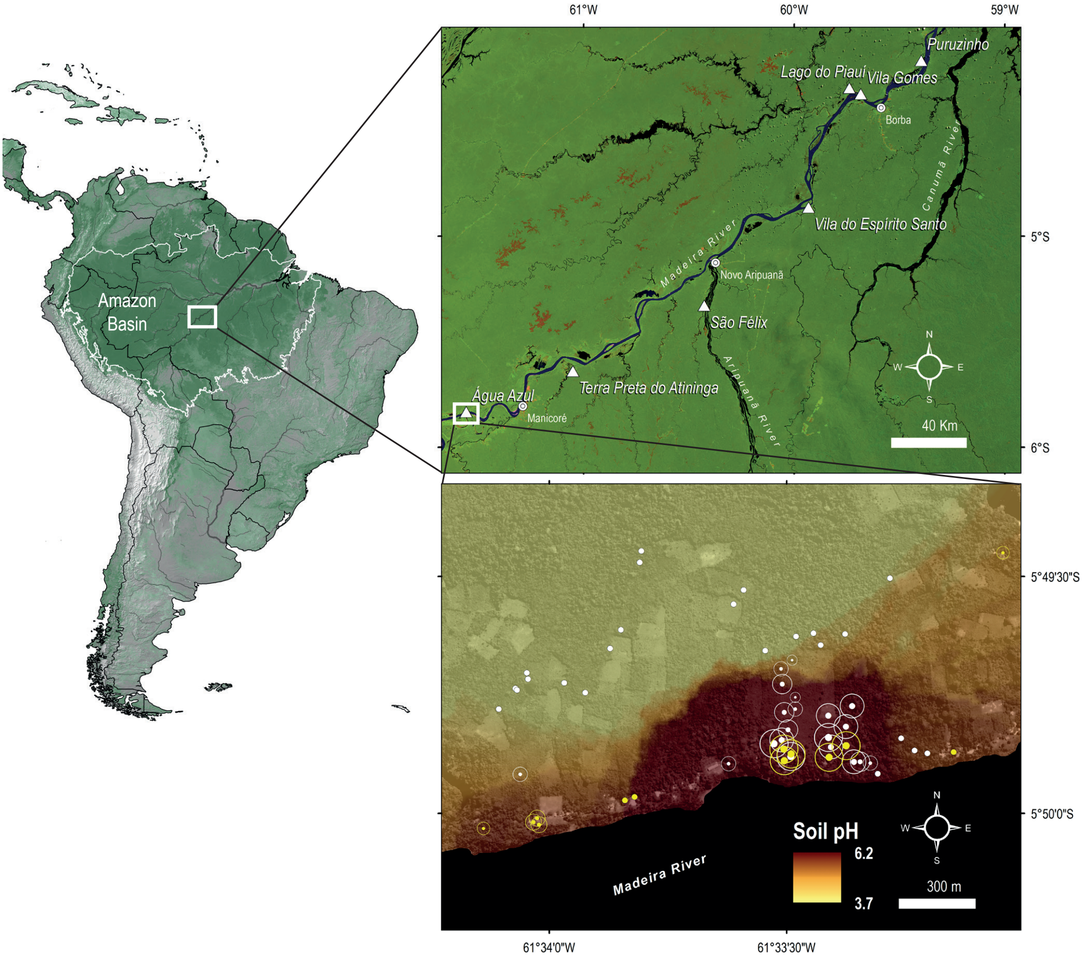

Figure 1.1. Location of study sites and representation of variation in soil characteristics in the landscape. White triangles in the upper map represent the seven villages in three municipalities along the middle and lower Madeira River, and white circles indicate urban centers. The lower map shows the variation of soil pH in one village (Água Azul), represented with a kriging interpolation of soil data obtained at all points shown in the figure. Size of circles around points represent the density of ceramic fragments observed in the soil surface, yellow points indicate homegardens and white points indicate swiddens sampled in this village.

Figure 1.2. Representation of the different agroecosystems sampled in the villages along the middle and lower Madeira River: homegardens (a, b) and swiddens used for shifting cultivation (c, d). Pictures e and f show fragments of ceramic artifacts, commonly found in anthropogenic soils.

Chapter 2

The role of Amazonian anthropogenic soils in shifting cultivation: learning from farmers' rationales

André Braga Junqueira, Cornelia J. M. Almekinders, Tjeerd Jan Stomph,
Charles R. Clement, Paul C. Struik

(submitted)

Abstract

We evaluated farmers' rationales to understand their decision making in relation to the use of fertile anthropogenic soils (Amazonian Dark Earths – ADE) and for dealing with changes in shifting cultivation in central Amazonia. In order to decide about crop management options to attain their livelihood objectives, farmers rely on an integrated and dynamic understanding of their biophysical and social environment. Farmers associate fallow development with higher crop yields and lower weed pressure, but ADE is always associated with high yields and high weeding requirements. ADE is also seen as an opportunity to grow different crops, and/or grow crops in more intensified management systems; still, farmers often maintain simultaneously intensive swiddens on ADE and extensive swiddens on non-anthropogenic soils. Farmers acknowledge numerous changes in their socio-economic environment that affect their shifting cultivation systems, particularly their growing interaction with market economies and the incorporation of 'modern' agricultural practices. Shifting cultivation systems on ADE tend to be more prone to changes leading to intensification, and we identified cases (swiddens used for watermelon cultivation) in which market demand led to over-intensification and resulted in ADE degradation. This shows that increasing intensification can be a potential threat to ADE and can undermine the importance of these soils for agricultural production, for the conservation of agrobiodiversity and for local livelihoods. Given that farmers have an integrated knowledge of their context, and respond to socio-economic and agro-ecological changes in their environment, we argue that understanding farmers' knowledge and rationales is crucial to identify sustainable pathways for the future of ADE and of smallholder agriculture in Amazonia.

Keywords: Decision-making; Amazonian Dark Earths; Terra Preta; Amazonia; Swidden cultivation; Intensification

Introduction

Shifting cultivation is one of the most important forms of agriculture in the tropics, forming the subsistence base for many communities, while contributing substantially to local and regional markets (Coomes et al. 2000, Padoch and Pinedo-Vasquez 2010). Demographic (e.g., population growth, migration), economic (e.g., market integration), and political pressures (e.g., policies encouraging the production of cash crops or forest conservation) are driving major changes in shifting cultivation systems, resulting in agricultural intensification or other types of land use (van Vliet et al. 2012). The impacts of these changes on local livelihoods are both positive (e.g., increases in income, access to health care and education) and negative (e.g., loss of cultural identity, exacerbated inequities, increased emigration) (van Vliet et al. 2012).

Shifting cultivation systems are widespread in Amazonia and are the most common form of upland agriculture, practiced by the majority of the rural population and producing most of the food consumed in the region (Serrão et al. 1996, Coomes et al. 2000). Despite extensive land-use changes in Amazonia in the last decades (Laurance et al. 2001, Mittermeier et al. 2003, Soares-Filho et al. 2006), the number of studies that specifically relate these changes to shifting cultivation practices is limited (van Vliet et al. 2012, van Vliet et al. 2013).

The most important drivers of land use and livelihood changes in Amazonia are the development of markets, infrastructure, and social, environmental and land tenure policies (van Vliet et al. 2013). Trends in shifting cultivation systems in Amazonia are, however, hard to generalize. In some areas these systems are in the decline, due to labor shortages (Steward 2007), out-migration or increased off-farm income (Parry et al. 2010a); in other areas they are stable or increasing, for example due to growing population pressure (van Vliet et al. 2013). This variation reflects the cultural, socioeconomic and environmental diversity of Amazonia, and also the complexity of diversification strategies developed by smallholders in the region (Steward 2007, Padoch et al. 2008, van Vliet et al. 2013).

Farmers acknowledge and deal with changes in their agro-ecological and socio-economic environment in many different ways. Changing economic conditions mediated by institutional factors can trigger individual and collective responses that result in land-use changes (Lambin et al. 2001). Instead of being only 'pushed and pulled' by external driving forces, however, farmers are active and informed actors in their responses to changes in their environment (Cramb et al. 2009, Feintrenie et al. 2010). Farmers' decisions to continue with shifting cultivation or to change their land-use practices involve their perceptions and attitudes towards risks, and can be based as much on economic rationales as on tradition or other reasons (Nielsen et al. 2006).

Different environmental and socio-economic contexts provide different opportunities and constraints for agricultural diversification and livelihood strategies (Almekinders et al. 1995). Households are constantly confronted with choices that must be weighed to guarantee their production and reproduction (McCusker and Carr 2006). Local and national markets and policies can create opportunities or constraints for certain types of land use (Lambin et al. 2001), but farmers' opportunities also depend on the type and heterogeneity of the landscapes that they can manage. Environments with poor soils, steep slopes and intense rainfall, for example, are not amenable to certain types of agricultural intensification (Cramb 2005). Especially in societies that rely heavily on agriculture, soil heterogeneity can play an important role, as different soils may favor or restrict certain crop assemblages or management strategies, offer different opportunities for resource use and management, and also co-evolve with knowledge, practices and with the crops themselves. In Central Amazonia, anthropogenic soils add considerable heterogeneity to the soil landscape and play an important role in local cultivation systems.

Amazonian Dark Earths (ADE, or *Terra Preta*) are patches of highly fertile anthropogenic soils formed at pre-Columbian habitation sites (Neves et al. 2003). Today many of them are inhabited and/or used as part of shifting cultivation systems, representing opportunities for diversification of agricultural production and livelihood strategies. ADE contrast strongly with adjacent non-anthropogenic soils, which in most of Amazonia are unfertile and acidic (Chauvel et al. 1987). The differences in soils are reflected in differences in weed community composition and growth (Major et al. 2003, Major et al. 2005b), in the assemblage of cultivated crops and landraces (Fraser et al. 2011a, Fraser et al. 2011b, Kawa et al. 2011, Fraser et al. 2012), and in the composition and usefulness of fallow vegetation (Junqueira et al. 2010b, Junqueira et al. 2011). Shifting cultivation systems on ADE are very heterogeneous and often more intensified when compared to other upland soils, with shorter fallow periods (German 2003b, Fraser et al. 2012) and/or focused on nutrient-demanding crops (Kawa et al. 2011). Production systems on ADE are considered a model for sustainable agriculture (Glaser et al. 2001, Glaser 2007, Kawa and Oyuela-Caycedo 2008), based mainly on the idea that fertile soils can be farmed more intensively and, therefore, would reduce the need to open new areas for cultivation. However, there has been little research to understand how the current use of ADE and the drivers and consequences of their intensive cultivation are explained by farmers' knowledge and reasoning. This would allow us to understand farmers' decision-making under changing conditions, and to identify relevant research and effective strategies to support sustainable shifting cultivation systems and to improve farmers' livelihoods.

In this paper we explore farmers' practices and rationales related to shifting cultivation on ADE and adjacent non-anthropogenic soils. We focus on (1) the way farmers use ADE as part of their shifting cultivation system, (2) how farmers deal with demographic, socioeconomic and political changes in their context, and (3) how these changes affect the way they consider and use ADE. We take as a point of departure farmers' knowledge and rationales in the 'shifts' themselves – that is when existing swiddens are 'abandoned' (i.e., are left under a more or less intensively managed fallow vegetation) and new ones are established. These decisions to abandon one and open another are strategic moments in the management of shifting cultivation systems, and have immediate as well as long-term implications, affecting fallow periods, productivity and farmers' livelihood opportunities. By focusing on ADE, it is possible to evaluate the role that soil heterogeneity has in farmers' decision-making and in the diversification of cultivation systems and livelihood strategies. This information is important for identifying potential opportunities and threats to shifting cultivation systems in Amazonia, as well as for developing more efficient interventions aiming to support local livelihoods and thus to increase the sustainability of cultivation systems on ADE and on non-anthropogenic soils in a changing environment.

Methods

Research design and interviews

This research was carried out along the middle and lower Madeira River, Central Amazonia, Brazil (Chapter 1, Figure 1.1) between 2006 and 2013. We conducted open and semi-structured interviews with ~200 farmers in 21 villages in different geographical and socioeconomic contexts, and in-depth interviews were conducted with a subsample of 90 farmers in seven villages spread along a ~400 km stretch of the Madeira River. Interviews focused on local cultivation and management practices, perceptions and rationales about soils (especially about ADE), criteria for abandoning cultivated swiddens and opening new ones, and perceptions of and interactions with local and regional changes.

The study area and studied systems

The Madeira River and the occurrence of ADE

The Madeira River is one of the largest tributaries of the Amazon River, located in the south-western and central part of the Amazon Basin (Chapter 1, Figure 1.1). Along the river, two major environments can be distinguished by their biotic and abiotic environmental contrasts: the uplands and the floodplains. Floodplains are subjected to the annual flood pulse of the river; this fertile, dynamic and highly seasonal environment is home to a specific flora and fauna, as well as to specific forms of human occupation and resource management, all of which are strongly shaped by the annual flood pulse (Junk and Piedade 2010). The uplands are more stable environments as they are not subjected to flooding from the major rivers (although there is seasonality determined by rainfall), and they are generally composed of unfertile acidic soils.

ADE occur along the whole Madeira River and its tributaries, and archaeological sites with this type of soil transformation are especially frequent along the middle and lower Madeira (Fraser et al. 2011b, Moraes and Neves 2012). ADE sites along the Madeira typically occur in patches varying in size from 2 to 50 ha and are situated on high bluffs on the margins of the rivers. The abundance of ADE along the Madeira River results from a history of long-term and relatively dense human occupation in the past (Moraes and Neves 2012). The region experienced severe depopulation following European conquest, and the population only began to increase again towards the end of the 19th century with the 'rubber boom' (Weinstein 1983). The contact between colonists and the local indigenous populations had severe demographic and cultural impacts on the latter, and gave origin to a mixed-blood population called 'caboclos' (Adams et al. 2009), who today form the majority of the population along the Madeira River. The 'caboclos' form a diverse and highly heterogeneous population, whose culture emerged from the fusion between local and imported elements, and who incorporated indigenous knowledge, technologies and practices of natural resource use and management to different extents (Adams et al. 2009).

Local livelihoods, resource management and shifting cultivation systems

Local livelihoods along the Madeira River are strongly reliant on the use and management of natural resources. Although there is growing interaction with cities and increasing use of industrialized products, agriculture [focusing on annual and bi-annual crops, mainly manioc (*Manihot esculenta* Crantz)], agroforestry, the gathering of forest products, hunting and fishing form the basis of subsistence and commercial activities. Fishing is an activity that is performed on a daily basis, being the most important source of protein in local diets. Hunting is also a very common practice, and although the frequency with which people engage in this activity and their rates of success are much lower than in fishing, it is also an important source of protein.

The gathering of non-timber forest products (NTFPs) plays a very important role in subsistence and also as a commercial activity. Rubber (*Hevea brasiliensis* (Wild. ex Adr. Juss.) Mueller Arg.) production along the Madeira has never returned to the level of importance observed during the rubber boom, but rubber tapping is common and represents an important source of income for some families. The Brazil nut (*Bertholletia excelsa* Humb. & Bonpl.) is economically the most important NTFP, and recently there have been important subsidies from the government that are stimulating more people to engage in gathering. Many other NTFPs are gathered and commercialized, but in smaller quantities, including fibres [*'*cipó ambé' (*Phylodendron* spp.), *'*cipó-titica*'* (*Heteropsis* spp.), 'jacitara*'* (*Desmoncus* spp.), palm leaves [*'*palha branca' (*Attalea* spp.)], medicinal plants, and fruits [*'*açaí' (*Euterpe precatoria* Mart. and *E. oleracea* Mart., *'*bacaba*'* (*Oenocarpus bacaba* Mart. and *O. minor* Mart.), *'*patauá*'* (*O. bataua* Mart.), *'*uchi*'* (*Endopleura* spp.), *'*piquiá*'* (*Caryocar villosum* (Aubl.) Pers.), etc.].

Plant cultivation and management are present in several forms across the landscape. In home-gardens, management is very intensive and decisions are taken at the individual plant level, resulting in a floristic composition and structure that is almost entirely anthropogenic. Beyond home-gardens are swiddens for cultivation of annual crops, generally within a radius of a couple of kilometers from houses. They are very diverse and heterogeneous in their composition of species and landraces, management strategies, area, and many other characteristics, and it is in these environments where most of the food consumed and commercialized is produced. When abandoned they form the 'capoeira' (fallow), which lasts for 3-15 years before being opened again for cultivation. The swiddens are mainly cultivated with annual or biannual crops, although fruit trees and palms are planted and/or favored in some swiddens, which results in secondary forests with a high abundance of useful plants (Junqueira et al. 2010b, Junqueira et al. 2011). Manioc is, by far, the most cultivated crop; it is the most important component of the local diet, and also the most important crop economically and culturally (Fraser 2010b, Fraser et al. 2012). No other crop in the region is the focus of such elaborated knowledge, and such detailed, ingenious and labor-intensive practices in cultivation and processing.

Results

Farmers' knowledge and considerations on opening and abandoning swiddens

Why, when and where to open swiddens

There is considerable variation in the number and size of swiddens that farmers open in a year (normally it varies between one and four, most often two), but nearly all households maintain at least one active swidden to fulfil the family's need for manioc flour, the local staple food. Farmers have been making swiddens for manioc in this landscape for generations, and to be self-sufficient in manioc flour is an important part of their identity: it is a behavior that is expected from a member of the community. Apart from its important subsistence and cultural value, farmers also cultivate manioc for sale (mostly as flour), and this is often their most important source of monetary income ('the swidden is the bank of the farmer'; text fragments between single quotation marks are English translations of quotes from interviews). While a cultivated swidden provides an opportunity to meet both subsistence and monetary needs, its success requires careful planning from the very beginning, with the decision of opening being crucial. Months ahead of opening, farmers are already thinking of their future swiddens, discussing them with their relatives, and considering why the swidden will be opened ('This one is just for my family to eat.'; 'This swidden is for the house we are going to build.'), how it will be opened, planted and maintained (i.e., the labor required, the seeds and planting materials that will be needed), and where it will be opened. These considerations are interdependent.

Essentially, the decisions to open and abandon swiddens are the outcome of balancing labor requirements with other demands. Farmers open a new swidden when the older one(s) in cultivation become too burdensome to maintain (i.e., require more weeding) and yields are unsatisfactory. For non-anthropogenic upland soils (NAS) this generally starts to occur after the first cropping cycle. Swiddens on NAS are dominated by bitter manioc, and farmers say that the length of the cropping cycle varies from six months to three years, depending on the landraces that are cultivated and the time it takes for harvesting (most often harvesting starts 9-10 months after planting and lasts from a couple of months to more than a year). The opening of a swidden requires enormous effort, as it is mostly manual work and usually involves cutting dense vegetation. Farmers say that June/July is the best period for opening a new swidden because of the low rainfall, which permits sufficient drying to allow it to burn well. Also, when opening during this time of the year, the planting coincides with the start of the raining season (September/October), and farmers say this provides better conditions for plant growth. There is, however, considerable variation in opening and planting times, especially for crops other than bitter manioc (e.g., maize, banana, watermelon).

Many farmers consider that ADE is suitable for the cultivation of 'almost everything', where 'whatever you plant grows', owing to the relatively high fertility of these soils (although fertility is a concept that is not present in farmers' vocabularies, nor does it fit well with how soils are understood; see below). According to farmers, some crops that are commonly cultivated on the floodplains can only be cultivated successfully on uplands when grown on ADE, like watermelon, maize or beans. This association between specific crops and ADE has an important influence on farmers' decisions about where to open their swiddens or on which crop they will focus.

For the decision about where to open their swiddens, farmers rely on their historical knowledge of the landscape (e.g., previous land uses) combined with a current 'reading' of the soil and vegetation in order to choose a place that suits their needs. This 'reading' is essential, especially because farmers recognize that environments are dynamic, and that their properties or suitability for cultivation change over time (see below). Their decision on establishing a new swidden, or how to cultivate and manage it, reflects an integrated knowledge of the soil and vegetation, as affected by their management practices.

Ease of access, proximity and land tenure also play important roles in the decision about where to open a new swidden. Since most of the transportation of people and products is by foot or canoe, farmers prefer to establish their swiddens as close as possible to their houses or, in the case of bitter manioc, to the place where the manioc is processed into flour (although the processed product of course also needs to be transported). In most villages, the area used and managed by households is comprised of a mosaic of private lands (which can be formalized or not) and state-owned lands. Although population density is very low and land is not scarce in most villages, access to land tends to be more regulated closer to habitation sites, where both formal (e.g., private properties) and informal rules (e.g., the historical occupation of a given area, kinship ties) are more important and can influence the establishment of new swiddens (‘Here at the front [at the river margin] everyone has their own piece of land, back there [further inland] we can make our swiddens wherever we want.’). Farming on private lands might require agreements with the owner, which can involve payment in cash or in labor. Since ADE occur in relatively small areas, closer to habitation sites, and allow the cultivation of crops that cannot be cultivated elsewhere, access to these areas tends to be most regulated by both formal and informal land tenure rules. These situations (and their many variations) result in a more unequal access to ADE when compared to NAS, which affects farmers’ decisions on opening their swiddens (‘I would be interested in using terra preta, but I do not have it in my land.’).

Understanding soils and anthropogenic origins of ADE

Farmers recognize the variation in soil properties and always associate them with vegetation differences in terms of fallow development (‘On this type of clay the fallow takes longer to grow.’), weeding requirements (‘Terra preta requires more weeding than other types of land.’) or crop suitability (‘This soil is loose, it is better for manioc.’; ‘Maize only grows on terra preta.’). For the identification of soils they use physical characteristics, especially texture and color. Soil names commonly start with the words ‘barro’ (clay) or ‘areia’ (sand), followed by a descriptor that is generally a color or a word that details or emphasizes a textural aspect of the soil: ‘solto’ (loose), ‘fofo’ (soft). Soils that do not easily fit into these general categories are described as ‘misturado’ (mixed), and several combinations of these terms are used to describe them, e.g., ‘barro amarelo misturado com areia’ (yellow clay mixed with sand). The term ‘terra preta’ (black earth) is used in reference to soils that are darker and loose, and therefore does not always correspond to the scientific definition of anthropogenic soils. When they refer to sites that are darkest and/or with ceramic fragments, which generally correspond to the archaeological sites, they usually add a descriptor meaning ‘true’, or ‘legitimate’ or referring to specific characteristic of these soils, e.g., ‘terra preta com caiaué’ (black earth with caiaué – a palm species, *Elaeis oleifera* (Kunth) Cortés).

People who live on ADE patches or who use them for agriculture or agroforestry are constantly in contact with archaeological artefacts, including lithic materials (stone axes, mortars), earthworks (ditches, excavated trails) and ceramic fragments. There is general agreement that these are remains of former indigenous residents, but there is no consensus about the origin of the soil itself. ADE is seen by most people as a natural place with specific properties, favored for habitation by the Indians – which would explain the occurrence of the material artefacts ('Indians only liked to live where there is terra preta.'). In this understanding there is an essential separation between the characteristics of the soil (the specific properties of ADE) and the evidence of past human activity (artefacts).

People actively manage soils in many ways, although in very small areas, and recognize that management can modify soil properties: in their explanations and practices for soil enrichment, fire always takes a central place. Most people do not think that the ADE patches, large and relatively abundant in the landscape, were created by humans ('Terra preta was created by nature itself.'). A minority of people, however, think that the soil itself may have resulted from human activity in the past. Their explanations for the formation of ADE are related to current practices of soil management, especially to the formation of 'terra queimada' (burned earth) in small fires in home-gardens and 'caieiras' (sites where charcoal is produced). Interestingly, their reasoning about the creation of ADE resembles the academic understanding of how these soils were formed, incorporating the temporal dimension ('They [the Indians] were doing this for a long time.'), the magnitude of the historical human occupation of the landscape ('There were many people, far more than we are today.'), and also the practices of resource use and management that might have led to these transformations (cultivation, fires).

Reading the vegetation

Apart from the recognition of variation in soil properties per se, farmers obtain a more complete understanding of soils by observing characteristics of the vegetation (and vice versa). In particular, the observations that relate to labor requirements are prominent. The stage of development of the vegetation is recognized by the farmers as a direct indicator of the amount of labor required to open the swiddens and to maintain their productivity. Opening an older fallow (described locally with terms such as 'tall', 'thick' or 'old' fallow) means cutting more and larger trees, which requires more labor. On the other hand, farmers say that swiddens opened in older fallows tend to have less weed growth and higher productivity. This balance between labor needed to open and maintain swiddens and productivity of the swidden came to the fore in practically every conversation we had with farmers, and is summarized in this quote: 'Older fallows require less weeding and produce more, but require more work to cut.'. Ease of access and proximity also play an important role in this balance: 'The tall fallows are far, so we do it [open swiddens] in the short ones.'.

When it comes to ADE, farmers recognize several contrasts with other upland soils. Farmers say that the vegetation grows faster on ADE (which implies higher weeding requirements, see below), but they also mention that fallows on ADE are denser in the understory, have a higher abundance of palms and lianas, and do not grow as tall as fallows on NAS. Fallows on ADE are thought to be hard to walk through, but at the same time they are easier to open because they tend to be 'softer' (i.e., the trees can be cut more easily). As with NAS, the development of the vegetation on ADE is used as an indicator of the quality for cultivation. The fact that older fallows require less weeding and give higher yields is, however, not strongly emphasized when they talk about ADE. Farmers say that ADE always requires a lot of weeding, even if swiddens are opened from old fallows, and that ADE always produces well, even if swiddens are opened from young fallows ('Terra preta requires a lot of work to weed, but everything that you plant grows well.'). Letting the fallow grow, therefore, is not so important to recover productivity or to reduce the need for weeding, and they say this is one of the reasons why swiddens on ADE tend to be opened from younger fallows then on NAS. Also, farmers say that old fallows on ADE are harder to find, and therefore they have fewer options when choosing from fallows in different stages of development on ADE than they have with NAS. Still, given the overlap between ADE and current habitation sites, patches of ADE are often closer and more accessible, which is a factor in farmers' decisions: 'This one [terra preta] requires a lot of weeding, but it is close to home.'.

The high weeding requirement for cultivation on ADE is the most common and salient consideration of farmers in their decisions about opening a swidden on these soils. They mention that the number of weedings required before harvesting manioc is almost twice as high on ADE as on NAS. For this reason, they generally open smaller swiddens on ADE than on NAS, and some farmers even avoid cultivating ADE. We recorded several situations in which farmers opened swiddens on ADE but only managed to weed a fraction and had to abandon the remainder.

This 'reading' of the fallow, therefore, enables farmers to project immediate and future labor requirements to obtain a potential yield. This 'reading' recognizes the different soil-vegetation associations of NAS and ADE through time. The diagrams in Figure 2.1 represent these differences schematically.

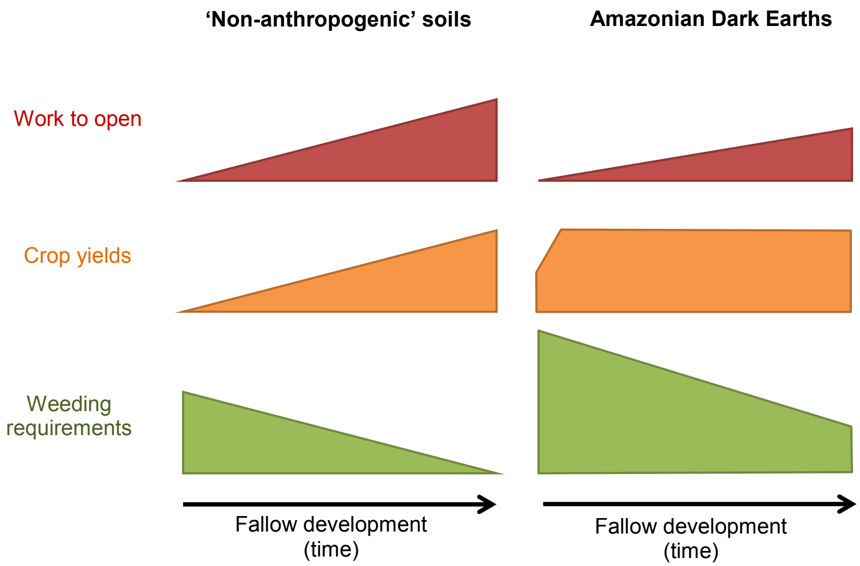

Figure 2.1. Conceptual diagram showing relationships between fallow length and work required to open a swidden, expected crop yields and weeding requirements for 'non-anthropogenic' (NAS) and anthropogenic soils (Amazonian Dark Earths, ADE).

The practices of establishing and abandoning swiddens and the role of ADE

The practice of opening new swiddens

As indicated, opening a new swidden is very labor intensive. Cutting a fallow is normally a male-only group activity called 'puxirum' (a word of Tupi origin that refers to collective activities), organized by the owner of the swidden-to-be. A few days or weeks before his 'puxirum', the farmer invites a number of fellow farmers to participate. The organizing farmer then owes every person that participates the same amount of work in return, which could be half, one or a few days' work. The duration of the 'puxirum' and the number of people involved depends on the age of the fallow and the size of the swidden. Thus, older fallows require longer 'puxiruns' because they have larger trees and more of them have hard wood, which makes felling more laborious. Shorter 'puxiruns' involve 3-4 farmers and can last for a few days, but in general a 'puxirum' is thought to last only one day, from early morning to the middle of the afternoon, and some of them involve as many as 20 people. When opening a new swidden, the farmer will have to consider the number of days he will have to work outside his swidden in return for the 'puxirum', as well as the labor that he and his family will have to invest in weeding, harvesting and other activities in the swidden. Although 'puxiruns' are still the most common form of organization of collective work, farmers say that it is gradually being replaced by wage labor (see below).

The owner of the swidden-to-be is the one who decides the exact size and location of the new swidden. He marks the perimeter with stakes, such that the other people who join the 'puxirum' know the limits of the 'roçagem', the term for cutting all the vegetation from the understory and the smaller trees with machetes. Larger trees are left to be felled later with axes or chainsaws, in an activity that is called 'knock down' or 'derrubada'. The 'derrubada' can be done simultaneously or a few days after the 'roçagem'. After these steps, the vegetation is left to dry for some time before burning. This interval between cutting and burning of the vegetation can last from ten days to a month, depending on the age of the fallow (older fallows need longer to dry), but also on the weather ('We need a few days of strong summer before we can burn.'). Farmers say that the quality of the burn is very important – a 'bad' burn leaves green vegetation behind, and this will result in more rapid regrowth and an earlier need for weeding than if the swidden had burned properly. Also, they say that what allows cultivation is the burned vegetation that is turned into ashes (and also some charcoal); therefore they associate 'better' burns with higher yields. Often there is a second burning, the 'coivara', in which trees that were not burned properly are piled and burned again. Farmers say that the main reason for making 'coivaras' is to 'clean' their swiddens better (i.e., leave more space for their crops). Farmers also say that each 'coivara' leaves charcoal and ashes accumulated, leading to modification in soil properties that are suitable for the cultivation of specific crops, such as banana (*Musa* x *paradisiaca* L.), chili pepper (*Capsicum* spp.), yam (*Dioscorea* spp.), etc.

Since farmers state that swiddens on ADE are opened from younger and 'softer' (i.e., easier to cut) fallows, and also are smaller than NAS swiddens, the labor required for opening swiddens on ADE tends to be lower, less often requiring 'puxiruns' and 'coivaras'. Some swiddens on ADE, however – especially those under more intensive cultivation – may contain an abundance of very aggressive shrubs or treelets (e.g., *Acacia* sp., *Chomelia anisomeris* Müell. Arg.), and farmers say that in these situations their opening requires a lot of effort.

The decision to abandon swiddens

Farmers describe soils as being 'tired or 'weak' ('terra cansada' or 'terra fraca') when they produce unsatisfactory manioc yields and/or when they are infested with weeds. Farmers report that planting a second time in the same swidden leads to reduced crop yields and higher weeding requirements. Therefore, a typical manioc swidden on NAS is used for one cropping cycle, which may last from one to three years: during the first 8-12 months the swidden is weeded more intensively; then manioc harvesting starts, which may last from a few months up to two years. Once harvesting is finished, farmers usually let the fallow vegetation grow. A swidden is, however, not abandoned completely; the fallows are also managed and contain many useful species, some of which were saved from cutting or burning during opening of the swidden, and others which may have been planted or spontaneously appeared and were favored during the period when the swidden was being managed more intensively. When farmers finish harvesting manioc or other annual/biannual crops, the enriched fallow is subject to lower intensity management.

On ADE, farmers say that they prefer planting crops that produce faster (including specific earlier maturing manioc landraces), so they can reduce the need to weed on these soils as much as possible. On the other hand, successive cropping cycles occur much more often on ADE ('We are always replanting on that area [terra preta], we plant there all the time.'). Swiddens on ADE are more frequently used in multi-season crop rotations (e.g., maize – sweet manioc – beans) and/or replanting ('Replanting only works if you do it on terra preta.'), consequently the swidden can be in cultivation for several years before being abandoned (although the perception that successive plantings on the same plot makes the land 'tired' also applies to ADE). In NAS swiddens, replanting is not a common practice. It is occasionally done in a small part of the original swidden (often while the first crop is still being harvested), or in swiddens that have been opened from old fallows, where 'land is stronger' and can sustain two successive cycles.

Changing local context: education, markets and organizations

Farmers acknowledge changes in their cultivation systems to different extents and at different time scales. They consider these changes to affect their practices as well as the usefulness of their knowledge and associated cultural values. Changes in access to formal education are frequently mentioned by farmers, as these can drive out-migration of children and teenagers and therefore change household labor availability. People along the Madeira River increasingly have access to formal education due to improvements in the infrastructure provided by government. Furthermore, having all children at school is a condition for receiving money from the 'Bolsa Família', the largest Brazilian social program, which provides significant cash income for most of the families in the region. In almost every village there are schools for young children, but teenagers frequently have to move or travel on a daily basis to larger villages or cities where there is available infrastructure for their continued education. The majority of the families interviewed had at least one son or daughter studying away from the village. Farmers often refer to this sort of migration and the intensification of it over the last couple of decades when explaining changes in the management of their swiddens ('Before we used to do big swiddens, now our children have left and we cannot do it anymore.').

Farmers also acknowledge their increasing interaction with cities and their growing engagement with the market economy. They report a range of associated changes, such as increased access to commercial opportunities ('Today everything planted is sold.') through better transportation and market organization (e.g., associations, cooperatives). They also report changes related to the adoption of 'modern' cultivation techniques, frequently stimulated by state extension organizations. These include the reduction in the number of landraces cultivated (particularly manioc landraces) and the focus on a few 'improved', economically profitable ones, the increasing use of fertilizers and pesticides (especially in the cultivation of watermelon), and the increase in mechanization (although limited to weeding machines, chainsaws and small tractors or motors). As well as providing agronomical recommendations, extension organizations also mediate farmers' access to credit. The presence of these organizations varies strongly between villages and farmers often complain about their absence or the lack of technical follow-up from extension agents. Still, most of the farmers we interviewed said that they have accessed credit through these organizations. Most often, extension organizations tie this access to credit to the diversification of production activities, thereby stimulating farmers to 'buy' technology packages that usually are associated with more intensive cultivation (e.g., improved landraces, fertilizers, etc.).

These changes also change perceptions. Farmers – particularly younger ones – consider traditional cultivation techniques 'old-fashioned', especially cultural and symbolic practices (e.g., synchronizing certain management practices to lunar phases, planting part of the swidden immediately after burning to 'protect' it, etc.). Farmers who maintain these practices refer to them with a certain shyness and reticence, as if these traditional practices inherited from the 'old ones' ('dos antigos') have become less important than 'modern' practices ('I don't know the names [of the manioc landraces], it was the old ones who gave these names to the manioc.'). Despite the fact that manioc occupies a central role in local livelihoods and is the most commonly cultivated crop, farmers point out that young people are less interested in its cultivation, changing their focus to other cash crops or to paid work ('Now nobody here wants to work with manioc anymore.'). Labor relationships, in general, are becoming increasingly monetized. The traditional collective 'puxiruns' are gradually being replaced by the payment of daily wages ('Before when we did 'puxirum' we invited a lot of people, but everyone had their [manioc] swiddens. Today not many people make swiddens, so when you invite someone you have to pay [with money].').

Cultivation systems on ADE are subject to the same trends: reduced labor availability related to out-migration, the increasing engagement with markets and the adoption of new crops and/or cultivation practices. The trends do affect ADE differently as compared to NAS, however. Farmers say ADE cultivation has always been different than on other soils and 'tuned' to the specific characteristics of this soil, but they acknowledge that the increasing adoption of cash-crops and the intensification of production (through fallow shortening or semi-permanent cultivation) have been particularly pronounced on ADE, especially over the last decades. Farmers recall that watermelon, for example, was only grown on floodplains until approximately 30 years ago, when they started planting it on ADE. In some villages (particularly those with better access to markets), watermelon became a major cash crop and led to higher pressure on ADE: farmers started using these areas almost every year, 'reserving' them for watermelon only, and even started renting pieces of ADE land specifically for the cultivation of this crop. This resulted, farmers say, in the 'weakening' of the soil in some places, with declining yields and increasing need for fertilizers and pesticides, and these areas now need to be left to fallow for longer periods so that they can recover their 'strength'. Farmers also mention that in certain situations extension organizations stimulate them (via knowledge sharing, but also by mediating access to credit) to cultivate ADE with annual or perennial cash-crops that don't grow as well in other upland soils, such as cacao, citrus or papaya. The intrinsic characteristics of ADE, therefore, favored changes towards intensification and 'modernization' of cultivation systems on these soils and attracted initiatives with similar approaches from extension organizations.

Discussion

The role of ADE in shifting cultivation: diversification and intensification

Our study showed that farmers along the Madeira River have an integrated understanding of soils and vegetation dynamics. This knowledge enables them to 'read' the fallow and provides them with indicators of future crop yields, and immediate and future labor requirements. They balance these with their crop production opportunities and livelihood needs. This forms the basis of their decision making – particularly that related to opening and abandoning swiddens.

Farmers know that increased fallow development is associated with increased crop yields and labor requirements in shifting cultivation. Relationships between fallow development, labor and yields appeared early in the shifting cultivation literature (Nye and Greenland 1960, Boserup 1965, Clarke 1976), although these have not been thoroughly addressed with empirical measurements (Mertz 2002, Nielsen et al. 2006, Mertz et al. 2008). We provide evidence from local rationales that the 'reading' of the fallow is a major source of information upon which farmers rely to make their decisions in shifting cultivation. From farmers' perspectives, however, this association between fallow development and crop yields or labor requirements in shifting cultivation is much weaker on ADE than on NAS, since ADE is always associated with high labor requirements due to weed pressure. The high weed pressure on ADE has also been reported in other studies with a focus on the current cultivation of these soils (German 2003a, Major et al. 2003, Major et al. 2005b, Fraser and Clement 2008, Fraser 2010a, b). This aspect of ADE is very salient in farmers' reasoning and influences many decisions about opening swiddens, their cultivation practices and the cultivation cycle. Farmers recognize these different relationships in ADE and NAS and use them to decide about opening swiddens, predict future yields and labor needs.

Despite the high weeding requirements on ADE, these soils are highly valued by many farmers as they offer important opportunities for diversification and intensification (shorter fallow periods and cropping cycles). The suitability of ADE to cultivate a wider diversity of crops broadens farmers' options for cultivation; the different ways in which farmers deal with these possibilities translates into a great heterogeneity of swiddens on ADE in terms of crop composition, ranging from the staple bitter manioc (Fraser 2010a) to multi-crop swiddens (Kawa et al. 2011) to monoculture cash-crop swiddens strictly oriented to the market (e.g., those used for watermelon cultivation).The intensification of shifting cultivation is advantageous in situations where farmers need to produce quickly (for subsistence or for the market) or when there are significant labor constraints for opening new areas. From the farmers' perspective, opening a swidden on ADE may represent an opportunity to grow different crops, and/or grow crops in different (and often more intensified) management systems, although cultivating on ADE has higher labor costs for weeding. By taking farmers' rationales as a starting point, we showed not only their integrated knowledge of the dynamics of soils and fallows, but also how socio-economic factors are incorporated into decisions about their production goals and limitations (i.e., different crops, landraces and labor availability).

ADE and local perceptions and rationales about changing cultivation systems

Farmers along the Madeira River acknowledge numerous changes in their socio-economic environment, on different spatial and temporal scales, that affect their shifting cultivation systems. Among the most important current trends mentioned by farmers is the out-migration of teenagers to towns in pursuit of formal education and their abandonment of agricultural activities, resulting in increasing labor constraints. The growing interaction with market economies and the incorporation of 'modern' agricultural practices are also stressed by farmers. They report that more abundant transportation options and the development of market structures have increased opportunities to sell specific products, and that the role of agriculture is gradually shifting from 'for subsistence only' towards partly subsistence and partly commerce-oriented cultivation. These farmer-perceived changes echo patterns described elsewhere in Amazonia (Rudel et al. 2002, Gray et al. 2007, Marquardt et al. 2012, van Vliet et al. 2013). Improved transportation and market opportunities, farmers say, have contributed to the cultivation of new crops, a focus on fewer 'improved' crop landraces, the growing use of fertilizers and pesticides, and (incipient) mechanization. Farmers also mention that access to these new management strategies is facilitated and stimulated by extension organizations through bringing knowledge, but mainly through access to credit.

In some villages with relatively good geographic and market access, farmers report intensive cultivation of ADE, in some situations with no or extremely short fallow periods, and a pronounced focus on cash crops. This has resulted in degraded fallows (i.e., with reduced regeneration and high dominance of aggressive weeds and shrubs) and in the growing dependency on fertilizers or pesticides to maintain satisfactory yields on ADE, and may hence be called ‘over-intensification’. Given the intrinsic characteristics of ADE, shifting cultivation systems on these soils tend to be more prone to changes leading to intensification, which according to farmers is being driven mainly by increased market access and interventions from extension organizations. This has implications for understanding the potential role of ADE in how farmers deal with change. On one hand, these soils can increase the opportunities for diversification of cultivation strategies, which is generally beneficial for livelihoods (Ellis 1998). On the other hand, they can attract certain forms of intensification that follow the typical Green Revolution path (Evenson and Gollin 2003), in which the goal of maximizing productivity occurs at the expense of a greater dependency of markets and external inputs, often with adverse environmental and social impacts (Godfray et al. 2010, Padoch and Sunderland 2013).

From local rationales to the future of ADE

In the consideration of ADE as a model for sustainability, intensification of production on these soils is assumed (Glaser et al. 2001, Kawa and Oyuela-Caycedo 2008). Our study identified cases (swiddens used for watermelon cultivation) in which market demand led to ‘over-intensification’ as it resulted in ADE degradation. To date, farmers and researchers have assumed that degradation of ADE (as well as NAS) can be solved with longer fallow periods for these soils to regain their fertility and to reduce weed pressure. Hiraoka et al. (2003) report a case of long-term vegetable farming on ADE south of Santarém, where ADE fertility is maintained by periodic fallowing. In fact, we also identified many cases in which farmers manage ADE under moderately-intensive systems that seem to be relatively sustainable in the long-term. However, with increasing market pressures and stimulus from the extension agency to cultivate ADE with nutrient-demanding crops with strong market demand, cases of over-intensification on ADE are likely to occur more often, leading not only to depletion of soil nutrients, but also to increased use of agrochemicals. This shows that increasing intensification can be a potential threat to ADE and undermine the importance of these soils for agricultural production, for the conservation of agrobiodiversity and for local livelihoods.

We have also found that farmer rationales for the use of ADE involves more than soil fertility per se, with its capacity to sustain more intensive cultivation. Labor requirements of soils and crops are a salient feature in farmers’ discourses. Opening swiddens and weeding are extremely labor-intensive activities, which explains why labor is such an important element in farmers' decisions about which soils to use and which swiddens to open. Farmers acknowledge changes in their social environment, driven mainly by increased transportation, communication and education opportunities, resulting in out-migration, greater market integration, and the presence of extension organizations. Some of these changes limit labor availability and/or increase the costs of labor. It is likely, therefore, that farmers will simultaneously maintain extensive long-fallow swiddens on soils with lower fertility (because of their lower labor demand) and smaller, more intensive short-fallow swiddens on ADE. This 'multi-functionality' can be an effective strategy to cope with risk, particularly suited to the fragile market structures, insecure land tenure and little access to credit that characterize most of rural Amazonia (van Vliet et al. 2012), and therefore should be further explored by extension agents and/or initiatives supporting farmers in developing their production and livelihood options.

Conclusions

Future developments are difficult to predict in the dynamic context of rural Amazonia. Farmers whose livelihoods depend strongly on agricultural production will respond to agro-ecological as well as socio-economic changes in their context and adapt their farming strategies accordingly. They are likely to take well-informed decisions, given their integrated knowledge and understanding of the dynamic interactions of soils and vegetation. However, the observation that over-intensification can lead to ADE degradation suggests the need to research the role of fallows in ADE resilience, as well as nutrient depletion and other biophysical and social consequences of intensified ADE production systems. We argue that in order to develop sustainable pathways for the future of smallholder agriculture on ADE and on NAS, it is crucial to understand farmers' knowledge and rationales and integrate it into the research, development and extension network. In addition, exploring options to optimize the production of diverse systems, involving ADE as well as NAS, requires attention. Finally, attempting to enhance productivity of ADE while disregarding other biophysical and social components of the system may lead to biased support for farmers who practice shifting cultivation in Amazonia.

Acknowledgements

We thank the local residents of the villages along the Middle Madeira for their invaluable help, support and friendliness, without which this research would not have been possible. We would also like to thank the Institute for Sustainable Agriculture and Forestry Development of Amazonas State (*Instituto de Desenvolvimento Agropecuário e Florestal Sustentável do Estado do Amazonas*), the Chico Mendes Institute for Biodiversity Conservation (*Instituto Chico Mendes para a Conservação da Biodiversidade*) and the Brazilian International Institute of Education (*Instituto Internacional de Educação do Brasil*) for logistical support. This research was authorized by the Brazilian National Research Ethics Commission (*Comissão Nacional de Ética em Pesquisa*, CAAE#011488712.3.0000.0006, Auth.#231.032). Research authorization for villages inside conservation units (Água Azul – Rio Amapá Sustainable Development Reserve, and São Félix do Aripuanã – Juma Sustainable Development Reserve) was obtained from the Amazonas State Centre for Conservation Units (*Centro Estadual de Unidades de Conservação,* Proc.#1017/2012). We thank Simon Jeffery for improving an earlier version of this manuscript.

Chapter 3

Soil heterogeneity affects the diversity of cultivation strategies: the case of Amazonian anthropogenic soils

André Braga Junqueira, Tjeerd Jan Stomph, Charles R. Clement, Paul C. Struik

(submitted)

Abstract

Large areas in Amazonia are increasingly experiencing environmental and socio-economic changes that directly affect smallholder farming, with potential negative effects for agrobiodiversity and livelihoods. The diversification of agroecosystems can foster their resilience, but farmers' opportunities to diversify depend on the availability and heterogeneity of environments they can use and manage. In this paper we investigate the effects of soil heterogeneity on the diversity of cultivation strategies used by farmers in Central Amazonia. We focus on the effect of soil variation between anthropogenic upland soils (ADE) and surrounding soils on the size and location of cultivation plots, on the cultivation cycle, and on the diversity and assemblage of crops. We found that the gradient in soil fertility between non-anthropogenic soils and ADE is associated with more intensive cultivation (shorter fallow periods, higher frequency of cultivation, shorter cycles and higher labor requirements) and with changes in the crop assemblages, but with similar or larger numbers of species cultivated. Current smallholder farming systems along soil gradients between ADE and non-anthropogenic soils are examples that soil fertility can favor synergies between intensification and diversification.

Keywords: Shifting cultivation; Terra Preta; Intensification; Diversification; Smallholder farming.

Introduction

Small-scale agriculture is the basis of the livelihoods of thousands of families in Amazonia, with smallholder farmers representing the vast majority of the rural population in the region (Godar et al. 2014). Large areas in Amazonia are increasingly experiencing the expansion of large-scale agriculture, of cattle-ranching and infrastructure (roads, dams, etc.), rural-urban migration, and increasing interaction of rural populations with cities and market economies (Padoch et al. 2008, Parry et al. 2010a, Davidson et al. 2012, van Vliet et al. 2013). These phenomena are in general associated with the increasing adoption of 'modern' intensive agriculture practices (e.g., use of agrochemicals, cultivation of one or a few cash-crops) and/or the abandonment of small-scale agricultural activities (Steward 2007). The inputs and practices brought by these changes, as well as the new socio-economic arrangements that they demand, may negatively impact human health and local livelihoods, and potentially be detrimental to environmental quality and biodiversity (Matson et al. 1997, Jackson et al. 2007). Smallholder farmers are particularly vulnerable to these impacts, as they have few other livelihood strategies (Tilman et al. 2002) and little capital to invest in adaptation strategies (Morton 2007, Lin 2011).

In this dynamic context of rural Amazonia, desirable pathways for the development of smallholder farming systems can be achieved by enhancing the capacity of smallholders to adapt to and shape change (Berkes et al. 2003, Elmqvist et al. 2003, Walker et al. 2004, Smit and Wandel 2006). The diversification of agroecosystems – in different forms (e.g., intra- and inter-specific, structural) and scales (within crop, within field, at landscape level) – fosters their resilience (Lin 2011). Diverse agricultural landscapes are associated with enhanced nutrient recycling, microclimate regulation, pest control and pollination (Tscharntke et al. 2005, Jackson et al. 2007, Perfecto and Vandermeer 2008). At the farm level, diversification can bring various benefits, such as increased food security (Frison et al. 2011), more diverse and stable income, less vulnerability to market fluctuations (Di Falco 2012), more efficient pest and disease control, increased yields [depending on the crop combinations; Letourneau et al. (2011)], and overall increased productivity of the farming system (Altieri and Nicholls 2004, Thrupp 2004).

Farmers' opportunities to diversify their cultivation systems are influenced by several factors, among which environmental heterogeneity is a central one (Denevan 1984, Almekinders et al. 1995). In Central Amazonia, smallholder agriculture is practiced mainly through shifting cultivation, at current population densities well suited to the poor and acidic soils that predominate in the uplands (Nye and Greenland 1960, Altieri 2004). These systems use crops well adapted to poor soils and are mostly low input: the intensification of land use without extra inputs is usually associated with reduction in yields (Mertz 2002, Mertz et al. 2008), decrease in the availability of non-crop plant resources (Dalle and de Blois 2006), increased labor requirements (Nielsen et al. 2006), and loss of resilience of secondary forests that regrow after abandonment (Jakovac et al. 2015). In central Amazonian uplands, however, patches of high-fertility anthropogenic soils are also found; these add considerable heterogeneity to landscapes and are associated with different opportunities for the diversification of cultivation strategies.

Amazonian Dark Earths (ADE, or *terra preta*) are anthropogenic soils created by the concentrated deposition of carbonized organic materials from the cultural activities of pre-Columbian populations between 500 and 2,500 years ago (Neves et al. 2003, Glaser and Birk 2012). ADE exhibit on average high levels of most macro- and micro-nutrients (apart from potassium), as well as higher organic matter content and pH (Glaser and Birk 2012). Patches of ADE are currently used by local people for homegardens, agroforests, secondary and mature forests, and swiddens[1] in shifting cultivation (German 2003b, Hiraoka et al. 2003, German 2004, Fraser 2010a, Junqueira et al. 2010b, Fraser et al. 2011a, Fraser et al. 2011b, Junqueira et al. 2011). Previous studies have indicated that ADE are associated with more intensified cultivation systems, with shorter fallow periods and focused on fast-maturing manioc landraces (Fraser et al. 2012) and/or nutrient-demanding cash crops (Hiraoka et al. 2003, Kawa et al. 2011). These studies, however, have considered ADE as a defined soil category, which neither conforms to how farmers perceive and classify soils (Chapter 2), nor to the heterogeneity in soil properties found between ADE and adjacent soils (Fraser et al. 2011c).

In this paper, we look at how anthropogenic soils in Central Amazonia affect the diversity of cultivation strategies (i.e., *how* cultivation is practiced and *what* is cultivated) used by smallholder farmers. We combine data from soil samples, botanical inventories and farmer interviews to investigate whether the gradients in soil properties between anthropogenic and adjacent soils influence (1) the size and location of cultivation plots, (2) the characteristics of the shifting cultivation cycle, and (3) the diversity and assemblage of crops and landraces cultivated. In contrast to previous studies about cultivation on ADE, we analyze the whole

[1] We use the term ‘swidden’ to refer to the cropping phase of a plot in shifting cultivation.

gradient in soil properties between ADE and adjacent soils, we investigate multiple aspects of the cultivation cycle (swidden size and distance, labor investment, cycle frequency and length) and we consider the whole assemblage of crops cultivated, at both the species and the landrace level. This provides not only a more comprehensive understanding of how ADE is incorporated into local cultivation systems in Amazonia, but also allows us to evaluate in a wider sense the effects of soil heterogeneity – particularly soil fertility – on the cultivation strategies used by smallholder farmers in the tropics.

Methods

Study area

This study was carried out in riverside communities located along the middle and lower Madeira River, in Central Amazonia (Chapter 1, Figure 1.1). The local climate is a transition between *Af* and *Am* in the Köppen system, with annual rainfall of 2,600-2,800 mm and mean temperatures between 27 and 28°C (Alvares et al. 2013). Despite increasing deforestation close to roads and small cities, forests and/or other apparently natural vegetation types occupy most of the landscape in this region. These are composed predominantly of evergreen *terra firme* forests and flooded forests along the rivers, with patches of savannahs further from the rivers (Rapp Py-Daniel 2007).

Soils in the uplands (i.e., in areas that are not subjected to the river floods) are generally poor and acidic ferralsols, with small patches of acrisols, lixisols and podzols; in the active floodplain of the Madeira River (and also on paleoriverine land forms) fertile gleysols occur (IBGE (2010); classification sensu WRB (2014)). Anthropogenic soils (anthrosols) are commonly found in the landscape, particularly on bluffs along the Madeira River, its tributaries and lakes, and many of them are located under current villages or towns (Moraes and Neves 2012). Patches of ADE are heterogeneous in color, texture and chemical properties, and vary in size from 1 to ~50 ha (Fraser et al. 2011b, Moraes and Neves 2012).

The local population is composed mostly of *caboclos*, descendants of the intermarriage between local indigenous people with migrants from other parts of Brazil in the late 19th and early 20th centuries (Adams et al. 2009). Main subsistence and economic activities include the cultivation of manioc and/or other annual crops in shifting cultivation systems, agroforestry, the extraction of forest products (e.g., Brazil nut *Bertholletia excelsa* Bonpl., rubber *Hevea* *brasiliensis* (Willd. ex A. Juss.) Müll. Arg.), hunting and fishing. Despite these commonalities, the *caboclos* form a heterogeneous group in which multiple historical trajectories coexist, as well as diverse forms of resource use and management, and different levels of interaction with cities and markets.

Sampling design

We selected seven villages along the middle and lower Madeira River and its tributaries, spread along a stretch of approximately 400 km (Chapter 1, Figure 1.1). Selected villages were located on or close to patches of ADE, were well-spaced along the river, and were located on uplands (i.e., not subjected to annual river floods, nor located on paleoriverine land forms). Villages were variable in number of inhabitants (varying from ≈12 to ≈35 families), distance from and ease of access to cities and/or the Madeira River, land tenure (two villages are located inside protected areas), and land use and occupation history.

In each village, we selected between 9 and 17 farmers; farmers were chosen so that their cultivation plots (swiddens) would cover the largest possible variation in soil characteristics, from anthropogenic to non-anthropogenic soils[2]. For each farmer, we obtained information for all of his/her swiddens using semi-structured interviews, and for at least one of his/her swiddens we also obtained information *in situ* on the cultivation of the plot, excluding those located on floodplains. In total, our dataset comprises 90 farmers and 215 swiddens, for 114 of which we have detailed information obtained *in situ*.

Data collection

Soil samples

In each swiddens for which we obtained *in situ* information, we collected composite soil samples (composed of five subsamples) collected between 0 and 20 cm depth, after removing roots and/or other un-decomposed litter. Subsamples were evenly spread through the swidden, avoiding areas that had been burned recently or that showed atypical soil features. We also recorded the presence of ceramic fragments on the soil surface, since the presence of

[2] We use the term ‘non-anthropogenic soils’ to refer to soils lacking ceramic fragments and the dark superficial anthropic horizon characteristic of ADE, but these areas may also show subtler signs of anthropogenic modification in the soil (e.g., surface charcoal) due to previous cultivation.

archaeological artefacts is often associated with the 'typical' nutrient-enriched ADE (Glaser and Birk 2012). Soil samples were taken to the Soil and Plant Thematic Laboratory at INPA, where they were air-dried, cleaned of roots and sieved through a 2-mm mesh. Samples were analysed for textural parameters (percentage of sand, silt and clay), organic matter content and chemical properties [pH in H2O, available phosphorous (P), exchangeable calcium (Ca), magnesium (Mg), potassium (K) and aluminium (Al), and total iron (Fe), zinc (Zn), and manganese (Mn)]. All soil analyses were performed according to the methodology used by EMBRAPA (2011).

Management and biophysical data

In all swiddens we visited we conducted semi-structured interviews *in situ* with the farmer that owned the field; when necessary, interviews were later complemented by *ex situ* interviews with the farmers and other members of the household. Interviews were focused on the previous use of the swidden and on its current management (the full list and description of variables is shown in Table 3.1). We measured the size of each swidden and its distance to the farmer's house using a GPS device.

In order to assess the diversity and the assemblage of crop species and crop landraces[3] cultivated in each swidden, we conducted floristic inventories. During these inventories, which were always done with the participation of the farmer and/or other members of his/her family, we recorded all crop landraces cultivated in the swidden (including annual, biannual and perennial crops) based on the farmers' nomenclature for the landraces. Names that were very similar (e.g., 'common avocado' and 'avocado'), or that obviously referred to the same morphological landrace (e.g., 'ingá-de-metro' and 'ingá-de-macaco' are two different names for the same landrace of *Inga edulis* Mart.) were later grouped under the same landrace name. For each landrace sampled we established a correspondence to a scientific name at the species level, and when identification in the field was not possible the landrace was photographed and/or collected for later identification at INPA's herbarium. Data from floristic inventories were used to calculate the richness of crop species and landraces, the density of species and landraces (i.e., richness *per* area) and to build a species (or landraces) *vs.* swiddens presence-absence matrix that was further used for ordinations of the crop assemblages (Table 3.1).

[3] We use the definition of landrace proposed by Villa et al. (2005): 'a landrace is a dynamic population(s) of a cultivated plant that has historical origin, distinct identity and lacks formal crop improvement, as well as often being genetically diverse, locally adapted and associated with traditional farming systems'.

Table 3.1. Description of the variables used to characterize cultivation strategies in 114 plots sampled in 7 communities along the middle and lower Madeira River, Central Amazonia, Brazil.

Variable		Unit	Description
Predictors			
	PCA1 and PCA2	multivariate	Axes summarizing the variation in soil chemistry and texture, respectively, based on values of Ca, P, Mg, Mn, Zn, K, Fe, Al, pH (H_2O), organic matter and % of silt, clay and sand.
Dependent variables			
	Plot size	m^2	Size of plot, measured with GPS
	Distance	m	Distance of a plot to the house of the owner in a straight line
	Number of previous cycles	unit	Number of previous swidden-fallow cycles in the area before opening the current plot
	Length of the previous fallow	years	Length ("age") of fallow that was cleared to establish the current plot
	Cycle length	days	Average length of the cultivation cycle in the current plot
	Weeding requirements	#weeding/month	Number of times the area needs to be weeded before harvesting the crop
	Species richness	#species	Number of crop species (annuals, trees and all) cultivated in a plot
	Landrace richness	#landraces	Number of crop landraces (manioc, annuals, trees and all) cultivated in a plot
	Species density	#species/area	Number of crop species (annuals, trees and all) cultivated in a plot divided by plot area
	Landrace density	#landraces/area	Number of crop landraces (manioc, annuals, trees and all) cultivated in a plot divided by plot area
	Species composition	multivariate	Composition (presence/absence) of crop species (annuals, trees and all) cultivated in a plot
	Landrace composition	multivariate	Composition (presence/absence) of crop landraces (manioc, annuals, trees and all) cultivated in a plot

[1] For our definition of landrace see section 'Management and biophysical data', footnote 3.

Data analysis

Results of the soil analyses were analyzed using a Principal Components Analysis (PCA). Prior to ordination, soil variables with skewed distributions were log-transformed ($\log_e$), data in percentages (% of clay and sand) were transformed by the arcsine of their square root, and all soil variables were centred and standardized. PCA was done to summarize the variation in soil properties, i.e., to reduce the dimensionality of the multivariate soil data; since the first two axes of the PCA explained a large part (68.4 %) of the variation in soil data (Figure 3.1), the scores of each swidden on these two axes were used as predictors in further analyses. As we are interested in the whole gradient in soil properties between ADE and adjacent soils, we do not use the binary classification ADE/non-anthropogenic soils in our analyses. We do, however, present descriptive results separately for swiddens with and without ceramic fragments (and we represent these categories in Figure 3.1) to highlight the differences between this binary classification and our gradient approach.

In order to test the effects of soil on swidden characteristics we used mixed effect models, using village as a random factor (to take into account the nested sampling design, with several plots sampled within the same village), the scores of the PCA1 and PCA2 axes as fixed factors (i.e., predictors), and the different variables measured for the swiddens as dependent variables (Table 3.1). All dependent variables that had skewed distributions were log-transformed. The model selection process was done according to the protocol proposed by Zuur et al. (2009). For each analysis, we calculated the 'marginal' and 'conditional' R^2 (R^2_m and R^2_c, i.e., the proportion of the variance explained, respectively, by the fixed components and by the whole model, including the random and fixed components, following Nakagawa and Schielzeth (2013) and Johnson (2014)).

To test the effects of soil on the composition (or 'assemblages') of crop species and landraces, we used an indirect gradient analysis, normally used in community ecology (ter Braak et al. 2004). Because of the large difference in the number of individuals per plot between species (i.e., species like maize or manioc are normally present in thousands, while others like banana and most trees are present in dozens, at most), we considered only the presence-absence of each species/landrace in the swiddens. First, the presence-absence composition matrix (species/landraces vs. swiddens) was used to calculate the floristic similarity between every pair of plots, based on the Sørensen similarity index. We then used an ordination technique [Principal Coordinates Analysis (PCoA)] to reduce the dimensionality of the composition dataset, producing a subset of linear descriptors (ordination axes) that best summarized the variation in the composition of species/landraces. The scores of each plot along these ordination axes were then used as dependent variables in mixed effect models, using the same protocol described above for other characteristics of the plots. Separate PCoA were run for manioc landraces, annual/biannual species and landraces, perennial species and landraces, and for all crops together (species and landraces). In order to visualize the distribution of species and landraces along the soil gradients, we plotted the occurrence of each species/landrace against the swiddens ordered by their scores in each ordination axis. PCAs were performed using the software CANOCO5 (ter Braak and Šmilauer 2012) and PCoAs and mixed effects models were run with *R* with the packages *vegan* (Oksanen et al.

2013), *lme4* (Bates et al. 2014) and *MuMIn* (Barton 2013).

Results

Variation in soil properties

Soil chemical and physical characteristics varied substantially among the swiddens sampled. The first and second axes of the PCA explained 55.1% and 13.3% of the variation in the soil data, respectively. Soil variables that were most positively correlated with PCA1 were Ca, pH, Mg, Mn, Zn and P, while Al and Fe were most negatively correlated with PCA1 (Figure 3.1). The variable most positively correlated with the PCA2 was the percentage of sand, while those most negatively correlated with PCA2 were percentage of clay and organic matter content. Swiddens with ceramic fragments were in general more fertile and formed a more heterogeneous group than those without ceramic fragments (Figure 3.1; Table 3.2). Despite this general tendency, there is no clear threshold between these groups in the PCA (Figure 3.1), and they show high standard deviations (SD) for nearly all soil variables analyzed (Table 3.2).

Axis PCA1 represents a gradient in soil fertility between non-anthropogenic soils and ADE, ranging from low-fertile, acidic Ferralsols (left of Figure 3.1) to the fertile and more heterogeneous anthropogenic soils with ceramic fragments (right of Figure 3.1). Axis PCA2 represents a gradient in soil texture and organic matter, ranging from clayey soils with higher organic matter content (bottom of Figure 3.1) to sandier soils with lower organic matter content (top of Figure 3.1); this axis, however, is not associated with a gradient between ADE and non-anthropogenic soils, since swiddens with high or low fertility (or with/without ceramic fragments) occur along the whole range of axis PCA2 (Figure 3.1).

The diversity of cultivation strategies

The swiddens sampled showed very large variability in all characteristics analyzed. The large diversity of cultivation strategies employed by the farmers is reflected in the large standard deviations (SD) and ranges for all variables measured (Table 3.3). Swiddens are in general opened from areas that have been used for cultivation before and have been regenerating for about nine years; however, these parameters show wide variability, ranging from areas that have been used many times in the past and/or opened from very young fallows to mature forests that have never been used for cultivation in farmers' living memory. The length of the cultivation period is on average 323 days, ranging from ~90 days (for short-cycle crops such as watermelon or maize) to ~2 years (for some manioc landraces). During this period, swiddens require on average one weeding every 105 days, although some require much more intensive labor. When compared with swiddens without ceramic fragments, swiddens with ceramic fragments showed lower average values for plot size, distance, previous fallow age and cycle length, and higher average values for the number of previous cycles and weeding requirements. The standard deviation was larger in swiddens without ceramic fragments for the variables plot size, distance and previous fallow age, and it was larger in those with ceramics for the variables cycle length and weeding requirements (Table 3.3).

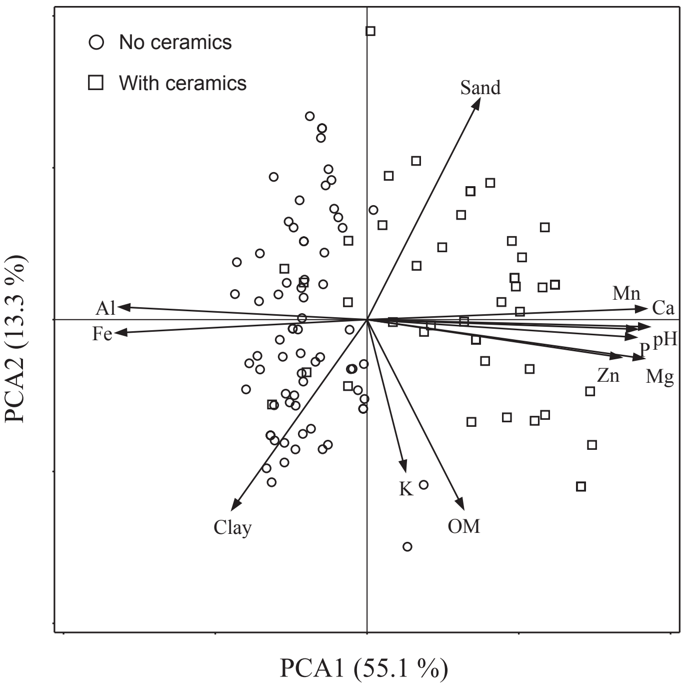

Figure 3.1. Principal Components Analysis biplot with the soil characteristics of 114 swiddens comprising non-anthropogenic and anthropogenic soils along the middle and lower Madeira River, Central Amazonia, Brazil. Numbers in parenthesis show the percentage of the variation in soil properties explained by each axis. The direction and length of the arrows indicate the direction and magnitude in which each variable contributes to the configuration of the points, respectively. The angle between each arrow and the axes is inversely proportional to the correlation between each variable and the axes constructed in the ordination.

Swiddens are cultivated with an average of 3.6 species and 6.1 landraces, although they are also quite variable, ranging from monocrop / mono-landrace swiddens to very diverse swiddens cultivated with up to 29 landraces. Average numbers for species richness were higher in swiddens with ceramic fragments for annuals, perennials and for all species together (Table 3.3). At the landrace level, swiddens with ceramic fragments showed higher average landrace richness values for annuals and perennials, while swiddens without ceramics showed higher values for manioc landraces and for all landraces together (Table 3.3). The full list of species and landraces found in swiddens and their relative frequencies are shown in Chapter 6, Table A6.1.

Table 3.2. Results of chemical and texture analyses of soil samples collected in 114 swiddens along the gradient between non-anthropogenic and anthropogenic soils along the middle and lower Madeira River, Central Amazonia, Brazil. Numbers are average (± standard deviation) and range (minimum – maximum) values for swiddens where no ceramic fragments were found and where ceramic fragments were found (more likely to be anthropogenic soils). Numbers in parenthesis indicate the number of swiddens in each category.

Variable[1]	Unit	No ceramics (70)						With ceramics (44)					
		Avg	±	SD	Min	-	Max	Avg	±	SD	Min	-	Max
pH (H_20)		4.25	±	0.44	3.63	-	6.06	5.34	±	0.60	4.08	-	6.51
Ca	cmolc.kg^{-1}	0.38	±	0.47	0.03	-	2.70	4.06	±	2.99	0.10	-	10.28
Mg	cmolc.kg^{-1}	0.17	±	0.15	0.07	-	1.15	0.78	±	0.50	0.08	-	1.76
Al	cmolc.kg^{-1}	3.06	±	1.55	0.05	-	7.30	0.94	±	1.23	0.00	-	3.95
K	cmolc.kg^{-1}	0.11	±	0.04	0.04	-	0.25	0.12	±	0.08	0.03	-	0.41
P	mg.kg^{-1}	8.35	±	5.08	1.51	-	27.35	89.68	±	147.27	4.04	-	580.02
Fe	mg.kg^{-1}	222.3	±	79.3	80.3	-	528.9	93.8	±	69.8	3.6	-	313.3
Zn	mg.kg^{-1}	0.73	±	0.55	0.10	-	4.10	4.31	±	5.44	0.10	-	29.00
Mn	mg.kg^{-1}	3.45	±	3.54	1.00	-	27.30	29.20	±	18.98	1.00	-	73.30
OM	g.kg^{-1}	36.1	±	10.3	16.2	-	70.1	39.2	±	15.0	15.2	-	89.0
Sand	%	28.8	±	16.1	2.0	-	65.0	15.5	±	10.8	2.0	-	44.0
Silt[2]	%	36.6	±	19.1	4.2	-	82.5	37.5	±	16.4	1.7	-	81.3
Clay	%	34.6	±	20.9	2.5	-	86.0	47.0	±	17.7	0.7	-	80.4

[1] pH (in water), calcium (Ca), magnesium (Mg), aluminum (Al), potassium (K), phosphorous (P), iron (Fe), zinc (Zn), manganese (Mn), organic matter content (OM) and percentages of sand, silt and clay.
[2] The percentage of silt was not used in the analyses.

Table 3.3. Variation in the characteristics of the 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. Numbers are average (± standard deviation) and range (minimum – maximum) values for swiddens where no ceramic fragments were found and where ceramic fragments were found (more likely to be anthropogenic soils). Numbers in parenthesis indicate the number of swiddens in each category.

Variable	Unit	No ceramics (70)						With ceramics (44)					
		Avg	±	SD	Min	-	Max	Avg	±	SD	Min	-	Max
Plot size	m^2	5245	±	4101	900	-	20204	2989	±	2945	102	-	13694
Distance	m	882	±	1084	26	-	7948	492	±	654	41	-	2382
Number of previous cycles[1,2]	unit	3.3	±	2.4	0.0	-	10.0	7.7	±	2.5	2.0	-	10.0
Previous fallow age[1]	years	11.5	±	13.5	1.0	-	50.0	4.4	±	4.2	1.0	-	20.0
Cycle length	days	361	±	84	180	-	686	254	±	129	90	-	638
Weeding requirements	#/month	0.21	±	0.08	0.08	-	0.46	0.44	±	0.19	0.15	-	0.86
Species richness	#												
Annual species		1.49	±	1.76	0	-	7	2.14	±	1.76	0	-	8
Perennial species		0.61	±	1.58	0	-	8	1.34	±	1.85	0	-	7
All species		3.29	±	3.00	1	-	16	4.20	±	2.85	1	-	11
Landrace[3] richness	#												
Manioc landraces		3.74	±	2.34	0	-	9	1.34	±	1.45	0	-	6
Annual landraces[4]		2.10	±	2.74	0	-	12	2.48	±	2.15	0	-	9
Perennial landraces		0.77	±	2.10	0	-	11	1.39	±	1.93	0	-	7
All landraces		6.61	±	5.09	1	-	29	5.20	±	3.34	1	-	12

[1]Areas that have never been used for cultivation before (i.e., that have been opened from mature forests) have been given the value 0 for the variable *Number of previous cycles* and the value 50 for the variable *Previous fallow age.*
[2] Areas that have been used 10 or more times in the past have been given the value 10.
[3] For our definition of landrace see section 'Management and biophysical data', footnote 3.
[4] Does not include manioc landraces.

The effect of soil variation on cultivation strategies

Soil effects on swidden characteristics and diversity

The soil gradient between ADE and non-anthropogenic soils is associated with changes in most swidden characteristics we analyzed. Soil fertility (PCA1) was significantly correlated with most of the variables measured (Table 3.4; Figures 3.2, 3.3). Soil fertility was negatively correlated with plot size and distance, showing that swiddens on more fertile soils tend to be closer to the houses (Figure 3.3a) and smaller (Figure 3.2e). Fertility was positively correlated with the number of previous cycles (Figure 3.2c) and negatively correlated with the age of the fallow (Figure 3.2a), showing that swiddens on more fertile soils tend to be opened from younger fallows and in areas that have been used more often in the past. Soil fertility was also negatively correlated with the length of the cultivation period (Figure 3.3c), indicating that fertile soils are preferred for the cultivation of species/landraces with shorter cycles. Finally, fertility was positively correlated with weeding requirements (Figure 3.3e), showing that swiddens on fertile soils require more weeding to be maintained. The variation in soil texture (PCA2) was not significantly correlated to any of the variables mentioned above (Table 3.4).

The number of species and landraces cultivated in the swiddens, in general, was not influenced by soil fertility, although swiddens on more fertile soils tended to be cultivated with fewer manioc landraces (Table 3.4; Figure A3.1g). PCA2 was positively related to the number of annual species (Figure A3.2d) and landraces (Figure A3.1d), as well as to the number of perennial species (Figure A3.2f) and landraces (Figure A3.1f), indicating that these species and landraces tend to be cultivated more often on sandier soils. When the area of the swiddens was taken into account (i.e., dividing richness by the area of the swiddens), the models had better fits (indicated by higher values of R^2; Table 3.4) and soil fertility was positively related to the density of annual species (Figure A3.4c) and landraces (Figure A3.3c), to the density of all species (Figure A3.4a) and landraces (Figure A3.3a), and to the density of manioc landraces (Figure A3.3g); PCA2 was positively related to the density of annual species (Figure A3.4d) and landraces (Figure A3.3d; Table 3.4). These results show that swiddens in more fertile soils tend to have a higher density of landraces and species, particularly of annual/biannual crops.

Soil effects on the assemblage of crop and landraces

The ordinations of the crop assemblage (PCoAs) explained between 7.1 and 29.8% of the variation in the dataset, depending on the level (species or landraces) and the group considered (manioc, annuals, perennials or all species/landraces; Table 3.5). Since the assemblage of landraces is more heterogeneous than the species assemblage, the percentages of the variation explained by the ordination axes (i.e., PCoA1 and PCoA2) were lower at the landrace level than those at the species level (Table 3.5).

The gradient between ADE and adjacent soils – especially the fertility gradient – was associated with changes in the assemblages of crop species and landraces (Table 3.5). The first axis of the ordination of the composition of manioc landraces (PCoA1) was significantly influenced by the variation in soil fertility (PCA1), but the very low value of R^2_m as compared with R^2_c indicates that most of the variation in the assemblage of manioc landraces is due to differences between villages (Table 3.5). The composition of annual crops, both at the species and landrace level, was significantly influenced by soil fertility (Table 3.5). There were also significant effects of soil fertility on the composition of perennial species and landraces (Table 3.5). When all landraces were analyzed together, the landrace composition (axis PCoA2) was significantly influenced only by PCA2, although with very low R^2_c (Table 3.5). At the species level, the overall species assemblage (both PCoA1 and PCoA2) was significantly influenced by soil fertility but not by soil texture (Table 3.5).

The occurrence of manioc landraces, annual species and perennial species varied along the gradient of soil fertility (PCA1) and texture (PCA2) (Figures A3.5, A3.6, A3.7). For manioc landraces, the 'sweet' landraces (i.e., those with low cyanide content that can be consumed without elaborate processing) tend to occur more often in swiddens on more fertile soils (Figure A3.5, left). For annual/biannual species (Figure A3.6) and for perennial species (Figure A3.7), the change in species assemblage along the soil fertility gradient can be more clearly visualized, reflecting the stronger effects identified in the mixed effect models (Table 3.5). Annual species like *Nicotiana tabacum* L., *Zea mays* L. and *Cucurbita moschata* Duchesne are associated with more fertile soils, while others like *Musa* x *paradisiaca* L. and *Capsicum chinense* Jacq. occur along the whole soil gradient; bitter manioc also occurs in a wide soil fertility range, but it occurs less frequently in swiddens in more fertile soils (Figure A3.6). Perennial species like *Carica papaya* L., *Citrus* spp. and *Theobroma cacao* L. are associated with more fertile soils, while others such as *Anacardium occidentale* L. and the palm *Oenocarpus minor* Mart. occur in swiddens in low-fertility soils. Similar patterns can also be visualized at the landrace level, both for annual/biannual landraces (Figure A3.8) and for perennial landraces (Figure A3.9).

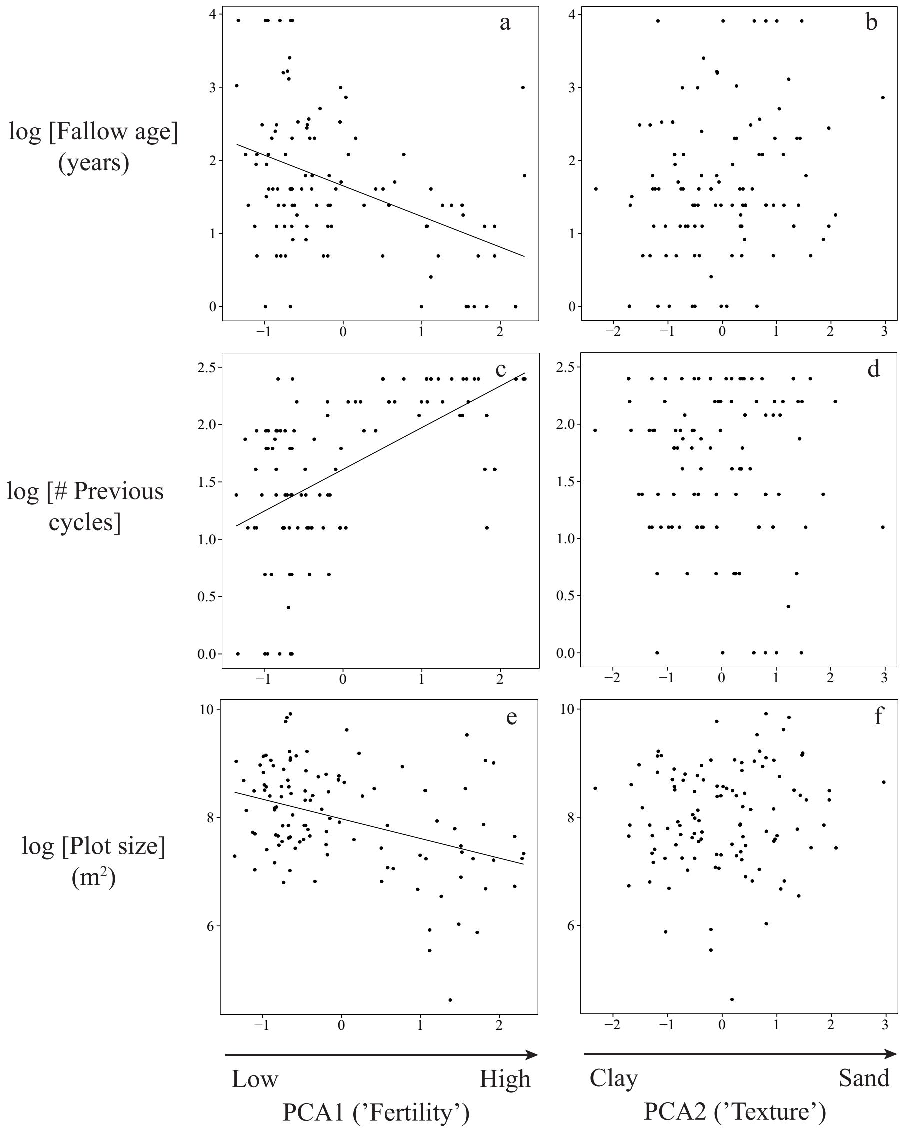

Figure 3.2. Effects of soil fertility and texture on the characteristics of 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. The x axes represent the variation in soil fertility and texture, summarized by the first two axes of a Principal Components Analysis (PCA1 and PCA2). All dependent variables are log-transformed. Lines represent the linear fit of mixed effect models (Table 3.4).

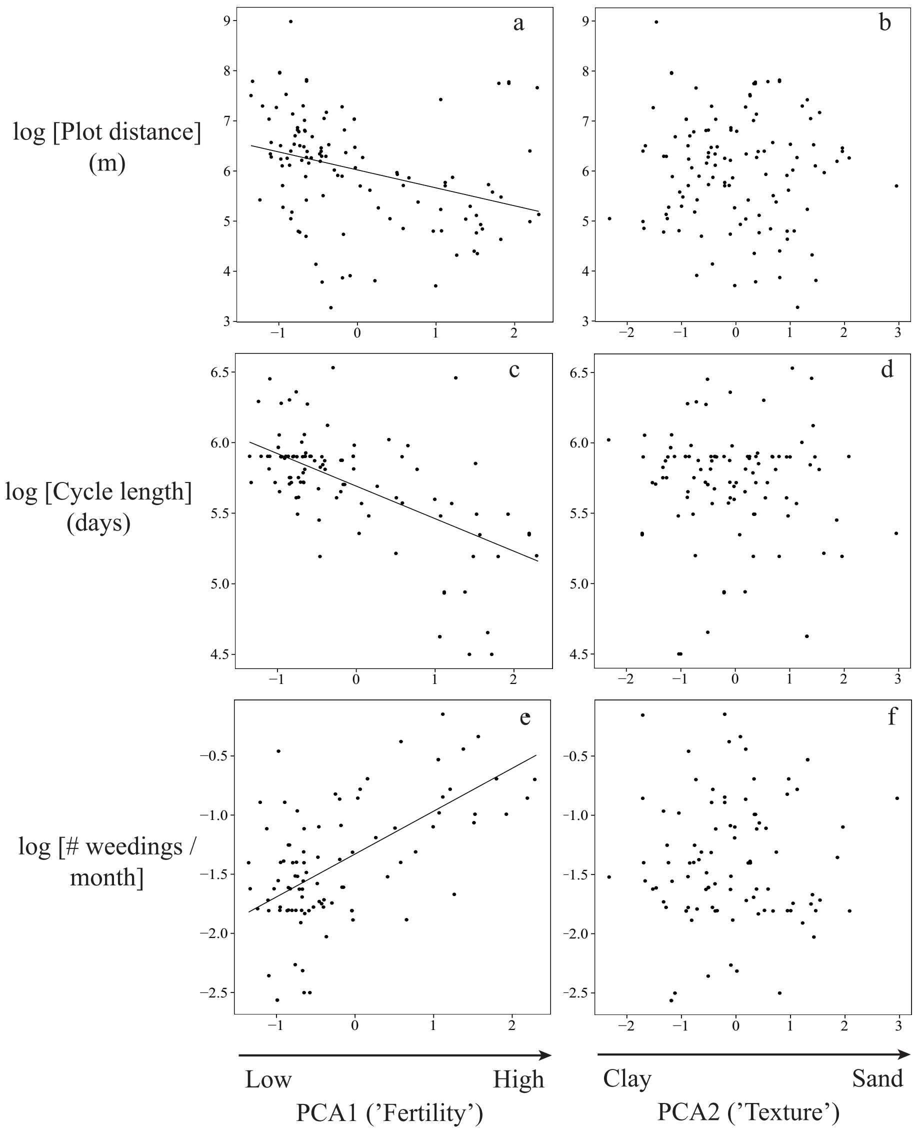

Figure 3.3. Effects of soil fertility and texture on the characteristics of 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. The x-axes represent the variation in soil fertility and texture, summarized by the first two axes of a Principal Components Analysis (PCA1 and PCA2). All dependent variables are log-transformed. Lines represent the linear fit of mixed effect models (Table 3.4).

Table 3.4. Summary of the effects of soil properties on swidden characteristics. PCA1 (fertility) and PCA2 (texture) refer to the two main axes of the Principal Components Analysis of soil data (cf. Figure 3.1). Values in columns PCA1, PCA2 and PCA1*PCA2 are the standardized coefficients of these predictors and of their interaction in linear mixed effect models, and asterisks indicate their statistical significance (*p ≤ 0.05; **p ≤ 0.01; ***p ≤ 0.001). Values of marginal ($R^2_{(m)}$) and conditional ($R^2_{(c)}$) R^2 indicate the proportion of the variance explained by the fixed predictors of the model, and the fit of the whole model with fixed and random factors, respectively (Nakagawa and Schielzeth 2013). Column 'Model type' refers to the structure of the random component of the model (with varying intercept (I) or with varying intercept and slope (I+S)), obtained using the model selection procedure suggested by Zuur et al. (2012).

Dependent variable		N	PCA1	PCA2	PCA1* PCA2	$R^2_{(m)}$	$R^2_{(c)}$	Model type
#Previous cycles		108	**0.56*** **	0.00		0.34	0.44	I+S (PCA1)
Fallow age		107	**-0.43*** **	0.17		0.22	0.22	I
Plot size		113	**-0.39*** **	0.05		0.15	0.25	I
Plot distance		114	**-0.33*** **	-0.06		0.10	0.10	I
Cycle length		100	**-0.55*** **	-0.10		0.35	0.47	I+S (PCA1)
Weeding requirements		94	**0.62*** **	0.15		0.37	0.50	I
# Landraces	Manioc	96	**-0.32** **	-0.19		0.13	0.26	I
	Annuals	76	-0.08	**0.35** **	**-0.27***	0.16	0.33	I
	Trees	37	-0.24	**0.45** **	**-0.34***	0.32	0.32	I
	All	113	-0.04	-0.14		0.02	0.13	I+S (PCA1)
# Species	Annuals	76	0.08	**0.37** **		0.13	0.29	I
	Trees	37	-0.15	**0.46** **	**-0.32***	0.28	0.28	I
	All	113	0.27	0.02		0.08	0.22	I+S (PCA1)
# Landraces / area	Manioc	96	**0.20***	-0.13	**0.21***	0.07	0.37	I
	Annuals	76	**0.39*** **	**0.23***		0.19	0.33	I
	Trees	36	0.19	0.16		0.05	0.26	I
	All	112	**0.23***	-0.09		0.06	0.23	I
# Species / area	Annuals	76	**0.44*** **	**0.23***		0.23	0.36	I
	Trees	36	0.25	0.15		0.07	0.28	I
	All	112	**0.45*** **	0.01		0.20	0.31	I

[1] For our definition of landrace see section 'Management and biophysical data', footnote 3.
[2] Does not include manioc landraces.

Table 3.5. Summary of the effects of soil properties on swidden crop composition. PCA1 (fertility) and PCA2 (texture) refer to the two main axes of the Principal Components Analysis of soil data (cf. Figure 3.1). PCoA1 and PCoA2 refer to the two main axes of Principal Coordinates Analysis, constructed from a presence/absence matrix (swiddens vs. species/landraces) based on the Sørensen similarity index; column '%' refers to the proportion of the variation in species/landrace composition that is explained by each PCoA axis. Values in columns PCA1, PCA2 and PCA1*PCA2 are the standardized coefficients of these predictors and of their interaction in linear mixed effect models, and asterisks indicate their statistical significance (*p ≤ 0.05; **p ≤ 0.01; ***p ≤ 0.001). Values of marginal ($R^2_{(m)}$) and conditional ($R^2_{(c)}$) R^2 indicate the proportion of the variance explained by the fixed predictors of the model, and the fit of the whole model with fixed and random factors, respectively (Nakagawa and Schielzeth 2013). Column 'Model type' refers to the structure of the random component of the model (with varying intercept (I) or with varying intercept and slope (I+S)), obtained using the model selection procedure suggested by Zuur et al. (2012).

Dependent variable		N	PCoA axis	%	PCA1	PCA2	PCA1* PCA2	$R^2_{(m)}$	$R^2_{(c)}$	Model type
Landrace[1] composition										
	Manioc	96	PCoA1	11.4	**0.09***	0.09		0.01	0.88	I
			PCoA2	10.5	0.03	-0.05		0.00	0.50	I
	Annuals[2]	76	PCoA1	15.3	**-0.41*****	0.10		0.17	0.25	I
			PCoA2	13.4	**-0.49*****	-0.16		0.24	0.39	I
	Perennials	37	PCoA1	13.9	**-0.41***	0.16		0.19	0.27	I
			PCoA2	12.0	**-0.44****	0.03		0.20	0.37	I
	All	113	PCoA1	7.8	-0.01	0.04		0.00	0.58	I+S (PCA1)
			PCoA2	7.1	0.00	**0.08***		0.01	0.82	I+S (PCA1)
Species composition										
	Annuals	109	PCoA1	29.8	**-0.62*****	-0.06		0.38	0.59	I
			PCoA2	15.6	0.22	0.02		0.06	0.06	I+S (PCA1)
	Perennials	37	PCoA1	17.3	-0.05	-0.01		0.00	0.30	I
			PCoA2	14.7	**-0.38***	0.18		0.17	0.27	I
	All	113	PCoA1	26.5	**-0.65*****	-0.07		0.42	0.62	I
			PCoA2	12.3	**-0.33***	-0.01		0.13	0.13	I+S (PCA1)

[1] For our definition of landrace see section 'Management and biophysical data', footnote 3.
[2] Does not include manioc landraces.

Discussion

The heterogeneity of soils and cultivation strategies

It has long been established that anthropogenic soils are more fertile than adjacent non-anthropogenic soils (e.g. (Sombroek 1966, Smith 1980). Despite the recognition of the wide variability in soil properties within and between ADE patches (Glaser and Birk 2012), most often these soils are treated as discrete soil categories. Our results show that the categorization ADE/non-ADE (in our case, based on the presence/absence of ceramic fragments) is indeed associated with contrasts in soil fertility, but it is insufficient to represent the soil heterogeneity found in upland swiddens. Instead, this heterogeneity is better represented by considering the whole soil gradient, as suggested by Fraser et al. (2011c), also because a clearly discrete categorization doesn't fit well into farmers' understanding of soils (Chapter 2). When developing and adapting their cultivation strategies, farmers may take into account the variation in soils at very fine scales (Brouwer et al. 1993, Tittonell et al. 2005b, Chikuvire et al. 2007). Hence, we argue that to better understand the relationships between soils and local cultivation strategies, detailed soil variation needs to be taken into account.

Our results also highlight the ample variation in cultivation strategies used by local farmers. Even on poor upland soils, there is considerable heterogeneity in all swidden characteristics we analyzed, including the age of the fallow cleared to establish the swidden, swidden size, distance, number of previous cycles, cycle length, weeding requirements, richness of species and landraces and crop assemblage. This large variation reflects the heterogeneity in cultivation and livelihood strategies used by 'traditional' farmers in Amazonia (Coomes et al. 2000, Caviglia-Harris and Sills 2005, Oestreicher et al. 2014), which may deviate from what is considered 'ideal' but suits their immediate needs, opportunities and constraints. We show that this variation, which occurs even within relatively homogeneous upland soils, is amplified and shaped by the occurrence of patches of anthropogenic soils created in pre-Columbian times. Our results draw attention to the need to consider long-term anthropogenic impacts in the landscapes to better understand the diversity in smallholder cultivation and resource management in Amazonia.

The effects of soil on the dynamics of cultivation

The variation in soil fertility between ADE and adjacent soils is associated with differences in most characteristics of the swiddens and of the shifting cultivation cycle. Swiddens on more fertile soils tend to be opened from younger fallows, and in areas that have been used for more cultivation cycles in the past. Previous studies have shown that swiddens on ADE are opened from younger fallows when compared with adjacent non-anthropogenic soils (German 2004, Fraser et al. 2011b). Our results show that this association occurs continuously along the soil gradient, i.e., the more fertile the soil the younger the fallow cleared to establish the swidden. In shifting cultivation, the fallow has the goal to both restore soil fertility (depleted during the cropping phase due to crop nutrient export and leaching) and to control weeds (Nye and Greenland 1960, de Rouw 1995, Hölscher et al. 1997, Smith et al. 1999, Szott et al. 1999). Farmers along the middle and lower Madeira River associate older fallows with higher yields and lower weeding requirements, but they refer to this relationship as being much more important on 'non-anthropogenic' soils than on ADE: the latter is always associated with high yields and high weeding requirements (Chapter 2). The fact that ADE allow shorter fallow periods without compromising yields is likely due to (1) the higher nutrient content in these soils, so that nutrient depletion during cultivation has a smaller effect on them as compared with poorer soils, and (2) to the higher cation exchange capacity of ADE, which reduces nutrient losses by leaching and also allows them to recover faster (Glaser and Birk 2012). Despite these advantages, farmers report cases in which ADE have been exhausted and fallows degraded due to intensive cultivation with no (or very short) fallow periods (data not shown). These results indicate, in a broader sense, that enhanced soil fertility allows more intensive cultivation by smallholder farmers in Amazonia, but proper management is still crucial to prevent soil and fallow degradation.

Patches of anthropogenic soils are in general located on river bluffs (Denevan 1996), which is also where many of the present-day villages are located. This explains why swiddens on more fertile soils tend to be located closer to farmers' houses, although we have also registered situations in which farmers were willing to travel further to cultivate more nutrient demanding crops in more fertile soils. The relative ease of access of ADE patches as compared to adjacent soils is also a foremost reason for the higher frequency of use of these areas in the past.

The strongest effects of soil fertility on swidden characteristics were on cycle length and weeding requirements. ADE is associated with strong weed proliferation, with a different composition of vigorously-growing species (Major et al. 2003, Major et al. 2005b). The perception of the high weeding requirements on ADE is widespread among farmers along the Madeira River and is a central element in their rationales and decision-making in shifting cultivation (Chapter 2). Weeding is done with machetes and/or hoes, and according to farmers is one of the most laborious activities during the shifting cultivation cycle. We have shown that the gradient in soil fertility between ADE and adjacent soils is associated with a gradient in weeding requirements, with more fertile soils requiring almost twice as much weeding as low-fertility soils. These high weeding requirements on ADE are due not only to soil fertility itself, but also to the shorter fallow periods on more fertile soils, both of which can favor the increase and persistence of the weed seed bank (Major et al. 2003, Major et al. 2005b). The high weeding requirements on ADE also relates to the fact that swiddens on more fertile soils tend to be smaller and the cropping cycles tend to be shorter: planting smaller fields and growing species or landraces with shorter cycles is an appropriate strategy to deal with the high weeding requirements of the more fertile soils. These findings echo the patterns found by Fraser et al. (2011b), and Fraser et al. (2012) where short-cycle annual crops are cultivated more often on ADE, including short-cycle bitter manioc landraces.

Taken together, our results show that the soil fertility gradient between non-anthropogenic soils and ADE is positively associated with more intensified cultivation, with the same area being used more frequently, but on the other hand requiring higher labor investments to be maintained. Moreover, the continuous variation we observed in all plot characteristics along the soil fertility gradient shows that farmers perceive and make use of environmental heterogeneity, fine-tuning their cultivation systems to the specific soil conditions of each of their plots. Despite the fact that farmers' decisions rely on numerous biophysical and social factors, we show that soil heterogeneity – particularly soil fertility – plays an important role in the dynamics of smallholder agriculture in Amazonia.

The effects of soil on crop diversity and community composition

The number of species and landraces cultivated in the plots is related to the variation in soil fertility and texture, but the significance and magnitude of this association depends on the group of landraces or species considered (i.e., manioc, annuals, perennials or all species/landraces together). Our results show that plots on more fertile soils tend to be cultivated with fewer manioc landraces. Manioc is the most important staple crop cultivated by farmers along the middle and lower Madeira (and in many other regions in Amazonia), both for subsistence and for commerce (Murrieta and Dufour 2004). Most manioc landraces are well adapted to the poor soils that predominate in the uplands, but farmers also cultivate specific landraces, with specific ecological adaptations (fast growth, low starch content) on the fertile floodplains and on ADE (Fraser et al. 2012). We show that plots on more fertile soils tend to be cultivated with fewer landraces, probably because (1) when cultivating manioc in poor soils, farmers often combine fast-maturing landraces with slow-maturing landraces, resulting in a higher landrace richness, and also because (2) bitter manioc (which corresponds to most manioc landraces along the Madeira River) is cultivated less often on fertile soils (Figures A3.5, A3.6). However, when we evaluated species/landraces density (i.e., number of species/landraces *per* area), we found that plots on more fertile soils had a higher density of manioc landraces, of annual species and landraces, and a higher overall density of species and landraces. In short, these results show that the diversity of species and landraces cultivated on more fertile soils was equivalent or higher than on low-fertility soils. Although agricultural intensification is generally associated with (agro-)biodiversity loss (Matson et al. 1997, Vandermeer et al. 1998, Jackson et al. 2007, Tscharntke et al. 2012), these smallholder cultivation systems on ADE provide useful examples of synergies between intensification and agrobiodiversity conservation.

Overall, the crop assemblages cultivated in swiddens were influenced by soil fertility, with little effect of soil texture, and the effects were stronger at the species level than at the landrace level. The gradient in soil properties – mainly soil fertility – was associated with changes in crop assemblages of manioc landraces, annuals (species and landraces), perennials (species and landraces) and of the whole species assemblage. The effect of soil fertility and texture on the assemblage of manioc landraces was significant but weak, as most of the variation in the assemblage of manioc landraces was due to differences between villages. Fraser et al. (2012) found clear differences in the composition of manioc landraces between non-anthropogenic soils, ADE and floodplains. The differences between our results and those of Fraser et al. (2012) are likely due to differences in our methodological approach and sampling design: (1) we sampled a larger geographical area than Fraser et al. but less intensively (i.e., fewer swiddens per village), and the differences in manioc landrace composition between villages were much larger than that within villages; (2) while we used presence/absence data, Fraser et al. also used abundance data (i.e., the number of individuals of each landrace cultivated in the swidden), which tends to amplify the differences in assemblages; (3) while our sampling design purposely incorporated transitional soils along the gradient between ADE and non-anthropogenic soils, Fraser et al. considered these as separate categories and focused on the 'typical' ADE with 'very dark brown or black coloring, high fertility and pottery shards' (Fraser et al. 2012). Still, our results show that manioc landraces that were associated with more fertile soils were mostly 'sweet landraces' (i.e., those with low toxicity that can be readily consumed without processing into flour), while bitter landraces were associated with poor soils. The domestication of manioc (some 9,000 years ago) likely occurred in fertile dump-heaps around habitation sites, where initial human selection pressures selected for sweet varieties, and in a later stage bitter varieties better adapted to low-fertility soils appeared (Arroyo-Kalin 2010). Although farmers have also selected bitter landraces well adapted to the fertile floodplains and anthropogenic soils (Fraser et al. 2012), the association between sweet landraces and fertile soils that we observed in modern swiddens reflects the history of the domestication of the crop.

We also found significant effects of soil fertility on the assemblages of annual species and their landraces and on the assemblages of perennial species and their landraces. For annual crops, we found a clear association between soil fertility and nutrient-demanding crops, such as melon, cucumber, tobacco and maize, species that on the uplands along the Madeira River are found almost exclusively on ADE. Among trees, those that were associated with high-fertility soils included species that have been shown to regenerate spontaneously on ADE, such as papaya and *Spondias mombin* (Clement et al. 2003, Junqueira et al. 2010b), as well as nutrient-demanding species and landraces of *Citrus* and cacao. The clearest and strongest effects of soil fertility on the crop assemblage were observed when all species were analyzed together. Our results show that, despite an overall effect of soil fertility on the crop assemblage, different crop species and landraces occur predominantly in different parts of the soil gradient, reflecting their adaptation to the soil through farmers' management. As a result, the overall diversity of the agroecosystem at the landscape level is enhanced by soil heterogeneity.

From the local use of ADE to a wider understanding of the effect of soil fertility on smallholder agriculture

Apart from providing a more detailed and integrated view of cultivation systems on ADE, our results have implications for the broader understanding of the relationships between soil heterogeneity and smallholder cultivation strategies in Amazonia and beyond. It has long been recognized, from ethnographic research, that indigenous groups in Amazonia use different soil types to cultivate different crops (Eden 1974, Hames 1983, Stocks 1983, Behrens 1989). More recently, studies in land-use dynamics have shown that soil quality is an important driver of trajectories of land use and deforestation in colonization frontiers (Moran et al. 2000, Moran et al. 2002, Soler et al. 2009, Castro and Singer 2012). In indigenous shifting cultivation systems, López and Sierra (2011) show that riverine areas in Ecuadorian Amazonia are used more intensively than interfluvial areas where soils are poorer. Nonetheless, our study is the first to look in detail into the effects of soil heterogeneity on 'traditional' smallholder cultivation systems in Amazonia, providing empirical evidence that farmers adjust crop assemblages and the intensity of cultivation according to soil fertility at the plot level. These results highlight the need to consider farmers' use of soil heterogeneity to improve our understanding of smallholder cultivation systems in Amazonia and to plan more effective interventions aiming to foster their agroecological and social relevance.

Conclusion

Our study shows that the presence of ADE increases soil heterogeneity in Amazonian uplands, increasing farmers' opportunities for both intensification and diversification. The more fertile part of the soil gradient between non-anthropogenic soils and ADE was associated with more intensive cultivation, with shorter fallow periods, higher frequency of cultivation, shorter cycles and higher labor requirements. Despite their more intensive cultivation, these fertile soils were cultivated with a diverse and distinct assemblage of crop species and landraces. Current smallholder farming systems along soil gradients between ADE and non-anthropogenic soils are examples that soil fertility can favor synergies between intensification and diversification.

Acknowledgements

We are truly grateful to the residents of the villages along the middle and lower Madeira for their invaluable help, support and friendliness. We thank the Institute for Sustainable

Agriculture and Forestry Development of Amazonas State (Instituto de Desenvolvimento Agropecuário e Florestal Sustentável do Estado do Amazonas), the Chico Mendes Institute for Biodiversity Conservation (Instituto Chico Mendes para a Conservação da Biodiversidade) and the Brazilian International Institute of Education (Instituto Internacional de Educação do Brasil) for logistical support. This research was authorized by the Brazilian National Research Ethics Commission (Comissão Nacional de Ética em Pesquisa, CAAE#011488712.3.0000.0006, Auth.#231.032). Research authorization for villages inside conservation units (Água Azul – Rio Amapá Sustainable Development Reserve, and São Félix do Aripuanã – Juma Sustainable Development Reserve) was obtained from the Amazonas State Centre for Conservation Units (Centro Estadual de Unidades de Conservação, Proc.#1017/2012).

Appendix 3

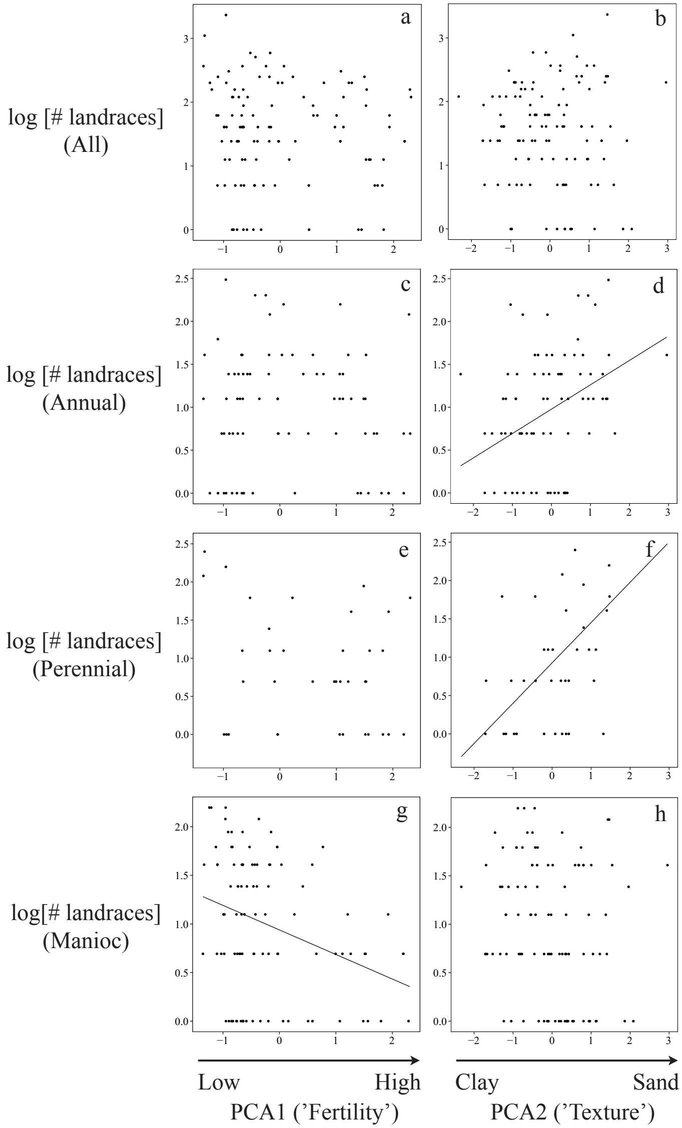

Figure A3.1. Effects of soil fertility (left) and texture (right) on the richness of crop landraces cultivated in 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. The x axes represent the variation in soil fertility and texture, summarized by the first two axes of a Principal Components Analysis (PCA1 and PCA2), and the y axes represent the number of all landraces present in the swidden (a, b), the number of annual landraces (c, d), the number of perennial landraces (e, f) and the number of manioc landraces (g, h). Lines represent the linear fit of mixed effect models (Table 3.4). For our definition of landrace see section 'Management and biophysical data', footnote 3.

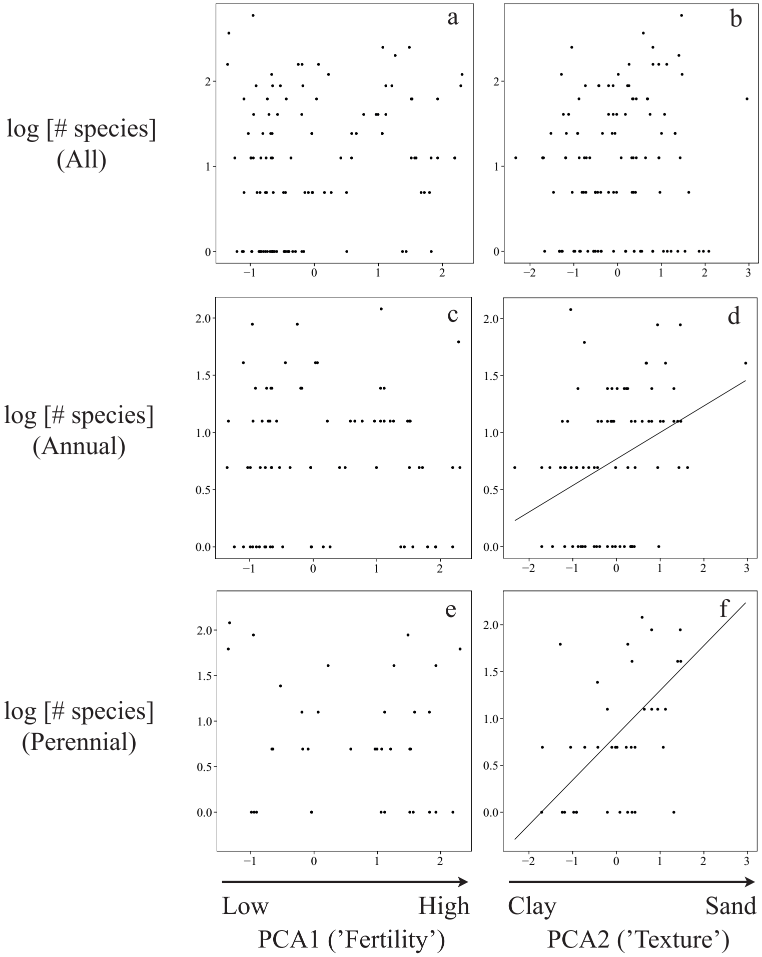

Figure A3.2. Effects of soil fertility and texture on the richness of crop species cultivated in 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. The x axes represent the variation in soil fertility and texture, summarized by the first two axes of a Principal Components Analysis (PCA1 and PCA2), and the y axes represent the number of all species present in the swidden (a, b), the number of annual species (c, d) and the number of perennial species (e, f). Lines represent the linear fit of mixed effect models (Table 3.4).

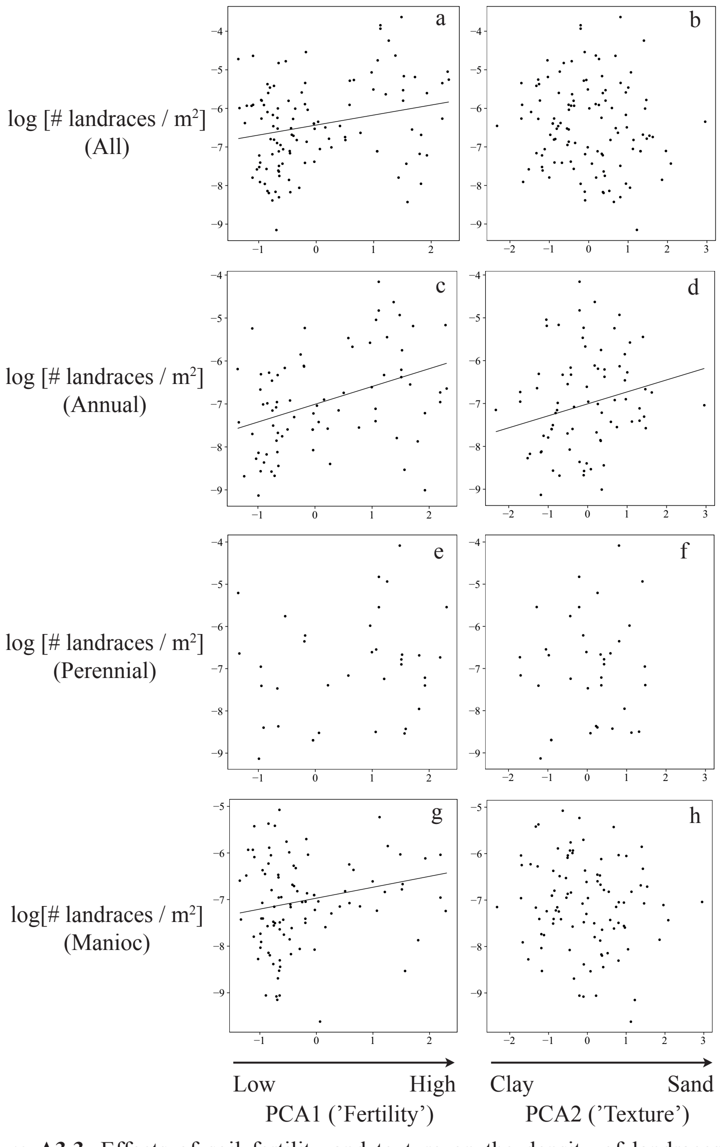

Figure A3.3. Effects of soil fertility and texture on the density of landraces (#landraces per area) cultivated in 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. The x axes represent the variation in soil fertility and texture, summarized by the first two axes of a Principal Components Analysis (PCA1 and PCA2), and the y axes represent the density of all landraces present in the swidden (a, b), the density of annual landraces (c, d), the density of perennial landraces (e, f) and the density of manioc landraces (g, h). Lines represent the linear fit of mixed effect models (Table 3.4). For our definition of landrace see section 'Management and biophysical data', footnote 3.

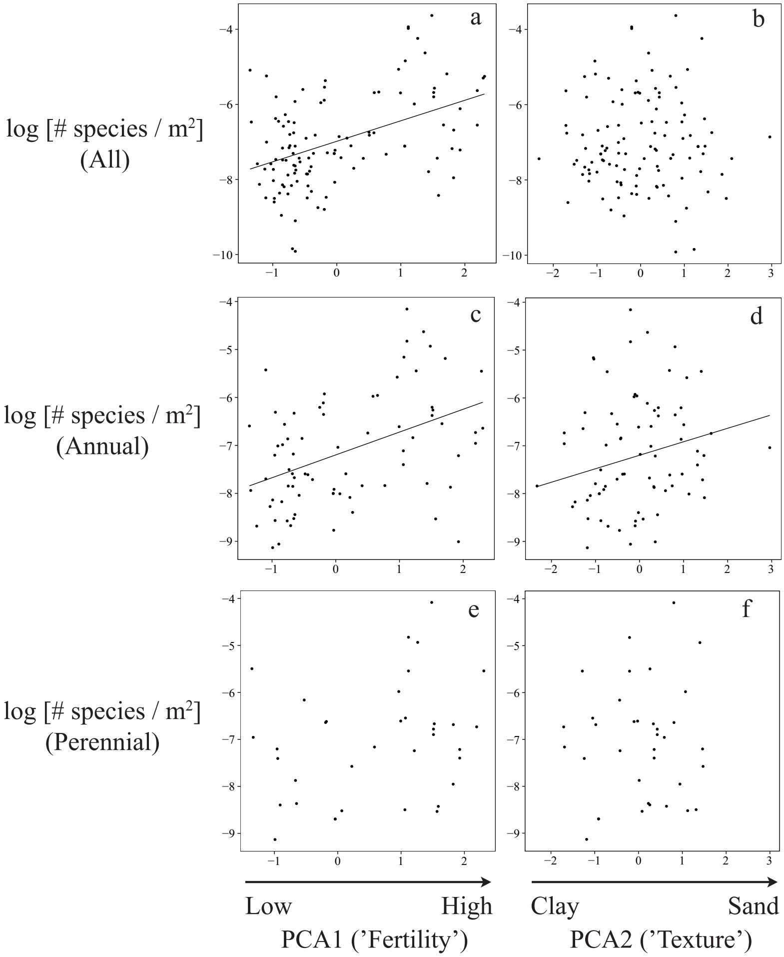

Figure A3.4. Effects of soil fertility and texture on the density of species (#species per area) cultivated in 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. The x axes represent the variation in soil fertility and texture, summarized by the first two axes of a Principal Components Analysis (PCA1 and PCA2), and the y axes represent the density of all species present in the swidden (a, b), the density of annual species (c, d) and the density of perennial species (e, f). Lines represent the linear fit of mixed effect models (Table 3.4).

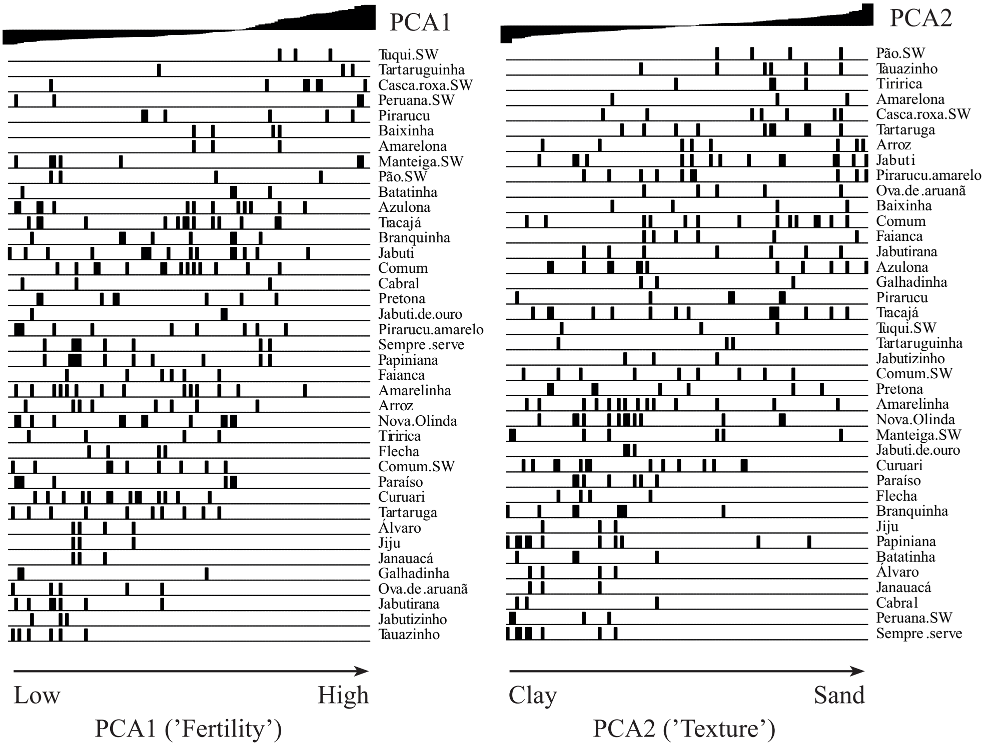

Figure A3.5. Distribution of manioc landraces along gradients of soil fertility (left) and texture (right) in 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. Plots are ordered from left to right according to their scores along the axes PCA1 (left) and PCA2 (right). Each vertical bar represents the occurrence of a given landrace (lines) in a given plot (columns). Sweet manioc landraces are indicated with 'SW'. Only landraces that occurred in three or more swiddens are shown.

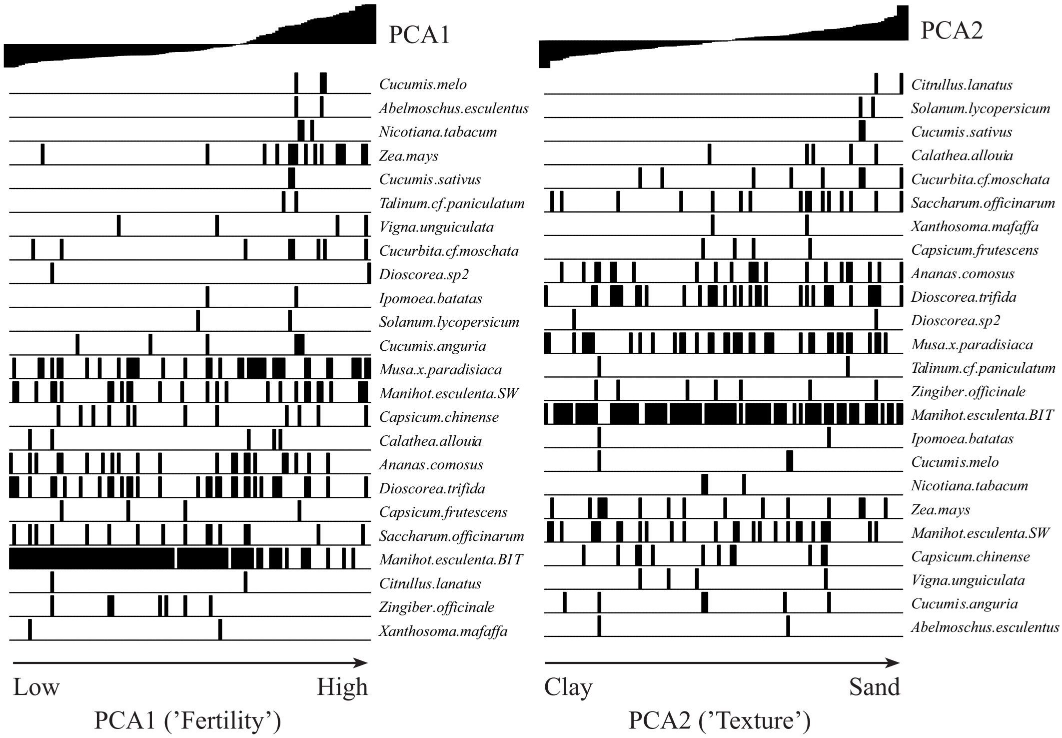

Figure A3.6. Distribution of annual/biannual species along gradients of soil fertility (left) and texture (right) in 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. Plots are ordered from left to right according to their scores along the axes PCA1 (left) and PCA2 (right). Each vertical bar represents the occurrence of a given species (lines) in a given plot (columns). Manioc (*Manihot esculenta* Crantz) was separated into bitter (BIT) and sweet (SW) landraces. Only species that occurred in two or more swiddens are shown.

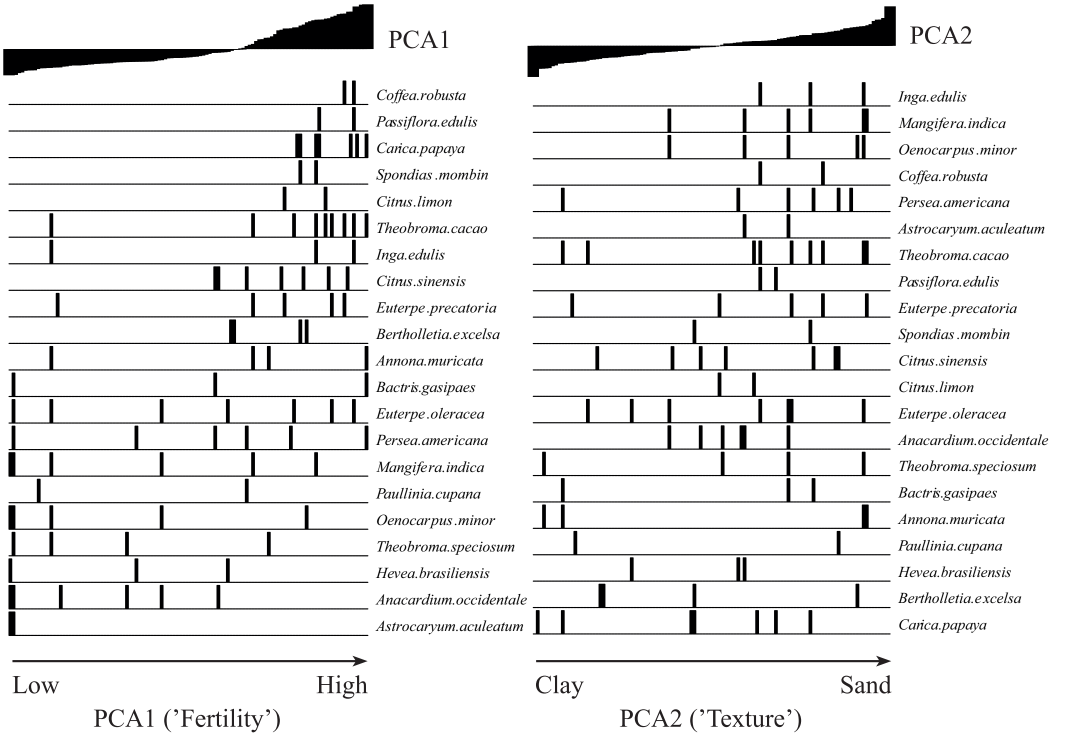

Figure A3.7. Distribution of perennial species along gradients of soil fertility (left) and texture (right) in 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. Plots are ordered from left to right according to their scores along the axes PCA1 (left) and PCA2 (right). Each vertical bar represents the occurrence of a given landrace (lines) in a given plot (columns).Only species that occurred in two or more swiddens are shown.

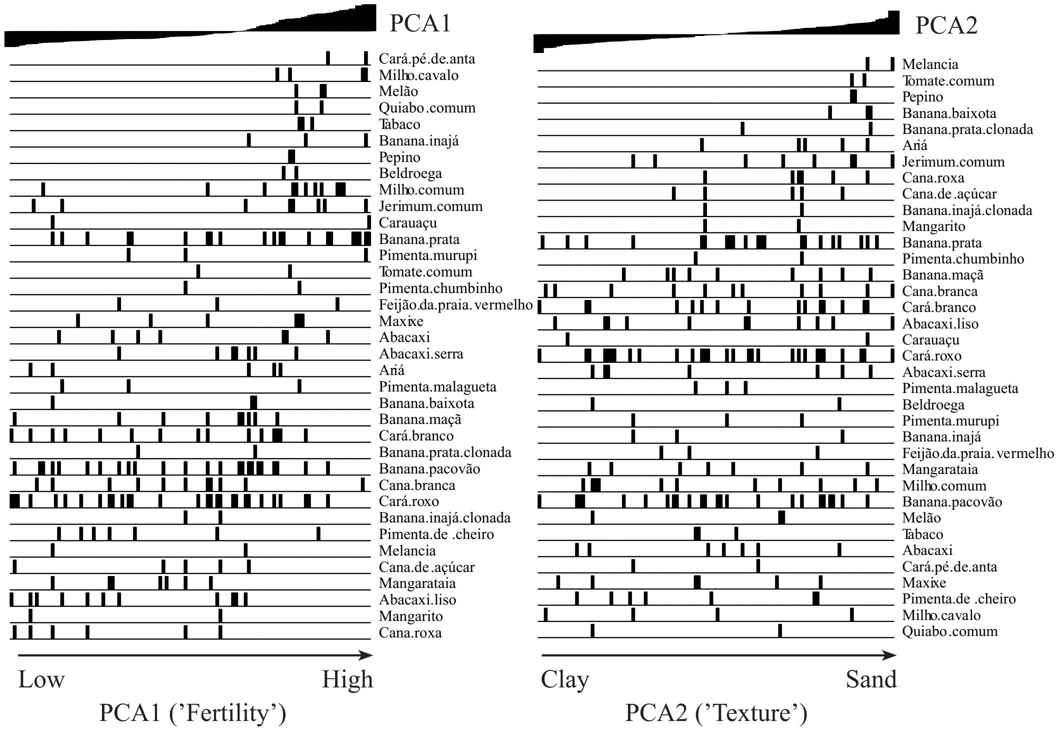

Figure A3.8. Distribution of annual/biannual landraces along gradients of soil fertility (left) and texture (right) in 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. Plots are ordered from left to right according to their scores along the axes PCA1 (left) and PCA2 (right). Each vertical bar represents the occurrence of a given landrace (lines) in a given plot (columns). Manioc (*Manihot esculenta* Crantz) landraces are not shown. Only landraces that occurred in two or more swiddens are shown. For our definition of landrace see section 'Management and biophysical data'.

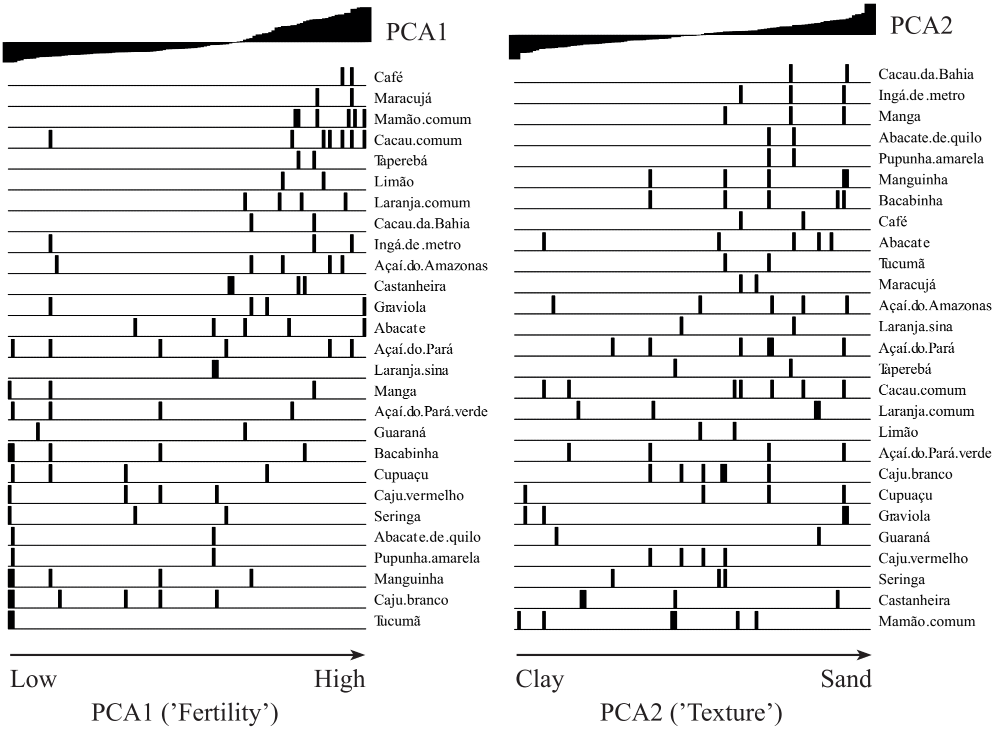

Figure A3.9. Distribution perennial landraces along gradients of soil fertility (left) and texture (right) in 114 swiddens sampled along the middle and lower Madeira River, Central Amazonia, Brazil. Plots are ordered from left to right according to their scores along the axes PCA1 (left) and PCA2 (right). Each vertical bar represents the occurrence of a given landrace (lines) in a given plot (columns). Only landraces that occurred in two or more swiddens are shown. For our definition of landrace see section 'Management and biophysical data'.

Chapter 4

Soil fertility gradients shape the agrobiodiversity of Amazonian homegardens

André Braga Junqueira, Nathalia Bezerra de Souza, Tjeerd Jan Stomph, Cornelia J. M. Almekinders, Charles R. Clement, Paul C. Struik

(submitted)

Abstract

The importance of homegardens for the conservation of agrobiodiversity, the maintenance of farm ecosystem processes, and the economic and food security of rural populations worldwide is increasingly recognized. While biophysical and socio-economic conditions are considered to influence homegarden management, and affect their ecological and societal relevance, little is known about how variation in soil properties affects these agroecosystems. By combining soil data with extensive botanical inventories, we investigated how variation in soil fertility and texture influence the structure, diversity and the floristic composition of homegardens in Central Amazonia. We sampled 70 homegardens located along the gradient from low-fertility Ferralsols to Amazonian Dark Earths (ADE), i.e., fertile anthropogenic soils created by pre-Columbian populations at least 500 years ago. Our results show that several characteristics of homegardens are significantly influenced by variation in soil texture and fertility. While differences in soil texture are due to natural soil variation, observed heterogeneity in soil fertility was largely the result of centuries-old and modern pre-Columbian soil transformations. Homegardens on sandier soils tended to be more diverse in plant species and to have more individual plants; homegardens on more fertile soils tended to have fewer trees and palms, more herbs, shrubs and climbers, and a higher total number of species and landraces; variation in soil fertility significantly influenced the composition of species and landraces. Our results show that agrobiodiversity patterns in homegardens are significantly influenced by both natural and anthropogenic variation in soil properties. Pre-Columbian and modern soil enrichment increases soil heterogeneity in the landscape, resulting in strong soil fertility gradients that shape the agrobiodiversity of current Amazonian homegardens.

Keywords: Amazonia; Soil heterogeneity; Terra Preta; Amazonian Dark Earths; Agroforestry; Ethnoecology

Introduction

Homegardens are 'intimate, multistory combinations of various trees and crops, sometimes in association with domestic animals, around the homestead' (Nair and Kumar 2006; p. 1). They are important agroecosystems in tropical regions worldwide, providing economic benefits and food security for local people, as well as favoring the on-farm conservation of water, soil and biodiversity (Kumar and Nair 2004). Homegardens are considered agroforestry production systems (Nair 1993, Porro et al. 2012), although "homegarden" is a very generic concept (Kumar and Nair 2004). In the Amazon Basin, homegardens and other agroforestry systems were the first cultivation systems developed by pre-Columbian populations. They are widespread throughout the basin, and play an important role in local people's subsistence and income (Miller and Nair 2006, Miller et al. 2006).

Owing to their complex and long-term historical development, Amazonian homegardens are very diverse and heterogeneous (Miller and Nair 2006), similar to homegardens elsewhere in the world (Kehlenbeck et al. 2007). This diversity also results from an interplay between different socio-cultural and agro-ecological factors that can influence how homegardens and their associated agrobiodiversity are managed (Kumar and Nair 2004, Kehlenbeck et al. 2007, Perrault-Archambault and Coomes 2008, Clarke et al. 2014). Despite the recognition that soil characteristics can play an important role in the design, management and diversity of homegardens and other agroforestry systems (Szott et al. 1991, Kehlenbeck and Maass 2004), the effects of soil variation on homegardens have seldom been investigated [but see Fraser et al. (2011a)].

Soils in the Amazon Basin are highly variable, but a large part of the basin (~60 %) is occupied by acidic, weathered and nutrient-poor ferralsols and acrisols (Quesada et al. 2011). Homegardens on uplands are often established on these poor soils, but management practices such as burning and mulching, as well as the non-intentional concentration of different sources of organic matter in the surroundings of the habitation sites, result in the accumulation of nutrients over time in these environments (WinklerPrins 2009, Pinho et al. 2011). However, many homegardens are found on patches of fertile anthropogenic soils created in pre-Columbian times called Amazonian Dark Earths (ADE), or *Terra Preta* (Glaser and Birk 2012). These pre-Columbian anthropogenic soils were likely formed through soil-enrichment processes similar to those that occur in modern homegardens (Schmidt and Heckenberger 2009, Schmidt et al. 2014), and they add considerable heterogeneity to upland soils where they occur (Fraser et al. 2011c). Farmers have developed specific knowledge and cultivation practices for the use of ADE, and today these soils are part of different land-use systems, including swiddens under shifting cultivation (German 2003b, 2004, Kawa et al. 2011, Fraser et al. 2012; Chapters 2 and 3), secondary forests (Junqueira et al. 2010b, Junqueira et al. 2011), and homegardens (Hiraoka et al. 2003, Major et al. 2005a, Klüppel 2006, Fraser et al. 2011a, Kawa et al. 2015).

Homegardens are one of the most common types of land use on ADE, since current habitation sites (and their surrounding homegardens) are commonly situated on ADE patches (Hiraoka et al. 2003, Fraser et al. 2011a). When compared with homegardens on nutrient-poor adjacent soils, homegardens on ADE show distinct crop assemblages and a greater importance of exotic species (Major et al. 2005a, Klüppel 2006, Fraser et al. 2011a). These studies, however, considered ADE and adjacent soils as discrete soil categories, although each of these categories may encompass ample soil heterogeneity – especially ADE, as these soils result from complex cultural processes (Neves et al. 2003, Fraser et al. 2011c). Since farmers 'fine-tune' the management and crop assemblages of their cultivation systems to the specific soil conditions of each plot (Chapters 2 and 3), looking at the whole range of soil heterogeneity among ADE and adjacent soils instead of categorizing them allows a thorough understanding of the effects of soil diversity components on homegarden agrobiodiversity patterns.

In this article we investigate the effect of soil variation on the agrobiodiversity of homegardens in Central Amazonian uplands. In contrast to previous studies, our sampling strategy took into account the entire soil fertility and texture gradient among ADE and adjacent upland soils where homegardens are found. Moreover, we performed extensive in-situ inventories of species and landraces cultivated in homegardens, including both cultivated and spontaneous plants. This provides a broader and more detailed understanding of how ADE may influence homegarden agrobiodiversity in Amazonia and, in a wider sense, of the role of natural and anthropogenic soil variation in tropical homegardens and other agroforestry systems. Such knowledge is relevant for understanding the impacts of pre-Columbian and more recent soil transformation on current Amazonian agrobiodiversity. We hypothesize that the variation in soil properties among ADE and adjacent soils is associated with changes in the structure, diversity and plant composition of homegardens.

Methods

Study site

This study was conducted along the middle and lower Madeira River, in Central Amazonia (Chapter 1, Figure 1.1). Mean annual temperatures vary between 27 and 28 °C and annual rainfall varies between 2,600-2,800 mm (Alvares et al. 2013). Most of the land cover in the region is natural vegetation, composed predominantly of evergreen forests on uplands and flooded forests on floodplains (Rapp Py-Daniel 2007). In the uplands, soils are mostly ferralsols, although acrisols, lixisols and podzols also occur; the floodplains of the Madeira River are located on gleysols (IBGE 2010).

Archaeological evidence suggests that human occupations in the middle and lower Madeira date back to more than 7,000 years ago, but more sizable population expansions and substantial formation of anthropogenic soils reached their peak only around the year 1,000 AD (Moraes and Neves 2012). Today, patches of anthropogenic soil ranging from <2 to more than 50 ha in size are commonly found in the region, usually on bluffs along the main river, tributaries and lakes (Fraser et al. 2011b, Moraes and Neves 2012, Levis et al. 2014). Many of these patches are located under present villages or small cities.

The current population in the region is composed mostly of a heterogeneous mixture of local indigenous people and migrants who came to the region – especially from northeastern Brazil –during the 'rubber boom' in the late 19th and early 20th centuries (Adams et al. 2009). The population of the three municipalities where we focused our study (Borba, Novo Aripuanã and Manicoré; Chapter 1, Figure 1.1) is ~103,000 inhabitants, approximately half of whom live in the urban centers and the other half is distributed in villages in the rural areas (IBGE 2011). The local rural population has historically relied on fishing, hunting, agriculture, and on the gathering of forest products [e.g., rubber *Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg., Brazil nut *Bertholletia excelsa* Bonpl.] for subsistence and economic activities. Agriculture is practiced mainly in shifting cultivation systems and is focused on manioc (*Manihot esculenta* Crantz), the most important staple and economic crop. Other economically important crops produced in the region include banana (*Musa paradisiaca* L.), cacao (*Theobroma cacao* L.) and watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai] (Chapters 2 and 3).

Homegardens are found surrounding the houses in every village in the region, and also often in urban areas. These agroecosystems are of great cultural importance to local residents, where many social interactions take place, and are prized for their aesthetic and symbolic value as much as for utilitarian or economic purposes. Homegardens provide a wide range of plants used for many different purposes (firewood, construction, shade, fibers, pigments, medicines, ritual/magic plants, spices, fruits, etc.), and are also where domestic animals are raised (chickens, pigs, ducks, etc.). Homegardens in the region are very heterogeneous, but they typically include an open area around the house, which is kept weeded and swept, surrounded by a more shaded 'agroforest-like' environment, where most trees are found, resulting in a complex vertical structure. The share of the subsistence and economic products that are produced in homegardens is also highly variable among households, but as a rule homegardens are only one component of a wider farming system, in which most of the staple food and economic crops are produced in swiddens farther from the houses in shifting cultivation systems.

Sampling design

We selected seven villages along a stretch of approximately 400 km, located on the margins of the Madeira River or its tributaries (Chapter 1, Figure 1.1). Selected villages were located partially or entirely on patches of anthropogenic soils, and were not subjected to river floods. In each village, we selected between 6 and 13 homegardens (total 70 homegardens), so that they comprised the largest possible variation in soil color and density of ceramic fragments within the village (Chapter 1, Figure 1.1). ADE patches are consistently associated with concentrations of ceramic fragments in the soil (Neves et al. 2003). Although our sampling strategy and analytical approach focused on the whole soil gradient between ADE and adjacent soils, we considered the presence/absence and the density of ceramic fragments on the soil surface as an indicator of the degree of pre-Columbian influence on the soil.

In each homegarden, together with at least one of the homegarden owners, we conducted a detailed floristic inventory and collected other biophysical and management data. First, we asked the owners how long ago the homegarden had been established. Then we measured the approximate extent of the homegarden as determined by the owners, and within this perimeter we inventoried all individual plants that were either planted or favored (i.e., those that grew spontaneously but that were kept by the owners). Common species were identified with botanical species names in the field, and when species were unknown they were photographed and/or collected for further identification at the National Institute of Amazonian Research (INPA) herbarium. For each plant, we also asked the owners the local name of the plant (hereafter landrace[1]). At a later stage, names that referred to the same morphological landrace were grouped under the same landrace name. We also visually estimated the height of each plant, and we classified them according to the degree of direct exposure to sunlight (hereafter called 'shading index'): 1 – more than 75% of the plant exposed; 2 – from 75 to 50%; 3 – from 50 to 25% and 4 – less than 25% exposed.

We also collected soil samples in each homegarden. Within the homegarden perimeter we collected five subsamples, sampled from 0-20 cm depth, which were then mixed in a composite sample. Subsample-sites were spread across the whole homegarden, avoiding atypical soil features (e.g., areas that had recently been burned, ant nests, etc.). During the collection of soil samples and also during the floristic inventory, we recorded the presence/absence and density of ceramic fragments on the soil surface. Based on visual estimations in the field, we categorized homegardens according to the abundance of ceramic fragments on the surface using a scale ranging from 0 to 5: 0 – no ceramic fragments; 1 – very rare (≤ 1 fragment per 16 m^2); 2 – rare (~1 fragment per 9 m^2); 3 – common (~1 fragment per 4 m^2); 4 – abundant (~1 fragment per m^2); 5 – very abundant (>1 fragment per m^2). Visible fragments were eliminated from the soil sample. Soil samples were air-dried, sieved through a 2 mm mesh and taken to INPA's soil laboratory, where they were analyzed for chemical properties (pH in H_2O, available phosphorous, exchangeable calcium, magnesium, potassium, and aluminum, and total manganese, iron and zinc), organic matter content and texture (% of sand, silt and clay) according to the methodology used by EMBRAPA (2011). In order to better understand the spatial variation in soil properties and current processes of soil transformation, we compared (within each village) the soil properties between homegardens and adjacent areas, using a database of 114 soil samples taken in swiddens used for shifting cultivation (Chapter 3).

Data analyses

The soil data were analyzed with a Principal Components Analysis (PCA). Prior to the PCA, soil variables with skewed distributions were log-transformed (apart from soil pH), and data

[1] We use the definition of Villa et al. (2005): 'a landrace is a dynamic population (s) of a cultivated plant that has historical origin, distinct identity and lacks formal crop improvement, as well as often being genetically diverse, locally adapted and associated with traditional farming systems'.

in percentages (silt, sand and clay) were transformed by the arcsine of their square root. Since texture variables are complementary (i.e., they add up to 100%), we included only two of them in the PCA (% sand and % clay). The first and second axes of the PCA were used to summarize the variation in soil fertility and texture, and the PCA scores were used as predictor variables in further analyses.

For each homegarden, we calculated parameters related to structure and diversity. Structural parameters calculated were number of individuals (total and grouped *per* life form: trees + palms and shrubs + herbs + climbers), number of spontaneous individuals, average and standard deviation (SD) of height, and average and SD of shading index (SD values were interpreted as indicators of the heterogeneity of homegarden height and shading). Diversity parameters calculated for each homegarden were number of species and landraces, species and landrace richness rarefied for 40 individuals, and the inverse Simpson Diversity Index for species and landraces. All plants that were cultivated in pots or in raised beds were excluded from the analyses, since the soils used in these pots are often enriched with compost and/or manure, and therefore are not representative of the soils of the homegardens.

Data on floristic composition was analyzed with a Principal Coordinates Analysis (PCoA). First, the homegarden vs. species (or landraces) matrices were used to construct similarity matrices, based on the Chao similarity index (Chao et al. 2005). PCoA was performed based on these similarity matrices, the two first axes of the PCoA were used to summarize the variation in floristic composition, and the PCoA scores were used as dependent variables in further analyses [c.f. 'indirect gradient analysis' (ter Braak et al. 2004)].

In order to test the effects of soil variation in the structure, diversity and floristic composition of homegardens, we used mixed effects models (Zuur et al. 2009), with 'village' as a random factor. Scores of the first two axes of the PCA were used as predictor variables, together with homegarden age and size (in order to account for possible effects of these variables on the parameters analyzed). All structural and diversity parameters, as well as the scores of the ordination of floristic composition (PCoA) were included as dependent variables in separate mixed models. In order to choose the optimum random structure of each model (i.e., with random intercept or with random intercept and slope for each predictor), we used the model selection procedure suggested by Zuur et al. (2009). Since the random slope did not improve significantly any of our models, only random intercepts were used.

Results

Soil chemistry and texture

We observed large variation in soil color and texture in the homegardens we sampled, ranging from very dark to light brown or light yellow, and from very sandy to very clayey soils. In the 70 homegardens sampled, we found ceramic fragments in 41 of them, but we observed great variation in the field regarding the density of ceramic fragments found on the soil surface. Among the 41 homegardens with ceramic fragments, six were classified as with 'very rare' ceramic fragments, eight with 'rare', five with 'common', 12 with 'abundant' and 10 with 'very abundant' ceramic fragments.

Chemical and physical properties of homegarden soils varied substantially (Table A4.1). Homegardens where ceramic fragments were found on the soil surface showed higher values of pH, available P, exchangeable Ca and Mg, total Zn and Mn and organic matter content, while those without ceramic fragments had higher levels of exchangeable Al and total Fe. For soil texture, homegardens with ceramic fragments tended to be slightly sandier (Table A4.1). When compared to soils from adjacent swiddens within the same village, soils from homegardens were more fertile, showing higher average values for most nutrients, especially available phosphorous (Figure 4.1; Table 4.1).

The first two axes of the PCA with soil data explained 70.4% of the variation of soil chemistry and texture. The first axis of the PCA was negatively correlated with exchangeable Fe and Al, and positively correlated with pH, OM and all other chemical variables except exchangeable potassium. The second axis of the PCA was positively correlated with the percentage of sand and negatively correlated with the percentage of clay and potassium (Figure 4.2). In summary, axis PCA1 summarizes the variation in soil fertility (higher values correspond to more fertile soils) and axis PCA2 summarizes the variation in soil texture (higher values correspond to sandier soils); hereafter we call PCA1 the 'fertility axis' and PCA2 the 'texture axis'. Homegardens without ceramic fragments are grouped to the left side of the graph, while those with higher density of ceramic fragments tend to be located towards the right side of the figure (Figure 4.2). This shows that the soil fertility gradient is positively associated with the density of ceramic fragments found in homegarden soils, while there seem to be no clear differences regarding the density of ceramics along the texture gradient.

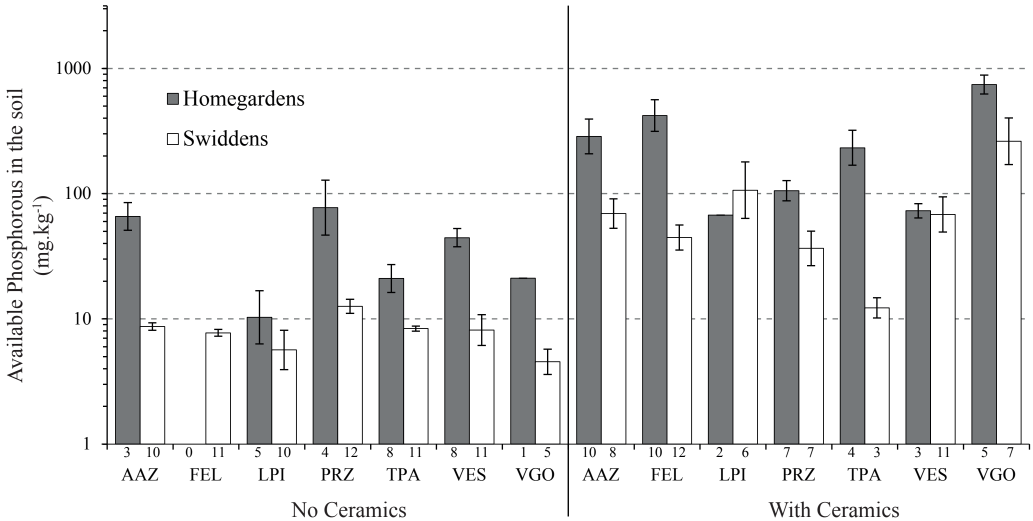

Figure 4.1. Available phosphorous in the soil of 70 homegardens and 114 adjacent swiddens (Chapter 3) sampled along the middle and lower Madeira River, Central Amazonia. Letters and numbers under the bars indicate the 7 different villages where the study was carried out (AAZ – 'Água Azul'; FEL – 'São Félix'; LPI – 'Lago do Piauí'; PRZ – 'Puruzinho'; TPA – 'Terra Preta do Atininga'; VES – 'Vila do Espírito Santo'; VGO – 'Vila Gomes'), and the number of soil samples taken in each village and environment, respectively. Vertical lines indicate standard errors.

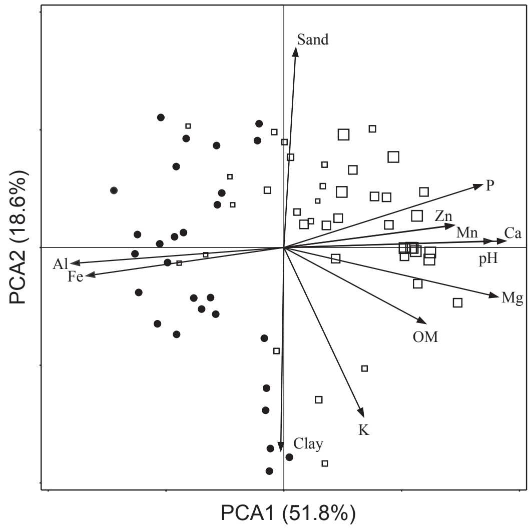

Figure 4.2. Principal Components Analysis (PCA) of soil data obtained in 70 homegardens sampled along the middle and lower Madeira River, Central Amazonia. Variables included in the analysis are macro and microelements [exchangeable Aluminum (Al), Potassium (K), Magnesium (Mg) and Calcium (Ca), total Iron (Fe), Zinc (Zn) and Manganese (Mn) and available Phosphorous (P)], organic matter content (OM) and percentages of sand and clay. Each point in the graph represents a homegarden (n=70). Open squares and closed circles represent homegardens with (n=41) and without ceramic fragments (n=29), respectively, and the size of the squares represent the density of ceramic fragments, visually assessed in the field. Numbers in parentheses indicate the percentage of the total variation in soil data explained by each PCA axis.

Homegarden structure and diversity

The homegardens sampled had been established between 1 and 48 years ago, with an average size of ~2300 m^2 and with considerable variation in most structural parameters analyzed (Table 4.1). In total, we sampled 9157 individual plants, including 4107 trees (44.8%), 1724 palms (18.8%), 1408 shrubs (15.3%), 1719 herbs (18.8%) and 199 lianas/vines (2.2%). Among the 8840 individuals (96.5% of the total) for which we had information on whether they had been planted or grew spontaneously, 2129 (24.1%) were spontaneous individuals that were maintained and/or favored by the owners.

Table 4.1. Characteristics of the homegardens (n=70) sampled in seven villages along the middle and lower Madeira River, Central Amazonia. Average ± standard deviation (Avg±SD) and range (Min-Max) are shown for each variable. For our definition of landrace see section 'Sampling design'.

Variable		Without ceramics (n = 29)	With ceramics (n = 41)	All homegardens (n = 70)
Size (m^2)	Avg±SD	2196 ± 2057	2380 ± 2546	2303 ± 2341
	Min-Max	200 - 9130	336 - 15080	200 - 15080
Age (years)	Avg±SD	16.4 ± 11.3	15.9 ± 10.8	16.1 ± 10.9
	Min-Max	1 - 48	1 - 40	1 - 48
#Individual plants	Avg±SD	112.1 ± 76.2	144.0 ± 104.8	130.8 ± 94.8
	Min-Max	19 - 340	15 - 537	15 - 537
#Spontaneous plants	Avg±SD	20.6 ± 15.4	39.3 ± 51.7	31.8 ± 41.9
	Min-Max	0 - 65	0 - 251	0 - 251
Height (m)	Avg±SD	4.7 ± 1.8	4.1 ± 1.5	4.3 ± 1.6
	Min-Max	0.8 - 7.3	1.2 - 8.0	0.8 - 8.0
Shading index	Avg±SD	1.82 ± 0.50	1.84 ± 0.56	1.83 ± 0.54
	Min-Max	1.20 - 2.75	1.00 - 3.15	1.00 - 3.15
#Landraces	Avg±SD	31.1 ± 14.6	36.6 ± 16.0	34.3 ± 15.5
	Min-Max	12 - 66	5 - 64	5 - 66
#Species	Avg±SD	27.7 ± 13.0	32.7 ± 14.2	30.6 ± 13.9
	Min-Max	12 - 62	5 - 61	5 - 62

The 9157 individuals sampled belonged to 269 species and 378 landraces (the list of species and landraces sampled in homegardens and their relative frequencies are shown in Chapter 6, Table A6.1). Trees were the most diverse group, with 117 species and 152 landraces, followed by herbs (71 species, 100 landraces), shrubs (47 species, 76 landraces), palms (14 species, 21 landraces) and climbers (20 species, 29 landraces). Among tree species, those with most landraces were *Persea americana* Mill. (10), *Mangifera indica* L. (7) and *Anacardium occidentale* L. (5); for herbs, *Musa paradisiaca* L. (20) and *Ananas comosus* (L.)

Merr. (6); for shrubs, *Capsicum chinense* Jacq. (14) and *Manihot esculenta* Crantz (9); for palms, *Bactris gasipaes* Kunth (4), *Euterpe oleracea* Mart. (3) and *Cocos nucifera* L. (3); and for climbers, *Solanum lycopersicum* L. (9) and *Vitis vinifera* L. (2).

The first axes of the Principal Coordinates Analyses (PCoA) explained 13.3% (PCoA1) and 10.6% (PCoA2) of the species composition, and 10.2% (PCoA1) and 9.4% (PCoA2) of the landrace composition (Figure 4.3). The PCoA figures show that homegardens without ceramic fragments tended to be grouped to the right side of the graphs while those with higher densities of ceramic fragments tended to be located towards the lower center (Figure 4.3a, b). Despite the large overlap between points in the figures, these results suggest that the variation in species/landrace composition in homegardens was related to the density of ceramic fragments, which in turn was positively associated with soil fertility (Figure 4.2). The relatively low proportion of the total variation explained by the first two PCoA axes reflects the high heterogeneity and diversity of the species/landrace composition of homegardens, and was also due to the fact that many species/landraces were rare [100 species (37.2%) and 152 landraces (40.2%) occurred in only one homegarden]. Still, these axes summarize the most important changes in species/landrace composition, and allow testing whether these changes were correlated with soil fertility and texture gradients.

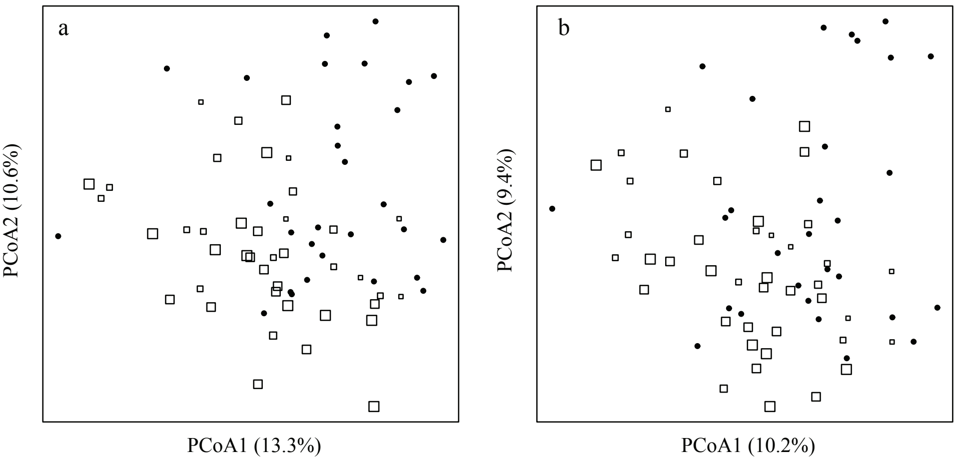

Figure 4.3. Principal Coordinates Analyses (PCoA) of the floristic composition of crop (a) species and (b) landraces sampled in 70 homegardens along the middle and lower Madeira River, Central Amazonia. Each point represents a homegarden, and the distance between them represents their floristic dissimilarity, calculated with the Chao similarity index. Open squares and closed circles show homegardens with (n=41) and without (n=29) ceramic fragments, respectively, and the size of the squares indicates the density of ceramic fragments, visually assessed in the field. Numbers in parentheses show the percentage of the total variation that is explained by each PCoA axis. For our definition of landrace see section ‘Sampling design’, footnote 1.

Effects of soil fertility and texture on the structure, diversity and floristic composition of homegardens

There were significant effects of soil fertility (PCA1) and texture (PCA2) on several of the structural variables analyzed (Table 4.2). Soil fertility did not influence the total number of individuals nor the number of spontaneous individuals, but it was negatively correlated with the number of trees + palms and positively correlated the number of herbs + shrubs + lianas. All other structural variables measured (average and SD height, average and SD shading index) were not influenced by soil fertility. Soil texture (sand content, PCA2) was positively correlated with the total number of individuals, to the number of spontaneous individuals, as well as to the number of trees + palms; the number of herbs + shrubs + lianas was not influenced by soil texture. None of the other structural variables (average and SD height, average and SD shading index) was influenced by soil texture. In short, these results indicate that homegardens on more fertile soils tended to have fewer trees and palms and more herbs, shrubs and lianas, and that homegardens on sandier soils tended to have more trees and palms, more herbs, shrubs and lianas, and a higher total number of plants (Table 4.2).

Regarding the diversity of species and landraces in homegardens, we found a significant positive effect of soil fertility (PCA1) in the total number of species and landraces. However, we found no effects of soil fertility on any other diversity measure (richness rarefied for 40 individuals and Inverse Simpson index; Table 4.2). For soil texture, we found a positive correlation between the texture axis (sand content, PCA2) and all diversity measures we used. In summary, this shows that homegardens on more fertile and sandier soils tended to have more species and landraces, and that homegardens on sandier soils tended to have higher diversity.

We found significant effects of soil fertility (PCA1) on the composition of both species and landraces, and on both PCoA axes summarizing the variation in floristic composition (Table 4.2). The gradient in soil texture (PCA2) significantly influenced only the composition of landraces, and only the axis PCoA2, which explained 9.4% of the total variation in landrace composition (Table 4.2). These results show that part of the variation in the composition of species and landraces was driven by soil variation, especially soil fertility.

Table 4.2. Effects of soil fertility and texture, and homegarden age and size on the structure, diversity and floristic composition of 70 homegardens sampled along the middle and lower Madeira River, Central Amazonia. PCA1 and PCA2 are the two first axes of Principal Components Analysis with soil variables, explaining 51.8% and 18.6% of the original variation in soil data. Values in columns PCA1, PCA2, Age and Size are standardized regression coefficients of these predictors in linear mixed effect models, and asterisks indicate their significance (*$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$). Values of marginal (R^2_m) and conditional (R^2_c) R^2 indicate the proportion of the variance explained by the fixed predictors of the model, and the fit of the whole model, respectively (Nakagawa and Schielzeth, 2013). For our definition of landrace, see section 'Sampling design', footnote 1.

Variable		**N**	**PCA1 ('Fertility)**	**PCA2 ('Texture')**	**Age**	**Size**	**R^2_m**	**R^2_c**
Number of individuals								
	Total	70	0.05	**0.39*****	0.06	**0.60*****	0.56	0.56
	Spontaneous	65	0.04	**0.21***	0.07	**0.56*****	0.38	0.38
	Trees + Palms	70	**-0.16***	**0.31*****	**0.17***	**0.65*****	0.66	0.67
	Herbs + Shrubs + Lianas	68	**0.26***	0.21	-0.16	**0.38****	0.26	0.37
Height								
	Average	58	-0.03	-0.28	0.05	**0.40****	0.23	0.33
	Standard deviation	58	0.03	0.05	0.16	**0.43****	0.27	0.31
Shading index								
	Average	58	0.05	0.04	**0.34***	0.22	0.20	0.22
	Standard deviation	58	0.01	0.10	**0.33***	0.19	0.20	0.28
Species richness								
	Absolute value	70	**0.22***	**0.30****	0.15	**0.52*****	0.49	0.49
	Rarefaction 40 individuals	70	0.10	**0.34****	0.23	0.13	0.23	0.23
	Simpson diversity	70	0.09	**0.26***	0.18	0.14	0.15	0.15
Landrace richness								
	Absolute value	70	**0.19***	**0.33*****	0.11	**0.54*****	0.50	0.51
	Rarefaction 40 individuals	70	0.08	**0.38****	0.19	0.10	0.23	0.23
	Simpson diversity	70	0.11	**0.28***	0.15	0.13	0.14	0.14
Species composition								
	PCoA1 (13.3 %)	70	**-0.39*****	-0.05	**0.30****	**0.28****	0.40	0.43
	PCoA2 (10.6 %)	70	**-0.37*****	-0.10	**-0.27****	-0.08	0.25	0.64
Landrace composition								
	PCoA1 (10.2 %)	70	**-0.38****	-0.06	**0.23***	**0.29***	0.34	0.40
	PCoA2 (9.4 %)	70	**-0.35*****	**-0.23***	**-0.23****	**-0.18***	0.30	0.72

Discussion

Natural and anthropogenic soil variation in homegardens

The homegardens we sampled showed considerable variation in soil properties, especially in soil fertility. Apart from the natural soil variation that occurs between villages, this heterogeneity can be attributed to anthropogenic soil modifications, in both pre-Columbian (i.e., since the patches of ADE were created) and more recent times (i.e., since the villages were founded ~120 years ago). When compared with their surroundings, homegarden soils usually show increased fertility, due to the intentional and non-intentional concentration of organic matter close to the houses (Gajaseni and Gajaseni 1999, Miller and Nair 2006, WinklerPrins 2009, Pinho et al. 2011). This difference tends to become larger but also more heterogeneous with time, given the different histories of individual homegardens (Pinho et al. 2011). The fact that we found consistently higher fertility in homegardens than in adjacent swiddens (Figure 4.1; Table A4.1) suggests that these processes of soil enrichment are currently taking place in the villages we studied, and have likely been occurring since the villages were founded. However, the very large amplitude in the concentration of some nutrients [particularly P, an ubiquitous indicator of past human activity (Holliday and Gartner 2007)], and the strong association between soil fertility and the density of ceramic fragments (Figures 1.1 and 4.2) indicate that a large part of the variation in homegardens soils is due to the centuries-old soil transformations that resulted in the creation of the ADE patches. The overlap between pre-Columbian and 'modern' anthropogenic soil modification results in a complex soil landscape, in which both ADE and surrounding soils are still being transformed.

We found a clear fertility gradient in the soils of the homegardens we sampled, ranging from acidic, Al and Fe-saturated soils to fertile soils with abundant ceramic fragments, higher levels of pH, organic matter and of all other nutrients (except potassium). This continuous variation in soil fertility and in the occurrence/abundance of ceramic fragments, which occurred both within and between villages, shows that there is no clear threshold between 'anthropogenic' and 'non-anthropogenic' soils, but instead gradients in soil properties, as also reported by Fraser et al. (2011c). While the gradient in soil fertility is largely associated with the transition between pre-Columbian ADE and surrounding soils, the variation in soil texture seems to be much more related to natural soil variation, as it is more evenly distributed between soils with different fertility levels and it is not related with the density of ceramic fragments.

All previous studies on the relationships between ADE and agrobiodiversity have addressed these anthropogenic soils as a discrete category (e. g., German 2003b, 2004, Major et al. 2005a, Major et al. 2005b, Klüppel 2006, Junqueira et al. 2010b, Fraser et al. 2011a, Fraser et al. 2011b, Junqueira et al. 2011, Kawa et al. 2011, Fraser et al. 2012, Kawa et al. 2015). Although the 'typical' ADE with abundant ceramic fragments and very dark color may be easily distinguishable from the 'typical' surrounding ferralsols, between these two extremes there is considerable variation in soil properties, especially when different ADE patches in different villages are taken into consideration (see, for example, the large standard deviations within the groups 'with' and 'without ceramics' in Table A4.1, and the lack of a clear threshold between these categories in Figure 4.2). Our results highlight the need to consider soil variation in its entirety in order to provide a comprehensive understanding of the role of anthropogenic soils in the agrobiodiversity of homegardens.

The heterogeneity and diversity of homegardens

Our results show that homegardens along the Madeira River are very heterogeneous in their vegetation structure, diversity and floristic composition. The homegardens we sampled, typically surrounding every house in the villages, ranged from relatively simple and small gardens, with a few individuals and species grown in full sun, to complex multi-strata and multi-species agroforests. While in some homegardens the boundaries (as indicated by the owners) were more easily defined, in many others these environments showed gradual transitions to surrounding forests or cultivation fields. Heterogeneity between homegardens is attributed to the variation in biophysical and socio-cultural factors, and also reflects the different individual preferences and specific needs of their owners (Kumar and Nair 2004). Among these sources of variation, we show here that variation in soil properties – due to natural and/or to anthropogenic processes – is an important element favoring homegarden heterogeneity.

Another remarkable characteristic of the homegardens we sampled is their high species and landrace richness (Chapter 6, Table A6.1). The total number of 269 species in our sample of 70 homegardens is among the highest in homegarden studies worldwide (Kumar and Nair 2004; p. 139), and the second highest found in Amazonian homegardens [after Perrault-Archambault and Coomes (2008), who found 309 species, although with a much larger and ethnically-diverse sample (300 homegardens in 15 villages)]. Also, the number of species we found is substantially higher than that reported by Fraser et al. (2011a), who interviewed 63 farmers in 16 villages in the same region and recorded 85 species. This contrast is probably due to the fact that Fraser et al.'s (2011a) inventories were based on interview data (free listings) and excluded medicinal species, while ours are based on an extensive botanical inventory, including all cultivated plants and also spontaneous individuals that were maintained in the homegarden. The homegardens we sampled also showed considerable diversity at the intra-specific level: farmers recognized different landraces for 33 species (11.7% of the total), and some of the species (such as banana) had as many as 20 landraces, adding up to a total of 378 landraces in our sample. These results provide strong evidence supporting the important role of homegardens for agrobiodiversity conservation, both at the species and at the intraspecific levels.

Effects of size and age on homegarden diversity

Our results show that the structure, diversity and composition of homegardens are influenced – to different extents – by homegarden size and age. It is relatively well known that these characteristics of homegardens can influence their agrobiodiversity patterns (e.g., Kumar and Nair 2004, Kehlenbeck et al. 2007), therefore we incorporated them in our models to account for their possible effects. In general, the patterns we found for the effects of homegarden age and size matched our expectations: we found that larger homegardens tend to have more species [similar to Perrault-Archambault and Coomes (2008)] and more individuals [similar to Albuquerque et al. (2005)], and tend to be taller and more heterogeneous in their vertical structure. Regarding the effects of age, we found that older homegardens tend to have more trees and palms [echoing patterns found by Coomes and Ban (2004), who showed an increase in absolute and relative contribution of fruit trees with garden age], are more shaded (on average) and have more heterogeneous shading. We did not find, however, an effect of age on homegarden diversity, as shown by Coomes and Ban (2004) in the Peruvian Amazon. This may be due to the fact that new homegardens often incorporate some pre-existing plants and thus may start with relatively high diversity, but also because some old homegardens may show low diversity due to individual preferences of its owner. Finally, we found that differences in size and age are associated with changes in the assemblage of species and landraces present in homegardens. These results highlight the need to take into account intrinsic characteristics of homegardens in order to explain how agrobiodiversity patterns correlate to other biophysical and socio-economic variables.

Effects of soil texture and fertility on homegarden diversity

We show that several characteristics of homegardens are influenced by the variation in soil fertility and texture. Although the variation in soil texture was not as large as in fertility, and despite the relatively low explanation of the PCA 'texture' axis as compared with the 'fertility' axis, most of the variables we measured were significantly correlated with soil texture. Overall, homegardens on sandier soils tended to have more individuals, more species, and more spontaneous individuals.

Sandier soils in general have lower water retention capacity than clayey soils (Silver et al. 2000, Luizão et al. 2004), which could restrict the cultivation of drought-intolerant species. However, rainfall is abundant in the region, with an average yearly precipitation of ~2,400 mm, and the driest months (July and August) still receiving ~50 mm per month (INMET 2015). Moreover, homegarden soils are also constantly receiving organic matter inputs (from the disposal of organic residues by the household and from the vegetation cover), which favors the maintenance of higher moisture content in the soil [especially in sandier soils; Lehmann et al. (2003b)].

It is possible that the effects of soil texture are related to differences in successful establishment of crop and volunteer seedlings. Soils with higher clay content may show higher mechanical resistance than sandier soils [depending on interactions between soil water, bulk density and compaction; Smith et al. (1997), Vaz et al. (2011)], which is disadvantageous for root growth (Laboski et al. 1998, Restom and Nepstad 2004). This can be particularly problematic in initial stages of plant growth, and might be one of the causes for the overall lower diversity we found on clayey soils. The fact that we found a positive association between sand content and the number of spontaneous individuals indicates that homegardens on sandier soils may indeed provide better conditions for the initial establishment of these plants. These results, however, must be interpreted with caution, given that the variation in soil texture represents a relatively small portion (15.8%) of the soil variation in our dataset.

We show that the strong gradient in soil fertility associated with the transition between adjacent soils and ADE is correlated with changes in the structure, diversity and floristic composition of homegardens. In general, soil fertility was negatively correlated with the number of perennial individuals (trees and palms), and positively correlated with the number of annual/biannual herbs, shrubs and climbers, as well as with the total number of species and landraces cultivated in the homegardens. The higher abundance of trees and palms in lower fertility soils is likely due to the fact that palm and tree species that occur in higher frequencies and abundances in homegardens are well adapted to infertile soils, such as cupuaçu [*Theobroma grandiflorum* (Willd. ex Spreng.) K. Schum.], rubber, cashew (*Anacardium occidentale* L.), açaí (*Euterpe oleracea* Mart. and *E. precatoria* Mart.), bacabinha (*Oenocarpus minor* Mart.), etc. Among shrubs, herbs and climbers, we found more species that require higher nutrient concentrations to grow, such as coffee (*Coffea robusta* (L.) Linden), banana, chili peppers (*Capsicum* spp.), beans [*Vigna unguiculata* (L.) Walp. and *Phaseolus vulgaris* L.], so these species tend to be more abundant in more fertile soils. Species and landraces that are well adapted to low-fertility conditions are also cultivated in more fertile soils, although in smaller quantities; as a result, homegardens on more fertile soils tend to show a higher total number of species and landraces. This is also likely due to the fact that homegardens on ADE combine species that are often cultivated in the fertile floodplains (such as cacao and banana) with those that are common in ferralsols (Fraser et al. 2011a). Overall, our results indicate that more fertile soils increase the opportunities for farmers to grow more crop species and landraces in their homegardens.

Despite the high heterogeneity and diversity of homegardens, we found that the assemblages of species and landraces in homegardens were significantly influenced by the variation in soil properties, particularly by the fertility gradient between adjacent soils and ADE. Studies comparing non-anthropogenic soils with ADE (as discrete soil categories) have shown differences in the species composition for homegardens (Fraser et al. 2011a), secondary forests (Junqueira et al. 2010b) and in the composition of manioc landraces in swiddens under shifting cultivation (Fraser et al. 2012). Our study shows that along the strong fertility gradient between adjacent soils and ADE gradual changes occurred in the composition of the species and landraces cultivated and also in their relative abundances; in other words, the magnitude of differences in species/landraces composition was proportional to differences in soil fertility. These differences in the composition of species and landraces may arise from a combination of natural ecological and anthropogenic processes. Firstly, as our results indicate, different soils may allow the spontaneous regeneration of different species/landraces that, if maintained during management by the homegarden owners, will influence the ‘final’ assemblage of the homegarden. Secondly, if the same species/landrace is planted in different soils, the rates of mortality and success will differ depending on how suited to specific sections of the soil gradient that given species/landrace is. Lastly, although homegardens are places where people experiment with new crops (Kumar and Nair 2004), farmers are knowledgeable – due to their long-term interaction with soils and plants – about which crops are suited to the soil conditions of their homegarden, and will likely avoid planting crops that they know will not perform well. Taken together, the combination of these ‘natural’ ecological processes with farmer agency ultimately results in a close association between the species/landraces assemblage of homegardens and the specific soil conditions on which they are established.

Conclusions

The heterogeneity in soil texture and fertility significantly affect the structure, diversity and the floristic composition of homegardens. While differences in soil texture are due to natural soil variation, the heterogeneity in soil fertility results from ‘recent’ (~120 years) soil enrichment and from anthropogenic soil transformations in pre-Columbian times, evidenced by the clear association between soil fertility and the density of ceramic fragments. We show that agrobiodiversity patterns in homegardens are significantly influenced by both natural and anthropogenic variation in soil properties. The overlap of pre-Columbian and ‘modern’ soil enrichment increases soil heterogeneity in the landscape, resulting in clear soil fertility gradients that shape the agrobiodiversity of current Amazonian homegardens.

Acknowledgements

We are thankful to the local residents from the villages Água Azul, Lago do Piauí, Puruzinho, São Félix, Terra Preta do Atininga, Vila do Espírito Santo and Vila Gomes for their support and friendliness. We thank the Institute for Sustainable Agriculture and Forestry Development of Amazonas State (Instituto de Desenvolvimento Agropecuário e Florestal Sustentável do Estado do Amazonas), the Chico Mendes Institute for Biodiversity Conservation (Instituto Chico Mendes para a Conservação da Biodiversidade) and the Brazilian International Institute of Education (Instituto Internacional de Educação do Brasil) for logistical support. We also thank the lab technicians from INPA's soils laboratory for their help with the soil analyses. This research was authorized by the Brazilian National Research Ethics Commission (Comissão Nacional de Ética em Pesquisa, CAAE#011488712.3.0000.0006, Auth.#231.032). Research authorization for villages inside conservation units (Água Azul – Rio Amapá Sustainable Development Reserve, and São Félix do Aripuanã – Juma Sustainable Development Reserve) was obtained from the Amazonas State Centre for Conservation Units (Centro Estadual de Unidades de Conservação, Proc.#1017/2012). NBS received a MSc scholarship from the Coordination for the Improvement of Higher Education Personnel (CAPES).

Appendix 4

Table A4.1. Chemical and physical characteristics of soils from homegardens (n=70) and swiddens (n=114; from Chapter 3) sampled in seven villages along the middle and lower Madeira River, Central Amazonia. Exchangeable Calcium (Ca), Magnesium (Mg), Aluminum (Al), Potassium (K), total Iron (Fe), Zinc (Zn) and Manganese (Mn), available Phosphorous (P), organic matter content (OM) and percentages of clay, silt and sand.

Variable	Unit		Without ceramics		With ceramics	
			Homegardens (n=29)	Swiddens (n=70)	Homegardens (n=41)	Swiddens (n=44)
pH (H_20)		Avg ± SD	4.62 ± 0.39	4.25 ± 0.44	5.36 ± 0.65	5.34 ± 0.6
		Min - Max	3.71 - 5.30	3.63 - 6.06	3.76 - 6.28	4.08 - 6.51
Ca	$cmol_c.kg^{-1}$	Avg ± SD	0.79 ± 1.02	0.38 ± 0.47	6.09 ± 4.26	4.06 ± 2.99
		Min - Max	0.07 - 4.13	0.03 - 2.7	0.16 - 14.41	0.10 - 10.28
Mg	$cmol_c.kg^{-1}$	Avg ± SD	0.24 ± 0.23	0.17 ± 0.15	0.71 ± 0.43	0.78 ± 0.5
		Min - Max	0.08 - 0.94	0.07 - 1.15	0.08 - 1.84	0.08 - 1.76
Al	$cmol_c.kg^{-1}$	Avg ± SD	3.51 ± 2.55	3.06 ± 1.55	1.01 ± 1.75	0.94 ± 1.23
		Min - Max	0.25 - 9.65	0.05 - 7.3	0.00 - 7.50	0.00 - 3.95
K	$cmol_c.kg^{-1}$	Avg ± SD	0.18 ± 0.11	0.11 ± 0.04	0.16 ± 0.07	0.12 ± 0.08
		Min - Max	0.06 - 0.50	0.04 - 0.25	0.06 - 0.33	0.03 - 0.41
P	$mg.kg^{-1}$	Avg ± SD	38.07 ± 38.06	8.35 ± 5.08	312.27 ± 323.65	89.68 ± 147.27
		Min - Max	2.67 - 185.77	1.51 - 27.35	14.48 - 1167.36	4.04 - 580.02
Fe	$mg.kg^{-1}$	Avg ± SD	271.7 ± 120.5	222.3 ± 79.3	102.6 ± 95.8	93.8 ± 69.8
		Min - Max	99.9 - 529.3	80.3 - 528.9	30.9 - 503.3	3.6 - 313.3
Zn	$mg.kg^{-1}$	Avg ± SD	2.59 ± 2.94	0.73 ± 0.55	8.09 ± 6.79	4.31 ± 5.44
		Min - Max	0.50 - 14.90	0.10 - 4.10	0.60 - 26.30	0.10 – 29.0
Mn	$mg.kg^{-1}$	Avg ± SD	11.76 ± 16.63	3.45 ± 3.54	40.58 ± 21.82	29.2 ± 18.98
		Min - Max	1.30 - 62.20	1.00 - 27.30	3.30 - 78.90	1.00 - 73.30
OM	$g.kg^{-1}$	Avg ± SD	31.05 ± 11.54	36.14 ± 10.31	43.07 ± 16.96	39.25 ± 15.03
		Min - Max	14.66 - 73.56	16.18 - 70.11	19.58 - 93.30	15.21 - 88.98
% Clay	%	Avg ± SD	28.5 ± 22.0	34.6 ± 20.8	18.8 ± 15.5	47.0 ± 17.7
		Min - Max	2.0 - 81.0	2.5 - 85.9	1.0 - 81.0	0.7- 80.4
% Silt	%	Avg ± SD	35.5 ± 22.4	36.6 ± 19.1	36.2 ± 14.3	37.5 ± 16.4
		Min - Max	3.9 - 79.7	4.2 - 82.5	6.5 - 64.4	1.7 - 81.3
% Sand	%	Avg ± SD	36.0 ± 26.7	28.8 ± 16.1	45.0 ± 16.6	15.45 ± 10.8
		Min - Max	5.2 - 92.1	2.0 - 65.0	3.6 - 71.5	2.0 - 44.0

Chapter 5

Soil fertility, livelihood strategies and land-use patterns in central Amazonia

André Braga Junqueira, Tjeerd Jan Stomph, Paul Ingenbleek,
Cornelia J. M. Almekinders, Charles R. Clement, Paul C. Struik

Abstract

The most widespread form of small-scale farming in Amazonia is shifting cultivation, which is well adapted to the low-fertility soils that predominate in uplands but under increased land pressure (driven by demographic and/or market pressure) it shows a decline in productivity and may expand into surrounding forests. However, in Amazonia also occur patches of Amazonian Dark Earths (ADE), anthropogenic soils with enhanced carbon and nutrient levels that resulted from the activities of pre-Columbian populations. ADE have been considered models for sustainable agriculture, based on the idea that by recreating some of their properties it would be possible to sequester carbon in the soil and favor intensive cultivation, reducing the pressure on surrounding forests. The main question we address in this chapter is: do farmers with more access to fertile soils (and to ADE) open smaller areas for cultivation? Using biophysical and socio-economic data obtained from 73 households in 7 villages in Central Amazonia, we focus on the relationship between the use of ADE and land-use patterns, taking into account the variation in farmers' economic activities (agricultural and non-agricultural) and in their social and economic resources. We show that the relationship between farmers' use and access to fertile soils (ADE) and the need to open areas for shifting cultivation is strongly dependent on the labor availability of the household. The area used for cultivation was also influenced by a households' livelihood activities (especially by its level of engagement with market-oriented agriculture) and by its economic wealth. Farmers' access to increased soil fertility does not necessarily lead to reduced pressure on forests. Instead of driving specific trends in land use, fertile soils are incorporated into local livelihoods as part of an extensive repertoire of resource management activities; most often, farmers with enough available labor manage multiple plots, combining more intensive cultivation on ADE with typical long-fallow shifting cultivation on poorer soils. Initiatives promoting the improvement of soils by mimicking the properties of ADE should not assume that this will lead to reduced forest pressure in smallholder shifting cultivation systems, and should be cautious in endorsing single technological solutions involving agricultural intensification for populations who have historically relied on a diverse economic and natural resource portfolio.

Keywords: Shifting cultivation; Amazonian Dark Earths; Terra Preta; Intensification

Introduction

The livelihoods of thousands of people in Amazonia and in other tropical areas of the world rely on small-scale agriculture and on the use and management of forest and aquatic resources. Rural Amazonia is increasingly experiencing, particularly in the last decades, socio-economic, demographic and land-use changes, driven by the expansion of agricultural frontiers, infra-structure projects and urbanization (Laurance et al. 2001, Mittermeier et al. 2003, Padoch et al. 2008, van Vliet et al. 2013). In this dynamic context, Amazonian farmers constantly develop and change their livelihood strategies, combining in different ways various forms of agriculture with the extraction of forest and aquatic products and off-farm activities (Brondízio 2004, Emperaire and Eloy 2015). In order to support sustainable pathways for these socio-ecological systems, it is crucial to understand how farmers' opportunities and constraints for resource use and management relate to their biophysical and socio-economic context, and what are the social and ecological outcomes of their different livelihood strategies.

In Amazonian uplands, one of the most widespread forms of small-scale agriculture is shifting cultivation, in which a short cultivation period (≈1-3 years) is followed by a fallow phase (≈5-25 years) (Padoch and Pinedo-Vasquez 2010); it may also involve different degrees of fallow management targeting useful plants (Denevan and Padoch 1987, Junqueira et al. 2011). Shifting cultivation is well suited to the nutrient-poor soils that predominate in uplands, and to the technologies available to smallholder farmers (i.e., no external inputs, no mechanization); under low population pressure it results in a multi-functional landscape where important ecological processes are maintained (Finegan and Nasi 2004). However, when shifting cultivation is intensified (through a shortening of the fallow period and/or increase in the frequency of cultivation) it results in the degradation of fallows and reduced crop yields (Jakovac et al. 2015). Therefore, it is usually expected that under conditions of demographic growth and/or increasing market demand, farmers may also expand their shifting cultivation areas into old-growth forests, although it has been shown that trends for the expansion or reduction of shifting cultivation in Amazonia are very context-dependent (van Vliet et al. 2013). Still, under the assumption that intensification of cultivation would lead to reduced pressure on forests, most research and development initiatives have focused on replacing shifting cultivation for more intensive and/or permanent cultivation systems (Emperaire and Eloy 2015).

One of the constraints to more intensive and/or permanent agriculture in Central Amazonia is the overall low fertility of upland soils. However, in Central Amazonian uplands patches of the so-called Amazonian Dark Earths (ADE, or '*Terra Preta'*) are found, fertile anthropogenic soils that resulted from the activities of Amazonian populations in pre-Columbian times (Neves et al. 2003, Glaser and Birk 2012). Apart from their enhanced nutrient levels, these soils are also less susceptible to nutrient leaching and hold high concentrations of organic matter [especially charcoal, or 'black carbon'; Glaser et al. (2001), Lehmann et al. (2003a)]. Due to these unique characteristics, ADE have been proposed as 'models for sustainable agriculture', based on the idea that they could promote carbon storage and sequestration in the soil while favoring agricultural intensification, thus reducing the pressure on forests (Glaser et al. 2001, Glaser 2007). It has been shown that, at the plot level, fertile anthropogenic soils are indeed associated with more intensified cultivation, with shorter fallow periods, higher frequency of cultivation and higher weeding requirements (Chapter 3). However, the extent to which the more intensive use of ADE influences wider patterns of land use related to smallholder farming remains to be tested.

The main question we address in this chapter is: do farmers with more access to fertile soils (including ADE) open smaller areas for cultivation? In order to focus on this particular relationship between the use of ADE and land-use patterns, we used a comprehensive framework, taking into account the variation not only in farmers' use of soils and land, but also in their economic activities (agricultural and non-agricultural) and in their social and economic resources (e.g., labor availability, economic wealth). Through this approach, we test the hypothesis that the access to and use of ADE reduces the need to open new areas, and we discuss the role of these fertile soils in local livelihood strategies and in land-use patterns.

Methods

Study setting

The study area is located along the middle and lower Madeira River, in Central Amazonia. Seven villages located along a stretch of approximately 400 km of the Madeira and its tributaries were studied (Chapter 1, Figure 1.1). Despite increasing land-use pressure, the landscape of the region is still largely covered by 'natural' vegetation, composed mostly of *terra firme* upland forests, with flooded forests along the rivers and small patches of savannas.

Areas under agricultural or other anthropic land uses are found mainly along the rivers, close to cities and along the few roads located in the vicinity of urban areas.

The overall population density is very low (< 2 hab./km^2), approximately half of which is concentrated in cities and the other half lives in rural areas (IBGE 2011), distributed in small villages that range from a few families to a couple of thousands inhabitants. The population of the region is composed mainly of 'historical peasants', or *caboclos*, a culturally and ethnically heterogeneous group that emerged from the contact between indigenous societies and migrants that came to the region mostly during the rubber boom [i.e., in the late 19th century (Adams et al. 2009)]. Their subsistence and commercial activities are very heterogeneous, combining to different degrees plant cultivation, extraction of forest products, animal husbandry, hunting, fishing and off-farm activities (e.g., Brondízio 2004, Castro 2009, Futemma 2009). In spite of this diversity, agriculture is the most important livelihood activity for people along the Madeira River, and it is widely practiced both in floodplains and in uplands. The most common form of agriculture in uplands is shifting cultivation, and it is particularly focused on the production of manioc (*Manihot esculenta* Crantz) for flour (*farinha*), the main staple food and also an important cash product (Fraser 2010b).

Sampling design and analytical approach

In each village, we interviewed 7 to 14 households. We chose the households so they would cover the largest possible heterogeneity (within the village) regarding the use of different soils for cultivation. We interviewed the household head(s) (HH) using questionnaires and semi-structured interviews, focusing on demographic and socioeconomic characteristics (Table 5.1). We also collected biophysical data *in situ* (soil samples, area) in their swiddens used for shifting cultivation (Chapter 3). As an estimation of the total area used by a household for cultivation, we summed the area of all plots currently under cultivation and those that had been opened during the 12 months previous to the interview (including plots located on floodplains).

In order to estimate the access of each household to fertile ADE, we used soil data obtained from soil samples collected in farmers' swiddens (Chapter 3). Since soil fertility is strongly associated with the gradient between ADE and adjacent soils (Chapters 2 and 3), we used the level of soil fertility at the farm level as a proxy for the household's access to ADE. For areas for which we didn't obtain soil data from the field the soil parameters were estimated from the nearest sample. To obtain a single parameter that would represent soil fertility at the farm level, first we analyzed soil data with a Principal Components Analysis (PCA), and the score of each plot along the first axis of the PCA (which summarized the variation in soil fertility) was used as its indicator of fertility. Then we calculated a weighted average soil fertility score (SFS) at the farm level following Tittonell et al. (2005a) using the equation:

$$\text{Soil Fertility Score} = \sum_{i=1}^{n} \text{SF}_\text{i} \times \frac{\text{FArea}_\text{i}}{\text{TAarea}} \qquad \text{(Equation 1)}$$

where n = number of plots (swiddens) currently used by the household, SF_i = score of soil fertility at the plot level (PCA score), $FArea_i$ = area of each particular plot and TArea = total area cultivated by the household. The soil fertility score was calculated considering only plots located on uplands.

The demographic and socioeconomic variables we included were household size (total number of residents), average age and level of formal education of the HH, available labor (expressed in man equivalent.day^{-1}, weighted by age and gender of household members), dependency ratio (number of children and elders divided by number of adults) and cash income from retirement pension and/or from government social programs (*Bolsa família, Bolsa floresta;* Table 5.1). As an indicator of economic wealth, we quantified the monetary value of a set of 40 physical assets owned by the household, including the house (weighted by the size and construction materials), tools (power generators, chainsaws, boats, etc.) and electrical appliances (television, refrigerator, etc.).

In order to assess the diversity of livelihood strategies used locally, we quantified the relative importance of different economic activities to the household, including agriculture, hunting/fishing, collection and management of forest resources and off-farm wage labor. We asked each HH which were the most important products that they produced and/or commercialized from agriculture, from forest products and from hunting/fishing. For each product mentioned, HHs were asked to classify them according to their degree of commercialization [‘commerce score’ (CS): 0 – all for household consumption, to 4 – all for selling to the market]. We then added these values to calculate an index that represented the relative commercial importance of agriculture, of forest resources and of hunting/fishing for each household, using the following equation:

$$\text{AgS, FpS or HfS} = \sum_{i=1}^{n} \text{CS}_\text{i} \qquad \text{(Equation 2)}$$

where AgS, FmS and HfS are the 'agriculture score', the 'forest products score' and the 'hunting/fishing score', respectively, *n* = the number of 'most important' products mentioned by the household and CS = the commerce score of each product mentioned. As an indicator of household off-farm activities, we calculated their monthly income from off-farm labor, adding their cash income from salaries (e.g., school teachers, health agents) to their cash income from wage labor (estimated from the frequency in which they performed the activity).

Data were analyzed using mixed effect models, with area under cultivation as a dependent variable, village as a random factor, and as predictor variables: the demographic and socioeconomic characteristics of the household (available labor, age, education, etc.); its main economic activities (agriculture score, forest product score, hunting/fishing score and off-farm labor); the area cultivated on floodplains; and the average soil fertility of its fields. The variable 'household size' was not included in the model since it was strongly correlated with available labor. Variables with skewed distributions were log- or square-root transformed. To select the variables that were maintained in our final model we used the model selection procedure proposed by Zuur et al. (2009).

Results

Variation in the use of land, soils, socioeconomic characteristics and livelihood activities

The households we interviewed maintained on average 2.4 (±1.1) swiddens, with an average size of 0.47 (±0.38) hectares, adding up to a total area of 1.17 (±0.84) ha, but these parameters showed a large variation among households (Table 5.2; Figure 5.1). Soil fertility also varied substantially between swiddens (Chapter 3), and the different combinations of swidden sizes and soils resulted in a large variation in the soil fertility score at the farm level (Table 5.2). Relatively few households had fields on floodplains, except for those in the village 'Vila do Espírito Santo', where most farmers interviewed maintained fields on the extensive floodplain located in front of the village (apart from their fields on uplands; Figure 5.1). The average area cultivated on floodplains was 0.27 (±0.65) ha, but similarly to the other variables there was also a large variation among villages [in some villages ('Lago do Piauí', 'Terra Preta do

Atininga' and 'Vila Gomes') none of the interviewed households had fields on the floodplain; Table 5.2].

Table 5.1. Socioeconomic and biophysical variables obtained from 73 households in 7 villages located along the middle and lower Madeira River, Central Amazonia.

Variable	Unit	Description
Soil and land use		
Area opened for cultivation	ha	Area used by the household for shifting cultivation. Includes swiddens currently used and those that have been opened in the 12 months before the interview
Soil fertility score	index	Soil fertility at the farm level, based on PCA scores of each field and weighted by the proportion of each field to the area cultivated by the household (see Equation 1)
Floodplain area	ha	Area used by the household that is located on the floodplain
Demographic and socioeconomic characteristics of the household		
Household size	residents	Total number of residents in the household
Dependency ratio	index	Number of residents younger than 14 and older than 65 years old divided by the number of residents within this age range
HH age	years	Average age of household head(s)
HH formal education	years	Average number of school years of household heads
Labor available	$man.day^{-1}$	Labor available at the household level, weighted by age and gender
Income aid	R$	Cash income from retirement pension and government social programs
Economic wealth	kR$	Monetary value of a set of 40 physical assets owned by the household, including the house, tools and electronics
Economic activities of the household		
Agriculture score	index	Score based on the number of main agricultural products mentioned by the household and their degree of commercialization (see Equation 2)
Forest products score	index	Score based on the number of main forest products mentioned by the household and their degree of commercialization (see Equation 2)
Hunting/fishing score	index	Score based on the number of main animal products mentioned by the household, and their degree of commercialization (see Equation 2)
Off-farm income	R$	Cash income obtained from off-farm labor, including salaries and wage labor

The sampled households showed a large variation regarding their demographic and socioeconomic characteristics as well as in combination of economic activities, both within and among villages (Table 5.2; Figure 5.2). All households we interviewed practiced agriculture for subsistence, and nearly all of them were also engaged to some degree in market-oriented agriculture (Figure 5.2). The gathering of forest products and hunting/fishing were common to most households, but their relative importance seemed to be more related to differences in resource availability at the village level (see, for example, the importance of hunting/fishing in the village 'Lago do Piauí' and of the extraction of forest products in the village 'Terra Preta do Atininga'; Figure 5.2). Nearly all households received cash aid, particularly from government social programs (*Bolsa Família*) and from retirement pensions

Table 5.2. Averages and standard deviations for land use, soil fertility score, socioeconomic characteristics and economic activities for 73 households in 7 villages along the middle and lower Madeira River, Central Amazonia (acronyms above the columns indicate the different villages: AAZ – 'Água Azul'; FEL – 'São Félix'; LPI – 'Lago do Piauí'; PRZ – 'Puruzinho'; TPA – 'Terra Preta do Atininga; VES – 'Vila do Espírito Santo'; VGO – 'Vila Gomes'). Numbers in parenthesis indicate the number of households interviewed in each village.

Variable	AAZ (12)	FEL (9)	LPI (9)	PRZ (11)	TPA (13)	VES (12)	VGO (7)	All villages (73)
Soil and land use								
Number of swiddens	2.6 ± 1.1	2.7 ± 1.3	1.9 ± 0.9	2.7 ± 0.8	1.8 ± 0.8	2.3 ± 0.9	3.1 ± 1.8	2.4 ± 1.1
Area under cultivation (ha)	1.26 ± 0.79	1.29 ± 1.02	0.82 ± 0.76	1.47 ± 1.09	1.04 ± 0.65	1.09 ± 0.69	1.20 ± 1.03	1.17 ± 0.84
Soil fertility score	1.85 ± 1.46	2.19 ± 1.62	1.59 ± 0.95	1.54 ± 0.68	0.89 ± 0.37	1.96 ± 0.92	1.59 ± 1.82	1.64 ± 1.17
Floodplain area (ha)	0.27 ± 0.60	0.05 ± 0.16	0 ± 0	0.05 ± 0.18	0 ± 0	1.27 ± 0.98	0 ± 0	0.27 ± 0.65
Demographic and socioeconomic characteristics of the households								
Size (# of residents)	5.5 ± 2.8	5.7 ± 2.6	3.0 ± 1.8	3.2 ± 1.3	6.2 ± 3.1	5.2 ± 2.4	3.6 ± 2.1	4.8 ± 2.6
Dependency ratio	0.67 ± 0.53	1.15 ± 0.86	0.53 ± 0.98	0.34 ± 0.50	1.00 ± 0.96	0.91 ± 0.89	0.86 ± 0.69	0.78 ± 0.81
HH age (years)	46.9 ± 14.6	39.9 ± 10.5	49.0 ± 10.7	45.2 ± 9.2	43.1 ± 12.7	44.2 ± 13	53.8 ± 19.3	45.6 ± 12.9
HH formal education (years)	8.2 ± 6.4	9.6 ± 4.1	3.1 ± 3.0	9.7 ± 6.5	9.2 ± 4.8	10.2 ± 7.2	5.7 ± 4.5	8.2 ± 5.8
Labor available (man.day^{-1})	3.6 ± 1.6	2.9 ± 1.5	2.1 ± 1.0	2.4 ± 1.0	3.6 ± 1.8	3.0 ± 1.2	2.1 ± 1.5	2.9 ± 1.5
Income aid (R$/month)	444 ± 351	360 ± 215	524 ± 454	353 ± 383	215 ± 128	458 ± 301	692 ± 557	415 ± 357
Economic wealth (kR$)	11.3 ± 6.2	8.0 ± 4.7	8.1 ± 2.5	10.0 ± 5.7	9.0 ± 4.1	14.5 ± 18.3	6.7 ± 3.8	10.0 ± 8.7
Economic activities of the households								
Agriculture score	0.38 ± 0.21	0.42 ± 0.13	0.22 ± 0.14	0.41 ± 0.12	0.11 ± 0.07	0.57 ± 0.26	0.30 ± 0.14	0.34 ± 0.22
Forest products score	0.19 ± 0.22	0.23 ± 0.21	0.23 ± 0.15	0.15 ± 0.11	0.62 ± 0.29	0.03 ± 0.06	0.06 ± 0.06	0.23 ± 0.26
Hunting/fishing score	0.04 ± 0.12	0.10 ± 0.14	0.59 ± 0.29	0.12 ± 0.19	0 ± 0	0.06 ± 0.1	0.12 ± 0.15	0.13 ± 0.23
Off-farm income (R$/month)	387 ± 292	269 ± 350	418 ± 309	300 ± 341	532 ± 646	308 ± 558	255 ± 199	363 ± 428

(Figure 5.2). Most households were also involved in some kind of off-farm labor, including both formal jobs (school teachers, health agents, etc.) and informal wage labor, but similarly to the other variables there was large variation between the households regarding the relative importance of this activity to their economic portfolio (Figure 5.2). We also identified correlations between economic activities: the agriculture score was negatively related with the forest products score (Pearson's correlation ρ = -0.46), and the sum of scores (agriculture + forest products + hunting/fishing) was negatively related with the households' total cash income (off-farm income + income aid; ρ = -0.21), indicating that there are also trade-offs in the households' combination of economic activities (Figure 5.2).

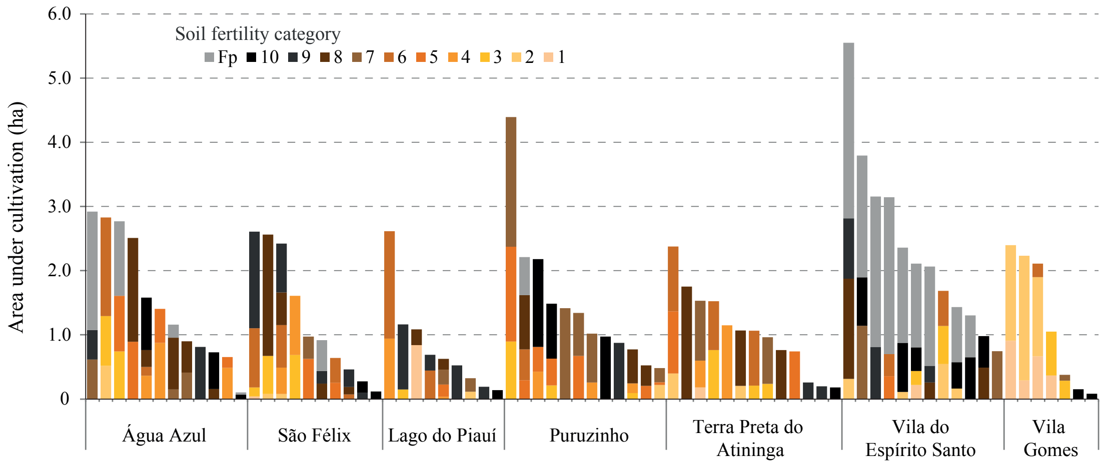

Figure 5.1. Total and field specific area under cultivation and related soil fertility for 73 households from 7 villages. Each stacked column represents a household, each part of a column represents an individual field, its height representing field size (ha), and the colors representing the soil fertility score of that field, based on its PCA score (for visualization purposes, scores were grouped into 10 equal-sized groups: 1 – lowest fertility; 10 – highest fertility). Columns in grey represent fields located in floodplains (Fp).

Effects of soils, socioeconomic variables and economic activities on land use

We found that the area under cultivation was significantly related to the soil fertility score, to labor availability, to the agriculture score, to the plant gathering score and to the economic wealth of the household (Table 5.3). This indicates that, in general, households that open larger areas use poorer soils, are wealthier and are more engaged in market-oriented agriculture and management of forest products (Figure 5.3). The effect of soil fertility on the area, however, depended on the labor available at the household, as indicated by the significant interaction between soil and labor in our model (Table 5.3; Figure 5.3a). The area under cultivation was neither significantly related to any of the other variables we tested (floodplain area, dependency ratio, formal education, animal gathering score, off-farm cash and aid cash) nor to their interactions.

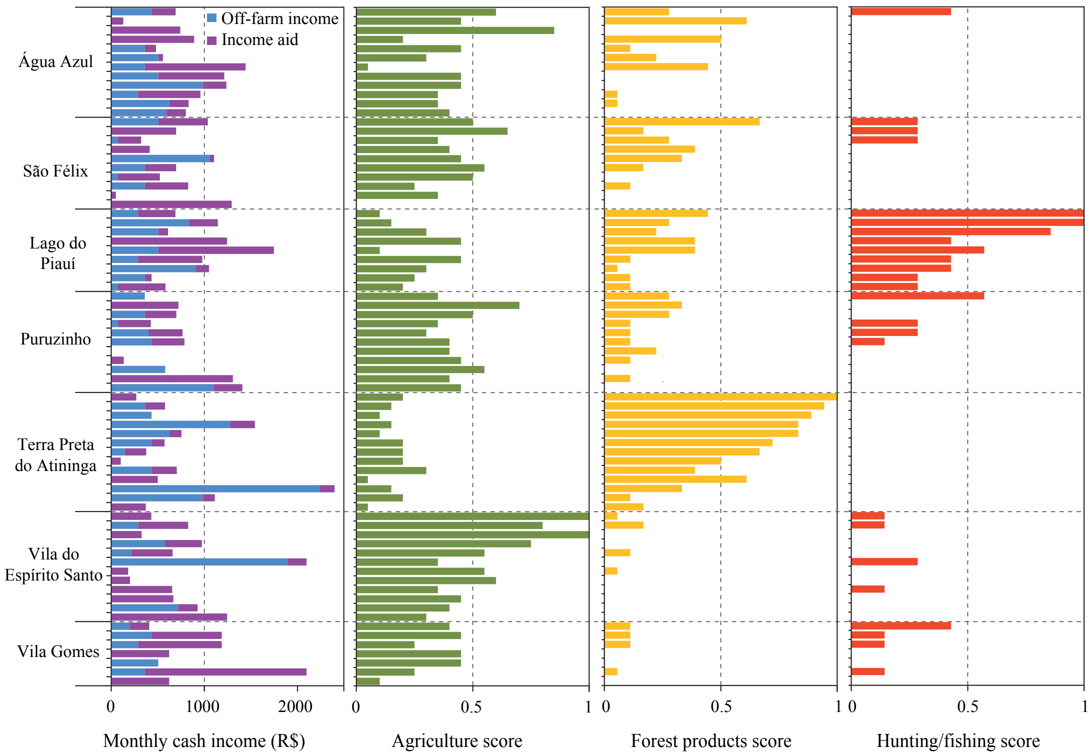

Figure 5.2. Monthly cash income [from pensions and/or government social programs ('Income aid') and salaries/wage labor ('Off-farm income')] and major economic activities (agriculture, gathering of forest products and hunting/fishing) for 73 households from 7 villages. Each bar represents a household, and its size represents the relative importance of each activity or source of income to the household. Scores for agriculture, gathering of forest products and hunting/fishing were standardized, so that they vary between 0 and 1.

Table 5.3. Results of mixed effect model analysis of the relationship between the area under cultivation (dependent variable) and socioeconomic variables and livelihood activities (predictors). Std. Coef = standardized regression coefficient; SE = standard error; Coef = regression coefficient). Values of R^2 for the whole model and for the fixed factors only were calculated based on Nakagawa and Schielzeth (2013).

Predictor	**Response variable: Area opened for cultivation**					
	Std. Coef	SE	Coef	SE	t	p
Soil fertility	-0.39	0.09	-45.94	9.49	-4.84	**0.000**
Labor available	0.14	0.09	1.54	2.43	0.63	0.528
Soil fertility * Labor available	0.20	0.09	7.96	3.52	2.26	**0.027**
Floodplain area	ns	ns	ns	ns	ns	ns
Dependency ratio	ns	ns	ns	ns	ns	ns
HH age (average)	0.17	0.09	6.82	3.48	1.96	0.055
HH formal education (average)	ns	ns	ns	ns	ns	ns
Income aid	ns	ns	ns	ns	ns	ns
Economic wealth	0.24	0.08	16.40	5.66	2.90	**0.005**
Agriculture score	0.50	0.11	36.58	7.75	4.72	**0.000**
Forest products score	0.32	0.10	13.09	4.23	3.09	**0.003**
Hunting/fishing score	ns	ns	ns	ns	ns	ns
Off-farm income	ns	ns	ns	ns	ns	ns
Number of observations	73					
R squared of whole model	0.55					
R squared of fixed effects	0.55					

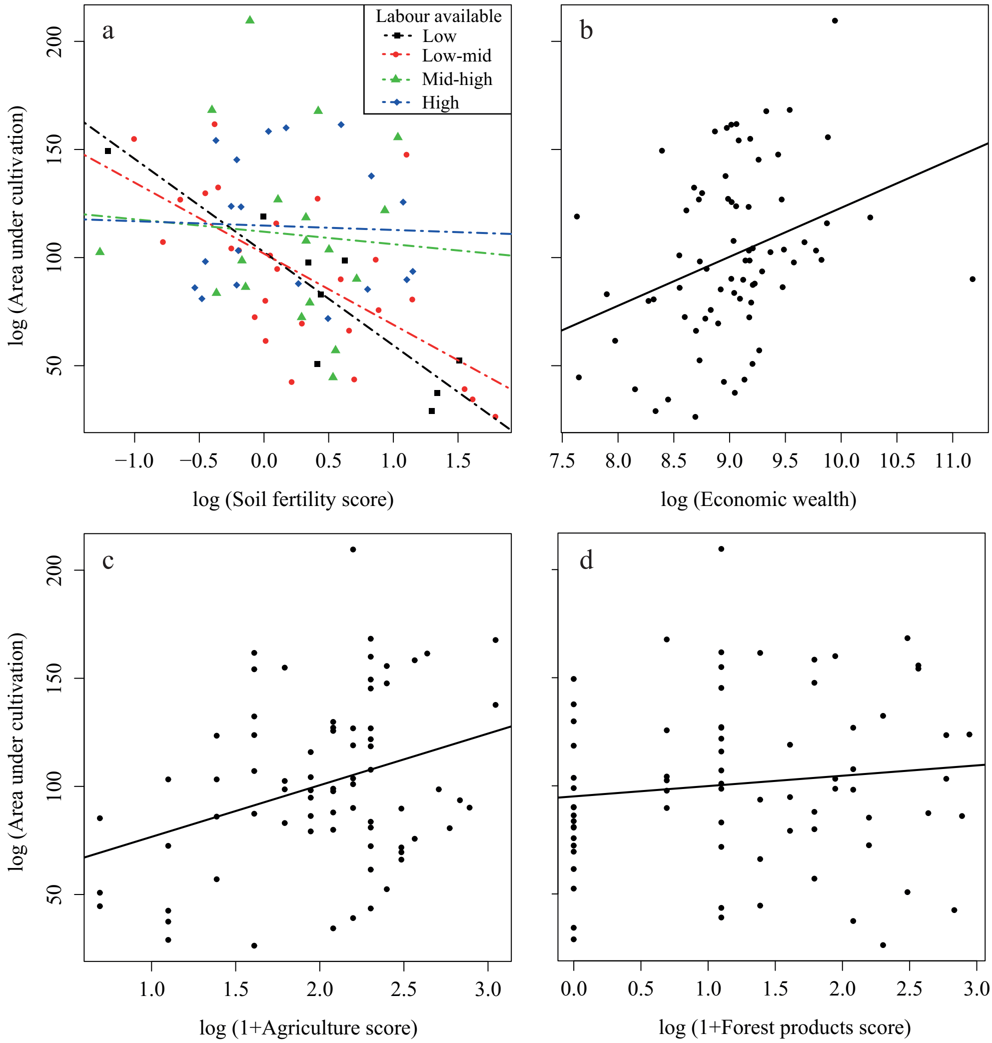

Figure 5.3. Relationships between (log transformed) area opened for cultivation and (log transformed) (a) soil fertility, (b) economic wealth, (c) agriculture score and (d) forest products score for 73 households along the middle and lower Madeira River, Central Amazonia, Brazil. The upper left panel represents the interaction between soil and labor in explaining the variation in area: labor values were divided in four quartiles ('low', 'low-mid', 'mid-high' and 'high'). Lines represent the linear fit of mixed effect models (Table 5.3).

Discussion

Our results show that the relationship between farmers' use of fertile soils (including ADE) and the need to open areas for shifting cultivation is strongly dependent on the labor availability of the household. The area used for cultivation was also influenced by a households' livelihood activities (especially by its level of engagement with market-oriented agriculture) and by its economic wealth. These results show that land-use patterns in shifting cultivation landscapes in Central Amazonia result from complex interactions between smallholders and their biophysical and socio-economic environment, and indicate farmers' access to increased soil fertility does not necessarily lead to reduced pressure on forests.

When making their land use and cultivation decisions, farmers take soil quality into account, along with other available resources and opportunities (Moran et al. 2002, Vosti et al. 2002; Chapter 1). Soil fertility plays an important role in shaping land-use pathways of colonist populations in agricultural frontiers in Amazonia (e.g., Pichón 1997, Moran et al. 2002, Vosti et al. 2002, Witcover et al. 2006, Soler and Verburg 2010). Economic models at the farm level relating soil quality to deforestation have shown mixed results: some studies show that farmers with better soils open more areas (e.g., Pichón 1997, Soler and Verburg 2010), others have indicated that better soil quality slows down deforestation (e.g., Andersen et al. 2002), while yet others show limited or no effects of soil quality on deforestation patterns (e.g., Vosti et al. 2002, Witcover et al. 2006). These studies have largely focused on colonist populations in relatively recently established (30-40 years ago) agricultural frontiers, while much less is known about native Amazonian populations (Godoy et al. 2009) and historical peasants (*caboclos*), who often inhabit areas subjected to more stable but still dynamic land-use patterns. We have shown that, in *caboclo* shifting cultivation systems in Central Amazonia, soil fertility is an important factor shaping current land-use patterns, but it may have contrasting effects on the area used for cultivation depending on the households' labor availability: while labor-constrained farmers tend to use smaller areas on more fertile soils, those with more labor available may use these soils under cultivation strategies that require larger areas. These results indicate that farmers' cultivation strategies are tailored to their biophysical and socio-economic resources and show that, in the context of smallholder shifting cultivation systems in Central Amazonia, a simple relationship between soil quality and deforestation patterns cannot be assumed [echoing patterns found in colonist populations elsewhere in Amazonia, e.g., Pichón (1997), Soler and Verburg (2010)].

Our results also highlight the diversity of livelihood and land-use strategies of smallholders in Central Amazonia. Although households may be more focused on one activity or another depending on the availability of natural resources, labor, market opportunities and personal preferences (as indicated by the trade-offs between livelihood activities), in general they show a wide resource base, mixing to different extents agriculture with the extraction of forest products, hunting/fishing and off-farm activities. *Caboclos* have historically been very flexible in their land-use decisions and cultivation strategies (Vogt et al. 2015), and their lack of specialization is important for them to achieve their food and economic security within a context of fragile market structures and poor infrastructure (Brondízio 2004, Castro 2009). This heterogeneity in livelihood strategies is further enhanced by farmers' use of different soils in their cultivation systems: their use and access to more fertile soils increases their opportunities for plant cultivation and management in uplands, since it allows them to grow more nutrient-demanding crops under more intensified cultivation systems (Chapters 2 and 3). However, instead of driving specific trends in land use, fertile soils are incorporated into local livelihoods as part of an extensive repertoire of resource management activities; most often, farmers with enough available labor manage multiple plots, combining more intensive cultivation on fertile soils (including ADE) with typical long-fallow shifting cultivation on poorer soils. These results provide support to the idea that the coexistence of intensified and extensive agriculture is part of a larger land use strategy of smallholder farmers (Brondízio 2004), and is one of the various ways in which shifting cultivation is maintained by smallholders in the dynamic socio-economic and environmental context of rural Amazonia (Emperaire and Eloy 2015).

The idea of ADE as a model for sustainable agriculture is based on the idea that multiple environmental benefits could be achieved by creating soils that mimic the properties of ADE, mainly the long-term sequestration of CO_2 in the soils and reduced pressure on forests through agricultural intensification (Glaser 2007). These potential benefits of ADE-like soils have fostered several research and development initiatives promoting the use of carbonized organic matter as a soil amendment ['biochar'; Glaser et al. (2002)], but it is unclear to what extent these initiatives (and the whole model of ADE as a model for sustainable agriculture) can benefit smallholder farmers (Kawa and Oyuela-Caycedo 2008). Looking at the current use of ADE allowed us not only to understand the relevance of these pre-Columbian archaeological soils to local people, but also to evaluate potential consequences of enhancing soil fertility (e.g., by re-creating ADE) in smallholder farming systems. Smallholder farmers can indeed benefit in many ways from using more fertile ADE, with increased opportunities for both intensification and diversification of cultivation strategies (Chapter 3), but we have shown that their access to soil of greater fertility does not reduce the need to open areas for cultivation. Moreover, even when access to more fertile soil is associated with the more intensive use of smaller areas for cultivation (as in the case of labor-constrained farmers), other aspects apart from land use *per se* need to be considered to evaluate the sustainability of these systems, such as how this intensive cultivation is practiced and its consequences for the environment and for local livelihoods (we have identified, for example, cases in which the intensive cultivation of watermelon ADE is done using large amounts of pesticides, with potential negative consequences for people's health; Chapter 6, Text box 6.1). Therefore, initiatives promoting the improvement of soils by mimicking the properties of ADE should not assume that this will lead to reduced forest pressure in smallholder shifting cultivation systems, and should be cautious in endorsing single technological solutions involving agricultural intensification for populations who have historically relied on a diverse economic and natural resource portfolio.

Acknowledgements

We thank the residents from the villages where we worked for their invaluable help and kindness. Logistical support for fieldwork was provided by the Institute for Sustainable Agriculture and Forestry Development of Amazonas State (Instituto de Desenvolvimento Agropecuário e Florestal Sustentável do Estado do Amazonas), by the Chico Mendes Institute for Biodiversity Conservation (Instituto Chico Mendes para a Conservação da Biodiversidade) and by the Brazilian International Institute of Education (Instituto Internacional de Educação do Brasil). We also thank the lab technicians from INPA's soil laboratory for their help with the soil analyses, and Yang Yu for assistance with the statistical analyses. This research was authorized by the Brazilian National Research Ethics Commission (Comissão Nacional de Ética em Pesquisa, CAAE#011488712.3.0000.0006, Auth.#231.032). Research authorization for villages inside conservation units (Água Azul – Rio Amapá Sustainable Development Reserve, and São Félix do Aripuanã – Juma Sustainable Development Reserve) was obtained from the Amazonas State Centre for Conservation Units (Centro Estadual de Unidades de Conservação, Proc.#1017/2012).

Chapter 6

General Discussion

André Braga Junqueira

General Discussion

Amazonia and other tropical areas around the world are experiencing land-use changes driven by the expansion of large-scale agriculture, infra-structure projects, urbanization and the growing engagement of local people with markets. These changes are increasingly affecting rural populations who rely on small-scale farming and on the use and management of forest resources for their daily subsistence and income. In order to support sustainable pathways of development for these rural populations, it is crucial to understand farmers' rationales and practices related to resource management, how these relate to farmers' biophysical and socio-cultural environments, and the ecological and social outcomes of different systems of resource use.

Throughout Amazonia patches of fertile anthropogenic soils (Amazonian Dark Earths, ADE) occur that are the result of cultural activities of Amerindian populations in pre-Columbian times (Neves et al. 2003, Glaser and Birk 2012). Apart from their archaeological relevance, these soils have gained considerable attention in the last decades due to their close association with past and present agrobiodiversity (Clement et al. 2003, Clement et al. 2009, Junqueira et al. 2010a), and their enhanced and long-lasting soil fertility (Glaser and Birk 2012). These improved soil properties are mainly due to the high content of carbonized ('pyrogenic') organic matter, which plays an important role in soil chemical and biological processes, apart from storing carbon in the soil (Glaser and Birk 2012). Due to these characteristics of ADE, the creation of soils that mimic their properties has been proposed as a model for sustainable agricultural development in Amazonia and beyond (Glaser et al. 2001, Glaser 2007).

Investigating the current use and management of ADE by local people allows understanding the role of these soils in sustaining past and present Amazonian agriculture and agrobiodiversity, and also evaluating – in a wider sense – the role of soil fertility and heterogeneity in smallholder cultivation systems. The aim of this thesis was to investigate how farmers understand and use anthropogenic soils in Central Amazonia, and how this understanding influences agrobiodiversity and land-use patterns. In this chapter, I synthesize the main findings of this thesis and discuss their implications for our current understanding of ADE and of the role of soil heterogeneity in smallholder cultivation systems. Also, I discuss how these findings can inform strategies aiming to increase social and ecological benefits of smallholder agriculture in Amazonia.

Local rationales and Amazonian Dark Earths: a co-evolution of soils, knowledge and practice

Understanding local knowledge about soils is essential to understand local realities of farmers (WinklerPrins and Sandor 2003). Smallholder farmers have a close and long-term interaction with soils, and their practical experience can provide many useful insights in evaluating land use in relation to soil quality (WinklerPrins 1999, WinklerPrins and Sandor 2003). In Chapter 2, I focused on farmers' rationales about the use of ADE, and on how their understanding of these anthropogenic soils relates to their decision-making during cultivation. I showed that farmers' understanding of ADE – and of soils in general – is based on their historical and shared knowledge about soil variation across the landscape, on physical attributes of the soil (e.g., color, texture), and on the recognition of different soil-vegetation interactions.

The term '*terra preta*' (black earth) is used by farmers to refer to soils that have darker color, loose texture, that are suitable for the cultivation of a wider variety of crops, and that are associated with specific weed and fallow dynamics (Chapter 2). Farmers recognize that the ceramic fragments they commonly find in these soils are evidence of previous human occupations, but most of them consider the soil itself to be of natural origin. Instead, their interpretation is that the 'old ones', or 'the indians', favored patches of *terra preta* as habitation and/or cultivation sites, which would explain the presence of ceramic fragments in these areas. This local understanding of *terra preta* – a natural soil type, whose favourable conditions for cultivation 'attracted' indigenous populations in the past – has long been reported in the scientific literature (Gourou 1949, Franco 1962, Falesi 1972, German 2003a) and it is widespread in the middle and lower Madeira River region. On the other hand, farmers recognize that soil properties are dynamic, changing during the cultivation (becoming 'weak' with continuous use) and the fallow period (becoming 'strong' with fallow development), and that more permanent but localized soil improvement can be achieved in swiddens ('*coivaras*') and homegardens ('*terra queimada*') [as also reported by Fraser et al. (2009), Schmidt and Heckenberger (2009), WinklerPrins (2009)]. Some farmers refer to these practices to explain the origin of ADE (Fraser et al. 2009; Chapter 2), but most of them do not interpret these relatively large patches of ADE as the product of previous indigenous occupations. In order to understand, classify and use soils, farmers rely on physical characteristics of soils and (mainly) on soil-vegetation interactions rather than on specific processes that might have originated them.

Despite this lack of agreement between farmers regarding the origins of ADE, there is considerable consensus on the soil-vegetation relationships of these soils. A general widespread perception about these soils is that they are suitable for the cultivation of 'almost everything' and always produce decent yields, but they require much more weeding during cultivation (German 2003a, Fraser 2010a, b; Chapter 2). I showed that farmers' decision-making in shifting cultivation on ADE is grounded on this differential understanding of soil-vegetation relationships, and weighed against the labor demand. When choosing an area to open a new plot, farmers predict future labor requirements and yields based on the fallow vegetation: younger fallows are easier to cut, but once opened they require more weeding and produce lower yields than fields opened from older fallows (Chapter 2, Figure 2.1). Although farmers recognize similar trends on ADE, they say these relationships are less pronounced on ADE than on surrounding soils, due the fact that ADE *always* require more weeding and *always* produce reasonable yields, regardless of the age of the previous fallow. Farmers refer to this particular understanding of ADE to explain their decisions when cultivating these soils: they say that fields on ADE are opened from younger fallows, are smaller and cultivated with shorter cropping periods as a strategy to avoid weeding.

Despite the lack of continuity between populations who created ADE and those who are currently using these soils along the Madeira River, farmers have developed knowledge on soil-plant relationships and cultivation strategies suited to different soils, including management techniques (e.g., changes in plot size, length of cultivation, length of fallow etc.) and crop assemblages (Fraser et al. 2012; Chapter 2). Local knowledge and experiences about ADE (and about soils in general), built upon decades of close interaction with these soils, allows identifying – from the perspective of farmers – advantages and constraints of their cultivation. The large amount of labor required for the intensive cultivation of more fertile soils (especially for weeding) is seen by farmers as a major constraint for their agricultural use; as a result, farmers prefer to combine smaller plots and short cultivation cycles on ADE with larger plots and longer cultivation cycles on poorer soils. This provides insights for evaluating initiatives aiming to promote intensification through soil fertility enhancement in smallholder cultivation systems. First, it shows that in the context of smallholder farmers in Amazonia (where labor is often limiting, and most of the work is done manually), intensification may not always be an appropriate option. Second, it indicates that it can be more advantageous (and more suitable to local conditions) to promote intensification as an addition and not as a replacement of existing cultivation systems.

The ‘gradient’ approach: embracing soil heterogeneity

ADE contrast clearly with surrounding soils due to their darker color, enhanced nutrient levels, and by the presence of cultural materials, such as ceramics or lithic fragments. Several studies have focused on comparing ADE with surrounding soils, and have shown strong contrasts between these two categories (Lehmann et al. 2003b). The ‘core’ areas of the ADE patches contrast strongly with surrounding soils, showing much darker color and nutrient concentrations that can be as much as 500 times greater than the surrounding soils. However, ADE show ample variation in soil properties, both within and between patches, since these soils result from complex cultural activities in the past and occur in different environmental contexts (Lehmann et al. 2003b, Neves et al. 2003). It has been argued that anthropogenic soils can be categorized into *‘terra preta’* (darker, enriched areas with abundant ceramic fragments) and *‘terra mulata’* [brownish areas, with intermediate characteristics and without ceramic fragments; Sombroek (1966), Woods and McCann (1999), Arroyo-Kalin (2010)]. However, these categorizations seem to be an oversimplification and do not represent well the heterogeneity of ADE. Instead, it has been proposed that ADE can be better understood as a continuum in soil properties (Fraser et al. 2011c).

All previous studies focusing on the use of ADE have considered these as a distinct soil category (German 2003a, German 2003b, 2004, Major et al. 2005b, Fraser 2010b, a, Junqueira et al. 2010b, Fraser et al. 2011a, Fraser et al. 2011b, Junqueira et al. 2011, Kawa et al. 2011, Fraser et al. 2012, Kawa et al. 2015). In this thesis, although I accounted for the presence and density of ceramic fragments as an indicator of pre-Colombian human occupation, I took into account the whole range of heterogeneity in soil physical and chemical characteristics between ADE and surrounding soils, both in the sampling design and in the analytical approach. I showed that several characteristics of cultivation cycles and crop composition change along the soil fertility gradient between ADE and adjacent soils (Chapters 3 and 4). This gradual change shows a close association between the diversity of soils, crops and cultivation strategies. Considering the whole range of soil variation improves our understanding of the current use of ADE and highlights the complexity and heterogeneity of these systems. Moreover, it improves our understanding of smallholder farming in general, stressing the importance of soil heterogeneity in the diversity of these agroecosystems. In the following sections, I discuss how this heterogeneity in soil properties associated with ADE is related with intensification, agrobiodiversity and land-use patterns.

Amazonian Dark Earths, opportunities and threats for agricultural intensification

Agricultural intensification has long been proposed as the solution for feeding a growing world population without area expansion. Increasing productivity per unit land or labor was a major goal of the 'green revolution' in the 1960s, but this achievement depended upon technologies (e.g., monocultures, fertilizers, pesticides) that have proven to have negative consequences for biodiversity, ecosystem processes and human health (Mooney et al. 2005, Pingali 2012). In the last decades, research on and development of intensification have shifted their focus towards models that would minimize the ecological footprint of agriculture (Struik et al. 2014), matching the goal to feed the world now and in the future with the maintenance and enhancement of ecosystem functions (Tittonell 2014). This new approach has led to the emergence of the concepts of 'sustainable' and 'ecological' intensification, which, despite the lack of consensus on their specific meanings and/or on how to realize these alternative forms of intensification, are becoming guiding principles in research and policy agendas (Struik and Kuyper 2014, Tittonell 2014). In Amazonia and other tropical regions of the world, the struggle to reduce deforestation is usually associated with the promotion of more intensive and permanent cultivation in smallholder farming systems (Emperaire and Eloy 2015).

In Amazonia, the most widespread form of small-scale cultivation since European arrival is shifting cultivation, in which some plots are cultivated for a relatively short time while several others are maintained for lengthy periods under fallow vegetation (Conklin 1961, Ruthenberg 1971). These systems are well adapted to low-fertility soils, to lack of external inputs (e.g., fertilizers, machinery) and to low population densities that characterize most of rural Amazonia. Under these conditions, shifting cultivation results in a landscape where important ecological and social functions are maintained: a mosaic of cultivation fields and fallows in different stages of regrowth [which are also used and managed by local people for other useful products (Denevan and Padoch 1987, Padoch and Pinedo-Vasquez 2010, Junqueira et al. 2011)] surrounded by mature forests. However, due to low soil fertility and to lack of nutrient inputs, when these systems are intensified (through the reduction of fallow periods and/or increase in the frequency of cultivation) they result in the degradation of fallows (e.g., reduction in biomass), and in the reduction of crop yields (Jakovac et al. 2015). Under conditions of demographic growth and/or market demands, therefore, shifting cultivation systems may also expand into surrounding forests [although these trends are hard to generalize given smallholders' various diversification strategies (van Vliet et al. 2013)]. Too much emphasis has been put on shifting cultivation as a primary cause for deforestation in the tropics (Geist and Lambin 2002), and deforestation by smallholder farmers represents only a fraction of total deforestation in Amazonia (Godar et al. 2014); still, it is important to support pathways for smallholder farming in Amazonia that minimize expansion into mature forests whilst guaranteeing farmers' food and economic security.

One of the most notable characteristics of ADE is their enhanced and long-lasting soil fertility, contrasting with the nutrient-poor soils that predominate in Amazonian uplands. This particular characteristic of these soils has underlined their potential for agricultural intensification in Amazonia, which is a major reason why ADE have gained increased attention beyond archaeology and have been considered models for sustainable agriculture (Glaser et al. 2001, Glaser 2007). Previous studies had shown that swiddens on ADE were opened from younger fallows and cultivated under shorter cropping periods [German (2004), Fraser et al. (2011b), Fraser et al. (2012); but see Peña-Venegas et al. (2014)]. Our results show that the soil fertility gradient between adjacent soils and ADE is associated with changes in several characteristics of the cycle dynamics associated with intensification: swiddens on more fertile soils have been used for more cultivation cycles in the past, are opened from younger fallows and are cultivated for shorter periods (Chapter 3). On the other hand, the more intensive cultivation of ADE – and their enhanced fertility itself – favors the creation of a dense weed seed bank in the soil, resulting in high weed pressure (Major et al. 2005b). I have shown that soil fertility was strongly associated with weeding requirements (Chapter 3), and that this high weed pressure occupies a central role in farmers' perceptions and decisions about the cultivation of ADE: weeding is the main reason why farmers open smaller plots and cultivate them for shorter periods of time (Chapter 2).

Despite the intensive use of ADE in the past and present, the fact that we still find high levels of fertility in these soils indicates that they are indeed able to sustain more intensive shifting cultivation than surrounding soils, but I have also identified cases where the prolonged and intensive use of ADE has resulted in the degradation of fallows and crop yields, and in the increased use of pesticides and fertilizers (Chapter 2; Text box 6.1 – the watermelon case). Also, the higher fertility of ADE and their intensive use results in a high weed pressure that poses constraints to the cultivation of these soils by smallholder farmers (Chapters 2 and 3). From a wider perspective, these results indicate that soil management practices that lead to long-lasting soil improvements can indeed favor the intensification of cultivation in Amazonia, but it cannot be assumed that this intensification will be 'sustainable' or 'ecological', neither that they would suit farmers' needs and resources. Inspired by ADE, management alternatives with the goal to improve soils in the long-term in Amazonia and favor intensification have been proposed, involving the incorporation of carbonized organic matter in the soil [e.g., 'slash-and-char' and 'biochar' (Glaser et al. 2002, Lehmann et al. 2002)]. For these technologies to actually contribute to local livelihoods and be useful models for sustainable agriculture (Glaser et al. 2007), they should

(1) take into account unintended consequences of soil fertility enhancement and intensification,

(2) evaluate how practices to create fertile soils (and cultivate them more intensively) suit the needs and resources of smallholder farmers, and

(3) favor more sustainable intensification pathways that optimize nutrient balances without increasing farmers' dependency on external inputs (pesticides, fertilizers) and compromising agrobiodiversity.

Text box 6.1. The watermelon case: unsustainable intensification of Amazonian Dark Earths?

The region of the middle and lower Madeira River is the largest producer of watermelon in Central Amazonia (IBGE 2012). Watermelon has been cultivated by smallholder farmers for decades, mainly on the fertile floodplains along the river, and together with banana and manioc it is today one of the most important cash-crops grown in the floodplains. Watermelon is considered by farmers an attractive cash-crop since it produces fast (90-120 days) and the market for it is generally guaranteed. On uplands, watermelon is cultivated almost exclusively on ADE (Fraser et al. 2011b); farmers say that it cannot be grown elsewhere. When growing it on ADE, farmers also take advantage of the fact that it can be produced earlier than on floodplains, and therefore can be sold for better prices.

I identified cases in which the prolonged (10-15 years) and intensive (i.e., cultivated every year, without a fallow period) cultivation of watermelon on ADE has led to a noticeable change in the structure and composition of the secondary vegetation, which became dominated by very aggressive herbs and spiny shrubs [e.g., 'limorana' (*Chomelia anisomeris* Müll. Arg.), 'malice' (*Mimosa* sp.)]. Farmers say that these areas are very difficult to manage (despite the lack of a fallow period, they still have to be opened every year) and, eventually, their cultivation becomes unfeasible. Farmers also mention that in the last couple of decades they have experienced several changes in how they grow watermelon on ADE, with the increasing use of 'improved' landraces (i.e., commercial varieties that they purchase in the market and/or are distributed by extension agencies) and of agrochemicals. While the vast majority of agriculture by smallholder farmers along the Madeira River is done with no or very little use of agrochemicals, the cultivation of watermelon involves the use of a large amount of pesticides and, more recently, of fertilizers.

The need to use fertilizers to grow watermelon on ADE seems controversial, but in fact it is a logical consequence of the prolonged and intensive use of these soils. While C, N and the soil organic matter can be maintained by input of plant-derived materials, maintaining enhanced levels of Ca, K, Mg and P requires further addition of materials (Glaser and Birk 2012). Also, some important nutrients for plant nutrition, such as K and N, are not necessarily higher in ADE than in surrounding soils (Lehmann et al. 2003b; Chapters 3 and 4) and might become limiting even if these soils still maintain high levels of other nutrients. Moreover, it is also possible that the frequent use of pesticides in watermelon cultivation negatively impacts the microbial community in the soil, which performs relevant functions for nutrient and carbon dynamics in ADE (Lehmann 2009).

The watermelon case can be seen as an example of unsustainable intensification of ADE. Stimulated by market demands and by extension institutions, farmers have progressively adopted technologies for the cultivation of watermelon on ADE that have mined soils, degraded fallows, and increased farmers' dependency on fertilizers and pesticides, posing threats to their health and to their economic security. Therefore, the potential of ADE to sustain more intensive cultivation and to grow more nutrient-demanding cash crops can also favor cultivation systems that are not well suited to the context of Amazonian smallholder farmers. In order to support more sustainable cultivation on ADE, environmental management projects and extension institutions should avoid stimulating conventional intensification pathways on these soils; instead, they should provide conditions (and assistance) for farmers to make use of the opportunities offered by ADE without degrading these soils (e.g., with proper nutrient management and/or with more perennial crops) and without increasing farmers' dependency on external inputs.

Amazonian Dark Earths and crop diversity

Beyond its intrinsic value, biodiversity plays important roles in agroecosystems, especially in low-input smallholder farming systems which rely more strongly on ecological processes associated with biodiversity (Jackson et al. 2007, Tscharntke et al. 2012). The actual contribution of plant diversity to the functioning of agroecosystems is highly variable and context-specific (Hajjar et al. 2008), and the relative role of potential mechanisms is a matter of debate (e.g., Swift et al. 2004). Still, it has increasingly been recognized that diverse agricultural landscapes are associated with important ecological processes, such as enhanced pest control, pollination and nutrient cycling (Tscharntke et al. 2005, Letourneau et al. 2011, Kremen and Miles 2012). In the context of smallholder farmers, growing a wide variety of crops and landraces allows them to deal better with market and environmental fluctuations, potentially enhancing their food and economic security (Frison et al. 2011, Di Falco 2012, Mijatović et al. 2012) and the overall social and ecological resilience of their agroecosystems (Lin 2011, Tscharntke et al. 2012). Smallholder cultivation systems in Amazonia have historically relied on a wide diversity of crops, but with the integration of rural populations in market economies, specialization in a limited number of crops is becoming increasingly common (e.g. Vadez et al. 2004, Steward 2013). Understanding the social and agro-ecological conditions that promote the maintenance of biodiverse cultivation systems in this context of rural change provides insights to guide policies aiming to conserve agrobiodiversity (Steward 2013) and its associated social and ecological benefits.

Farmers' opportunities and constraints to diversify their agroecosystems can be influenced by both socio-economic (e.g., market opportunities) and biophysical factors (e.g., soil quality and heterogeneity). The enhanced soil fertility of ADE favors the establishment of different species assemblages, including both cultivated and naturally-regenerating species. Previous studies have shown that under cultivation ADE show a different composition of weeds (Major et al. 2005b) and of crop species and landraces (Fraser et al. 2011b, Fraser et al. 2012) when compared with surrounding soils. Once fallowed, ADE also show differences in the composition of palms and trees in secondary forests (Junqueira et al. 2010b), and of understory plants in mature forests (Quintero-Vallejo et al. 2015). In this thesis, I have shown that the increase in soil fertility between adjacent soils and ADE are associated with an increase in the number of crop species and landraces cultivated, and, most importantly, with significant and gradual changes in crop assemblages, both in swiddens (Chapter 3) and in homegardens (Chapter 4).

These patterns show that the occurrence of ADE and the increased soil variation associated with these soils favor the diversification of cultivation by smallholder farmers. Farmers cultivate more species in more fertile soils, but to an even greater extent they cultivate *different* species in different soils, resulting in a higher diversity of crops cultivated at the farm level (and also in the whole landscape, since different farmers also use different soils). Therefore, it is the heterogeneity of soils – and not soil fertility per se – that allows farmers to grow a wider variety of crops, and to choose crop assemblages that suit their needs, resources and preferences. The management of the diversity of soils and crops by farmers results in a landscape with high diversity of crops (Table A6.1) and agroecosystems, with increased opportunities for farmers attaining food and economic security. In order to foster the diversification of cultivation systems in Amazonia, research and development interventions should support strategies that increase soil fertility and heterogeneity, and that incorporate farmers' knowledge and practices associated with different soils.

Our results also provide insights for understanding the role of ADE in past and present Amazonian agrobiodiversity. Given their close and long-term association with human settlements, ADE have likely been stages for the diversification of crops and cultivation practices since these soils started to be created. Their enhanced soil fertility might have provided advantages for the introduction of crops from outside Amazonia (e.g., maize, squash, beans) (Clement et al. 2003, Clement et al. 2009), and for the early domestication of native crops such as manioc (Arroyo-Kalin 2010). Other studies have pointed out that ADE act as agrobiodiversity reservoirs, by maintaining higher abundances of useful and domesticated species when compared with surrounding soils (Clement et al. 2003, Junqueira et al. 2010b, Junqueira et al. 2011). I show that today, the soil heterogeneity associated with ADE allows the cultivation of a more diverse species assemblage by smallholder farmers and increases agrobiodiversity in the landscape. Taken together, these results indicate that anthropogenic soils must receive special attention not only for their rich archaeological heritage, but also for the advantages they provide (and have provided in the past) for crop diversification and for the conservation of agrobiodiversity in smallholder cultivation systems.

Soil fertility, land-use patterns and the diversity of livelihood strategies

Given Amazonia's continental scale and its extraordinary ecological and socio-cultural diversity, livelihood and resource management strategies in the region are very heterogeneous. With their growing interaction with cities and markets, smallholder farmers in Amazonian are increasingly diversifying their array of livelihood activities [echoing trends in other tropical regions (Ellis 1998)], engaging more and more with market-oriented agriculture and plant management and/or with off-farm activities as sources of cash income (Steward 2007, 2013). Despite these generalizations, trends in smallholder agriculture in Amazonia are very context-specific, depending on local and regional economic drivers, infrastructure development, as well as on social, environmental and land-tenure policies (van Vliet et al.

2013). The diversity of livelihood strategies that we currently observe in rural Amazonia emerges from farmers' interactions with this dynamic socio-economic and biophysical environment. Understanding these interactions and the social, ecological and land-use outcomes of these different resource management strategies is crucial to support sustainable pathways for smallholder farming in Amazonia and elsewhere.

Soils play a key role in farmers' opportunities and constraints to attain food security and other livelihood objectives (Lal 2001). When making their land-use and cultivation decisions, farmers take soil quality into account, along with other available resources and opportunities (e.g., Ochoa-Gaona and González-Espinosa 2000, Moran et al. 2002, Vosti et al. 2002; Chapter 2). Differences in soil quality favor shifts in cultivation strategies and crop assemblages (Chapters 3 and 4), and may result in more or less land in cultivation and higher or lower deforestation rates (Witcover et al. 2006). Economic models of land-use systems in Amazonia have shown links between soil quality and deforestation, although with mixed results: some studies show that farmers with better soils open more areas (e.g., Pichón 1997, Soler and Verburg 2010), others have indicated that better soil quality slows deforestation (e.g., Andersen et al. 2002), while yet others show a limited or no effect of soils on deforestation patterns (e.g., Laurance et al. 2002, Witcover et al. 2006).

The idea that ADE are models for sustainable agriculture encompasses the argument that, being more fertile, these soils can sustain more intensive cultivation, reducing the need to open new areas (Glaser 2007). I showed that, at the plot level, the cultivation of ADE indeed is (and has been) more intensive, while ADE areas still show enhanced soil fertility levels (Chapter 3). However, in order to evaluate the extent to which the more intensive use of ADE at the plot level results in actual changes in land use (or deforestation) patterns, it is essential to analyze livelihoods at the household level, taking into account the availability of household resources (e.g., labor) and their different combinations/preferences of agricultural and non-agricultural activities. After all, it is the interaction between technologies, farmer characteristics and context that produces particular deforestation outcomes (Angelsen and Kaimowitz 2001).

In Chapter 5, I focused on the relationship between ADE and land use, testing the hypothesis that the use of ADE by smallholder farmers reduces their need to open areas for cultivation. I showed that farmers who cultivate larger areas are wealthier and are those with more available labor, with higher orientation towards commercial agriculture, and with (on average) poorer soils (Chapter 5, Table 5.3). However, I also found a significant interaction between labor and soil fertility, indicating that the relationship between soil fertility and area under cultivation was strongly influenced by the availability of labor at the household level. Farmers with access to the most fertile soils were also those with less labor available, suggesting that when labor-constrained, farmers tend to restrict their cultivation to more fertile areas (which are also closer to the houses; Chapter 3). Altogether, these results show that ADE can be incorporated in different ways in local livelihood strategies, resulting in different land-use patterns. Labor-constrained farmers tend to use smaller areas with very fertile soils, while those with more labor available and more commercial orientation open larger areas that may include or not ADE. These patterns show that the area used by farmers depends on the interaction between biophysical and socio-economic factors, challenging the assumption that increased soil fertility reduces the area needed for cultivation. While increased soil fertility can favor intensification at the plot level (Chapter 3), this does not necessarily translate into directional land-use changes: when farmers have access to ADE (and to more fertile soils in general), the (intensive) use of these soils is incorporated into a wider set of livelihood activities, including long-fallow shifting cultivation, extraction of forest/aquatic resources and off-farm activities.

Reducing forest conversion while enhancing ecosystem functions and supporting local livelihoods is a major goal and challenge for agriculture in Amazonia. Environmental management projects usually promote the replacement of shifting agriculture for more intensive or permanent cropping systems, with the aim to spare forests (Emperaire and Eloy 2015). By focusing on agricultural intensification alone, these projects often overlook the fact that rural populations in Amazonia rely on a diverse resource base, where agriculture is part of a larger economic strategy (encompassing several other activities, such as hunting, fishing, extraction/management of forest products, off-farm jobs, etc.), and where intensive and extensive cultivation may co-exist (Brondízio 2004). These initiatives also usually disregard local ecological knowledge and practices, promoting the reinvention of smallholder agriculture through ‘innovative’ technologies (Emperaire and Eloy 2015). Strategies that lead to enhanced and resilient soil fertility can favor more intensive cultivation and broaden farmers’ opportunities to attain their livelihood objectives. In order for these strategies to be effective in promoting sustainable agriculture in Amazonia and reducing forest conversion, they need to be co-developed with farmers incorporating their existing knowledge and practices, resources and needs, and should aim at increasing and not narrowing their opportunities for resource use and management.

Sustainable pathways for Amazonian Dark Earths

In this thesis, I have shown that cultivation systems on ADE are associated with specific knowledge, cultivation practices and agrobiodiversity, offering increased opportunities for farmers to intensify their cultivation systems and to grow a greater diversity of crops. Despite these advantages, I have also indicated that these soils can be associated with cultivation practices that can lead to environmental degradation and pose threats to local livelihoods (Text Box 6.1). It is relevant, therefore, to indicate future directions for research and development to support a more sustainable future for cultivation systems on ADE and, in a wider sense, for smallholder agriculture in Amazonia.

With farmers' increasing interaction with market economies, situations like the 'watermelon case' will likely become more common, particularly in peri-urban areas [as already happens in the vicinity of Manaus, for example; Hiraoka et al. (2003)]. In order to prevent that, extension institutions should avoid stimulating conventional intensification pathways on ADE that increase farmers' dependency on external inputs. Improved nutrient management is essential, and can be more easily achieved in perennial cultivation systems and/or with optimized fallow rotations. Crops that are better adapted to local conditions should also be favored, aiming to improve nutrient use efficiency and the control of pests and pathogens (thereby reducing the need for pesticides). Also, policies and institutions should promote more stable and diverse market opportunities so that farmers can opt for crops that suit their preferences and resources (e.g., labor availability, soil conditions) and reduce their vulnerability to market fluctuations.

Farmers in Amazonia have developed different strategies of resource use and management to deal with a context of increasing market access and urbanization (Emperaire and Eloy 2015). The use of ADE, for example, is highly variable within regions (e.g., this thesis) and between regions (e.g., Peña-Venegas et al. 2014). Initiatives aiming to improve local livelihoods and favor more sustainable pathways for development should make use of these different strategies, and not support single solutions that emphasize intensification as a replacement of the existing diversity of cultivation systems. Research and development strategies must be co-developed with farmers and incorporate local knowledge and practices, and the goals of environmental conservation must be weighed against benefits for local livelihoods.

The extent to which ADE (and technologies aiming to recreate some of the properties of these soils) are models for sustainable agriculture (Glaser 2007) is questionable. This thesis indicates that it cannot be assumed that the use of more fertile soils will be associated with sustainable cultivation, neither that it will reduce pressure on forests. Also, inputs and practices required for creating ADE-like soils and cultivating them more intensively may not always be available and/or suited to local livelihoods. On the other hand, this thesis has also shown that the soil *heterogeneity* associated with ADE increases the diversity of crops and agroecosystems, increasing farmers' opportunities to choose (and mix) crop assemblages and cultivation strategies that best suit their needs and resources. Initiatives aiming to promote sustainable pathways for agriculture in Amazonia will be more effective if they promote (and make use of) diversity of soils and of cultivation strategies.

Appendix 6

Table A6.1. Species and landraces sampled in 70 homegardens and 114 swiddens in 7 villages along the middle and lower Madeira River, Central Amazonia. The column 'Use' indicates the most important use for the species: 'med' = medicinal/magical, 'orn' = ornamental, 'fan' = food (annual / biannual), 'fpe' = food (perennial), 'tec' = technological, 'con' = construction, 'spo' = spontaneous (no use defined). NC="No ceramics", WC="With ceramics". Numbers are percentages, indicating the relative frequency of each species and landrace in each category. Numbers in parenthesis indicate the number of samples in each category.

Family	Scientific name	Use	Landrace	Homegardens			Swiddens		
				NC (29)	WC (41)	Total (70)	NC (70)	WC (44)	Total (104)
Acanthaceae	*Acanthaceae* sp.	med	Espanta-ladrão	3.4	2.4	2.9			
	Justicia calycina (Nees) V.A.W. Graham	med	Sara-tudo	3.4	9.8	7.1			
	Justicia pectoralis Jacq.	med	Remédio		2.4	1.4			
	Thunbergia grandiflora Roxb.	orn	No local name		2.4	1.4			
Amaranthaceae	*Alternanthera brasiliana* (L.) Kuntze	med	Terramicina	3.4	4.9	4.3			
	Amaranthus sp.	fan	Espinafre-do-Amazonas		2.4	1.4			
	Celosia argentea L.	orn	Crista-de-galo	6.9	7.3	7.1			
	Chenopodium ambrosioides L.	med	Mastruz	6.9	12.2	10.0			
	Gomphrena globosa L.	orn	Perpétua	3.4		1.4			
Amaryllidaceae	*Allium cepa* L.	fan	Cebola-brava		2.4	1.4			
	Eucharis sp.	med	Tajá		2.4	1.4			
Anacardiaceae	*Anacardium occidentale* L.	fpe		75.9	58.5	65.7	8.6		5.3
			Caju-amarelo	3.4	9.8	7.1			
			Caju-branco	51.7	19.5	32.9	8.6		5.3
			Caju-comum	31.0	19.5	24.3			
			Caju-da-campina						
			Caju-grande	3.4		1.4			
			Caju-vermelho	31.0	29.3	30.0	5.7		3.5
	Astronium lecointei Ducke	con	Muiracatiara		2.4	1.4			
	Mangifera indica L.	fpe		89.7	85.4	87.1	5.7	4.5	5.3
			Manga-clonada-IDAM		2.4	1.4			
			Manga-comum	72.4	75.6	74.3	2.9	2.3	2.6
			Manga-da-massa	3.4		1.4			
			Manga-espada	6.9		2.9			
			Manga-grande	13.8	4.9	8.6		2.3	0.9
			Manga-rosa	10.3	4.9	7.1			
			Manguií	20.7	19.5	20.0	5.7	2.3	4.4
	Spondias mombin L.	fpe	Taperebá	34.5	51.2	44.3		4.5	1.8
Annonaceae	*Annona glabra* L.	fpe	Ata	3.4	2.4	2.9			
	Annona montana Macfad.	fpe	Araticum		9.8	5.7			
	Annona mucosa Jacq.	fpe	Biribá	24.1	51.2	40.0			
	Annona muricata L.	fpe	Graviola	34.5	41.5	38.6	2.9	4.5	3.5
Apiaceae	*Eryngium foetidum* L.	fan	Chicória	10.3	7.3	8.6			
Apocynaceae	*Allamanda cathartica* L.	orn	Alamanda-amarela		4.9	2.9			
	Ambelania acida Aubl.	fpe	Pepino-do-mato	3.4	2.4	2.9			
	Catharanthus roseus (L.) G. Don	orn	No local name		2.4	1.4			
	Couma cf. *guianensis* Aubl.	tec	Sorva-do-mato		2.4	1.4			
	Couma utilis (Mart.) Müll. Arg.	tec	Sorvinha	3.4	2.4	2.9			
	Himatanthus articulatus (Vahl) Woodson	med	Sucuúba	13.8	2.4	7.1			
	Lacmellea gracilis (Müll. Arg.) Markgr.	tec	Jacataca	3.4	2.4	2.9			
	Plumeria pudica Jacq.	orn	Buquê-de-noiva	3.4	12.2	8.6			
	Tabernaemontana divaricata (L.) R. Br. ex Roem. & Schult.	spo	No local name	3.4		1.4			
	Thevetia peruviana K. Schum.	orn	Castanha-da-Índia	3.4	2.4	2.9			
Araceae	*Caladium bicolor* (Aiton) Vent.	med	Tajá		2.4	1.4			

Family	Scientific name	Use	Landrace	Homegardens NC (29)	Homegardens WC (41)	Homegardens Total (70)	Swiddens NC (70)	Swiddens WC (44)	Swiddens Total (104)
	Dieffenbachia seguine (Jacq.) Schott	med	Comigo-ninguém-pode		2.4	1.4			
	Xanthosoma sagittifolium (L.) Schott	fan	Mangarito				2.9		1.8
Araliaceae	*Polyscias fruticosa* (L.) Harms	med	Árvore-da-feilcidade		12.2	7.1			
	Polyscias guilfoylei (W. Bull) L.H. Bailey	orn	Taperebazinho		2.4	1.4			
	Polyscias scutellaria (Burm. f.) Fosberg	orn	Cuia-mansa		12.2	7.1			
Arecaceae	*Astrocaryum aculeatum* G. Mey.	fpe	Tucumã	58.6	34.1	44.3	2.9		1.8
	Astrocaryum murumuru Mart.	fpe	Murumuru		19.5	11.4		2.3	0.9
	Attalea maripa (Aubl.) Mart.	fpe	Inajá	3.4	2.4	2.9			
	Attalea phalerata Mart. ex Spreng.	fpe	Urucuri		24.4	14.3			
	Attalea speciosa Mart. ex Spreng.	fpe	Babaçu		7.3	4.3			
	Bactris gasipaes Kunth	fpe		65.5	41.5	51.4	1.4	4.5	2.6
			Pupunha-amarela	24.1	17.1	20.0	1.4	2.3	1.8
			Pupunha-branca	3.4		1.4			
			Pupunha-comum	51.7	26.8	37.1		2.3	0.9
			Pupunha-verde				1.4		0.9
			Pupunha-vermelha	17.2	26.8	22.9	1.4		0.9
	Cocos nucifera L.	fpe		41.4	65.9	55.7		2.3	0.9
			Coco-amarelo	3.4	22.0	14.3			
			Coco-comum	37.9	43.9	41.4		2.3	0.9
			Coco-verde		19.5	11.4			
	Elaeis oleifera (Kunth) Cortés	fpe	Caiaué	24.1	31.7	28.6		2.3	0.9
	Euterpe oleracea Mart.	fpe		72.4	48.8	58.6	5.7	6.8	6.1
			Açaí-do-Pará	69.0	43.9	54.3	5.7	4.5	5.3
			Açaí-do-Pará-verde	17.2	22.0	20.0	4.3	2.3	3.5
	Euterpe precatoria Mart.	fpe	Açaí-da-mata	44.8	43.9	44.3	1.4	9.1	4.4
	Mauritia flexuosa L. f.	fpe	Buriti	6.9	7.3	7.1			
	Oenocarpus bacaba Mart.	fpe	Bacaba	10.3	7.3	8.6			
	Oenocarpus bataua Mart.	fpe	Patauá	3.4		1.4			
	Oenocarpus minor Mart.	fpe	Bacabinha	75.9	56.1	64.3	5.7	2.3	4.4
Aristolochiaceae	*Aristolochia* sp.	med	Uecá	3.4	9.8	7.1			
Asparagaceae	*Agave angustifolia* Haw.	orn	No local name		7.3	4.3			
	Cordyline fruticosa (L.) A. Chev.	orn	Capa-rosa	3.4	2.4	2.9			
	Dracaena fragrans (L.) Ker Gawl.	orn	No local name		2.4	1.4			
	Sansevieria trifasciata Thunb.	med	Espada-de-São-Jorge		7.3	4.3			
Asteraceae	*Acmella oleracea* (L.) R.K. Jansen	fan	Jambú	10.3	17.1	14.3			
	Asteraceae sp.	med	Japanã-do-reino		2.4	1.4			
	Ayapana triplinervis (Vahl) R.M. King & H. Rob.	med	Japanã-branca		2.4	1.4			
	Gymnanthemum amygdalinum (Delile) Sch. Bip. ex Walp.	med	Boldo		7.3	4.3			
	Lactuca sativa L.	fan	Alface	3.4		1.4			
	Pluchea cf. *sagittalis* (Lam.) Cabrera	med	Macela		2.4	1.4			
	Stevia rebaudiana (Bertoni) Bertoni	tec	Adoçante		2.4	1.4			
	Tagetes erecta L.	orn	Cravo		4.9	2.9			
	Vernonanthura cf. *brasiliana* (L.) H. Rob.	med	No local name	3.4		1.4			
Bignoniaceae	*Crescentia cujete* L.	tec		41.4	51.2	47.1			
			Cuia-comum	41.4	48.8	45.7			
			Cuia-ferro		2.4	1.4			
			Cuia-graúda		4.9	2.9			
			Cuia-miúda		4.9	2.9			
	Fridericia chica (Bonpl.) L.G. Lohmann	med	Crajiru	10.3	14.6	12.9			
	Jacaranda copaia (Aubl.) D. Don	con	Parapará		2.4	1.4			
	Mansoa alliacea (Lam.) A.H. Gentry	med	Cipó-d'alho	10.3	9.8	10.0			

Family	Scientific name	Use	Landrace	Homegardens NC (29)	Homegardens WC (41)	Homegardens Total (70)	Swiddens NC (70)	Swiddens WC (44)	Swiddens Total (104)
Bixaceae	*Bixa* cf. *arborea* Huber	tec	Urucum-da-mata	3.4		1.4			
	Bixa orellana L.	fpe	Urucum	24.1	22.0	22.9			
	Cochlospermum orinocense (Kunth) Steud.	tec	Periquiteira	3.4		1.4			
Brassicaceae	*Brassica oleracea* L.	fan	Couve	6.9	2.4	4.3			
Bromeliaceae	*Ananas comosus* (L.) Merr.	fan		34.5	36.6	35.7	20.0	18.2	19.3
			Abacaxi-cabeça-de-onça	6.9	2.4	4.3			
			Abacaxi-comum	17.2	17.1	17.1	5.7	6.8	6.1
			Abacaxi-liso	6.9	12.2	10.0	12.9	4.5	9.6
			Abacaxi-redondo					2.3	0.9
			Abacaxi-roxo-liso	3.4	2.4	2.9	1.4		0.9
			Abacaxi-roxo-serra	3.4		1.4			
			Abacaxi-serra	10.3	17.1	14.3	5.7	6.8	6.1
Cactaceae	*Cereus jamacaru* DC.	orn	Jamacaru	10.3	2.4	5.7			
	Cereus sp.	orn	Cacto		2.4	1.4			
	Pereskia aculeata Mill.	orn	Espinheira-santa	3.4	4.9	4.3			
	Pereskia grandifolia Haw.	orn	Rosa-madeira		2.4	1.4			
Calophyllaceae	*Mammea americana* L.	fpe	Abricó	3.4	2.4	2.9			
Caricaceae	*Carica papaya* L.	fpe		31.0	56.1	45.7		15.9	6.1
			Mamão-comum	27.6	56.1	44.3		13.6	5.3
			Mamão-Havaí	10.3	7.3	8.6		2.3	0.9
	Jacaratia digitata (Poepp. & Endl.) Solms	fpe	Mamão-de-cachorro		2.4	1.4			
Caryocaraceae	*Caryocar villosum* (Aubl.) Pers.	fpe	Piquiá	6.9	4.9	5.7			
Clusiaceae	*Garcinia madruno* (Kunth) Hammel	fpe	Bacuri-de-espinho	3.4		1.4			
	Platonia insignis Mart.	fpe	Bacuri	17.2	12.2	14.3			
Combretaceae	*Terminalia catappa* L.	orn	Castanholeira		2.4	1.4			
Commelinaceae	*Tradescantia spathacea* Sw.	orn	Roxa	3.4	2.4	2.9			
Convolvulaceae	*Evolvulus nummularius* (L.) L.	orn	No local name		4.9	2.9			
	Ipomoea batatas (L.) Lam.	fan		10.3		4.3	1.4	2.3	1.8
			Batata-doce-branca	3.4		1.4	1.4		0.9
			Batata-doce-comum	6.9		2.9		2.3	0.9
Crassulaceae	*Kalanchoe pinnata* (Lam.) Pers.	med	Escama-de-pirarucu	3.4	22.0	14.3			
	Kalanchoe sp.	med	No local name		2.4	1.4			
Cucurbitaceae	*Citrullus lanatus* (Thunb.) Matsum. & Nakai	fan	Melancia	3.4	2.4	2.9	1.4	2.3	1.8
	Cucumis anguria L.	fan	Maxixe	10.3		4.3	4.3	6.8	5.3
	Cucumis melo L.	fan	Melão					6.8	2.6
	Cucumis sativus L.	fan	Pepino					4.5	1.8
	Cucurbita moschata Duchesne	fan	Abobrinha	3.4	2.4	2.9	2.9	13.6	7.0
	Cucurbita pepo L.	fan	Jerimum	10.3	12.2	11.4	1.4		0.9
	Luffa cylindrica (L.) M. Roem.	med	Buchinha		2.4	1.4			
Cycadaceae	*Cycas revoluta* Thunb.	orn	Cica		4.9	2.9			
Cyperaceae	*Cyperus articulatus* L.	med	Priprioca	3.4	7.3	5.7			
Dioscoreaceae	*Dioscorea* sp.	fan	Carauaçu				1.4	2.3	1.8
	Dioscorea trifida L. f.	fan		3.4	7.3	5.7	32.9	25.0	29.8
			Cará-branco				15.7	9.1	13.2
			Cará-comum	3.4	7.3	5.7	1.4		0.9
			Cará-pé-de-anta					4.5	1.8
			Cará-pombo					2.3	0.9
			Cará-roxo				30.0	18.2	25.4
Euphorbiaceae	*Acalypha brasiliensis* Müll. Arg.	tec	Marmeleiro		2.4	1.4			
	Acalypha sp.	tec	No local name		2.4	1.4			
	Codiaeum variegatum (L.) Rumph. ex A. Juss.	orn		3.4	22.0	14.3			
			No local name	3.4	9.8	7.1			
			No local name		14.6	8.6			
	Euphorbia milii Des Moul.	orn	Coroa-de-cristo	3.4	2.4	2.9			
	Euphorbia tirucalli L.	orn	Aveloz	3.4		1.4			
	Hevea brasiliensis (Willd. ex A. Juss.) Müll. Arg.	tec	Seringueira	55.2	51.2	52.9	4.3		2.6
	Jatropha curcas L.	med	Pinhão-branco	20.7	36.6	30.0			
	Jatropha gossypiifolia L.	med	Pinhão-roxo	27.6	43.9	37.1			

Family	**Scientific name**	**Use**	**Landrace**	**Homegardens** NC (29)	**Homegardens** WC (41)	**Homegardens** Total (70)	**Swiddens** NC (70)	**Swiddens** WC (44)	**Swiddens** Total (104)
	Jatropha podagrica Hook.	orn	Pinhão-barrigudo		2.4	1.4			
	Manihot esculenta Crantz (bitter)	fan		6.9	4.9	5.7	97.1	45.5	77.2
			Açaízinha					2.3	0.9
			Álvaro				5.7		3.5
			Amarelinha				18.6	2.3	12.3
			Amarelona				1.4	4.5	2.6
			Ararinha				1.4		0.9
			Arauari				2.9		1.8
			Arroz				10.0	2.3	7.0
			Arrozinho					4.5	1.8
			Aruari				2.9		1.8
			Árvore-branca				1.4		0.9
			Azulona				11.4	11.4	11.4
			Baixinha				1.4	6.8	3.5
			Batatinha				5.7		3.5
			Branquinha				10.0	2.3	7.0
			Cabral				4.3		2.6
			Caçarola				1.4		0.9
			Capão				2.9		1.8
			Castanha					2.3	0.9
			Comprida				2.9		1.8
			Comum		2.4	1.4	17.1	4.5	12.3
			Curuari				15.7	6.8	12.3
			Escama-de-pirarucu		2.4	1.4			
			Faianca				8.6		5.3
			Flecha				5.7		3.5
			Folha-fina				2.9		1.8
			Galhadinha				4.3		2.6
			Guia-roxa				2.9		1.8
			Jabuti				15.7	9.1	13.2
			Jabuti-de-ouro				4.3		2.6
			Jabutirana				10.0		6.1
			Jabutizinho				4.3		2.6
			Janauacá				4.3		2.6
			Jaraqui				2.9		1.8
			Jijú				4.3		2.6
			Jijuzinha				1.4		0.9
			Mãe-luca				2.9		1.8
			Maniva-branca					2.3	0.9
			Maniva-da-Lindalva				2.9		1.8
			Maniva-do-Élcio				1.4		0.9
			Maniva-do-Piauí				2.9		1.8
			Maria-bonita				1.4		0.9
			Mata-porco				1.4	2.3	1.8
			No local name				2.9		1.8
			Nova-Olinda				18.6		11.4
			Ova-de-aruanã	3.4		1.4	7.1		4.4
			Papiniana				12.9	4.5	9.6
			Paraíso				10.0		6.1
			Pirarucu				5.7	4.5	5.3
			Pirarucu-amarelo	3.4		1.4	10.0	6.8	8.8
			Pirarucu-branco				1.4		0.9
			Pretona				10.0	2.3	7.0
			Roxa				2.9		1.8
			Roxinha				1.4	2.3	1.8
			Sempre-serve				11.4		7.0
			Seu-Severino				1.4		0.9
			Tambaqui				1.4		0.9
			Tartaruga				12.9	2.3	8.8
			Tartaruguinha				1.4	4.5	2.6
			Tauazinha	3.4		1.4	8.6		5.3
			Tico-baco					2.3	0.9
			Tiririca				5.7		3.5
			Tracajá				15.7	6.8	12.3
			Uruari				1.4		0.9
			Vermelhinha				1.4		0.9

Family	Scientific name	Use	Landrace	Homegardens NC (29)	Homegardens WC (41)	Homegardens Total (70)	Swiddens NC (70)	Swiddens WC (44)	Swiddens Total (104)
	Manihot esculenta Crantz (sweet)	fan		6.9	24.4	17.1	21.4	27.3	23.7
			Branca	6.9	2.4	4.3			
			Casca-roxa				1.4	13.6	6.1
			Comum	3.4	17.1	11.4	12.9		7.9
			Macaxeira-acreana				1.4		0.9
			Macaxeira-manteiga				7.1	4.5	6.1
			Macaxeira-pão		2.4	1.4	2.9	4.5	3.5
			Macaxeira-Peruana				2.9	4.5	3.5
			Macaxeira-roxa		2.4	1.4			
			Macaxeira-tuqui					6.8	2.6
	Ricinus communis L.	orn	Mamona	3.4		1.4			
Fabaceae	*Arachis repens* Handro	orn	Amendoim-forrageiro	3.4	4.9	4.3			
	Caesalpinia ferrea Mart. ex Tul.	med	Jucá	6.9	9.8	8.6			
	Cassia leiandra Benth.	fpe	Mari-mari	17.2		7.1			
	Clitoria fairchildiana R.A. Howard	tec	Sombreiro	3.4	4.9	4.3			
	Diplotropis cf. *purpurea* (Rich.) Amshoff	con	Sucupira		2.4	1.4			
	Dipteryx odorata (Aubl.) Willd.	con	Cumaru		2.4	1.4			
	Erythrina variegata L.	orn	Brasileirinho		2.4	1.4			
	Hymenaea courbaril L.	med	Jutaí	6.9	17.1	12.9			
	Indigofera suffruticosa Mill.	tec	Anil		2.4	1.4			
	Inga cf. *cinnamomea* Spruce ex Benth.	fpe	Ingá-chato	17.2	14.6	15.7			
	Inga cf. *vera* Willd.	fpe	Ingá-pequeno	10.3	4.9	7.1			
	Inga edulis Mart.	fpe	Ingá-de-metro	69.0	41.5	52.9	1.4	4.5	2.6
	Inga sp.1	fpe	Ingá-da-capoeira		2.4	1.4			
	Inga sp.2	fpe	Ingá	3.4		1.4			
	Inga sp.3	fpe	Ingá-peludo		2.4	1.4			
	Inga sp.4	fpe	Ingá	3.4		1.4			
	Inga sp.5	fpe	Ingá-da-mata		2.4	1.4			
	Ormosia sp.	orn	Flamenguista	3.4		1.4			
	Phaseolus vulgaris L.	fan	Feijão-comum		2.4	1.4		2.3	0.9
	Schizolobium parahyba (Vell.) S.F. Blake	con	São-João		2.4	1.4			
	Senna multijuga (Rich.) H.S. Irwin & Barneby	tec	No local name	3.4		1.4			
	Senna occidentalis (L.) Link	spo	Fedegoso	3.4		1.4			
	Senna reticulata (Willd.) H.S. Irwin & Barneby	spo	Mata-pasto		2.4	1.4			
	Swartzia sp.	spo	Fava		2.4	1.4			
	Vigna unguiculata (L.) Walp.	fan		10.3		4.3	1.4	6.8	3.5
			Feijão-da-praia-branco	10.3		4.3		2.3	0.9
			Feijão-da-praia-vermelho				1.4	4.5	2.6
Icacinaceae	*Poraqueiba sericea* Tul.	fpe	Umari	3.4	2.4	2.9			
Iridaceae	*Eleutherine bulbosa* (Mill.) Urb.	med	Batatinha		4.9	2.9			
Lamiaceae	*Aeollanthus suaveolens* Mart. ex Spreng.	orn	Catinga-de-mulata	3.4	2.4	2.9			
	Clerodendrum splendens G. Don	orn	Sangue-de-Cristo		2.4	1.4			
	Leonotis nepetifolia (L.) R. Br.	med	Cordão-de-frade		4.9	2.9			
	Mentha spicata L.	fan	Hortelã-comum	3.4	7.3	5.7			
	Mesosphaerum suaveolens (L.) Kuntze	med		10.3		4.3			
			Sálvia	6.9		2.9			
			Sálvia-de-cheiro	3.4		1.4			
	Ocimum basilicum L.	fan	Alfavaca-manjericão	17.2	9.8	12.9			
	Ocimum campechianum Mill.	fan	Alfavaca	17.2	17.1	17.1			
	Plectranthus amboinicus (Lour.) Spreng.	fan	Hortelã-grande	3.4	7.3	5.7			
	Plectranthus barbatus Andrews	med	Boldo	3.4	12.2	8.6			
	Plectranthus scutellarioides	med	No local name	3.4		1.4			

Family	Scientific name	Use	Landrace	Homegardens NC (29)	Homegardens WC (41)	Homegardens Total (70)	Swiddens NC (70)	Swiddens WC (44)	Swiddens Total (104)
	(L.) R. Br.								
Lauraceae	*Aniba rosaeodora* Ducke	con	Pau-rosa		2.4	1.4			
	Lauraceae sp.	con	Pau-bravo		2.4	1.4			
	Licaria puchury-major (Mart.) Kosterm.	med	Puxuri		2.4	1.4	1.4		0.9
	Mezilaurus itauba (Meinsn.) Taub ex Mez	con	Itaúba	3.4		1.4			
	Persea americana Mill.	fpe		51.7	61.0	57.1	4.3	6.8	5.3
			Abacate-azul	6.9	12.2	10.0			
			Abacate-azul-bicudo		2.4	1.4			
			Abacate-caiana	3.4	7.3	5.7			
			Abacate-comum	37.9	39.0	38.6	2.9	6.8	4.4
			Abacate-de-quilo	17.2		7.1	5.7	2.3	4.4
			Abacate-paulista		4.9	2.9			
			Abacate-pequeno	3.4	2.4	2.9			
			Abacate-roxo	10.3	14.6	12.9			
			Abacate-roxo-bicudo		2.4	1.4			
			Abacate-verde-bicudo	3.4	4.9	4.3			
Lecythidaceae	*Bertholletia excelsa* Bonpl.	fpe	Castanheira	55.2	14.6	31.4	2.9	4.5	3.5
	Gustavia augusta L.	tec	Genipaporana		2.4	1.4			
	Lecythis pisonis Cambess.	con	Castanha-sapucaia	3.4		1.4			
Lythraceae	*Cuphea* sp.	orn	No local name	10.3	4.9	7.1			
	Lagerstroemia indica L.	orn	Resedá		9.8	5.7			
	Punica granatum L.	med	Romã		2.4	1.4			
Malpighiaceae	*Byrsonima* Rich. ex Kunth	fpe	Murici	6.9		2.9			
	Malpighia emarginata DC.	fpe	Acerola	24.1	29.3	27.1			
Malvaceae	*Apeiba tibourbou* Aubl.	tec	Oicima	6.9	2.4	4.3			
	Ceiba pentandra (L.) Gaertn.	tec	Samaúma		4.9	2.9			
	Gossypium barbadense L.	tec		13.8	12.2	12.9			
			Algodão-branco	6.9	2.4	4.3			
			Algodão-roxo	6.9	9.8	8.6			
	Guazuma ulmifolia Lam.	tec	Mutambo		4.9	2.9			
	Herrania mariae (Mart.) Decne. ex Goudot	fpe	Cacau-de-quina	13.8	46.3	32.9			
	Hibiscus acetosella Welw. ex Hiern	med	Caboclo-roxo	6.9	4.9	5.7			
	Hibiscus esculentus L.	fan		3.4		1.4		4.5	1.8
			Quiabo-comum	3.4		1.4		4.5	1.8
			Quiabo-redondo					2.3	0.9
	Hibiscus rosa-sinensis L.	orn		6.9	31.7	21.4			
			Pampolha-branca		7.3	4.3			
			Pampolha-comum	6.9	31.7	21.4			
			Pampolha-pintada	3.4	2.4	2.9			
	Hibiscus sabdariffa L.	fan	Vinagreira	20.7	7.3	12.9			
	Theobroma cacao L.	fpe		37.9	56.1	48.6	1.4	18.2	7.9
			Cacau-comum	34.5	56.1	47.1	1.4	13.6	6.1
			Cacau-da-Bahia	6.9	7.3	7.1		4.5	1.8
	Theobroma grandiflorum (Willd. ex Spreng.) K. Schum.	fpe	Cupuaçu	86.2	73.2	78.6			
	Theobroma speciosum Willd. ex Spreng.	fpe	Cacaurana	24.1	12.2	17.1	5.7		3.5
	Theobroma subincanum Mart.	fpe	Cupuí	3.4		1.4			
Marantaceae	*Calathea* sp.1	med	Ressurreição		2.4	1.4			
	Calathea sp.2	med	Puraquê		2.4	1.4			
	Goeppertia allouia (Aubl.) Borchs. & S. Suárez	fan	Ariá		9.8	5.7	4.3	4.5	4.4
	Marantaceae sp.	med	Vai-e-vem		2.4	1.4			
Melastomataceae	*Bellucia grossularioides* (L.) Triana	tec	Muúba		2.4	1.4			
	Tibouchina heteromalla (D. Don) Cogn.	orn	Orelha-de-onça		4.9	2.9			
Meliaceae	*Carapa guianensis* Aubl.	med	Andiroba	10.3	12.2	11.4			
	Guarea cf. *grandiflora* Decne. ex Steud.	con	Jataúba		2.4	1.4			
	Melia azedarach L.	orn	No local name		2.4	1.4			
Menispermaceae	*Abuta grandifolia* (Mart.) Sandwith	med	Abuta	3.4		1.4			
Moraceae	*Artocarpus altilis* (Parkinson)	fpe	Fruta-pão		19.5	11.4		2.3	0.9

Family	Scientific name	Use	Landrace	Homegardens NC (29)	Homegardens WC (41)	Homegardens Total (70)	Swiddens NC (70)	Swiddens WC (44)	Swiddens Total (104)
	Fosberg								
	Artocarpus heterophyllus Lam.	fpe	Jaca	20.7	22.0	21.4		2.3	0.9
	Brosimum sp.	spo	No local name	3.4		1.4			
	Ficus benjamina L.	orn	Benjamim		9.8	5.7			
	Ficus cf. *carica* L.	spo	Figueira	3.4		1.4			
	Ficus cf. *citrifolia* Mill.	spo	Apuí-da-capoeira		2.4	1.4			
	Ficus sp.1	spo	Apuí		2.4	1.4			
	Ficus sp.2	spo	No local name		2.4	1.4			
	Ficus sp.3	spo	Apuí	3.4		1.4			
	Morus nigra L.	fpe	Amora		2.4	1.4			
Musaceae	*Musa paradisiaca* L.	fan		65.5	75.6	71.4	30.0	40.9	34.2
			Banana-azul				1.4		0.9
			Banana-baixota	6.9	12.2	10.0	1.4	4.5	2.6
			Banana-branca	6.9		2.9			
			Banana-comum	10.3	9.8	10.0			
			Banana-costela-de-vaca		4.9	2.9			
			Banana-da-Neide	3.4		1.4			
			Banana-de-cheiro		2.4	1.4			
			Banana-duas-palmas		2.4	1.4			
			Banana-engana-ladrão				1.4		0.9
			Banana-inajá	10.3	7.3	8.6	1.4	4.5	2.6
			Banana-inajá-clonada				2.9		1.8
			Banana-maçã		12.2	7.1	10.0	4.5	7.9
			Banana-maçã-clonada		2.4	1.4			
			Banana-missora		4.9	2.9	1.4		0.9
			Banana-pacovão	41.4	46.3	44.3	25.7	13.6	21.1
			Banana-pacovi	3.4		1.4			
			Banana-prata	20.7	34.1	28.6	11.4	29.5	18.4
			Banana-prata-clonada	17.2	17.1	17.1	1.4	2.3	1.8
			Banana-pratão		2.4	1.4			
			Banana-São-Tomé-branca		2.4	1.4			
			Banana-São-Tomé-cruz		2.4	1.4			
			Banana-São-Tomé-roxa	6.9	12.2	10.0		2.3	0.9
Myristicaceae	*Virola* cf. *theiodora* (Spruce ex Benth.) Warb.	tec	Ucuúba		2.4	1.4			
Myrtaceae	*Eugenia stipitata* McVaugh	fpe	Araçá-boi	6.9	9.8	8.6			
	Eugenia uniflora L.	fpe	Pitanga	3.4	7.3	5.7			
	Plinia trunciflora (O. Berg) Kausel	fpe	Jabuticaba		2.4	1.4			
	Psidium acutangulum DC.	fpe	Goiaba-araçá	17.2	26.8	22.9			
	Psidium guajava L.	fpe		82.8	75.6	78.6		2.3	0.9
			Goiaba-branca	17.2	17.1	17.1			
			Goiaba-comum	48.3	41.5	44.3			
			Goiaba-vermelha	41.4	51.2	47.1		2.3	0.9
	Psidium sp.	fpe	Goiaba-da-mata	3.4		1.4			
	Syzygium cumini (L.) Skeels	fpe	Azeitona	27.6	34.1	31.4			
	Syzygium malaccense (L.) Merr. & L.M. Perry	fpe	Jambo-comum	34.5	56.1	47.1			
	Syzygium sp.	fpe	Jambo-branco					2.3	0.9
Ochnaceae	*Lacunaria jenmanii* (Oliv.) Ducke	fpe	Papo-de-mutum	3.4		1.4			
Orchidaceae	*Orchidaceae* sp.1	orn	Orquídea		4.9	2.9			
	Orchidaceae sp.2	orn	Orquídea		2.4	1.4			
Oxalidaceae	*Averrhoa bilimbi* L.	fpe	Limão-caiena		9.8	5.7			
	Averrhoa carambola L.	fpe	Carambola		9.8	5.7			
	Oxalis triangularis A. St-Hil.	orn	Trevo-roxo	3.4		1.4			
Passifloraceae	*Passiflora* cf. *quadrangularis* L.	fpe	Maracujá-graúdo	3.4		1.4			
	Passiflora edulis Sims	fpe	Maracujá	10.3	14.6	12.9		4.5	1.8
	Passiflora nitida Kunth	fpe	Maracujá-do-mato	3.4	2.4	2.9			
Pedaliaceae	*Sesamum indicum* L.	fan	Gergelim	17.2		7.1			

Family	Scientific name	Use	Landrace	Homegardens NC (29)	Homegardens WC (41)	Homegardens Total (70)	Swiddens NC (70)	Swiddens WC (44)	Swiddens Total (104)
Phyllanthaceae	*Phyllanthus niruri* L.	med	Quebra-pedra		4.9	2.9			
Phytolaccaceae	*Petiveria alliacea* L.	med	Mucura-caá	3.4	12.2	8.6			
Pinaceae	*Pinus* sp.	orn	Pinheiro		2.4	1.4			
Piperaceae	*Piper nigrum* L.	fan	Pimenta-do-reino		7.3	4.3			
	Piper peltatum L.	med	Capeba		22.0	12.9			
Plantaginaceae	*Scoparia dulcis* L.	med	Vassourinha	3.4		1.4			
Poaceae	*Chrysopogon zizanioides* (L.) Roberty	med	Patchuli	3.4		1.4			
	Coix lacryma-jobi L.	med	Lágrima-de-Nossa-Senhora	3.4	2.4	2.9			
	Cymbopogon citratus (DC.) Stapf	med	Capim-cheiroso	17.2	41.5	31.4			
	Cymbopogon nardus (L.) Rendle	med	Citronela		2.4	1.4			
	Gynerium sagittatum (Aubl.) P. Beauv.	tec	Cana-flecha		2.4	1.4			
	Saccharum officinarum L.	fan		10.3	17.1	14.3	17.1	9.1	14.0
			Cana-branca	6.9	4.9	5.7	11.4	6.8	9.6
			Cana-caiana					2.3	0.9
			Cana-comum	3.4		1.4			
			Cana-de-açúcar		14.6	8.6	7.1		4.4
			Cana-roxa				8.6		5.3
			Cana-taboca				1.4		0.9
			Cana-vermelha	3.4		1.4			
	Zea mays L.	fan		3.4		1.4	2.9	29.5	13.2
			Milho-cavalo					9.1	3.5
			Milho-comum	3.4		1.4	2.9	20.5	9.6
Portulacaceae	*Portulaca grandiflora* Hook.	med	Onze-horas	3.4	4.9	4.3			
	Portulaca pilosa L.	med	Amor-crescido	6.9	4.9	5.7			
	Portulaca sp.	med	Beldroega					4.5	1.8
Primulaceae	*Myrsine guianensis* (Aubl.) Kuntze	spo	Pororoca	3.4		1.4			
Rosaceae	*Rosa* sp.	orn			14.6	8.6			
			Rosa		12.2	7.1			
			Rosa-graúda		2.4	1.4			
Rubiaceae	*Alibertia edulis* (Rich.) A. Rich. ex DC.	fpe	Puruí	41.4	19.5	28.6			
	Coffea canephora Pierre ex A. Froehner	fpe		37.9	34.1	35.7		4.5	1.8
			Café-comum	3.4		1.4		4.5	1.8
			Café-do-campo	31.0	31.7	31.4			
			Café-moca	6.9	9.8	8.6			
	Genipa americana L.	fpe	Genipapo	13.8	26.8	21.4			
	Ixora coccinea L.	orn	No local name	6.9	4.9	5.7			
	Morinda citrifolia L.	med	Noni	20.7	34.1	28.6			
	Uncaria guianensis (Aubl.) J.F. Gmel.	med	Unha-de-gato		2.4	1.4			
Rutaceae	*Citrus aurantiifolia* (Christm.) Swingle	fpe		72.4	75.6	74.3		2.3	0.9
			Limão-comum	62.1	70.7	67.1		4.5	1.8
			Limão-Tahiti		2.4	1.4			
			Limãozinho	17.2	4.9	10.0			
	Citrus cf. *limettioides* Tanaka	fpe	Lima	10.3	43.9	30.0			
	Citrus medica L.	fpe	Limão-cidra	24.1	7.3	14.3			
	Citrus reticulata Blanco	fpe		37.9	61.0	51.4			
			Tangerina-comum	37.9	56.1	48.6			
			Tangerina-Paulista		2.4	1.4			
			Tangerina-ponkan		4.9	2.9			
	Citrus x *aurantium* L.	fpe		55.2	80.5	70.0	2.9	11.4	6.1
			Laranja-comum	41.4	68.3	57.1	1.4	6.8	3.5
			Laranja-da-terra	3.4	31.7	20.0			
			Laranja-da-sina	17.2	22.0	20.0	1.4	2.3	1.8
			Laranja-paulista		2.4	1.4		2.3	0.9
	Citrus x *limonia* L.	fpe	Limão-tangerina	34.5	31.7	32.9		4.5	1.8
	Murraya paniculata (L.) Jack	orn	Jasmim-caiana		2.4	1.4			
	Ruta graveolens L.	med	Arruda	6.9	7.3	7.1			
	Zanthoxylum huberi P.G. Waterman	spo	Tamanqueiro		2.4	1.4			

Family	Scientific name	Use	Landrace	Homegardens			Swiddens		
				NC (29)	WC (41)	Total (70)	NC (70)	WC (44)	Total (104)
Sapindaceae	*Nephelium lappaceum* L.	fpe	Rambutan		2.4	1.4			
	Paullinia cupana Kunth	fpe	Guaraná				2.9		1.8
	Talisia esculenta (A. St.-Hil.) Radlk.	fpe	Pitomba	20.7	41.5	32.9		2.3	0.9
Sapotaceae	*Manilkara bidentata* (A. DC.) A. Chev.	con	Massaranduba	3.4		1.4			
	Pouteria caimito (Ruiz & Pav.) Radlk.	fpe		51.7	24.4	35.7			
			Abiu-comum	48.3	24.4	34.3			
			Abiu-graúdo	3.4		1.4			
Simaroubaceae	*Quassia amara* L.	med	Quina		7.3	4.3			
Solanaceae	*Capsicum frutescens* L.	fan		24.1	26.8	25.7	4.3	2.3	3.5
			Pimenta-malagueta	24.1	24.4	24.3	2.9	2.3	2.6
			Pimenta-malagueta-amarela				1.4		0.9
			Pimenta-malaguetão	6.9	4.9	5.7			
	Capsicum annuum var. *annuum*	fan	Pimentão	6.9	2.4	4.3		2.3	0.9
	Capsicum annuum var. *glabriusculum* (Dunal) Heiser & Pickersgill	fan	Pimenta-de-mesa	3.4	4.9	4.3			
	Capsicum cf. *baccatum* L.	fan	Pimenta-crista-de-galo	3.4		1.4			
	Capsicum chinense Jacq.	fan		41.4	61.0	52.9	10.0	11.4	10.5
			Pimenta-chumbinho	6.9	12.2	10.0	1.4	2.3	1.8
			Pimenta-comum	3.4		1.4			
			Pimenta-de-cheiro	31.0	39.0	35.7	7.1	4.5	6.1
			Pimenta-doce	3.4	4.9	4.3			
			Pimenta-doce-amarela	3.4		1.4			
			Pimenta-doce-cheirosa		2.4	1.4			
			Pimenta-doce-vermelha	3.4		1.4			
			Pimenta-do-IDAM	3.4		1.4			
			Pimenta-Josefa	3.4		1.4			
			Pimenta-laranja	3.4		1.4			
			Pimenta-murupi	6.9	9.8	8.6	2.9	2.3	2.6
			Pimenta-ova-de-aruanã		2.4	1.4			
			Pimenta-queimosa	6.9	17.1	12.9		2.3	0.9
			Pimenta-umbigo-de-nó	3.4		1.4			
	Nicotiana tabacum L.	fan	Tabaco					6.8	2.6
	Solanum americanum Mill.	med	Malva-mura		4.9	2.9			
	Solanum lycopersicum L.	fan		24.1	9.8	15.7	1.4	2.3	1.8
			Tomate-azedo		2.4	1.4			
			Tomate-comprido	3.4		1.4			
			Tomate-comum	3.4	2.4	2.9	1.4	2.3	1.8
			Tomate-de-quilo	10.3	2.4	5.7			
			Tomate-grão-de-gato	3.4		1.4			
			Tomate-liso		2.4	1.4			
			Tomate-mão-de-onça		2.4	1.4			
			Tomate-Paulista	6.9		2.9			
			Tomate-pequeno	3.4		1.4			
	Solanum sessiliflorum Dunal	fan	Cubiu	6.9	4.9	5.7			
Talinaceae	*Talinum paniculatum* (Jacq.) Gaertn.	fan	Cariru-selvagem		4.9	2.9		4.5	1.8
	Talinum triangulare (Jacq.) Willd.	fan	Cariru	13.8	2.4	7.1		2.3	0.9
Urticaceae	*Cecropia* sp.	spo	Embaúba	3.4	4.9	4.3			
	Pourouma cecropiifolia Mart.	fpe	Mapati		2.4	1.4			
Verbenaceae	*Duranta erecta* L.	orn	Pingo-de-ouro		4.9	2.9			
	Lantana camara L.	orn			4.9	2.9			
			Lantana-amarela		2.4	1.4			
			Lantana-branca		2.4	1.4			
	Lippia alba (Mill.) N.E. Br. ex Britton & P. Wilson	med	Sálvia-de-Marajó	13.8	19.5	17.1			
	Lippia sp.	orn	No local name	3.4		1.4			

Family	Scientific name	Use	Landrace	Homegardens NC (29)	Homegardens WC (41)	Homegardens Total (70)	Swiddens NC (70)	Swiddens WC (44)	Swiddens Total (104)
Vitaceae	*Vitis vinifera* L.	fpe		3.4	4.9	4.3			
			Uva-roxa	3.4	2.4	2.9			
			Uva-verde		2.4	1.4			
Xanthorrhoeaceae	*Aloe vera* (L.) Burm. f.	med	Babosa	10.3	7.3	8.6			
Zingiberaceae	*Alpinia speciosa* (Blume) D. Dietr.	med	Vindicá		4.9	2.9			
	Zingiber officinale Roscoe	fan	Mangarataia	10.3	14.6	12.9	8.6	2.3	6.1
Indet	Indet	tec	Sabugueiro	3.4		1.4			

References

Adams, C., R. Murrieta, W. Neves, and M. Harris, editors. 2009. *Amazon peasant societies in a changing environment: political ecology, invisibility and modernity in the rainforest.* Springer, New York, USA.

Albuquerque, U. P., L. H. C. Andrade, and J. Caballero. 2005. Structure and floristics of homegardens in Northeastern Brazil. *Journal of Arid Environments* 62(3): 491-506.

Almekinders, C. J. M., L. O. Fresco, and P. C. Struik. 1995. The need to study and manage variation in agro-ecosystems. *Netherlands Journal of Agricultural Science* 43: 127-142.

Altieri, M. A. 2004. Linking ecologists and traditional farmers in the search for sustainable agriculture. *Frontiers in Ecology and the Environment* 2(1): 35-42.

Altieri, M. A., and C. I. Nicholls. 2004. An agroecological basis for designing diversified cropping systems in the tropics. *Journal of Crop Improvement* 11(1-2): 81-103.

Alvares, C. A., J. L. Stape, P. C. Sentelhas, J. L. de Moraes Gonçalves, and G. Sparovek. 2013. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* 22(6): 711-728.

Andersen, L. E., C. W. J. Granger, E. J. Reis, D. Weinhold, and S. Wunder. 2002. *The dynamics of deforestation and economic growth in the Brazilian Amazon.* Cambridge University Press, Cambridge, UK.

Angelsen, A., and D. Kaimowitz, editors. 2001. *Agricultural technologies and tropical deforestation.* CABI Publishing / Center for International Forestry Research (CIFOR), Wallingford, UK.

Arroyo-Kalin, M. 2010. The Amazonian formative: crop domestication and anthropogenic soils. *Diversity* 2(4): 473-504.

Balée, W. 2006. The research program of Historical Ecology. *Annual Review of Anthropology* 35(1): 75-98.

Balée, W. L., and C. L. Erickson. 2006. *Time and complexity in historical ecology: studies in the neotropical lowlands.* Columbia University Press, New York, USA.

Barlow, J., T. A. Gardner, A. C. Lees, L. Parry, and C. A. Peres. 2011. 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.

Barton, K. 2013. MuMIn: multi-model inference. R package version 1.9.0. http://CRAN.R-project.org/package=MuMIn.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2014. lme4: linear mixed-effect models using Eigen and S4. R package version 1.1-7. http://CRAN.R-project.org/package=lme4.

Behrens, C. A. 1989. The scientific basis for Shipibo soil classification and land use: changes in soil-plant associations with cash cropping. *American Anthropologist* 91(1): 83-100.

Berkes, F., J. Colding, and C. Folke. 2003. Introduction. Pages 1-29 *in* F. Berkes, J. Colding, and C. Folke, editors. *Navigating social-ecological systems: building resilience for complexity and change*. Cambridge University Press, Cambridge, UK.

Boserup, E. 1965. *The conditions of agricultural growth: the economics of agrarian change under population pressure.* George Allen & Unwin Ltd., London, UK.

Brondízio, E. 2004. Agriculture intensification, economic identity, and shared invisibility in Amazonian peasantry: caboclos and colonists in comparative perspective. *Culture & Agriculture* 26(1-2): 1-24.

Brouwer, J., L. K. Fussell, and L. Herrmann. 1993. Soil and crop growth micro-variability in the West African semi-arid tropics: a possible risk-reducing factor for subsistence farmers. *Agriculture Ecosystems & Environment* 45(3–4): 229-238.

Brown, C. B., and W. Lidstone. 1878. *Fifteen thousand miles on the Amazon and its tributaries.* Edward Stanford, London, UK.

Castro, F. 2009. Patterns of resource use by caboclo communities in the middle-lower Amazon. Pages 157-177 *in* C. Adams, R. Murrieta, W. Neves, and M. Harris, editors. *Amazon peasant societies in a changing environment: political ecology, invisibility and modernity in the rainforest.* Springer, New York, USA.

Castro, M., and B. Singer. 2012. Agricultural settlement and soil quality in the Brazilian Amazon. *Population and Environment* 34(1): 22-43.
Caviglia-Harris, J. L., and E. O. Sills. 2005. Land use and income diversification: comparing traditional and colonist populations in the Brazilian Amazon. *Agricultural Economics* 32(3): 221-237.
Chao, A., R. L. Chazdon, R. K. Colwell, and T.-J. Shen. 2005. A new statistical approach for assessing similarity of species composition with incidence and abundance data. *Ecology Letters* 8(2): 148-159.
Chauvel, A., Y. Lucas, and R. Boulet. 1987. On the genesis of the soil mantle of the region of Manaus, Central Amazonia, Brazil. *Experimentia* 43: 234-241.
Chikuvire, T. J., S. Mpepereki, and R. Foti. 2007. Soil fertility variability in sandy soils and implications for nutrient management by smallholder farmers in Zimbabwe. *Journal of Sustainable Agriculture* 30(2): 69-87.
Clarke, L., L. Li, G. D. Jenerette, and Z. Yu. 2014. Drivers of plant biodiversity and ecosystem service production in home gardens across the Beijing Municipality of China. *Urban Ecosystems* 17(3): 741-760.
Clarke, W. C. 1976. Maintenance of agriculture and human habitats within the tropical forest ecosystem. *Human Ecology* 4(3): 247-259.
Clement, C. R., and A. B. Junqueira. 2010. Between a pristine myth and an impoverished future. *Biotropica* 42(5): 534-536.
Clement, C. R., M. P. Klüppel, L. A. German, S. S. Almeida, J. Major, L. E. Aragão, J. C. Guix, E. Lleras, A. Winklerprins, S. B. Hecht, and J. M. McCann. 2009. Diversidade vegetal em solos antrópicos da Amazônia. Pages 146-161 *in* W. Teixeira, D. Kern, B. Madari, H.N. Lima, and W. Woods, editors. *As Terras Pretas de Índio da Amazônia: sua caracterização e uso deste conhecimento na criação de novas áreas*. Embrapa Amazônia Ocidental, Manaus, Brazil.
Clement, C. R., J. M. McCann, and N. J. H. Smith. 2003. Agrobiodiversity in Amazônia and its relationships with Dark Earths. Pages 159-178 *in* J. Lehmann, D. Kern, B. Glaser, and W. Woods, editors. *Amazonian Dark Earths - origin, properties and management*. Kluwer Academic Publisher, Dordrecht, Netherlands.
Conklin, H. C. 1961. The Study of Shifting Cultivation. *Current Anthropology* 2(1): 27-61.
Coomes, O. T., and N. Ban. 2004. Cultivated plant species diversity in home gardens of an Amazonian peasant village in northeastern Peru. *Economic Botany* 58(3): 420-434.
Coomes, O. T., F. Grimard, and G. J. Burt. 2000. Tropical forests and shifting cultivation: secondary forest fallow dynamics among traditional farmers of the Peruvian Amazon. *Ecological Economics* 32(1): 109-124.
Cramb, R. A. 2005. Farmers' strategies for managing acid upland soils in Southeast Asia: an evolutionary perspective. *Agriculture, Ecosystems & Environment* 106(1): 69-87.
Cramb, R. A., C. P. Colfer, W. Dressler, P. Laungaramsri, Q. Le, E. Mulyoutami, N. Peluso, and R. Wadley. 2009. Swidden transformations and rural livelihoods in southeast Asia. *Human Ecology* 37(3): 323-346.
Cristo-Araújo, M., V. M. Reis, D. Picanço-Rodrigues, and C. R. Clement. 2013. Domestication of Peach Palm in southwestern Amazonia. *Tipití: Journal of the Society for the Anthropology of Lowland South America* 11(2): 74-80.
Dalle, S. P., and S. de Blois. 2006. Shorter fallow cycles affect the availability of noncrop plant resources in a shifting cultivation system. *Ecology and Society* 11(2): 2.
Davidson, E. A., A. C. de Araujo, P. Artaxo, J. K. Balch, I. F. Brown, M. M. C. Bustamante, M. T. Coe, R. S. DeFries, M. Keller, M. Longo, J. W. Munger, W. Schroeder, B. S. Soares-Filho, C. M. Souza, and S. C. Wofsy. 2012. The Amazon basin in transition. *Nature* 481(7381): 321-328.
de Rouw, A. 1995. The fallow period as a weed-break in shifting cultivation (tropical wet forests). *Agriculture Ecosystems & Environment* 54(1-2): 31-43.
Denevan, W. M. 1984. Ecological heterogeneity and horizontal zonation of agriculture in the Amazon floodplain. Pages 311-336 *in* M. Schmink, and C.H. Wood, editors. *Frontier Expansion in Amazonia*. University of Florida Press, Gainesville, USA.

Denevan, W. M. 1992. Native American populations in 1492: recent research and a revised hemispheric estimate. Pages 17-37 *in* W.M. Denevan, editor *The native population of the Americas in 1492*. University of Wisconsin Press, Madison, USA.

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., and C. Padoch. 1987. Introduction: the Bora agroforestry project. Pages 8-46 *in* W.M. denevan, and C. Padoch, editors. *Swidden fallow agroforestry in the Peruvian Amazon*. The New York Botanical Garden, New York.

Denevan, W. M., J. M. Treacy, J. B. Alcorn, C. Padoch, J. S. Denslow, and S. F. Paitan. 1984. Indigenous agroforestry in the Peruvian Amazon: Bora indian management of swidden fallows. *Interciencia* 9(6): 346-357.

Di Falco, S. 2012. On the value of agricultural biodiversity. *Annual Review of Resource Economics* 4(1): 207-223.

Eden, M. J. 1974. Ecological aspects of development among Piaroa and Guahibo indians of the upper Orinoco basin. *Antropológica* 39: 25-56.

Ellis, F. 1998. Household strategies and rural livelihood diversification. *The Journal of Development Studies* 35(1): 1-38.

Elmqvist, T., C. Folke, M. Nyström, G. Peterson, J. Bengtsson, B. Walker, and J. Norberg. 2003. Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment* 1(9): 488-494.

EMBRAPA. 2011. *Manual de métodos de análise de solo*. Empresa Brasileira de Pesquisa Agropecuária, Centro Nacional de Pesquisa de Solos, Rio de Janeiro, Brazil.

Emperaire, L., and L. Eloy. 2015. Amerindian agriculture in an urbanising Amazonia (Rio Negro, Brazil). *Bulletin of Latin American Research* 34(1): 70-84.

Erickson, C. L. 2008. Amazonia: the Historical Ecology of a domesticated landscape. Pages 157-183 *in* H. Silverman, and W.H. Isbell, editors. *The Handbook of South American Archaeology*. Springer New York,

Erickson, C. L. 2010. The transformation of environment into landscape: the Historical Ecology of monumental earthwork construction in the Bolivian Amazon. *Diversity* 2(4): 618-652.

Evenson, R. E., and D. Gollin. 2003. Assessing the impact of the Green Revolution, 1960 to 2000. *Science* 300(5620): 758-762.

Falesi, I. C. 1972. O estado atual dos conhecimentos sobre os solos da Amazônia Brasileira. *IPEAN Boletim Técnico* 54: 17-67.

Faria, J. 1946. *A cerâmica da tribo Uaboí dos rios Trombetas e Jamundá.* Imprensa Nacional, Rio de Janeiro, Brasil.

Fearnside, P. M. 2005. Deforestation in Brazilian Amazonia: history, rates, and consequences. *Conservation Biology* 19(3): 680-688.

Feintrenie, L., S. Schwarze, and P. Levang. 2010. Are local people conservationists? Analysis of transition dynamics from agroforests to monoculture plantations in Indonesia. *Ecology and Society* 15(4): 37.

Finegan, B., and R. Nasi. 2004. The biodiversity and conservation potential of shifting cultivation landscapes. Pages 151-197 *in* G. Schroth, G.A.B.d. Fonseca, C.A. Harvey, C. Gascon, H.L. Vasconcelos, and A.-M.N. Izac, editors. *Agroforestry and biodiversity conservation in tropical landscapes*. Island Press, Washington, USA.

Franco, E. C. 1962. As 'terras pretas' do planalto de Santarém. *Revista da Sociedade dos Agrônomos e Veterinários do Pará* 8: 17-21.

Fraser, J., T. Cardoso, A. Junqueira, N. P. S. Falcão, and C. R. Clement. 2009. Historical Ecology and Dark Earths in whitewater and blackwater landscapes: comparing the middle Madeira and lower Negro rivers. Pages 229-264 *in* W.I. Woods, W.G. Teixeira, J. Lehmann, C. Steiner, A. WinklerPrins, and L. Rebellato, editors. *Amazonian Dark Earths: Wim Sombroek's Vision*. Springer Netherlands,

Fraser, J., A. B. Junqueira, and C. Clement. 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.

Fraser, J., A. B. Junqueira, N. Kawa, C. Moraes, and C. Clement. 2011b. Crop diversity on Anthropogenic Dark Earths in central Amazonia. *Human Ecology* 39(4): 395-406.

Fraser, J., W. Teixeira, N. Falcão, W. Woods, J. Lehmann, and A. B. Junqueira. 2011c. Anthropogenic soils in the Central Amazon: from categories to a continuum. *Area* 43(3): 264-273.

Fraser, J. A. 2010a. Caboclo horticulture and Amazonian Dark Earths along the middle Madeira River, Brazil. *Human Ecology* 38(5): 651-662.

Fraser, J. A. 2010b. The diversity of bitter manioc (*Manihot esculenta* Crantz) cultivation in a whitewater Amazonian landscape. *Diversity* 2(4): 586-609.

Fraser, J. A., A. Alves-Pereira, A. B. Junqueira, N. Peroni, and C. R. Clement. 2012. Convergent adaptations: bitter manioc cultivation systems in fertile anthropogenic dark earths and floodplain soils in central Amazonia. *PLoS ONE* 7(8): 1-13.

Fraser, J. A., and C. R. Clement. 2008. Dark Earths and manioc cultivation in central Amazonia: a window on pre-Columbian agricultural systems? *Boletim do Museu Paraense Emilio Goeldi, Ciências Humanas* 3(2): 175-194.

Frikel, P. 1959. Agricultura dos índios Munduruku. *Boletim do Museu Goeldi, Antropologia* 4: 1-35.

Frikel, P. 1968. Os Xikrin. *Publicações Avulsas do Museu Goeldi* 7: 3-119.

Frison, E. A., J. Cherfas, and T. Hodgkin. 2011. Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. *Sustainability* 3: 238-253.

Futemma, C. 2009. The use of and access to forest resources: the caboclos of the lower Amazon and their socio-cultural attributes. Pages 215-237 *in* C. Adams, R. Murrieta, W. Neves, and M. Harris, editors. *Amazon peasant societies in a changing environment: political ecology, invisibility and modernity in the rainforest*. Springer, New York, USA.

Gajaseni, J., and N. Gajaseni. 1999. Ecological rationalities of the traditional homegarden system in the Chao Phraya Basin, Thailand. *Agroforestry Systems* 46(1): 3-23.

Geist, H. J., and E. F. Lambin. 2002. Proximate causes and underlying driving forces of tropical deforestation. *BioScience* 52(2): 143.

German, L. 2003a. Ethnoscientific understandings of Amazonian Dark Earths. Pages 179-201 *in* J. Lehmann, D. Kern, B. Glaser, and W. Woods, editors. *Amazonian Dark Earths - origin, properties and management*. Kluwer Academics Publisher, Dordrecht, The Netherlands.

German, L. A. 2003b. Historical contingencies in the coevolution of environment and livelihood: contributions to the debate on Amazonian Black Earth. *Geoderma* 111: 307-331.

German, L. A. 2004. Ecological praxis and blackwater ecosystems: a case study from the Brazilian Amazon. *Human Ecology* 32(6): 653-683.

Glaser, B. 2007. Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century. *Philosophical Transactions of the Royal Society: Biological Sciences* 362(1478): 187-196.

Glaser, B., and J. J. Birk. 2012. State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). *Geochimica et Cosmochimica Acta* 82: 39-51.

Glaser, B., L. Haumaier, G. Guggenberger, and W. Zech. 2001. The "Terra Preta" phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften* 88: 37-41.

Glaser, B., J. Lehmann, and W. Zech. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. *Biology and Fertility of Soils* 35(4): 219-230.

Godar, J., T. A. Gardner, E. J. Tizado, and P. Pacheco. 2014. Actor-specific contributions to the deforestation slowdown in the Brazilian Amazon. *Proceedings of the National Academy of Sciences, USA* 111(43): 15591-15596.

Godfray, H. C. J., J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas, and C. Toulmin. 2010. Food security: the challenge of feeding 9 billion people. *Science* 327(5967): 812-818.

Godoy, R., V. Reyes-García, V. Vadez, W. R. Leonard, S. Tanner, T. Huanca, and D. Wilkie. 2009. The relation between forest clearance and household income among native Amazonians: results from the Tsimane' Amazonian panel study, Bolivia. *Ecological Economics* 68(6): 1864-1871.

Gourou, P. 1949. Observações geográficas na Amazônia. *Revista Brasileira de Geografia* 3: 335-408.

Gray, C. L., R. E. Bilsborrow, J. L. Bremner, and F. Lu. 2007. Indigenous land use in the Ecuadorian Amazon: a cross-cultural and multilevel analysis. *Human Ecology* 36(1): 97-109.

Hajjar, R., D. I. Jarvis, and B. Gemmill-Herren. 2008. The utility of crop genetic diversity in maintaining ecosystem services. *Agriculture, Ecosystems & Environment* 123(4): 261-270.

Hames, R. 1983. Monoculture, polyculture, and polyvariety in tropical forest swidden cultivation. *Human Ecology* 11(1): 13-34.

Heckenberger, M. J., A. Kuikuro, U. T. Kuikuro, J. C. Russel, M. Schmidt, C. Fausto, and B. Franchetto. 2003. Amazonia 1492: pristine forest or cultural parkland? *Science* 301: 1710-1714.

Heckenberger, M. J., J. C. Russel, J. R. Toney, and M. J. Schmidt. 2007. The legacy of cultural landscapes in the Brazilian Amazon: implications for biodiversity. *Philosophical Transactions of the Royal Society: Biological Sciences* 362: 197-208.

Hilbert, P. 1955. A cerâmica arqueológica da região de Oriximiná. *Publicação do Instituto de Antropologia e Etnologia do Pará* 9: 1-76.

Hiraoka, M., S. Yamamoto, E. Matsumoto, S. Nakamura, I. Falesi, and A. R. C. Baena. 2003. Contemporary use and management of Amazonian Dark Earths. Pages 387-406 *in* J. Lehmann, D. Kern, B. Glaser, and W. Woods, editors. *Amazonian Dark Earths: Origin, Properties, Management*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Holliday, V. T., and W. G. Gartner. 2007. Methods of soil P analysis in archaeology. *Journal of Archaeological Science* 34(2): 301-333.

Hölscher, D., B. Ludwig, R. F. Möller, and H. Fölster. 1997. Dynamic of soil chemical parameters in shifting agriculture in the Eastern Amazon. *Agriculture, Ecosystems & Environment* 66(2): 153-163.

IBGE (2010) *Mapa de solos do estado do Amazonas*: Instituto Brasileiro de Geografia e Estatística. Available at: http://mapas.ibge.gov.br/tematicos/solos (Accessed: 3/3/2015).

IBGE (2011) *Sinopse do censo demográfico 2010*: Instituto Brasileiro de Geografia e Estatística. Available at: http://www.ibge.gov.br/home/estatistica/populacao/censo2010/default.shtm (Accessed: 3/3/2015).

IBGE (2012) *Produção agrícola municipal: culturas temporárias e permanentes*. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística, Departamento de Agropecuária. Available at: http://www.ibge.gov.br/home/estatistica/economia/pam/2012/default.shtm (Accessed: 6/6/2015).

INMET (2015) *Banco de dados meterológicos para ensino e pesquisa*: Instituto Nacional de Meteorologia. Available at: http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep (Accessed: 3/3/2015).

Jackson, L. E., U. Pascual, and T. Hodgkin. 2007. Utilizing and conserving agrobiodiversity in agricultural landscapes. *Agriculture Ecosystems & Environment* 121(3): 196-210.

Jakovac, C. C., M. Peña-Claros, T. W. Kuyper, and F. Bongers. 2015. Loss of secondary-forest resilience by land-use intensification in the Amazon. *Journal of Ecology* 103(1): 67-77.

Jeffery, S., T. M. Bezemer, G. Cornelissen, T. W. Kuyper, J. Lehmann, L. Mommer, S. P. Sohi, T. F. J. van de Voorde, D. A. Wardle, and J. W. van Groenigen. 2015. The way forward in biochar research: targeting trade-offs between the potential wins. *GCB Bioenergy* 7(1): 1-13.

Johnson, P. C. D. 2014. Extension of Nakagawa & Schielzeth's R2GLMM to random slopes models. *Methods in Ecology and Evolution* 5(9): 944-946.

Junk, W. J., and M. T. F. Piedade. 2010. An introduction to South American wetland forests: distribution, definitions and general characterization. Pages 3-26 *in* W.J. Junk, M.T.F. Piedade, F. Wittmann, J. Schöngart, and P. Parolin, editors. *Amazonian floodplain forests: ecophysiology, biodiversity and sustainable management*. Springer, Dordrecht, The Netherlands.

Junk, W. L., P. B. Bayley, and R. E. Sparks 'The flood pulse concept in river-floodplain systems'. *Proceedings of the International Large River Symposium*: Canadian Special Publication of Fisheries and Aquatic Sciences, 110-12.

Junqueira, A. B., N. Kawa, J. A. Fraser, and C. R. Clement. 2010a. Explorando a relação entre agrobiodiversidade e solos antrópicos no médio Rio Madeira, Amazonas, Brasil. Pages 137-160 *in* L.C. Ming, M.C.M. Amorozo, and C.W. Kffuri, editors. *Agrobiodiversidade no Brasil: experiências e caminhos da pesquisa*. NUPEEA, Recife.

Junqueira, A. B., G. Shepard, and C. Clement. 2011. 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.

Junqueira, A. B., G. H. Shepard, and C. R. Clement. 2010b. Secondary forests on anthropogenic soils in Brazilian Amazonia conserve agrobiodiversity. *Biodiversity and Conservation* 19(7): 1933-1961.

Kawa, N., J. Clavijo Michelangeli, and C. Clement. 2015. Household agrobiodiversity management on Amazonian dark earths, oxisols, and floodplain soils on the lower Madeira river, Brazil. *Human Ecology* 32(2): 339-353.

Kawa, N. C., and A. Oyuela-Caycedo. 2008. Amazonian Dark Earth: a model of sustainable agriculture of the past and future? *The International Journal of Environmental, Cultural, Economic & Social Sustainability* 4(3): 9-16.

Kawa, N. C., D. Rodrigues, and C. R. Clement. 2011. Useful species richness, proportion of exotic species, and market orientation on Amazonian Dark Earths and oxisols. *Economic Botany* 65(2): 169-177.

Kehlenbeck, K., H. S. Arifin, and B. L. Maass. 2007. Plant diversity in homegardens in a socio-economic and agro-ecological context. Pages 297-319 *in* T. Tscharntke, C. Leuschner, M. Zeller, E. Guhardja, and A. Bidin, editors. *The stability of tropical rainforest margins, linking ecological, economic and social constraints of land use and conservation*. Springer Verlag, Berlin.

Kehlenbeck, K., and B. L. Maass. 2004. Crop diversity and classification of homegardens in Central Sulawesi, Indonesia. *Agroforestry Systems* 63(1): 53-62.

Kern, D., G. D'aquino, T. Rodrigues, F. Frazao, W. Sombroek, T. Myers, and E. Neves. 2003. Distribution of Amazonian dark earths in the Brazilian Amazon. Pages 51-75 *in* J. Lehmann, D. Kern, B. Glaser, and W. Woods, editors. *Amazonian Dark Earths - origin, properties and management*. Kluwer Academics Publisher, Dordrecht, Netherlands.

Klüppel, M. P. (2006) *Sistemas agrícolas e plantas medicinais em Terras Pretas de Índio da Amazônia Central.* MSc. Dissertation, INPA / UFAM, Manaus, Brazil.

Kremen, C., and A. Miles. 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecology and Society* 17(4): 40.

Kumar, B. M., and P. K. R. Nair. 2004. The enigma of tropical homegardens. *Agroforestry Systems* 61-62(1-3): 135-152.

Laboski, C. A. M., R. H. Dowdy, R. R. Allmaras, and J. A. Lamb. 1998. Soil strength and water content influences on corn root distribution in a sandy soil. *Plant and Soil* 203(2): 239-247.

Lal, R. 2001. Managing world soils for food security and environmental quality. *Advances in Agronomy* 74: 155-192.

Lambin, E. F., B. L. Turner, H. J. Geist, S. B. Agbola, A. Angelsen, J. W. Bruce, O. T. Coomes, R. Dirzo, G. Fischer, C. Folke, P. S. George, K. Homewood, J. Imbernon, R. Leemans, X. Li, E. F. Moran, M. Mortimore, P. S. Ramakrishnan, J. F. Richards, H. Skånes, W. Steffen, G. D. Stone, U. Svedin, T. A. Veldkamp, C. Vogel, and J. Xu. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change* 11(4): 261-269.

Laurance, W. F., A. K. M. Albernaz, G. Schroth, P. M. Fearnside, S. Bergen, E. M. Venticinque, and C. Da Costa. 2002. Predictors of deforestation in the Brazilian Amazon. *Journal of Biogeography* 29(5-6): 737-748.

Laurance, W. F., M. A. Cochrane, S. Bergen, P. M. Fearnside, P. Delamônica, C. Barber, S. D'Angelo, and T. Fernandes. 2001. The future of the Brazilian Amazon. *Science* 291(5503): 438-439.

Lehmann, J. 2009. Terra preta Nova – where to from here? Pages 473-486 *in* W. Woods, W. Teixeira, J. Lehmann, C. Steiner, A. WinklerPrins, L. Rebellato, and J. Lehmann, editors. *Amazonian Dark Earths: Wim Sombroek's Vision*. Springer, Dordrecht, The Netherlands.

Lehmann, J., J. P. J. Da Silva, M. Rondon, C. M. Da Silva, J. Greenwood, T. Nehls, C. Steiner, and B. Glaser 'Slash-and-char: a feasible alternative for soil fertility management in the Central Amazon?'. *17th World Congress of Soil Sciences*, Thailand, 14-21 August, 2002.

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

Lehmann, J., D. Kern, l. German, J. McCann, G. C. Martins, and A. Moreira. 2003b. Soil fertility and production potential. Pages 105-124 *in* J. Lehmann, D. Kern, B. Glaser, and W. Woods, editors. *Amazonian Dark Earths - origin, properties and management*. Kluwer Academics Publisher, Dordrecht, Netherlands.

Letourneau, D. K., I. Armbrecht, B. S. Rivera, J. M. Lerma, E. J. Carmona, M. C. Daza, S. Escobar, V. Galindo, C. Gutierrez, S. D. Lopez, J. L. Mejia, A. M. Rangel, J. H. Rangel, L. Rivera, C. A. Saavedra, A. M. Torres, and A. R. Trujillo. 2011. Does plant diversity benefit agroecosystems? A synthetic review. *Ecological Applications* 21(1): 9-21.

Levis, C., M. S. Silva, M. A. Silva, C. P. Moraes, E. K. Tamanaha, B. M. Flores, E. G. Neves, and C. R. Clement. 2014. What do we know about the distribution of Amazonian Dark Earth along tributary rivers in central Amazonia? Pages 305-311 *in* S. Rostain, editor *Antes de Orellana: actas del 3er encuentro internacional de arqueología Amazónica*. Instituto Francés de Estudios Andinos, Quito, Ecuador.

Levis, C., P. F. d. Souza, J. Schietti, T. Emilio, J. L. P. d. V. Pinto, C. R. Clement, and F. R. C. Costa. 2012. Historical human footprint on modern tree species composition in the Purus-Madeira interfluve, central Amazonia. *PLoS ONE* 7(11): e48559.

Lin, B. B. 2011. Resilience in agriculture through crop diversification: adaptive management for environmental change. *BioScience* 61(3): 183-193.

Lins, J., H. P. Lima, F. B. Baccaro, V. F. Kinupp, G. H. Shepard, Jr., and C. R. Clement. 2015. Pre-Columbian floristic legacies in modern homegardens of central Amazonia. *PLoS ONE* 10(6): e0127067.

Lombardo, U., and H. Prümers. 2010. Pre-Columbian human occupation patterns in the eastern plains of the Llanos de Moxos, Bolivian Amazonia. *Journal of Archaeological Science* 37(8): 1875-1885.

López, S., and R. Sierra. 2011. A resource demand model of indigenous production: the Jivaroan cultivation systems of Western Amazonia. *Agricultural Systems* 104(3): 246-257.

Luizão, R. C. C., F. J. Luizão, R. Q. Paiva, T. F. Monteiro, L. S. Sousa, and B. Kruijt. 2004. Variation of carbon and nitrogen cycling processes along a topographic gradient in a central Amazonian forest. *Global Change Biology* 10(5): 592-600.

Major, J., C. R. Clement, and A. DiTommaso. 2005a. 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.

Major, J., A. diTommaso, L. German, and J. McCann. 2003. Weed population dynamics and management on amazonian dark earth. Pages 433-454 *in* J. Lehmann, D. Kern, B. Glaser, and W. Woods, editors. *Amazonian Dark Earths - origin, properties and management*. Kluwer Academics Publisher, Dordrecht, Netherlands.

Major, J., A. Ditommaso, J. Lehmann, and N. Falcao. 2005b. Weed dynamics on Amazonian Dark Earth and adjacent soils of Brazil. *Agriculture, Ecosystems & Environment* 111(1-4): 1-12.

Marquardt, K., R. Milestad, and R. Porro. 2012. Farmers' perspectives on vital soil-related ecosystem services in intensive swidden farming systems in the Peruvian Amazon. *Human Ecology* 41(1): 139-151.

Matson, P. A., W. J. Parton, A. G. Power, and M. J. Swift. 1997. Agricultural intensification and ecosystem properties. *Science* 277(5325): 504-509.

McCusker, B., and E. R. Carr. 2006. The co-production of livelihoods and land use change: case studies from South Africa and Ghana. *Geoforum* 37(5): 790-804.

McKey, D., S. Rostain, J. Iriarte, B. Glaser, J. J. Birk, I. Holst, and D. Renard. 2010. Pre-Columbian agricultural landscapes, ecosystem engineers, and self-organized patchiness in Amazonia. *Proceedings of the National Academy of Sciences* 107(17): 7823-7828.

McMichael, C. H., M. W. Palace, M. B. Bush, B. Braswell, S. Hagen, E. G. Neves, M. R. Silman, E. K. Tamanaha, and C. Czarnecki. 2014. Predicting pre-Columbian anthropogenic soils in Amazonia. *Proceedings of the Royal Society B* 281(1777): 20132475.

McMichael, C. H., D. R. Piperno, M. B. Bush, M. R. Silman, A. R. Zimmerman, M. F. Raczka, and L. C. Lobato. 2012. Sparse pre-Columbian human habitation in western Amazonia. *Science* 336(6087): 1429-1431.

Meggers, B. J. 1954. Environmental limitation on the development of culture. *American Anthropologist* 56(5): 801-824.

Meggers, B. J. 1971. *Amazonia: man and culture in a counterfeit paradise.* Aldine/Atherton, Chicago, USA.

Mertz, O. 2002. The relationship between length of fallow and crop yields in shifting cultivation: a rethinking. *Agroforestry Systems* 55(2): 149-159.

Mertz, O., R. L. Wadley, U. Nielsen, T. B. Bruun, C. J. P. Colfer, A. de Neergaard, M. R. Jepsen, T. Martinussen, Q. Zhao, G. T. Noweg, and J. Magid. 2008. A fresh look at shifting cultivation: fallow length an uncertain indicator of productivity. *Agricultural Systems* 96(1-3): 75-84.

Mijatović, D., F. Van Oudenhoven, P. Eyzaguirre, and T. Hodgkin. 2012. The role of agricultural biodiversity in strengthening resilience to climate change: towards an analytical framework. *International Journal of Agricultural Sustainability* 11(2): 95-107.

Miller, R. P., and P. K. R. Nair. 2006. Indigenous agroforestry systems in Amazonia: from prehistory to today. *Agroforestry Systems* 66(2): 151-164.

Miller, R. P., J. W. Penn Jr., and J. Van Leeuwen. 2006. Amazonian homegardens: their ethnohistory and potential contribution to agroforestry development. Pages 43-60 *in* B.M. Kumar, and P.K.R. Nair, editors. *Tropical homegardens: a time-tested example of sustainable agroforestry*. Springer, Dordrecht, The Netherlands.

Mittermeier, R. A., C. G. Mittermeier, T. M. Brooks, J. D. Pilgrim, W. R. Konstant, G. A. B. da Fonseca, and C. Kormos. 2003. Wilderness and biodiversity conservation. *Proceedings of the National Academy of Sciences* 100(18): 10309-10313.

Mooney, H., A. Cropper, and W. Reid. 2005. Confronting the human dilemma. *Nature* 434(7033): 561-562.

Moraes, C. P., and E. G. Neves. 2012. O ano 1000: adensamento populational, interação e conflito na Amazônia Central. *Amazônica* 4(1): 122-148.

Moran, E. F., E. Brondizio, and S. McCracken. 2002. Trajectories of land use: soils, succession and crop choice. Pages 193-217 *in* C. Wood, and R. Porro, editors. *Deforestation and land use in the Amazon*. University of Florida Press, Gainesville.

Moran, E. F., E. S. Brondizio, J. M. Tucker, M. C. da Silva-Forsberg, S. McCracken, and I. Falesi. 2000. Effects of soil fertility and land-use on forest succession in Amazonia. *Forest Ecology and Management* 139: 93-108.

Morton, J. F. 2007. The impact of climate change on smallholder and subsistence agriculture. *Proceedings of the National Academy of Sciences, USA* 104(50): 19680-19685.

Murrieta, R. U. I. S. S., and D. L. Dufour. 2004. Fish and farinha: protein and energy consumption in Amazonian rural communities on Ituqui Island, Brazil. *Ecology of Food and Nutrition* 43(3): 231-255.

Nair, P. K. R. 1993. *An introduction to agroforestry.* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Nair, P. K. R., and B. M. Kumar. 2006. Introduction. Pages 1-10 *in* B.M. Kumar, and P.K.R. Nair, editors. *Tropical homegardens: a time-tested example of sustainable agroforestry*. Springer, Dordrecht, The Netherlands.

Nakagawa, S., and H. Schielzeth. 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution* 4(2): 133-142.

Neves, E. G., J. B. Petersen, R. N. Bartone, and C. A. da Silva. 2003. Historical and socio-cultural origins of Amazonian Dark Earths. Pages 29-50 *in* J. Lehmann, D. Kern, B. Glaser, and W. Woods, editors. *Amazonian Dark Earths - origin, properties and management*. Kluwer Academics Publisher, Dordrecht, Netherlands.

Nielsen, U., O. Mertz, and G. T. Noweg. 2006. The rationality of shifting cultivation systems: labor productivity revisited. *Human Ecology* 34(2): 201-218.

Nye, P. H., and D. J. Greenland. 1960. *The soil under shifting cultivation.* Commonwealth Agricultural Bureau, Harpenden, UK.

Ochoa-Gaona, S., and M. González-Espinosa. 2000. Land use and deforestation in the highlands of Chiapas, Mexico. *Applied Geography* 20(1): 17-42.

Oestreicher, J., N. Farella, S. Paquet, R. Davidson, M. Lucotte, F. Mertens, and J. Saint-Charles. 2014. Livelihood activities and land-use at a riparian frontier of the Brazilian Amazon: quantitative characterization and qualitative insights into the influence of knowledge, values, and beliefs. *Human Ecology* 42(4): 521-540.

Oksanen, J., F. G. Clanghet, R. Kindt, P. Legendre, P. R. Minchin, R. B. O'Hara, G. L. Simpson, P. Solymos, M. H. M. Stevens, and H. Wagner. 2013. vegan: community ecology package. R package version 2.0-7. http://CRAN.R-project.org/package=vegan.

Olsen, K. M., and B. A. Schaal. 1999. Evidence on the origin of cassava: phylogeography of *Manihot esculenta*. *Proceedings of the National Academy of Sciences of the United States of America* 96(10): 5586-5591.

Padoch, C., E. Brondizio, S. Costa, M. Pinedo-Vasquez, R. R. Sears, and A. Siqueira. 2008. Urban forest and rural cities: multi-sited households, consumption patterns, and forest resources in Amazonia. *Ecology and Society* 13(2): 2.

Padoch, C., and M. Pinedo-Vasquez. 2010. Saving slash-and-burn to save biodiversity. *Biotropica* 42(5): 550-552.

Padoch, C., and T. Sunderland. 2013. Managing landscapes for greater food security and improved livelihoods. *Unasylva* 64(241): 3-13.

Parry, L., B. Day, S. Amaral, and C. Peres. 2010a. Drivers of rural exodus from Amazonian headwaters. *Population and Environment* 32(2): 137-176.

Parry, L., C. A. Peres, B. Day, and S. Amaral. 2010b. Rural-urban migration brings conservation threats and opportunities to Amazonian watersheds. *Conservation Letters* 3(4): 251-259.

Pärssinen, M., D. Schaan, and A. Ranzi. 2009. Pre-Columbian geometric earthworks in the upper Purús: a complex society in western Amazonia. *Antiquity* 83(322): 1084-1095.

Peña-Venegas, C., T. Stomph, G. Verschoor, L. Lopez-Lavalle, and P. Struik. 2014. Differences in manioc diversity among five ethnic groups of the Colombian Amazon. *Diversity* 6(4): 792.

Peña-Venegas, C. P. (2015) *People, soil and manioc interactions in the upper Amazon region.* PhD. Thesis, Wageningen University, Wageningen.

Pereira, N. 1974. *Panorama da alimentação indígena: comidas, bebidas e tóxicos na Amazônia Brasileira.* Livraria São José, Rio de Janeiro, Brasil.

Perfecto, I., and J. Vandermeer. 2008. Biodiversity conservation in tropical agroecosystems: a new conservation paradigm. *Annals of the New York Academy of Sciences* 1134: 173-200.

Perrault-Archambault, M., and O. T. Coomes. 2008. Distribution of agrobiodiversity in home gardens along the Corrientes River, Peruvian Amazon. *Economic Botany* 62(2): 109-126.

Pichón, F. J. 1997. Settler Households and Land-Use Patterns in the Amazon Frontier: Farm-Level Evidence from Ecuador. *World Development* 25(1): 67-91.

Pingali, P. L. 2012. Green Revolution: impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences* 109(31): 12302-12308.

Pinho, R. C., S. S. Alfaia, R. P. Miller, K. Uguen, L. D. Magalhães, M. Ayres, V. Freitas, and R. Trancoso. 2011. Islands of fertility: soil improvement under indigenous homegardens in the savannas of Roraima, Brazil. *Agroforestry Systems* 81(3): 235-247.

Porro, R., R. P. Miller, M. R. Tito, J. A. Donovan, J. L. Vivan, R. Trancoso, R. F. van Kanten, J. E. Grijalva, B. L. Ramirez, and A. L. Gonçalves. 2012. Agroforestry in the Amazon region: a pathway for balancing conservation and development. Pages 391-428 *in* P.K.R. Nair, and D. Garrity, editors. *Agroforestry - the future of global land use*. Springer, Dordrecht, The Netherlands.

Quesada, C. A., J. Lloyd, L. O. Anderson, N. M. Fyllas, M. Schwarz, and C. I. Czimczik. 2011. Soils of Amazonia with particular reference to the RAINFOR sites. *Biogeosciences* 8(6): 1415-1440.

Quintero-Vallejo, E., Y. Klomberg, F. Bongers, L. Poorter, M. Toledo, and M. Peña-Claros. 2015. Amazonian Dark Earth shapes the understory plant community in a Bolivian forest. *Biotropica* 47(2): 152-161.

Rapp Py-Daniel, L. 2007. Capítulo 3: caracterização da área amostrada. Pages 35-42 *in* L. Rapp Py-Daniel, C.P. Deus, A.I. Henriques, D.M. Pimpão, and O.M. Ribeiro, editors. *Biodiversidade do*

médio Madeira: bases científicas para propostas de conservação. Instituto Nacional de Pesquisas da Amazônia, Manaus, Brazil.
Restom, T. G., and D. C. Nepstad. 2004. Seedling growth dynamics of a deeply rooting liana in a secondary forest in eastern Amazonia. *Forest Ecology and Management* 190(1): 109-118.
Rittl, T. F., B. Arts, and T. W. Kuyper. 2015. Biochar: an emerging policy arrangement in Brazil? *Environmental Science & Policy* 51: 45-55.
Rostain, S. 2010. Pre-Columbian earthworks in coastal Amazonia. *Diversity* 2(3): 331-352.
Rudel, T. K., D. Bates, and R. Machinguiashi. 2002. A tropical forest transition? Agricultural change, out-migration, and secondary forests in the Ecuadorian Amazon. *Annals of the Association of American Geographers* 92(1): 87-102.
Ruthenberg, H. 1971. *Farming systems in the tropics*. Clarendon Press, Oxford, UK.
Schaan, D. 2010. Long-term human induced impacts on Marajó island landscapes, Amazon estuary. *Diversity* 2(2): 182-206.
Schmidt, M. J., and M. J. Heckenberger. 2009. Amerindian anthrosols: Amazonian Dark Earth formation in the upper Xingu. Pages 163-191 *in* W.I. Woods, W.M. Teixeira, J. Lehmann, C. Steiner, A. Winklerprins, and L. Rebellato, editors. *Amazonian Dark Earths: Wim Sombroek's vision*. Springer, New York, USA.
Schmidt, M. J., A. Rapp Py-Daniel, C. de Paula Moraes, R. B. M. Valle, C. F. Caromano, W. G. Teixeira, C. A. Barbosa, J. A. Fonseca, M. P. Magalhães, D. Silva do Carmo Santos, R. da Silva e Silva, V. L. Guapindaia, B. Moraes, H. P. Lima, E. G. Neves, and M. J. Heckenberger. 2014. Dark earths and the human built landscape in Amazonia: a widespread pattern of anthrosol formation. *Journal of Archaeological Science* 42: 152-165.
Serrão, E. A. S., D. Nepstad, and R. Walker. 1996. Upland agricultural and forestry development in the Amazon: sustainability, criticality and resilience. *Ecological Economics* 18(1): 3-13.
Silva, B., J. Araújo, I. Falesi, and R. Rêgo. 1970. *Os solos da área Cacau Pirêra - Manacapuru.* Instituto de Pesquisas e Experimentação Agropecuárias do Norte, Belém.
Silver, W. L., J. Neff, M. McGroddy, E. Veldkamp, M. Keller, and R. Cosme. 2000. Effects of soil texture on belowground carbon and nutrient storage in a lowland Amazonian forest ecosystem. *Ecosystems* 3(2): 193-209.
Smit, B., and J. Wandel. 2006. Adaptation, adaptive capacity and vulnerability. *Global Environmental Change* 16(3): 282-292.
Smith, C. W., M. A. Johnston, and S. Lorentz. 1997. The effect of soil compaction and soil physical properties on the mechanical resistance of South African forestry soils. *Geoderma* 78(1–2): 93-111.
Smith, H. H. 1879. *Brazil: the Amazons and the coast.* Charles Scribner's Sons, New York, USA.
Smith, J., P. van de Kop, K. Reategui, I. Lombardi, C. Sabogal, and A. Diaz. 1999. Dynamics of secondary forests in slash-and-burn farming: interactions among land use types in the Peruvian Amazon. *Agriculture Ecosystems & Environment* 76(2-3): 85-98.
Smith, N. 1980. Anthrosols and human carrying capacity in Amazonia. *Annals of The Association of American Geographers* 70(4): 553-566.
Soares-Filho, B. S., D. C. Nepstad, L. M. Curran, G. C. Cerqueira, R. A. Garcia, C. A. Ramos, E. Voll, A. McDonald, P. Lefebvre, and P. Schlesinger. 2006. Modelling conservation in the Amazon basin. *Nature* 440(7083): 520-523.
Soler, L. d. S., M. I. S. Escada, and P. H. Verburg. 2009. Quantifying deforestation and secondary forest determinants for different spatial extents in an Amazonian colonization frontier (Rondonia). *Applied Geography* 29(2): 182-193.
Soler, L. d. S., and P. Verburg. 2010. Combining remote sensing and household level data for regional scale analysis of land cover change in the Brazilian Amazon. *Regional Environmental Change* 10(4): 371-386.
Sombroek, W. 1966. *Amazon soils: a reconnaissance of the soils of the Brazilian Amazon region.* Centre for Agricultural Publications and Documentations, Wageningen, The Netherlands.
Sombroek, W., D. Kern, T. E. Rodrigues, M. d. S. Cravo, T. C. Jarbas, W. Woods, and B. Glaser 'Terra Preta and Terra Mulata: pre-Columbian Amazon kitchen middens and agricultural fields,

their sustainability and their replication'. *17th World Congress of Soil Science*, Bangkok, Thailand, 14-21 August 2002.

Steward, A. 2007. Nobody farms here anymore: livelihood diversification in the Amazonian community of Carvão, a historical perspective. *Agriculture and Human Values* 24(1): 75-92.

Steward, A. 2013. Reconfiguring agrobiodiversity in the Amazon estuary: market integration, the Açaí trade and smallholders' management practices in Amapá, Brazil. *Human Ecology* 41(6): 827-840.

Stocks, A. 1983. Candoshi and Cocamilla swiddens in eastern Peru. *Human Ecology* 11(1): 69-84.

Struik, P. C., and T. W. Kuyper. 2014. Editorial overview: sustainable intensification to feed the world: concepts, technologies and trade-offs. *Current Opinion in Environmental Sustainability* 8: vi-viii.

Struik, P. C., T. W. Kuyper, L. Brussaard, and C. Leeuwis. 2014. Deconstructing and unpacking scientific controversies in intensification and sustainability: why the tensions in concepts and values? *Current Opinion in Environmental Sustainability* 8: 80-88.

Swift, M. J., A. M. N. Izac, and M. van Noordwijk. 2004. Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? *Agriculture, Ecosystems & Environment* 104(1): 113-134.

Szott, L., C. Palm, and R. Buresh. 1999. Ecosystem fertility and fallow function in the humid and subhumid tropics. *Agroforestry Systems* 47(1): 163-196.

Szott, L., C. A. Palm, and P. A. Sanchez. 1991. Agroforestry in acid soils of the humid tropics. *Advances in Agronomy* 45: 275-301.

Teixeira, W. G., G. C. Martins, and H. N. Lima. 2006. An Amazonian Dark Earth profile description from a site located in the floodplain (várzea) in the Brazilian Amazon. Pages 293-300 *in* G.M. Rios, and S. Camargo, editors. *Pueblos y paisajes antiguos de la selva Amazónica*. Universidad Nacional de Colombia / Taracaxum, Bogotá / Washington.

ter Braak, C. J. F., I. C. Prentice, and H. Caswell. 2004. A theory of gradient analysis. *Advances in Ecological Research* 34: 235-282.

ter Braak, C. J. F., and P. Šmilauer. 2012. *Canoco reference manual and user's guide: software for ordination, version 5.0.* Microcomputer Power, Ithaca, USA.

Thrupp, L. A. 2004. The importance of biodiversity in agroecosystems. *Journal of Crop Improvement* 12(1-2): 315-337.

Tilman, D., K. G. Cassman, P. A. Matson, R. Naylor, and S. Polasky. 2002. Agricultural sustainability and intensive production practices. *Nature* 418(6898): 671-677.

Tittonell, P. 2014. Ecological intensification of agriculture - sustainable by nature. *Current Opinion in Environmental Sustainability* 8: 53-61.

Tittonell, P., B. Vanlauwe, P. A. Leffelaar, E. C. Rowe, and K. E. Giller. 2005a. Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. *Agriculture, Ecosystems & Environment* 110(3–4): 149-165.

Tittonell, P., B. Vanlauwe, P. A. Leffelaar, K. D. Shepherd, and K. E. Giller. 2005b. Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. *Agriculture Ecosystems & Environment* 110(3–4): 166-184.

Tscharntke, T., Y. Clough, T. C. Wanger, L. Jackson, I. Motzke, I. Perfecto, J. Vandermeer, and A. Whitbread. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation* 151(1): 53-59.

Tscharntke, T., A. M. Klein, A. Kruess, I. Steffan-Dewenter, and C. Thies. 2005. Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. *Ecology Letters* 8(8): 857-874.

Vadez, V., V. Reyes-García, R. A. Godoy, V. L. Apaza, E. Byron, T. Huanca, W. R. Leonard, E. Pérez, and D. Wilkie. 2004. Does integration to the market threaten agricultural diversity? panel and cross-sectional data from a horticultural-foraging society in the Bolivian Amazon. *Human Ecology* 32(5): 635-646.

van Vliet, N., C. Adams, I. C. G. Vieira, and O. Mertz. 2013. "Slash and burn" and "shifting" cultivation systems in forest agriculture frontiers from the Brazilian Amazon. *Society & Natural Resources* 26(12): 1454-1467.

van Vliet, N., O. Mertz, A. Heinimann, T. Langanke, U. Pascual, B. Schmook, C. Adams, D. Schmidt-Vogt, P. Messerli, S. Leisz, J.-C. Castella, L. Jørgensen, T. Birch-Thomsen, C. Hett, T. Bech-Bruun, A. Ickowitz, K. C. Vu, K. Yasuyuki, J. Fox, C. Padoch, W. Dressler, and A. D. Ziegler. 2012. Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: a global assessment. *Global Environmental Change* 22(2): 418-429.

Vandermeer, J., M. van Noordwijk, J. Anderson, C. Ong, and I. Perfecto. 1998. Global change and multi-species agroecosystems: concepts and issues. *Agriculture Ecosystems & Environment* 67(1): 1-22.

Vaz, C. M. P., J. M. Manieri, I. C. de Maria, and M. Tuller. 2011. Modeling and correction of soil penetration resistance for varying soil water content. *Geoderma* 166(1): 92-101.

Villa, T. C. C., N. Maxted, M. Scholten, and B. Ford-Lloyd. 2005. Defining and identifying crop landraces. *Plant Genetic Resources: Characterization and Utilization* 3(3): 373-384.

Vogt, N. D., M. Pinedo-Vasquez, E. S. Brondízio, O. Almeida, and S. Rivero. 2015. Forest transitions in mosaic landscapes: smallholder's flexibility in land-resource use decisions and livelihood strategies from World War II to the present in the Amazon estuary. *Society & Natural Resources*: 1-16.

Vosti, S. A., J. Witcover, and C. L. Carpentier (2002) *Agricultural intensification by smallholders in the western Brazilian Amazon: from deforestation to sustainable land use*, Washington, D. C.: International Food Policy Research Institute.

Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society* 9(2): 5.

Weinstein, B. 1983. *The Amazon rubber boom: 1850-1920.* Stanford University Press, Stanford, USA.

WinklerPrins, A. 1999. Insights and applications local soil knowledge: a tool for sustainable land management. *Society & Natural Resources* 12(2): 151-161.

WinklerPrins, A. 2010. Locating Amazonian Dark Earths: creating an interactive GIS of known locations. *Journal of Latin American Geography* 9(3): 33 - 50.

WinklerPrins, A. M. G. A. 2009. Sweep and char and the creation of Amazonian Dark Earths in homegardens. Pages 205-211 *in* W.I. Woods, W.G. Teixeira, J. Lehmann, C. Steiner, A. WinklerPrins, and L. Rebellato, editors. *Amazonian Dark Earths: Wim Sombroek's Vision*. Springer Dordrecht, The Netherlands.

WinklerPrins, A. M. G. A., and J. A. Sandor. 2003. Local soil knowledge: insights, applications, and challenges - Preface. *Geoderma* 111(3-4): 165-170.

Witcover, J., S. A. Vosti, C. L. Carpentier, and T. C. d. A. Gomes. 2006. Impacts of soil quality differences on deforestation, use of cleared land, and farm income. *Environment and Development Economics* 11(03): 343-370.

Woods, W., and J. McCann. 1999. The anthropogenic origin and persistence of Amazonian Dark Earths. *Yearbook, Conference of Latin American Geographers* 25: 7-14.

WRB. 2014. *World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps.* World Soil Resources Report 106, FAO, Rome, Italy.

Zuur, A., E. N. Ieno, N. Walker, A. A. Saveliev, and G. M. Smith. 2009. *Mixed effects models and extensions in ecology with R.* Springer Science & Business Media, New York, USA.

Summary

Amazonia and many other tropical regions are increasingly experiencing environmental and socio-economic changes that directly affect smallholder farming, with potential negative effects for agrobiodiversity, environmental quality and livelihoods. In this dynamic context, it is crucial to study and support strategies for smallholder farming in Amazonia that guarantee farmers' economic and food security, while maintaining and enhancing ecosystem functions.

Especially in societies that depend heavily on agriculture, soils play a central role in local livelihoods, as different soils may favor or restrict certain crops and cultivation strategies and also co-evolve with knowledge, practice and the crops themselves. In Amazonian uplands, soils are usually poor and acidic, and farmers have developed crops and cultivation systems (e.g., shifting cultivation) well suited to these conditions. However, patches of high-fertility anthropogenic soils are also found, called *terra preta* or Amazonian Dark Earths (ADE). These soils, which result from pre-Columbian human activity, have changed our understanding of the degree and extent to which people transformed the Amazonian landscape in the past, and inspired the development of technologies aiming to improve tropical soils and agriculture (e.g., 'biochar'). Due to their high carbon content and enhanced fertility, ADE have been considered models for sustainable agriculture, based on the idea that transforming soils by mimicking some of the properties of ADE would benefit farmers, sequester carbon and reduce pressure on forests. In this thesis, I analyzed the current use of ADE and surrounding soils by smallholder farmers in Central Amazonia, aiming to evaluate the relevance of anthropogenic soils and of soil heterogeneity to farmers, and to identify opportunities and constraints associated with the cultivation of fertile soils. More specifically, I focused on the role that these soils play in farmers' rationales and decision-making regarding cultivation (Chapter 2), the relationships between these soils and farmers' opportunities to intensify and diversify their cultivation systems (and their associated agrobiodiversity; Chapters 3 and 4), and the relationships between ADE and land-use patterns (Chapter 5). I used approaches from social and biological sciences for an integrated analysis of qualitative and quantitative data obtained from farmers' interviews and from biophysical measurements taken in their agroecosystems.

In Chapter 2, I used an ethnographic approach to evaluate farmers' rationales and decision making in relation to their use of ADE. I showed that farmers associate fallow development with higher crop yields and lower weed pressure, but ADE is always associated

with high yields and high weeding requirements. ADE is also seen as an opportunity to grow different crops, and/or grow crops in more intensified management systems; still, farmers usually maintain simultaneously more intensively managed swiddens on their more fertile soils (ADE) and less intensively managed swiddens on less fertile soils. Farmers also acknowledge numerous changes in their socio-economic environment that affect their shifting cultivation systems, usually related to their growing interaction with market economies and to the incorporation of 'modern' agricultural practices. They say that cultivation systems on ADE have been particularly affected by these changes, referring to cases (swiddens used for watermelon cultivation) in which market demand led to over-intensification and resulted in ADE degradation. These results highlight the importance of focusing on farmers' knowledge and rationales for a thorough understanding of the use of ADE, and indicate that – from farmers' perspectives – over-intensification can potentially undermine the relevance of these soils for agricultural production, agrobiodiversity and local livelihoods.

In Chapter 3, I looked at shifting cultivation practices used by smallholder farmers in ADE and adjacent soils. Combining data from soil samples, botanical inventories and farmer interviews, I looked at the effect of soil variation along the gradient of typical high fertility ADE to typical low fertility surrounding soils on the size and location of cultivation plots, on several aspects of the shifting cultivation cycle (labor investment, cycle frequency and length of fallows and of cropping periods) and on the diversity and assemblage of crops. I found that more fertile soils are cultivated more intensively (with shorter fallow periods, higher frequency of cultivation, shorter cycles and higher labor requirements), with different crop assemblages, and have similar or larger numbers of crop species and/or landraces. Taken together, these results indicate that enhanced soil fertility can favor synergies between intensification and diversification in shifting cultivation.

Given the fact that many current villages in Central Amazonia are located on ADE patches, these soils are often found associated with homegardens and other agroforestry systems close to residential areas. Although the importance of homegardens for ecosystem processes and for the economic and food security of rural populations has been increasingly recognized, little is known about how these agroecosystems are influenced by soil variation. In Chapter 4, I used an approach similar to that in Chapter 3 (i.e., combining soil data with extensive botanical inventories) to investigate how soil variation associated with ADE influences the structure, diversity and the floristic composition in homegardens. I have shown that several characteristics of homegardens were significantly influenced by variation in soil texture (which is due to natural soil variation) and fertility (which is the result of centuries-old and modern anthropogenic soil transformations). Homegardens on sandier soils tended to be more diverse in plant species and to have more individual plants; homegardens on more fertile soils tended to have fewer trees and palms, more herbs, shrubs and climbers, and a higher total number of species and landraces; variation in soil fertility significantly influenced the composition of species and landraces. These results show that agrobiodiversity patterns in homegardens are significantly influenced by both natural and anthropogenic variation in soil properties.

One of the reasons why ADE have been considered a model for sustainable agriculture is the assumption that enhancing soil fertility would favor agricultural intensification and thus reduce pressure on forests. At the plot level, fertile anthropogenic soils were indeed associated with more intensified cultivation (Chapter 3), but the extent to which more intensive use of ADE influences wider land-use patterns remained to be tested. The main question I addressed in Chapter 5 was: do farmers with more access to ADE open smaller areas for cultivation? In order to focus on this particular relationship between the use of ADE and land-use patterns, I used a comprehensive framework, taking into account the variation in farmers' use of soils and land, and also their economic activities (agricultural and non-agricultural) and their social and economic resources. The relationship between farmers' use of and access to fertile soils (including ADE) and the area opened for shifting cultivation was strongly dependent on the labor availability of the household. The area used for cultivation was also related to a household's livelihood activities (especially by its level of engagement with market-oriented agriculture) and to its economic wealth. These results show that, instead of driving specific trends in land use, fertile soils are incorporated into local livelihoods as part of an extensive repertoire of resource management activities; most often, farmers with enough available labor manage multiple plots, combining more intensive cultivation on ADE with typical long-fallow shifting cultivation on poorer soils. Farmers' access to increased soil fertility, therefore, does not necessarily lead to reduced pressure on forests.

In sum, in this thesis I have shown that cultivation systems on ADE are associated with specific knowledge, practices and agrobiodiversity patterns. The soil heterogeneity associated with ADE increases the diversity of crops and agroecosystems, increasing farmers' opportunities to choose (and mix) crop assemblages and cultivation strategies that best suit their needs and resources. Despite these advantages, ADE can also be associated with intensification practices that can lead to environmental degradation and pose threats to local livelihoods. It cannot be assumed, therefore, that the use of more fertile soils will be associated with sustainable cultivation, nor that it will reduce pressure on forests. Initiatives aiming to promote sustainable pathways for agriculture in Amazonia should promote (and make use of) the heterogeneity of soils and of cultivation strategies, and should aim at increasing and not narrowing farmers' opportunities for resource use and management.

Acknowledgements

One of the many things that one learns during a PhD is that science is undoubtedly a collective endeavor. When I look back and think of all the people and institutions that supported me during these years, I feel extremely grateful and assured that this thesis would not exist if it was not for their support along this journey. I take this opportunity to acknowledge and thank them, and I already apologize for those that I forgot to mention.

First, I would like to thank my supervisory team: Paul Struik, Tjeerd Jan Stomph, Conny Almekinders and Charles Clement. Such a numerous and heterogeneous team was challenging, but since the beginning you made me feel at ease, and I feel privileged to have been supervised by an interdisciplinary team who worked together so harmoniously. Paul, you have been a fantastic promotor. Thank you for being so closely involved in this project, and for your trust since its beginning. I admire the way in which you go straight to the point always in a constructive and elegant way. Tjeerd Jan, it is simply great to work with people who are so passionate about science as you are. After our meetings I was so full of ideas that I seriously suspect you have developed your brainstorming skills in a rainforest. The time we spent together along the Madeira River was unforgettable and that experience certainly brought us closer together. Conny, thank you for taking me on this adventure into the 'social' world. I admire a lot your sensibility for issues related to smallholder farmers and your ability to 'tune' your mindset to theirs, and I am glad I had the opportunity to learn (a bit of) that from you. Charles, it has been almost ten years since I walked into your office for the first time. I cannot emphasize enough how important you have been for my personal and academic growth, and how thankful I am for all the support you gave me in all these years. My admiration for you keeps growing, and that goes well beyond science. I trust we will still share many ideas and beers in the future.

Doing fieldwork in rural Amazonia is always very challenging, but I am grateful I could count on the invaluable logistic support of some local institutions: Instituto de Desenvolvimento Agropecuário e Florestal Sustentável do Estado do Amazonas (IDAM), Centro Estadual de Unidades de Conservação do Amazonas (CEUC) and Instituto Internacional de Educação do Brasil (IEB). I would like to thank particularly some staff members for their support: Cleudo Oliveira, Oyama Pedraça, Acrísio Limeira, Roderico Limeira, Hugson Brito (IDAM Manicoré), José Ricardo Maciel, Ramiro Silva (IDAM Novo Aripuanã), José Tarcísio de Souza, Glauber Ferreira, Carlos Alberto Pereira, Renato de Lima, Maria Auxiliadora Ribeiro and Messias Alho (IDAM Borba), Silvia Elena Moreira (RDS do Amapá), Marcos Torres (RDS do Juma), Fabrício Tinto (RDS do Madeira), Francivane Fernandes and Roberta Amaral (IIEB).

Gostaria de expressar minha sincera gratidão aos moradores das comunidades da região do Rio Madeira, em especial àqueles das comunidades Água Azul, Terra Preta do Atininga, São Félix do Aripuanã, Vila do Espírito Santo, Lago do Piauí, Vila Gomes e Puruzinho. Obrigado por abrir as portas de suas comunidades e suas casas, por dividir seus saberes, pelas estórias à luz de lamparina e pelas refeições deliciosas que vocês gentilmente compartilharam comigo (ê saudade do peixe com farinha!). Um agradecimento especial às famílias que me hospedaram e me fizeram sentir em casa: Dona Emília e Seu Silvestre (Água Azul), Dona Maria e Chia (Terra Preta do Atininga), Dona Rosa e Seu Pedro (São Félix), Dona Maria e Seu Arife (Lago do Piauí), Dona Teresa e Seu Luís (Vila do Espírito Santo), Madá e Francimar (Vila Gomes), Seu Raimundo e Dona Maria (Puruzinho). Obrigado aos meus parceiros de campo Seu Silvestre e Chiquinho (Água Azul), Mila e Lubora (Terra Preta do Atininga), grandes conhecedores da floresta e com quem tanto aprendi durante as semanas em que trabalhamos na mata. Agradeço finalmente a alguns moradores que me deram uma ajuda especial: Luís Carlos (Terra Preta do Atininga), Sidnei (Água Azul), Seu Jorge e Dona Guadalupe (Vila Gomes), Jossi, Boboca e Daia (Puruzinho), Aldo e Chumbo (Vila do Espírito Santo), Mica e Aristóteles (Lago do Piauí) e Arnaldo e Donival (São Félix). Esse trabalho não teria sido possível sem o apoio e o carinho de todos vocês, muito obrigado por tudo.

At INPA, in Manaus, I would like to thank the Botany Post-Graduation Program (PPGBot), the Coordination of Technology and Innovation (COTI) and the Coordination of Capacitation (COCP), which provided infrastructure and institutional support during my stay there, especially Alberto Vicentini, Beatriz Ronchi Telles and the secretary Neide. Thank you also to the staff from the soils laboratory for analyzing the soil samples: Nonato Aquino, José Edivaldo Chaves, Evellyn Monteiro and especially Jonas de Oliveira Moraes Filho. Maria da Conceição Campelo (from the EMBRAPA soils lab) kindly helped finishing the analyses when the equipment broke down. The identification of the botanical samples was only possible with the help of Maria das Graças Vieira, José Ferreira Ramos, Mário Terra Araújo (valeu, bonitão) and Paulo Apóstolo Assunção (‘boca’, muito obrigado pela força, você é ‘o cara’ das plantas da Amazônia e quero continuar aprendendo muito contigo). Thank you also to the technicians Nory Erazo, Cosme da Mota, José Guedes de Oliveira and the curator Mike Hopkins (INPA herbarium), and to Valdely Kinupp (curator of the EAFM herbarium) for their assistance in processing and storing the plant samples. Nathalia Souza (parceirinha), thank you for all your help during fieldwork, with the soil analyses and with the homegarden dataset. Your charisma has heartened myself and many people along the Madeira as well, and I am happy to have contributed to your MSc dissertation.

I would like to thank all the staff and colleagues from the Centre for Crop Systems Analysis (CSA), with whom I interacted closely during the time I spent in Wageningen and who made me feel very welcome in the group. To the secretaries Sjanie van Wetten and Nicole Wolffensperger, and to Alex-Jan de Leeuw: thank you for all your help and support, and also for your contagious positive energy - you make our work environment much happier. To all the staff and colleagues from CSA and from our 'brother group' Plant Production Systems, for all the *gezelligheid* and for the very interesting scientific and not-so-scientific discussions, in particular: Aad, Lammert, Peter van der Putten, Willemien, Wopke, Xinyou, Niels, Gou Fang, Junqi Zu, Yu Yang, Weng Feng, Cesar, Márcia, Adugna, Nicodéme, Giovanni, Stella, Marcelo, Gisella, Jochem, Peter Vermeulen, Herman, Pepijn, Merel, Franca, Uta, Marloes, Jorad, Bob, Bin Chen, Catherine, Alejandro, Vu Nam, Dennis, Hao Zhang, Maja, Katrien, Bert Janssen, Lenny, Ken, Martin, Lotte, Greta, Esther, Jannicke, Gatien, Ilse, João, Madeleine, Renske, Guillaume, Wim, Mezegebu, Wytze, Maryia, Gatien, Juliana and Jiska. Thanks also to the staff and colleagues from the Knowledge, Technology and Innovation group.

Taking part in the Terra Preta Program (TPP) was a privilege - from both the personal and scientific point of view. I am very grateful to the coordinators Thom Kuyper and Marielos Peña-Claros for their huge dedication to this program and for creating such a friendly and welcoming atmosphere. During the international workshops of the TPP in The Netherlands, Brazil and Colombia, I had the opportunity to interact closely with experts from different fields, with whom I had very insightful scientific discussions. I would like to thank especially Eduardo Neves, Wenceslau Teixeira, Anne Rapp Py-Daniel, Manuel Arroyo-Kalin, Jose Iriarte, Bruno Glaser, Morgan Schmidt, Helena Lima, James Fraser, Lourens Poorter, Frans Bongers, Gaspar Morcote Rios, Bas Arts, Gerard Verschoor, Antoinette WinklerPrins, Marisol Toledo and Ellis Hoffland. And, of course, thanks to the 'engines' of the TPP, my friends from the 'cardumen': Isabel, Estela, Clara, Camilo (muchacho), Tati, Wellington, Angela, Paulo, Carlos, Joana and Edvaldo. It was a pleasure to swim with you guys in these cold - and sometimes turbid - waters, and I hope we can keep on working and partying together in the future. I would also like to thank some other researchers who kindly helped me, in different ways, during my research: Ricardo Godoy, Carla Morsello, William Denevan, Rui Murrieta, Thaise Emilio, Gerrit Gort, Cajo ter Braak, Freerk Wiersum, Paul Ingenbleek and Claudius van der Vijver.

It has been a great pleasure to make so many nice friends in Wageningen, with such big hearts, with whom I had the opportunity to share countless smiles: Johannes (Reiche), Ben, Johan, Cristina, Coen, Padraic, Renake, Julio, Rafa, Alex (Bai), Rutinha, Damian, Theo, Diana, Madelon, Bas, Peter, Cathelijn, Rogier, Laura, Raquel, Lotte, Cesar, Paula, Masha, Gonzalo, Estelita, Businessman, Tati, Isa, Lívia, Dorit, Pelin, Johannes (Schumacher), Peter (dique verde), Ísis, Lourens, Marielos and Franka. Our friendship has transcended cultures and languages, and I am sure it will also transcend time and distance; I hope our paths will cross again soon. Thank you also to all my 'old' friends for all their positive energies, especially: Fumaça, Mário, Berna, Carol, Saci, Ana, Nat, Carlão, Lud, Ramon, Gilton, Cassiano, Flávia, Ju Schietti, Fabrício, Thaíse, Brunão, Pri, Pardal, Ana, Nando, Bruno, Bemtivi, Ju Lins, Michelly, China, Chimbinha, Jotabê, Dri, Zeca, Guiga, Fer, Beto, Cintia, Zé Luís, Rita, Mário, Carrero, Du Prata, Trups, Flavinha, Helder, Minhoca, Tapioca, Giga, Alemão, Manozaira, Bogs, Noni, Gabi, Pedrão, Beca, Thayná, Berton, Paçoca, Gandhi, Guguinho, Mindu, Marcelo D2, Gabriel, Dani, Pan, Paulinha, Gato, Bemloco, Rosalitos, Japa, Guaru, Cris, Tali, Brutus, Dudu, Bozo, Du Santos, Má, Keka, Pistol, Klebão, Poia, Briza, Dani, Lalá, Lena, Fer, Bréu e João Gabriel, Carol, Átila, Laura, Aninha e João Bustamante.

Finally, I would like to thank my family for all their love and unconditional support: my parents Lu and Tulio, my brothers João and Thiago, my sisters-in-law Nat and Dani, my nieces Nicole and Alice and my nephew Caio: nothing makes me more happy than having my heart replete with you. To my uncles, aunts and cousins, especially Tio Carlinhos, Tia Leléia, Tia Letícia, Carlota e Rê; to my grandparents Procópio and Rachel, Paulo and Netinha, for the love and values that you passed on to our families; to Lib, for having engraved in my soul a list with the truly important things in life; to my 'borrowed' family, the Conte Jakovacs, for their immense kindness and for welcoming me into their beautiful family. Finally, Cata: waking up with you is like starting the day from its best part. Thank you for all your love, for your friendship, for all the joy and poetry that you put into our lives. Loving you makes me feel complete.

Obrigado, thank you, dank u wel!

List of publications

Published/accepted papers

Clement, C. R., W. M. Denevan, M. Heckenberger, **A. B. Junqueira**, E. G. Neves, W. G. Teixeira, and W. Woods. 2015. The domestication of Amazonia before European conquest. *Proceedings of the Royal Society B* 282: 20150813.

Poorter, L., M. van der Sande, J. Thompson, E. Arets, A. Alarcón, F. J. Alvarez-Sanchez, N. Ascarrunz, P. Balvanera, G. Barajas-Guzmán, A. Boit, F. Bongers, F. Carvalho, F. Casanoves, G. Cornejo-Tenorio, F. R. C. Costa, C. Castilho, J. Duivenvoorden, L. Dutrieux, B. Enquist, F. Fernandez, B. Finegan, L. Gormley, J. Healey, M. Hoosbeek, G. Ibarra-Manriquez, **A. B. Junqueira**, C. Levis, J. C. Licona, L. Lisboa, W. Magnusson, M. Martinez-Ramos, A. Martinez-Yrizar, L. Martorano, L. Maskell, L. Mazzei, J. Meave, F. Mora, R. Munoz, C. Nytch, M. Pansonato, T. Parr, H. Paz, M. Simoes-Penello, E. Perez-Garcia, L. Renteria, D. Rozendaal, A. Ruschel, B. Sakschewski, B. Salgado-Negret, J. Schietti, F. Sinclair, P. Souza, F. Souza, J. Stropp, H. ter Steege, N. Swenson, K. Thonicke, M. Toledo, M. Uriarte, P. Hout, P. Walker, N. Zamora, M. Pena-Claros, and J. Rodriguez-Velazquez. Diversity enhances carbon storage in tropical forests. (2015, in press). *Global Ecology and Biogeography*. DOI: 10.1111/geb.12364.

Fraser, J. A., A. Alves-Pereira, **A. B. Junqueira**, N. Peroni, and C. R. Clement. 2012. Convergent adaptations: bitter manioc cultivation systems in fertile anthropogenic dark earths and floodplain soils in central Amazonia. *PLoS ONE* 7(8): 1-13.

Junqueira, A. B., G. Shepard, and C. Clement. 2011. 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.

Fraser, J., **A. B. Junqueira**, and C. Clement. 2011. 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.

Fraser, J., **A. B. Junqueira**, N. Kawa, C. Moraes, and C. Clement. 2011. Crop diversity on Anthropogenic Dark Earths in central Amazonia. *Human Ecology* 39(4): 395-406.

Fraser, J., W. Teixeira, N. Falcão, W. Woods, J. Lehmann, and **A. B. Junqueira**. 2011. Anthropogenic soils in the Central Amazon: from categories to a continuum. *Area* 43(3): 264-273.

Fraser, J. A., **A. B. Junqueira**, N. C. Kawa, C. P. Moraes, and C. R. Clement. 2011. Crop diversity on Anthropogenic Dark Earths in central Amazonia. *Human Ecology* 39(4): 395-406.

Souza, S. M., **A. B. Junqueira**, A. C. C. Jakovac, P. A. Assunção, and J. A. Correia. 2011. Feeding behavior and ophiophagous habits of two poorly known Amazonian coral snakes, *Micrurus albicinctus* Amaral 1926 and *Micrurus paraensis* Cunha and Nascimento 1973 (Squamata, Elapidae). *Herpetology Notes* 4: 369-372.

Junqueira, A. B., G. H. Shepard, and C. R. Clement. 2010. Secondary forests on anthropogenic soils in Brazilian Amazonia conserve agrobiodiversity. *Biodiversity and Conservation* 19(7): 1933-1961.

Clement, C. R., and **A. B. Junqueira**. 2010. Between a pristine myth and an impoverished future. *Biotropica* 42(5): 534-536.

Submitted papers

Junqueira, A. B., C. J. M. Almekinders, T. J. Stomph, C. R. Clement, and P. C. Struik. The role of Amazonian anthropogenic soils in shifting cultivation: learning from farmers' rationales. (submitted). *Ecology and Society.*

Junqueira, A. B., N. B. Souza, T. J. Stomph, C. J. M. Almekinders, C. R. Clement, and P. C. Struik. Soil fertility gradients shape the agrobiodiversity of Amazonian homegardens. (submitted). *Agriculture, Ecosystems and Environment.*

Junqueira, A. B., T. J. Stomph, C. R. Clement, and P. C. Struik. Soil heterogeneity affects the diversity of cultivation strategies: the case of Amazonian anthropogenic soils. (submitted). *Agriculture, Ecosystems and Environment.*

Mühlen, G., A. Alves-Pereira, C. R. Carvalho, **A. B. Junqueira**, C. R. Clement, and T. Valle. Genetic diversity and population structure of Brazilian manioc varieties assessed with nuclear microsatellite markers show different patterns of diffusion for bitter and sweet varieties. (submitted). *Molecular Ecology*.

Poorter, L., F. Bongers, T. M. Aide, A. M. A. Zambrano, P. Balvanera, J. Becknell, V. Boukili, E. N. Broadbent, R. L. Chazdon, D. Craven, J. S. Almeida-Cortez, G. A. L. Cabral, B. de Jong, J. S. Denslow, D. Dent, S. J. DeWalt, J. M. Dupuy, S. M. Durán, M. M. Espírito-Santo, M. C. Fandino, J. Hall, J. L. H. Stefanoni, A. C. C. Jakovac, **A. B. Junqueira**, D. Kennard, S. Letcher, M. Lohbeck, E. Marín-Spiotta, M. Martínez-Ramos, P. Massoca, J. Meave, R. C. G. Mesquita, F. Mora, R. Muñoz, B. Muscarella, Y. R. F. Nunes, S. Ochoa-Gaona, E. Orihuela-Belmonte, M. Peña-Claros, E. A. Pérez-García, D. Piotto, J. S. Powers, J. Rodríguez-Velazquez, I. E. Romero-Pérez, J. Ruíz, L. Sanaphre, A. Sanchez-Azofeifa, N. Swenson, M. Toledo, M. Uriarte, M. Van Breugel, H. van der Wal, M. D. M. Veloso, T. V. Bentos, G. B. Williamson, and D. Rozendaal. Biomass resilience of tropical secondary forests. (submitted). *Nature*.

Fraser, J. A., M. Diabaté, W. Narmah, P. Beavogui, K. Guilavogui, H. de Foresta, **A. B. Junqueira**. Cultural valuation and biodiversity conservation in the Upper Guinea Forest, West Africa. (submitted). *Ecology and Society*.

Book chapters

Clement, C. R., **A. B. Junqueira**, P. A. Moreira, J. Lins, C. Levis, T. S. Cabral and P. P. Lima. Ecologia histórica e a criação da agrobiodiversidade na Amazônia: lições para a agroecologia. *In* J. Santilli, P. Bustamante, R. L. Barbieri, editors. *Agrobiodiversidade e agroecologia*. Coleção Transição Agroecológica, Associação Brasileira de Agroecologia / Embrapa, Brasília, Brazil. (in press).

Junqueira, A. B., N. Kawa, J. A. Fraser, and C. R. Clement. 2010. Explorando a relação entre agrobiodiversidade e solos antrópicos no médio Rio Madeira, Amazonas, Brasil. Pages 137-160 *in* L.C. Ming, M.C.M. Amorozo, and C.W. Kffuri, editors. *Agrobiodiversidade no Brasil: experiências e caminhos da pesquisa*. NUPEEA, Recife, Brazil.

Fraser, J. A., and **A. B. Junqueira**. 2010. How important is a use? Critical reflections on the conceptualization of use and importance in quantitative ethnobotany. Pages 113-126 *in* U.P. Albuquerque, and N. Hanazaki, editors. *Recent developments and case studies in ethnobotany*. NUPEEA / Brazilian Society of Ethnobiology and Ethnoecology, Recife, Brazil.

Fraser, J., T. Cardoso, **A. B. Junqueira**, N. P. S. Falcão, and C. R. Clement. 2009. Historical Ecology and Dark Earths in whitewater and blackwater landscapes: comparing the middle Madeira and lower Negro rivers. Pages 229-264 *in* W.I. Woods, W.G. Teixeira, J. Lehmann, C. Steiner, A. WinklerPrins, and L. Rebellato, editors. *Amazonian Dark Earths: Wim Sombroek's Vision*. Springer Netherlands.

Short biography

André Braga Junqueira was born at Pouso Alegre, Minas Gerais, Brazil, on the 18th of October 1982. He spent his childhood in close contact with the rural landscapes of the Mantiqueira Mountains, where his family owns a coffee farm. He attended primary school (1989-1996) and high school (1997-1999) at Pouso Alegre, including a 8-month period at the Worthing Sixth Form College (England).

From 2001 to 2005 he studied at the University of São Paulo (USP), where he obtained his BSc in Biological Sciences. During this time he became increasingly interested in the interaction between people and plants, and as a final project for his BSc he did an ethnobotanical study in the surroundings of a protected area in the northeast of São Paulo state. After graduating, he went to the Restoration Ecology Laboratory at the USP campus in Piracicaba (ESALQ), where he worked for one year in a participatory forest restoration project in a rural settlement (in fact he went to Piracicaba because he fell in love with his future wife, but that is a secret).

From 2006 to 2008 he did his MSc in Botany at the National Institute of Amazonian Research (INPA) in Manaus, under the supervision of two experienced Amazonian ethnoecologists (Dr. Charles R. Clement and Dr. Glenn H. Shepard Jr.). During his MSc dissertation, entitled 'Use and management of the secondary vegetation on terra preta by traditional communities at the middle Madeira River, Amazonas, Brazil', he worked in the interdisciplinary interface between plant ecology, soil science, archaeology, and social sciences. Given his long fieldtrips to the Madeira River, he developed a close connection with some local communities, where he would eventually return for his PhD. From 2008 to 2010 he worked as an assistant researcher at INPA, focusing his research activities on publishing his MSc and collaborating with Brazilian and foreign colleagues on other publications. He also was involved in a research project focused on the origins and domestication of Amazonian crops, which took him on field expeditions to different parts of Amazonia. During this time he also worked as a consultant for some smaller research and extension projects at other government institutions (Museu Paraense Emilio Goeldi, Brazilian Ministry of Education, National Indigenous Foundation) and NGOs (World Wildlife Fund, Fundação Vitória Amazônica).

In 2011 he started his PhD within the Terra Preta Programme of Wageningen University, in collaboration with INPA. His PhD project – which resulted in this thesis - focused on the current use of anthropogenic soils for agriculture and agroforestry, combining methodologies and approaches from natural and social sciences. André aims to keep on doing interdisciplinary research, working in close contact with local communities and promoting more sustainable pathways for their future.

Current affiliations of authors

André Braga Junqueira

Centre for Crop Systems Analysis, Wageningen University, 6708 PB Wageningen, The Netherlands

Knowledge, Technology and Innovation Group, Wageningen University, 6700 EW Wageningen, The Netherlands

Coordenação de Tecnologia e Inovação, Instituto Nacional de Pesquisas da Amazônia, 69067-375 Manaus, Brazil

Paul C. Struik

Centre for Crop Systems Analysis, Wageningen University, 6708 PB Wageningen, The Netherlands

Tjeerd Jan Stomph

Centre for Crop Systems Analysis, Wageningen University, 6708 PB Wageningen, The Netherlands

Cornelia J. M. Almekinders

Knowledge, Technology and Innovation Group, Wageningen University, 6700 EW Wageningen, The Netherlands

Charles Roland Clement

Coordenação de Tecnologia e Inovação, Instituto Nacional de Pesquisas da Amazônia, 69067-375 Manaus, Brazil

Nathalia Bezerra de Souza

Programa de pós-Graduação em Botânica, Instituto Nacional de Pesquisas da Amazônia, 69067-375 Manaus, Brazil

Paul Ingenbleek

Marketing and Consumer Behavior Group, Wageningen University, 6700 EW Wageningen, The Netherlands

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- The current use of anthropogenic soils by local Amazonian populations

Writing of project proposal (4.5 ECTS)

- Local perceptions, practices and implications for livelihoods and agrobiodiversity in traditional use of Amazonian Dark Earths (Terra Preta) (2011)

Post-graduate courses (9.6 ECTS)

- Linear models; PE&RC (2011)
- Generalized linear models; PE&RC (2011)
- Mixed linear models; PE&RC (2011)
- Multivariate analysis; PE&RC (2012)
- ALTER-NET Summer school on biodiversity and ecosystem services; ALTER-NET (2013)
- GUYAMAZ: Training for studying the evolutionary history of Amazonian crops and Amazonian biodiversity in Brazil and French Guyana; INPA (Manaus, Brazil) and IRD (Kourou, French Guyana) (2013)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Economic Botany: sustainability of NTFP extraction in Amazonia (2012)
- Biotropica: effect of historical disturbance on forest structure and floristic composition (2013)

Deficiency, refresh, brush-up courses (5.1 ECTS)

- Human ecology: theoretical approaches; INPA, Manaus, Brazil (2011)
- Spatial statistics; INPA, Manaus, Brazil (2013)
- Spring school: world soils and their assessment; ISRIC, Wageningen, the Netherlands (2014)
- Legal instruments for the protection and valuation of biodiversity and sociodiversity; UFAM, Manaus, Brazil (2014)

Competence strengthening / skills courses (3 ECTS)

- PhD Competence assessment; WGS (2011)
- Efficient writing strategies; WGS (2014)
- Project and time management; WGS (2014)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

- PE&RC Weekend (2011)
- PE&RC Day (2014)

Discussion groups / local seminars / other scientific meetings (7.1 ECTS)

- Terra Preta Program discussion group (2001, 2013, 2014, 2015)
- Seminar series, Plant Production Systems (2011, 2013, 2014, 2015)
- Sustainable intensification of agricultural systems discussion group (2014, 2015)
- Symposium: tropical forests and large-scale disturbances: new insights from plots, rings and soils (2014)
- Symposium: recovery of tropical forests (2014)

- Symposium: development to research: approaches for smallholder farming systems in Africa and China (2014)
- Symposium: evaluating anthropogenic changes in tropical forests (2015)

International symposia, workshops and conferences (15.7 ECTS)

- International workshop of the Terra Preta Program; Wageningen, the Netherlands (2011)
- II International workshop of the Terra Preta Program; Manaus, Brazil (2012)
- INREF Conference; Wageningen, the Netherlands (2012)
- 49^{th} Annual meeting of the Association for Tropical Biology and Conservation; Bonito, Brazil (2012)
- III International workshop of the Terra Preta Program; Leticia, Colombia (2013)
- Neotropical historical ecology workshop; London, UK (2014)
- Annual conference of the Society for Tropical Ecology; Zürich, Switzerland (2015)

Lecturing / supervision of practical's / tutorials (3.6 ECTS)

- Ecology of the Amazon rainforest; INPA, Brazil (2012)
- Economic botany; State University of Amazonas, Brazil (2012)
- Soil-plant interactions; WUR, the Netherlands (2015)

Supervision of MSc student (3 ECTS)

- Ethnoecology of Amazonian homegardens

Funding

This research was financially supported by the Interdisciplinary Research and Education Fund (INREF) through the Terra Preta Program, and by the Netherlands Organization for International Cooperation in Higher Education (NUFFIC)

Cover design by Steve Clark | Design Lagoon, United Kingdom

Printed by GVO Drukkers & Vormgevers B.V.| Ponson & Looijen, Ede, The Netherlands