문학석사학위논문

Calibrating the Effects of Anthrome Construction on Soil and Vegetation Structure in Caxiuanã National Forest, Brazil

브라질 카슈아나 국립공원에서의 인공적 생물군계 형성이 토양과 식생 구조에 미친 영향에 대한 연구

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Abstract

Calibrating the Effects of Anthrome Construction on Soil and Vegetation Structure in Caxiuanã National Forest, Brazil

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Amazonia has drawn the interest of researchers over the last few decades as a region where people modified their surrounding environment to sustain themselves. The process of modification is now known as 'landscape domestication,' and historical ecology was developed based on this idea. Among the several major issues surrounding the landscape domestication of pre-Columbian Amazonians, the scale of landscape domestication is an important issue that is connected with other major problems in the history of Amazonia. To explore the scale of the pre-Columbian landscape domestication, several researchers focused on developing methods to calibrate landscape domestication by interpreting the modern landscape of Amazonia.

This thesis presents regional research in the Caxiuanã National Forest (FNC) to provide a method to trace and calibrate pre-Columbian landscape domestication and understand how landscape domestication activities resulted in the creation of an anthropogenic biome (anthrome). With the data collected from the FNC and satellite images, the relationship between landscape domestication and soil, the link between soils and Enhanced Vegetation Index (EVI), and the correlation between landscape domestication and EVI are explored. The data are interpreted as indicating that (1) pedogenesis and pedoturbation are affected by landscape domestication; (2) soil properties affect the EVI values; (3) pre-Columbian landscape domestication has a positive correlation with the EVI values. The data also exhibit that the mutual and persistent interaction between humans and their surrounding environment ultimately led to the creation of anthromes, which significantly contributed to the formation of the modern landscape of Amazonia.

Keyword : landscape domestication; soil formation; remote sensing; spatial autocorrelation; optically stimulated luminescence; Amazonia
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List of Abbreviations

ABE	Amazonian Black Earth
ADE	Amazonian Dark Earth
AMS	Accelerator Mass Spectrometer
ANOVA	Analysis of variance
ASTER	Advanced Spaceborne Thermal Emmision and Reflection Radiometer
cal. BP	Calibrated years before present
ECFPn	Estação Cientifica Ferreira Penna
EDS	Electron-dispersive X-rays
EVI	Enhanced Vegetation Index
FNC	Caxiuanã National Forest
GIS	Geographic Information Systems
GPS	Global Positioning Systems
ICP-MS	Inductively Coupled Plasma Mass Spectrometer
KBSI	Korea Basic Science Institute
KIGAM	Korean Institute of Geoscience and Mineral Resources
LIA	Little Ice Age
MODIS	Moderate Resolution Imaging Spectroradiometer
MPEG	Museu Paraense Emílio Goeldi
NASA	National Aeronautics and Space Administration
NDVI	Normalized Differential Vegetation Index
OD	Overdispersion
OSL	Optically Stimulated Luminescence
SEM	Scanning Electronic Magnoscopy
SPOT	Systéme Probatoire d’Observation de la Terre
TL	Thermoluminescence
TPI	Terra Preta do Índio
VI	Vegetation Index
VNIR	Visible and near-infrared

Chapter 1. Introduction

The understanding of the prehistory of Amazonia, from the arrival of humans in the region until the arrival of Europeans in the Americas in 1492, has significantly changed since the late 1990s with the introduction of historical ecology (Erickson, 2008, Clement, et al., 2015). The more classical view on the prehistory of Amazonia is well recognized by the term, 'counterfeit paradise' (Meggers, 1971), which was introduced by archaeologists during the 1960s and 1970s. This classical theory on the pre-colonial Amazonian cultures viewed them as declining cultures, arriving at the peak of their cultural development and then declining due to the harsh environment of Amazonia with nutrient-poor soils and the lack of large game animals (Evans and Meggers, 1950, Meggers, 1971).

However, as Amazonian archaeology advanced, new discoveries were made, which provided evidence against the counterfeit paradise paradigm. Based on this new evidence, a new revisionist view on the prehistory of Amazonia was introduced by historical ecologists. One of the major advances in Amazonian archaeology was the discovery of Amazonian Dark Earth (ADE) (Sombroek, 1966, Smith, 1980). ADE is an anthropogenic nutrient-rich dark-colored soil, also known as *Terra Preta do Índio* (TPI) or Amazonian Black Earth (ABE), demonstrated that pre-Columbian Amazonian cultures were not culturally declining, but actually were actively managing and altering the environment for substance. Historical ecologists have termed this process of management and alteration of the environment as 'landscape domestication' (Balée, 1998, 2006, Erickson, 2008, Clement, et al., 2015). Since its introduction, landscape domestication has become one of the most important research foci in Amazonian archaeology.

There are several research topics that are subjected to the research of the landscape domestication in Amazonia, including domestication of plant species (Lins, et al., 2015, Levis, et al., 2017), forest management activities (Junqueira, et al., 2011), and formation of ADE (Hecht, 2003, WinklerPrins, 2009). One of the major research directions of the landscape domestication of Amazonia is its scale. Combined with the problem of gauging the population levels of pre-Columbian Amazonians, the scale of the impact that Amazonians made on the landscape is one of the most actively debated subjects related to landscape domestication in Amazonia (Bush and Silman, 2007, Bush, et al., 2008, McMichael, et al., 2012a, McMichael, et al., 2014, Clement, et al., 2015). Attempts were made to identify the scale of landscape domestication, mainly focused on the attempt to identify the scale of ADE distribution in Amazonia (Thayn, et al., 2011, McMichael, et al., 2014, Palace, et al., 2017), but due to the vast extent of Amazonia and the insufficient accumulation of survey data from across the entire region caused by the difficulty of surveys performed in the tropical rainforest, the debate goes on.

While various methods were applied to the research of the scale of landscape domestication in Amazonia, methods involving remote sensing were introduced as ways to overcome the problem of the scale of Amazonia (Thayn, et al., 2009, 2011, Palace, et al., 2017). These methods utilize remote sensing data obtained from satellite images and directly interprets the modern landscape as evidence of pre-Columbian landscape domestication. However, to trace and calibrate the landscape domestication activities of the past by interpreting the modern landscape, further understanding of the relationship between the pre-Columbian landscape domestication and the modern landscape of Amazonia is required.

The main research question of this thesis is how did pre-Columbian landscape domestication contributes to the formation of the present landscape of Amazonia? Amazonia is consisted of diverse forms of landscapes, consisted of different human-natural systems, which in total builds up a typical anthropogenic biome or anthrome (Clement, et al., 2015). Anthropogenic biomes, also termed as anthrome, indicates a biome where most of the biosphere has been transformed by humans, according to the tenets of anthroecology (Ellis, 2011, 2015). Amazonia, which is an area that has once been believed to be covered by pristine forests, untouched by humans (Evans and Meggers, 1950, Meggers, 1971), is now viewed as an area that has been largely affected by landscape domestication activities of pre-Columbians (Erickson, 2008, Clement, et al., 2015). This thesis views that the pre-Columbian landscape domestication activities created anthromes, which significantly contributed to the formation of the modern landscape of Amazonia. In this thesis, the relationship between the pre-Columbian landscape domestication and the present landscape is explored through the example of the Caxiuanã National Forest (Floresta Nacional de Caxiuanã, FNC).

To examine the extent to which the FNC was transformed into an anthrome, two interlinked research objectives will be defined and tested. The first dependent research objective is to identify how pre-Columbian landscape domestication activities affected the soil formation process. Soils are a fundamental element of the terrestrial biosphere since most of the terrestrial organisms reside on them, and a large portion of human activities has soils as their substratum (Brussaard, 1997). Amazonian archaeologists focused on soil as evidence to trace the pre-Columbian landscape domestication activities, especially with the discovery of ADE (Heckenberger and Neves, 2009, Rebellato, et al., 2009). The focus on soil was mainly due to that Amazonia contains relatively few numbers of archaeological sites when compared to rest of South America because of poor preservation condition due to its environment (Goldberg, et al., 2016, McMichael and Bush, 2019). Researchers have explored the ADE phenomenon, mostly with relevance to the chemical characteristics of the soils (Glaser, et al., 2001, Fraser, et al., 2011, Costa, et al., 2013). However, further exploration of the effects of landscape domestication activities, besides ADE formation, on soils is required.

The second dependent research objective traces and calibrates pre-Columbian landscape domestication across the modern landscape of

Amazonia. Landscape domestication activities in Amazonia have taken place in various forms, including anthropogenic burning, forest management, and ADE creation (Erickson, 2008). To trace pre-Columbian landscape domestication, diverse methods including archaeological excavations (Heckenberger, et al., 2007, Rebellato, et al., 2009), chemical analysis of soils (Costa, et al., 2013), and botanical approaches (Junqueira, et al., 2011, Levis, et al., 2017) have been undertaken. However, considering that landscape domestication is an integrative process of human-environment interaction (Balée, 2006), research on the effect of general behavioral activities is also required. If the soils are affected by landscape domestication, the terrestrial organisms residing on the soils would likely be influenced as well, which, therefore, will provide a method to trace and calibrate the pre-Columbian landscape domestication.

This thesis begins by reviewing the concept of landscape domestication (Chapter 2). The literature of historical ecology and its principal concepts is presented since landscape domestication is outlined as a central paradigmatic tenet of the research focus of historical ecology. The chapter will also deal with the concept of anthrome and its creation. Studies on the pre-Columbian landscape domestication in Amazonia will be reviewed. To introduce the methods that will be applied in this research, a brief background on how to analyze soil as an artifact and how to trace and calibrate the landscape domestication will be posed.

Chapter 3 will provide the geographical background of the FNC and methods that were applied to answer the primary research question. First, the research area, the FNC will be introduced, and the logic of the selection of it as the subject of research will be presented. Second, the way how optically stimulated luminescence (OSL) was implemented to analyze the effects of landscape domestication activities on soils will be offered. Third, the methods that were used to trace and calibrate landscape domestication will be outlined, along with the mechanism and logic on how and why the Enhanced Vegetation Index (EVI) was applied. Finally, the tools to understand how landscape domestication contributed to the formation of an anthrome in the research area will be proposed.

In Chapter 4, the results of the methods that have been acquainted in Chapter 3 will be put forward. This chapter will begin with the comparison of the OSL samples from different sampling locations. The outcome of the analysis to identify the effects of soil will be presented. A visualized map of EVI will be proposed, which was utilized for comparison with previously reported areas affected by landscape domestication and has functioned as a basis for the pedestrian survey. The chapter will end with the presentation of the results that have been employed to explore the contribution of landscape domestication in the anthrome creation.

Chapter 5 will discuss the results of the research in accordance with the research questions and theoretical framework. First, how landscape domestication affected the pedogenesis and pedoturbation of the Amazonian soils will be discussed. Second, the relationship between EVI and pre-Columbian landscape domestication, especially ADE sites, will be discussed. The reasons for the contrasting results with the previous research which have dealt with the relationship of landscape domestication and VIs will be reviewed. Finally, the discussion will explore how the pre-Columbian landscape domestication resulted in transforming the terrestrial biosphere into an anthrome and formed the Amazonian landscape as it is today.

This thesis seeks to understand the relationship between landscape domestication, soil, and the modern environment, which was indicated through EVI. While Thayn, et al. (2011) and Palace, et al. (2017) demonstrated the result that ADE sites, which is one form of landscape domestication, and EVI have a negative correlation, the data of this thesis exhibits a countering result, that areas affected by landscape domestication have higher EVI than the areas were not affected. The contradicting result is likely to have been caused by mainly two elements, the scale of the research area and consideration of variables, which include soil and modern human land use. The result implies that the interpretation of the landscape can be differed by the variables that are considered.

The overall data of the thesis demonstrate how an anthropogenic biome of the modern environment was created in Amazonia. The long-term effect of the pre-Columbian landscape domestication activities transforms the biosphere from its fundamental elements, such as soil. The effects of landscape domestication accumulate over time and results in the creation of anthrome. This thesis will function as one of the regional scale studies to understand how humans of the past have contributed to the formation of the modern environment as it is in Amazonia.

Chapter 2. Background

2.1. Historical Ecology, Landscape Domestication and Anthrome Formation

Historical ecology is a research program that focuses on understanding the past interaction between human societies and their surrounding environments and the consequences of the interactions, which include past and contemporary cultures and landscapes (Balée, 2006, Balée and Erickson, 2006, Armstrong, et al., 2017). It arose from ecologists' and conservation biologists' recognition of the importance of archaeological data to explain the contemporary environment, and archaeologists' realization of the potential of their research to be applied to modern environmental research and policy (Hayashida, 2005). Historical ecology can be seen as a revisionist view of ecological anthropology that grew out of researchers' experience in facing problems when applying ecological anthropology to complex societies (Balée, 2006). It takes an interdisciplinary characteristic by borrowing concepts from new ecology (Erickson, 2008) and taking revisionist viewpoints of the concepts derived from cultural ecology, cultural evolutionism, cultural materialism, and ecological systems theory (Balée, 2006), while encompassing data from various disciplines, such as paleoecology and history (Swetnam, et al., 1999).

Being a research program, historical ecology holds four main postulates (Balée, 1998). The four postulates are (1) all or most of the nonhuman biosphere has been practically influenced by the activities of the species *Homo sapiens*; (2) human activities do not necessarily degrade the environment into a more habitable one for humans; (3) societies of different types make different effects to their surrounding environments relevant to their regional contexts and their historical trajectories; (4) the interaction between human societies and landscapes can be understood and be researched as an integrated phenomenon in a broad variety of historical and ecological contexts (Balée, 1998, 2006).

As can be seen in the four postulates of historical ecology, one element that distinguishes historical ecology from other disciplines or research programs is its anthropocentrism (Balée, 2006). In other words, historical ecology views humans as active agents that transform their surrounding environments, rather than adapting to them (Balée, 2006). Another feature that makes historical ecology unique is the view that the transformed environment exerts a long-term influence on human culture as well as humans affect their surrounding environment (Balée, 2006). With these two views combined, historical ecologists focus on the processes and consequences of the constant interaction between human societies and the environment in which they are located, which are recorded in the 'landscape.'

The process of the interaction between the environments and human societies is termed as 'landscape domestication.' The definition of landscape domestication will be discussed first by separately reviewing the definitions of 'landscape' and 'domestication.' The term landscape has various definitions in the literature of ecology, geography, and archaeology. However, the term holds two characteristics in common through the various definitions, which are, (1) a landscape consists of multiple elements and (2) heterogeneity is created by the variety of these elements (Wiens, 2002). In historical ecology, 'landscape' is the space where the interaction between human cultures and their surrounding environments takes place, and it is considered as the most important object of analysis for historical ecologists (Balée and Erickson, 2006).

Understanding the definition of the term 'domestication' is a more complex problem and should be reviewed within the context of the use of the term within the academic community. The idea of domestication first emerged with the debates on the origin of agriculture and the 'Neolithic Revolution' (Terrell, et al., 2003). The initial thoughts on the Neolithic Revolution conceptualized human groups as existing on a dichotomy based on their subsistence strategies as either agriculturalists or hunter-gatherers (Smith, 2001). It was assumed that the transition from a hunter-gatherer society to an agriculturalist society was normally rapid radical and unidirectional (Smith, 2001). This led to the concepts of phases and periods and creating boundaries dividing hunter-gatherers and agriculturalists (Head, 2014). However, in the last few decades, a rethinking of the Neolithic Revolution and the origins of agriculture have occurred (Head, 2014). Archaeological evidence revealed that elements of the Neolithic Revolution appeared variably within space and time and the process of transition from hunter-gatherer societies was more complex than previously thought, making it more difficult to distinguish the boundaries between historical stages (Head, 2014). Furthermore, the concept of 'revolution' itself is contested by the introduction of new concepts such as intensification (Boserup, 1965) and 'complex' hunter-gatherers (Morgan, 2015), which demonstrate a gradient of land use for subsistence purposes.

The traditional understanding of domestication accepts that there are identifiable morphological and genetic changes between domesticates and non-domesticates at a certain point (Smith, 2001) and the term was often used interchangeably with the term agriculture (Zeder, 2015). However, as studies on the origins of agriculture and hunter-gatherer societies intensified, researchers started to think about domestication separately from agriculture. Since then, the definition of the term 'domestication' greatly diversified, and there is little consensus besides that domestication involves relationship in some form between a domesticator and a domesticate (Zeder, 2015).

Among the various definitions of domestication, the definition suggested by Terrell, et al. (2003) seems to be the closest to the term used in 'landscape domestication.' Terrell, et al. (2003) places the conduct of human agency as a core element of domestication, rather than genetic or morphological change or the intentionality of the domesticator. According to this idea, the term domestication is defined as people repeatedly exploiting certain resources (Terrell, et al., 2003). This idea of domestication has expanded the subject that can be domesticated by human agencies. Domestication by human agents is not merely limited to certain species of plants and animals, but it expands to the landscape where humans take action, as well as the pool of species occupying the same space (Terrell, et al., 2003).

However, although the term 'domestication' within the context of 'landscape domestication' seems to share common ideas with the idea of Terrell, et al. (2003), the term is not applied precisely the same among scholars (Arroyo-Kalin, 2015). While some researchers use the term domestication in a more expansive way to include landscape as its subject (Terrell, et al., 2003, Erickson, 2008, Levis, et al., 2018), others use the term closer to the traditional definition, as an intentional behavior to increase yields of certain resources (Clement, et al., 2015). The most critical difference between the understandings of domestication among researchers is the viewpoint on the importance of irreversible morphological or genetic changes as evidence of domestication (Arroyo-Kalin, 2015). Despite this difference, the two groups of researchers share that the landscape played an essential role during the advantage of the symbiotic relationship between humans and other species (Arroyo-Kalin, 2015).

Therefore, it is difficult to offer a clear-cut definition of landscape domestication that can be universally agreed upon. However, when considering the essential aspects of the term domestication, it is possible to obtain the general meaning of landscape domestication. In accordance with the review on the definition of domestication by Zeder (2015), the core elements that comprise the concept of domestication are domesticator, domesticate, mutualism, and persistency, if not permanent influence. With these elements of domestication put into consideration, in this thesis, the term 'landscape domestication' will be defined as 'the persistent process of mutual influence between human culture and natural environment on a certain space.'

The end product created by the landscape domestication process can be presented as an anthropogenic landscape or an anthropogenic biosphere. An anthropogenic landscape, in accordance with the anthroecology theory, can be explained as a landscape within an anthropogenic biome (Ellis, 2011, 2015). An anthropogenic biome, which is also called an 'anthrome' by those who subscribe to the tenets of anthroecology, is a biome where the terrestrial biosphere is transformed by humans and their activities performed on land (Ellis, 2011, 2015). From the anthroecological viewpoint, human systems can be viewed as a force driving biospheric changes (Ellis, 2011). In other words, human activities, such as clearance of vegetation through fire, hunting and even activities of industrial human systems, affect the selection of species and even the evolutionary process of the species (Ellis, 2011). As a result, the anthropogenic landscape is dominated by taxa that are selected by human systems and their activities and cannot function without human intervention (Ellis, 2011).

2.2. Anthrome Construction in Pre-Columbian Amazonia

During the early periods of Amazonian archaeology, Amazonia was understood as a 'counterfeit paradise', where inhabitants' subsistence options were inhibited by environmental limitations, such as soils with poor nutrient productivity and lack of large game animals, because of which the inhabitants were unable to develop complex societies (Evans and Meggers, 1950, Meggers, 1971). The early Amazonian archaeologists, such as Meggers (1971), viewed pre-Columbian Amazonians to make only short, small-scale occupations and lacked evidence of the appearance of complex societies, such as large population or ceremonial centers (Heckenberger, et al., 1999, Meggers, 2001). Furthermore, they viewed the pre-Columbian Amazonian cultures as declining cultures, arriving in Amazonia at the peak of their cultural development, and retrogressing after their arrival (Evans and Meggers, 1950, Meggers, 1971).

However, archaeological research conducted in Amazonia over the last few decades has revealed the presence of several large-scale complex societies, with the evidence of societies with social differentiation developed to a warlike complex chiefdom, large and densely settled populations, along with elaborate artwork and ritual practices (Roosevelt, 1999, Clement, et al., 2015). The presence of complex societies, along with the evolving view of humans as central agents in ecological niche construction, has proposed a new perspective on the history of Amazonia. Now, many scholars view pre-Columbian Amazonia as a mosaic landscape, where interactions between human and natural systems actively took place and are still taking place, rather than an area where human development was unilaterally limited by the tropical environment (Clement, et al., 2015). Several researchers now accept that the pre-Columbian societies of Amazonia domesticated their surrounding landscape to be more productive and predictable, whether the actions were intentional or not (Erickson, 2008, Clement, et al., 2015). Therefore, these researchers focus on anthropogenic aspects of the sustainability of the Amazonian rainforest. However, others maintain a viewpoint focusing more on environmental aspects to estimate the population capacity of the forest, arguing that the effect of landscape domestication was not significant (e.g., Bush and Silman, 2007, Bucciferro, 2016).

The landscape domestication process in Amazonia may have begun with the arrival of humans. The earliest secure evidence of the human presence in Amazonia is dated to early Holocene, approximately 10,000 to 11,000 cal. BP (Neves, et al., 2003), while remnants of human occupation in Santa Elina site, which is located in south of western Amazonia, has been dated to 23,120±260 BP, making Santa Elina one of few Late Pleistocene archaeological sites and the oldest site in South America (Vialou, et al., 2017).

One of the possible impacts that the early settlers of Amazonia made to the landscape has been hypothesized as causing the extinction of megafauna in Amazonia, such as large mastodons (*Haplomastodon waringi*) and ground sloths (*Eremotherium laurillardi*) (Roberts, et al., 2017). Whether the arrival of humans is the main cause of the extinction of megafauna in the Late Pleistocene is controversial (Borrero, 2009, Raczka, et al., 2017, Roberts, et al., 2017). However, those who support the hypothesis that humans have caused the extinction of the megafaunas suggest that the impact can be regarded as one of the cornerstone ecological episodes in the prehistory of South American landscape, since large herbivores functioned as major ecosystem engineers by creating niches in the landscape (Raczka, et al., 2017, Roberts, et al., 2017). MacFadden (2006) argues that during the Pleistocene, Amazonia would have mostly been open savannas with habitat islands of tropical rainforests because of the megafauna, rather than most of the areas being covered by tropical rainforests. This landscape created by local megafauna would have been transformed since the niche creation of the large herbivores would have come to a halt. However, even if humans have caused the megafauna extinction in the Americas, whether to view it as a form of landscape domestication is disputable, since there is little evidence of a constant and mutual relationship between human and environment during the event.

While the extinction of megafauna is disputed on whether to view it as an impact created by humans, researchers agree that anthropogenic burning is one of the first landscape domestication activity practiced since the arrival of humans in the Americas (Pinter, et al., 2011, Arroyo-Kalin, 2012). The anthropogenic forest fires provoked by the early humans of Amazonia created natural gaps or niches in the forest, which thereby replaced the role of niche constructors from large herbivores to humans (Roberts, et al., 2017). However, there is a disagreement on when the anthropogenic fires aggravated. When Arroyo-Kalin (2012) measured the abundance of the charcoal remains in several different areas, the frequency of the forest fire increases around 12,000 BP, which can be interpreted as the appearance of intensive episodes of anthropogenic burning. However, Rodríguez-Zorro, et al. (2017) argue that the increase of charcoal in the late Holocene is thought to have been due to a drier climate, and fires caused by humans intensified during the late Holocene.

The spatial perspective of forest fires caused by pre-Columbians, which is a subject that is closely related to the problem of the scale of landscape domestication, is an issue that also creates controversial arguments. Several researchers are supportive of the idea that the pre-Columbian forest burning was an intense and widespread phenomenon (Dull, et al., 2010, Koch, et al., 2019). They argue that the Little Ice Age (LIA) may have occurred due to the sharp decline of CO_2 emission, which has been caused by the demographic collapse in the Americas after the European encounter (Dull, et al., 2010, Koch, et al., 2019). However, others argue that anthropogenic fires were fairly limited to the lower Amazon basin and were sparse in the western Amazonia (McMichael, et al., 2012a, 2012b, Power, et al., 2013, Kelly, et al., 2018). Iriarte, et al., (2012) even argue that anthropogenic fires in Amazonia were rare, and Amazonia was more likely a 'fire-free' landscape before the arrival of Europeans. These controversial issues related to the pre-Columbian anthropogenic forest fires require further research integrating several disciplines such as archaeology and paleobotany, with the support of firm chronologies (Mayle and Iriarte, 2014).

After natural gaps were created by forest fires, they were either utilized or abandoned. When the cleared land was abandoned, it was covered by woody vegetation again, forming a secondary forest (Guariguata and Ostertag, 2001). However, secondary forests created by anthropogenic burning tend to have different characteristics when compared to primary forests. Ethnographers report that secondary forests are recognized as productive resources by local Amazonian communities and are often more utilized for activities such as agroforestry, which includes exercise of planting, coppicing, weeding, and hybridization (Toledo and Salick, 2006, Erickson, 2008, Junqueira, et al., 2011, Ambrósio Moreira, et al., 2017). These activities affect the composition of the plant species of the forest and the productivity and availability of useful forest resources (Erickson, 2008, Junqueira, et al., 2011, Ambrósio Moreira, et al., 2017).

Forests that have undergone a high degree of agroforestry or forest management activities are termed anthropogenic or domesticated forests (Levis, et al., 2018). Although secondary forests are more likely to be managed into anthropogenic forests, anthropogenic forests should be considered as a separate concept from secondary forests since hunter-gatherers who do not perform large scale forest clearance can create anthropogenic forests through forest management activities by altering the ecosystem of the forest through means, such as collecting edible fruits and nuts and discarding them (Politis, 1996). Since anthropogenic forests have been under significant influence of human management, they affect the genetic diversity and the distribution of the trees within the Amazon basin (Shepard and Ramirez, 2011, Levis, et al., 2018).

Secondary forests and anthropogenic forests created by agroforestry are one of the myriad examples of the anthropogenic landscape formation. Agroforestry can be understood as one of the major land management systems in Amazonia, and this system functions as a force driving the evolutionary change of the plant species within the biosphere. As a result, secondary forests and anthropogenic forests become rich in plant species useful to human beings, resulting in anthromes derived from and perpetuated by agroforestry.

When niches created by anthropogenic burning were not abandoned, pre-Columbian Amazonians have utilized them for several purposes, and the establishment of long-term settlements was an important type of using the land. Pre-Columbian settlements are relatively small in size, most of them being less than 2ha (Kern, et al., 2003), although there is the presence of large archaeological sites, such as Faldas de Sangay in Ecuador (Figure 1), which covers an area of 12km^2 (Roosevelt, 1999). Although the pre-Columbian settlements may be small in size, the effects that they incur to their surrounding landscapes were profound, since settlements act as a

Figure 1. The map of Amazonia and the location of the FNC and sites mentioned in the text.

center of human activities. Artificial structures including roads, canals, and raised fields were formed around settlements, which incorporated the clearing of trees and other vegetation and thereby impacting the landscape and the ecosystem (Erickson, 2001, Lombardo, et al., 2012). Garbage and waste produced by household activities were discarded near the settlements, which created a landscape formed of circular or curvilinear middens and terraces over time (Schmidt, et al., 2014). These garbage middens impacted the surrounding ecology by altering the soil and luring animals and insects. Many of the settlements included house gardens to produce useful plant products, such as spices, tobacco, and cotton, which have also involved land clearance and alteration of soil (Erickson, 2008, Browne Ribeiro, 2014). The accumulation of such impacts on the landscape made by the activities which took place around pre-Columbian settlements contributed to the transformation of the landscape into what Fowles (2009) terms as 'villagescape' and to the alteration of the terrestrial biosphere, which led to the creation of anthrome.

However, the way that settlements were formed and how they impacted their surrounding landscape and biosphere varied significantly by culture groups (Roosevelt, 1999, Rebellato, et al., 2009, Neves, 2011). Rebellato, et al., 2009 demonstrate that the landscape created by settlements change over time and by different cultural groups. Based on an archaeological excavation conducted in the Hatahara site located in the Central Amazon (Figure 1), Rebellato, et al. (2009) exhibit that the change of land use coinciding with the change of cultural group occupying the area. The shape and size of the sites vary significantly according to the cultural group or phase (Neves, 2011), which will develop into the different landscapes over time.

The pre-Columbian archaeological settlement sites in Amazonia are spatially and temporally correlated to a specific subclass of anthropogenic soils, ADE (Sombroek, 1966, Smith, 1980, Woods and McCann, 1999, Heckenberger, et al., 2003, Erickson, 2008, Neves, 2011, Glaser and Birk, 2012). ADE is characterized by its dark color, ranging from dark brown to black (Costa, et al., 2013), which is in contrast from the adjacent red- or yellow-colored tropical forest soils classified as Oxisols and Ultisols (Soil Survey Staff, 1999). Other aspects that are typical of ADE are the significant charcoal content (Glaser, et al., 2000, Madari, et al., 2003), Soil Organic Matter (SOM) inclusions (Glaser, et al., 2001, Glaser, 2007) and enhanced nutrient availability for plants (Smith, 1980, Fraser, et al., 2011, Costa, et al., 2013). Although formation processes of these anthropogenic soils have not been clarified in all contexts, many researchers agree that ADE was normally formed from the accumulation of household refuse, which includes charcoal from hearths, food residues, urine and feces (Sombroek, 1966, Smith, 1980, Woods and McCann, 1999). Traditional farmers of the Amazon generally recognize the superior plant nutrient availability of ADE against the adjacent natural soils, and utilize the black earth for various purposes, such as agriculture, home gardens, or locating certain useful forest plant species, such as Brazil nut trees (*Bertholletia excelsa*) and açaí palms (*Euterpe oleracea*) (Smith, 1980, Fraser, et al., 2011, Junqueira, et al., 2011).

Understanding the formation process of ADE has attracted the attention of scientists from various disciplines over the last two decades, especially because of its potential to provide an economic development model in tropical rainforests, more particularly in regard of sustainable agriculture and soil management (Glaser, et al., 2001, Steiner, et al., 2004, Glaser, 2007, Falcão, et al., 2009, Woods and Denevan, 2009, Glaser and Birk, 2012). ADE is also a subject of research for climatologists and ecologists as a carbon sink, which is a potent medium that can restrain global climate change (Sombroek, et al., 2003). For archaeologists, ADE provides evidence for social complexity and the economy of pre-Columbian Amazonian societies (Neves, et al., 2003, Roosevelt, 2013), intensification of agriculture in Amazonia (Arroyo-Kalin, 2010, 2012, Browne Ribeiro, 2017), interactions between different culture groups (Rebellato, et al., 2009), and demographic impacts wrought by colonialism (McMichael, et al., 2014, Clement, et al., 2015).

2.3. Exploring Past Human Activities through Soil in Amazonia

Soils are considered as an important source of information with significant potential of utilization in archaeological research since the human activities and effects of the environment are recorded in it, while it also preserves and affects the cultural records that are abided within them (Holliday, 2004). Amazonia is one of the frontiers in exploring soils as artifacts partially due to the poor preservation conditions within the Amazonian rainforest results in relatively few numbers of sites and artifacts (Goldberg, et al., 2016, McMichael and Bush, 2019), but also that landscape domestication activities of the pre-Columbian Amazonians left a significant impact to Amazonian soils in various ways, including management of settlements and home gardens (Browne Ribeiro, 2014, Schmidt, et al., 2014), burning the vegetation on them (Pinter, et al., 2011, Arroyo-Kalin, 2014) and managing the forests which grow on them (WinklerPrins, 2009, Levis, et al., 2018).

Much of the archaeological research on soils in Amazonia is focused on ADE, especially focusing on its chemical traits (Lehmann, et al., 2003, Birk, et al., 2011, Fraser, et al., 2011, Costa, et al., 2013). There is also research involving the analysis of soil micromorphology to investigate the pedogenesis of ADE and the formation process of ADE sites (Ruivo and Cunha, 2003, Schaefer, et al., 2004, Arroyo-Kalin, et al., 2009, Macedo, et al., 2017). The micromorphology analyses contributed in identifying the physical characteristics of the ADE, such as the textural variance from adjacent soils and ubiquitous inclusion of microscopic pottery, bones and organic matters (Ruivo and Cunha, 2003, Schaefer, et al., 2004, Arroyo-Kalin, et al., 2009).

In the case of the relationship between soils and other landscape domestication activities, besides the formation of ADE, are most frequently researched by investigating *terra mulata*. *Terra mulata* is a term that not all researchers agree on (Arroyo-Kalin, 2008, Fraser, et al., 2011), but when Amazonian archaeologists refer to this term, it indicates soils that are light brown or greyish in color, has slightly elevated levels of pH, phosphorus (P), calcium (Ca), manganese (Mn), magnesium (Mg) and zinc (Zn) and are normally found adjacent to *terra preta* (Fraser, et al., 2011). The researchers who categorize the *terra mulata* separately from *terra preta* often relate *terra mulata* to the effect of intensive agriculture (Sombroek, 1966, Woods and McCann, 1999, Hecht, 2003, Arroyo-Kalin, 2008).

Macedo, et al. (2017) provides integrated research on the general effects of landscape domestication activities on soils. Applying various methods, which include detailed soil profile description, soil micromorphology analysis, physicochemical analysis, scanning electronic magnoscopy (SEM) and electron-dispersive X-rays (EDS), Macedo, et al. (2017) compare the soils that have been affected by anthropic activities and those that have not. The results show that anthropic activities intensified the degradation of iron nodules in ADE, which increases the clay content in the soil (Macedo, et al., 2017). The degradation of the nodules was followed by destabilization of the structure, which promoted argilluviation, a downward movement of clay particles (Macedo, et al., 2017).

The result of Macedo, et al. (2017), that anthropic activities affect the pedogenesis and promote argilluviation may be tested by using OSL. OSL has been applied in the Amazonian archaeology, but they were mostly applied for dating purposes (Araujo, et al., 2013, Stenborg, et al., 2014, Cano, et al., 2017), which is the main function of OSL. OSL is a method that was developed to provide a better dating method for sediments than TL (Aitken, 1998). When minerals, such as quartz or feldspar, get deposited and are not exposed to sunlight, latent signal builds up in the minerals by the effects of radioactive elements, such as thorium (Th), uranium (U), and potassium-40 (^{40}K) within the sediment (Aitken, 1998). When these minerals are exposed to heat or light, they emit luminescence. When the luminescence is emitted by heating, it is called TL, while luminescence stimulated by light is called OSL. The basic way to calculate the age from OSL is to divide the 'equivalent dose (D_e),' which is the accumulated energy in the mineral, with the 'dose-rate (D_r),' which is the rate of secular equilibrium (age=D_e/D_r).

However, OSL is also utilized to study the pedogenesis and pedoturbation as well (Bush and Feathers, 2003, Arnold and Roberts, 2009, Stockmann, et al., 2013, Kristensen, et al., 2015). The movement of grains caused by sediment or soil mixing is a significant element that affects the OSL results, and especially, pedoturbation caused by pedogenesis is one of the major forces that affect the OSL results through soil mixing (Bush and Feathers, 2003, Arnold and Roberts, 2009). If landscape domestication activities do affect pedogenesis and promote argilluviation (Macedo, et al., 2017), the OSL results may differ by the degree of landscape domestication.

2.4. Utilizing Vegetation Indices to Trace and Calibrate Landscape Domestication

Since it has been demonstrated that soils are affected by landscape domestication activities in various ways, those who utilize remote sensing as a research tool started to focus on Vegetation Indices (VIs) as a device that can be used in Amazonian archaeology, mostly to locate or predict ADE sites (Russell, 2005, Thayn, et al., 2009, 2011, Palace, et al., 2017). VIs are spectral transformations of two or more bands, which is structured to enable the comparisons of terrestrial photosynthetic activity and canopy structural variations spatially and temporally (Huete, et al., 2002). Therefore, VIs can be used to monitor seasonal, inter-annual, and long-term variations of vegetational structural, phenological, and biophysical parameters (Huete, et al., 2002), and to interpret characteristics of plants such as photosynthetic activity and plant productivity (Ma, et al., 2001) and regional differences in the intensity or species composition of vegetation caused by anthropic effects (Tunc, et al., 2013). Since ADE demonstrates different characteristics that affect the conditions of vegetation, such as available nutrient content with their adjacent soils (Lehmann, et al., 2003), if the combination of vegetation species shows a certain degree of uniformity, the ADE will provide different VI values from non-ADE soils.

While the utilization of VIs in the Amazonian archaeology was mainly aiming to develop remote sensing methods that can remotely identify or predict ADE sites in a narrower range of research, on a broader scale it was focusing on contributing to the debate on the scale of landscape domestication in Amazonia. With discoveries of complex societies through continuous excavations (Roosevelt, 1999) and evidence for large-scale landscape domestication identified by in-depth archaeology, remote sensing and deforestation (Clement, et al., 2015), along with the viewpoint suggested by historical ecologists that the environment in total has undergone human influence (Balée, 1998, 2006), Amazonia has begun to be viewed as an area where a large portion, if not all, of its landscape, was domesticated by humans (Heckenberger, et al., 2007, Erickson, 2008, Clement, et al., 2015). However, this argument made by archaeologists, paleoecologists, and anthropologists is not agreed by every researcher. Those who disagree with the argument proposed by historical ecologists argue that there is no evidence that Amazonia was substantially transformed by pre-Columbian Amazonians (Bush and Silman, 2007) and the scale of 'landscape domestication' was not as large as some argue, but somewhat limited to specific areas (Barlow, et al., 2012, McMichael, et al., 2014). One argument made by researchers who oppose the idea of pan-Amazonian landscape domestication is that the scale of pre-Columbian landscape domestication has been exaggerated by archaeologists due to sampling bias (Barlow, et al., 2012). This problem of the scale of landscape domestication was followed up to the dispute on the contribution of the population crash of the Americas to the LIA (Reviewed in McMichael and Bush, 2019).

Following this debate on the scale of landscape domestication were studies that estimated, calculated, or at least organized the existing data into a database to better understand the size of domesticated landscapes. These attempts are mainly focusing on locating ADE sites, since ADE is the most frequently found archaeological feature in Amazonia, indicating long-term sedentary pre-Columbian settlements (WinklerPrins and Aldrich, 2010, McMichael, et al., 2014). Many of these of attempts have been made through the use of Geographic Information Systems (GIS) and satellite imagery (Russell, 2005, Thayn, et al., 2009, Thayn, et al., 2011, McMichael, et al., 2014, Palace, et al., 2017). Much research that attempts to identify the frequency of the ADE phenomenon in Amazonia relies on GIS and satellite imagery due to the limitations that conventional archaeological survey methods have in Amazonia. First, conventional archaeological surveys face logistical difficulties in the densely vegetated remote rainforests, where many of the ADE sites are located (Thayn, et al., 2009, 2011). The second limitation is the vast scale of the land of Amazonia, which is difficult to survey due to time, budget, and labor expenses needed (Thayn, et al., 2009, 2011).

Among these research projects that have attempted to locate ADE sites using GIS or satellite imagery, only a few of them employed VIs as their main tools (Russell, 2005, Thayn, et al., 2011, Palace, et al., 2017). Russell (2005) analyzed the effect of the land use of the local Xinguano on the upper Xingu landscape and created a predictive model of the archaeological sites, with also utilizing GIS and Global Positioning Systems (GPS), and VIs. While Russell (2005) performed research on a regional scale, Thayn, et al. (2011) and Palace, et al. (2017) broadened the scale of the research to a continental level, covering the entire Amazonia. While Russell (2005) focused on the effect of general landscape domestication on VIs, the others focused more specifically on ADE sites (Thayn, et al., 2011, Palace, et al., 2017). The latter also focused more on identifying the correlation between ADE sites, and both presented the result that ADE sites tended to have lower VI values when compared to ADE-free areas (Thayn, et al., 2011, Palace, et al., 2017).

Chapter 3. Material and Methods

3.1. Selecting the Research Area

This thesis will limit the study area to the border of the FNC, according to the research questions and available resources. One of the most important reasons for selecting the FNC is that it is a conservation unit managed by the Brazilian government, which infers that the effects of modern human activities on the landscape are relatively controlled when compared to other regions. This factor makes the FNC as an attractive area to research the relationship between the pre-Columbian landscape domestication and the modern environment. Another important reason is that detailed research on the environment of the FNC has been made due to the establishment of the Ferreira Penna Scientific Station (Estação Cientifica Ferreira Penna, ECFPn) by the Emílio Goeldi Museum of Pará (Museu Paraense Emílio Goeldi, MPEG) (Lisboa, et al., 2013) since 1990. The environmental research includes a detailed soil survey of the area near the ECFPn (Figure 2) (Costa, et al., 2005), which is not widely available in other regions. The mapped soil contains significant potential at exploring the relationship between soil and landscape domestication activities.

The FNC is located in the municipality of Portel and Melgaço, state of Pará, Brazil (Figure 1), and it covers an area of approximately 330,000 ha. The official border of the FNC is defined by the bank of Anapu River and the Caxiuanã and Pracuí bays to the east, from Caxiuanã Bay to the tributaries flowing from the Amazon River to the north, the tributaries of the Xingu River and Caxiuanã Bay to the west, and the standard parallel of 2˚ 15′ S to the south (Lisboa, et al., 2013). The defined area was designated as the FNC by Administrative Order 239, which was announced on November 28, 1961, by the Brazilian government with the purpose of preserving forested areas from logging and ranching operations (Lisboa, et al., 2013).

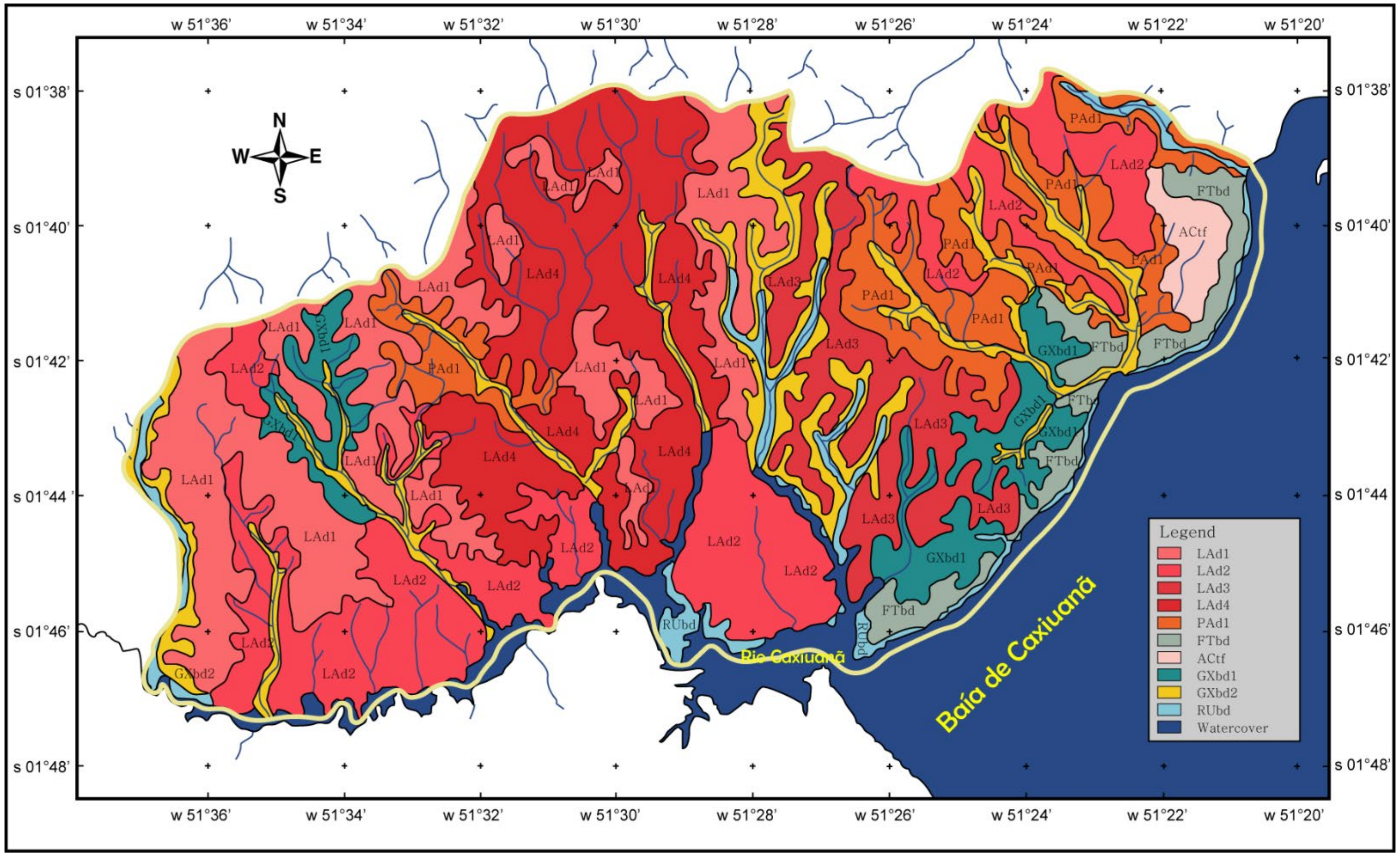

Figure 2. Soil map of northern Caxiuanã (Costa, et al., 2005). Digitized with the permission of the Museu Paraense Emílio Goeldi. The area covered is indicated as 'Soil Survey Area' in Figure 1.

Table 1. Description of soil types indicated in Figure 2 (Costa, et al., 2009). Soil classification according to Santos, et al. (2006)

Code	Soil Class and Description	Area (ha)
	YELLOW LATOSSOLO	
LAd1	YELLOW LATOSSOLO: typical dystrophic; very clayey texture; moderate A horizon; subtropical forest; flat, smooth and wavy relief	6,279
LAd2	YELLOW LATOSSOLO: typical dystrophic; medium texture; moderate A horizon; subtropical forest; flat, smooth and wavy relief	6,761
LAd3	YELLOW LATOSSOLO: typical dystrophic; clayey texture; moderate A horizon; subtropical forest; flat, smooth and wavy relief	2,745
LAd4	YELLOW LATOSSOLO: typical dystrophic; clayey texture; moderate A horizon; subtropical forest; flat, smooth and wavy relief + YELLOW LATOSSOLO: typical dystrophic; medium texture; moderate A horizon; subtropical forest; flat, smooth and wavy relief	5,900
	YELLOW ARGISSOLO	
PAd1	YELLOW ARGISSOLO: typical dystrophic; medium/clayey texture; moderate A horizon; subtropical forest; flat, smooth and wavy relief + YELLOW LATOSSOLO: typical dystrophic; medium texture; moderate A horizon; subtropical forest; flat, smooth and wavy relief	3,000

	CLAY ILLUVIATED PLINTOSSOLO	
FTbd	CLAY ILLUVIATED PLINTOSSOLO: typical dystrophic; medium/clayey texture; moderate A horizon; subtropical forest; flat, smooth and wavy relief + inclusion of CLAY ILLUVIATED PLINTOSSOLO: Ta Eutrophic anthropogenic; medium/clayey texture; anthropic A horizon; subtropical forest (of lowland)	1,309
	CHROMIC ALISSOLO	
ACtf	CHROMIC ALISSOLO: Ta clay illuviated (clay with activity ^{3}20 cmol kg^{-1}) plinthic; medium/clayey texture; moderate A horizon; subtropical forest, flat, smooth and wavy relief	504
	HAPLIC GLEISSOLO	
GXbd1	HAPLIC GLEISSOLO: Ta dystrophic (clay with high activity and low base saturation (<50%) in most of the first 100cm of the B or BA horizon) with aluminum character; silty texture; moderate A horizon; lowland equatorial forest; flat relief	2,000
GXbd2	HAPLIC GLEISSOLO: Tb typical dystrophic (clay with low activity and low base saturation (<50%) in most of the first 100cm of the B or BA horizon); silty texture; moderate A horizon; lowland equatorial forest; flat relief + FLUVIAL NEOSSOLO: Tb typical dystrophic; mixed texture; moderate A horizon; lowland equatorial forest; flat relief	3,500
	FLUVIC NEOSSOLO	
RUbd	FLUVIC NEOSSOLO: Ta typical dystrophic (clay with high activity and low base saturation (<50%) in most of the first 100cm of the B or BA horizon); mixed texture; moderate A horizon; lowland equatorial forest; flat relief + HAPLIC GLEISSOLO: Ta typical dystrophic; silty texture	1,000
	Total	33,000

The geological setting of the FNC is in the morphotectonic compartment of Gurupá, which spreads southward from the Amazon River (Lisboa, et al., 2013). Two representative geological profiles have been identified in the FNC. The first profile consists of a partly mottled kaolin horizon with a thickness of 5 m on the base with yellow Latosol discordantly covering the top of it (Lisboa, et al., 2013). The yellow Latosol is interpreted as potentially allochthonous (Lisboa, et al., 2013). The second profile has kaolin at its base with iron oxide inclusions within the layer, and the layer on top of the kaolin layer demonstrates a gradual change from kaolin to yellow Latosol measuring 20-30 cm thick (Lisboa, et al., 2013). Being consistent with the soil profile, the soil survey performed around the ECFPn demonstrated that the soils consisted of 40.87% Latosols, which was the greatest proportion among all soil classes (Costa, et al., 2005).

The climate of the FNC can be characterized as humid tropical (Lisboa, et al., 2013). The mean of the annual temperature is around 26℃, and the averages of the minimum and maximum temperatures are 23℃ and 33℃ (Sotta, et al., 2006, Lisboa, et al., 2013). The mean annual rainfall of the FNC is 2,272 (±193) mm with the 75% of the rainfall being in between December and June, while the months with the greatest precipitation are from January to March (Sotta, et al., 2006, Lisboa, et al., 2013).

The land setting of the FNC can be generally classified into five categories. Forests in firm land (*terra firme*), swamps (*igapó*), floodplains (*várzea*), grasslands created by forest clearance in different stages (*capoeiras*), and savanna area (*savanoide*) (Lisboa, et al., 2013). The land setting that comprises the greatest portion of the FNC is forests in *terra firme*, which occupies more than 80% of the total area (Lisboa, et al., 2013). The landscape of FNC is covered with more than 2,400 species of different plant species, including trees, bushes, fungi, and lichens (Lisboa, et al., 2013).

Human occupations were present in the FNC no later than 2150±75 BP according to the thermoluminescence (TL) dating of the pottery found in the area (Behling and da Costa, 2000, Coirolo and D'Aquino, 2005). By 2005, 32 archaeological sites were identified in the FNC, through surveys and several archaeological excavations that have been carried out by MPEG (Coirolo and D'Aquino, 2005). The sites identified are generally located on the banks of Caxiuanã Bay, rivers, or small streams flowing through the forest (*igarapé*), on higher ground than, rest of the landscape (Lisboa, et al., 2013). Altitude is said to be an important factor for the settlement locations of prehistoric people (Lisboa, et al., 2013) since archaeological sites tend to be located on *terra firme* rather than the lower wetlands.

The overall prehistoric population density in the FNC has been hypothesized to have been low, based on the relatively sparse amount of charcoal found in the core samples collected from the bottom of the Curuá River (Figure 1) (Behling and da Costa, 2000). However, excavations of archaeological sites, such as Ilha de Terra (Figure 1), identified extensive deposits of ADE associated with dense layers of cultural debris, with more than 1,300 fragments in five excavation units (Costa, 2003, Kern, 2004). ADE was identified in more than 90% of the sites identified in the FNC (Lisboa, et al., 2013). Also, excavation which took place in 2016, near the research station of the Brazilian Institute of Environment and Renewable Natural Resources (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, IBAMA) has also identified the deep layer of ADE along with an intense concentration of archaeological materials, mainly consisting of pottery. Since ADE associated with the intense deposits of cultural debris is commonly interpreted as a proxy for intensive human habitation (Smith, 1980, Clement, et al., 2015), there is a strong possibility of a revised prehistoric population estimate in the FNC in the future.

Various forms of material culture have been identified in the FNC. In the Ilha de Terra site, ceramics and funerary urns having similarities with the Marajoara culture have been identified, along with other archaeological materials, which precede them (Lisboa, et al., 2013). The Marajoara culture is a pre-Columbian culture that dates to 300-1600 BP

(Schaan, 2000, 2008). Its material remains are mostly found in the northeastern part of Marajó Island, the largest island among the archipelago located at the mouth of the Amazon River (Schaan, 2000). The two most distinguishing characteristics of the Marajoara culture are large artificial mounds, which typically range from one to five hectares and from three to ten meters high, and secondary burials in decorated funerary urns (Roosevelt, 1999, Schaan, 2000). However, a large part of the culture is yet to be researched, including issues such as social complexity and subsistence strategies (Schaan, 2008).

Along with Marajoara style ceramics, recent investigations are uncovering pottery of the Incised Rim Tradition and sites with more recent Koriabo complex materials (Fernandes, et al., 2019). Koriabo complex materials are thought to have originated in the Guianas around 650 BP (Rostain, 2008), although the actual place of origin is yet to be determined. While Koriabo complex materials are most frequently found in Guianas, there is a possibility that it could have originated from the middle Amazon (Rostain, 2008). The discoveries in the FNC are providing a link between Guianas and the Lower Amazon. The unique feature of the Koriabo complex materials is the distinctive style of decorations and shapes of the pottery, which includes fine incisions; very wide and shallow incisions; modeled appliqué ridges and nubbins representing animals such as frogs and turtles, or human faces, along with white, red and black painting (Rostain, 2008).

Although the FNC has been designated as a protected area by the Brazilian government, there are people who inhabit the area. The people living in the FNC today are descendants of the indigenous people who lived in the area for centuries, and migrants from other areas, who moved to the area more recently (Lisboa, et al., 2013). The immigrants who settled in the FNC migrated into the area during the period of rubber (*Hevea brasiliensis*) exploration and had a certain amount of influence on the current demography of the people living in the FNC (Lisboa, et al., 2013).

By 2013, there were five inhabited communities (villages) present in

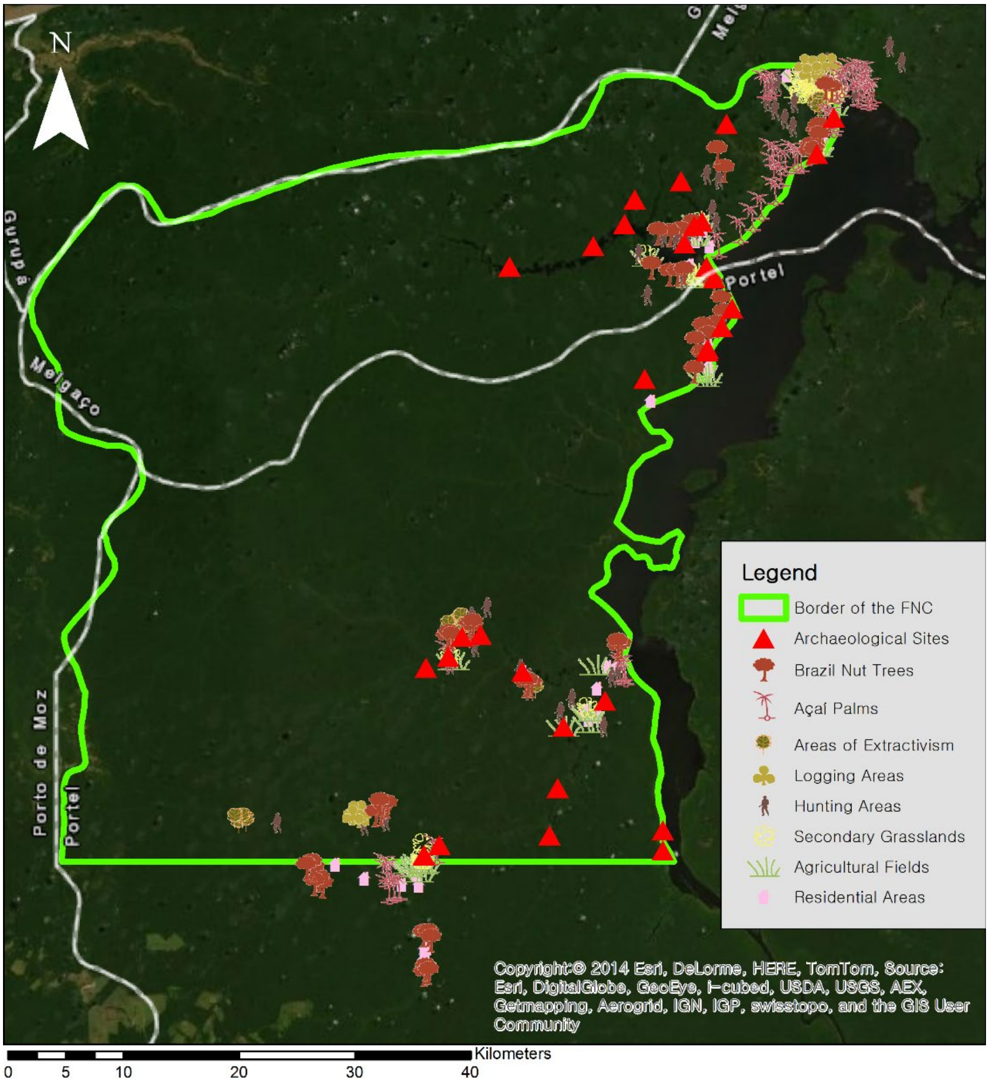

Figure 3. Location of archaeological sites and modern human activity areas in the FNC.

the FNC. The communities consist of small farmers, fishers, hunters, and gatherers who rely on the extraction of forest resources for their subsistence (Lisboa, et al., 2013). As of 2013, the total population in these five communities was 413, with a population density of 0.12 person/km^2 (Lisboa, et al., 2013). In contrast, the population density in the adjacent municipalities of Portel and Melgaço was 1.22 persons/km^2 and 3.6 persons/km^2, respectively (Lisboa, et al., 2013).

The population living in the FNC is small. However, the influence that they exert on the landscape has been significant. Although the scale of their influence on the landscape has not been assessed in detail, reviewing their farming strategy enables us to infer the degree of the local effect on the landscape. Farming usually takes place in grasslands created by forest clearance (*capoeirão* or *capoeiras baixas*) (Lisboa, et al., 2013). In general, each field has a fallow period which lasts from two to eight years, although some farmers reduced the fallow period to a year (Lisboa, et al., 2013). Therefore, the total area involved in farming during the total farming cycle is much greater than the area that is actively farmed in a certain period.

The normal process of farming starts with the clearance of the bush. The farmers clear the land using machetes and leave the cut shrubs on the land to dry. After cutting tall grasses and smaller trees, they fell the taller trees. Then they light the dried shrubs on fire and burn the entire land completely. After the fire goes out, the branches and wood that did not burn totally are collected and incinerated for a second time. The ash created from this burning process is used to enrich the soils. This entire process is called *coivara* (Lisboa, et al., 2013).

Considering the natural and human geography of the FNC, the region will provide a suitable background to answer the research questions. The archaeological evidence found in the FNC shows that the national forest is an area that went through a process of landscape domestication. However, considering the number and size of the archaeological sites that have been identified through surveys and excavations, the impact was relatively limited, which enables a comparison between the areas affected by landscape domestication and the areas that were not. Also, the fact that the people who still live in the FNC until today are still affecting the landscape will provide information on how modern human land use affects the evidence of the pre-Columbian landscape domestication.

3.2. Testing the Effect of Landscape Domestication on Soils using OSL

The first subject that needs to be tested in this thesis is whether landscape domestication affects the soils. Macedo, et al. (2017) provided a result that anthropic activities affect pedogenesis, which subsequently produces significant differences between soils. Research on OSL demonstrated that soil formation and pedoturbation affect the OSL results, and respectively, it can be concluded that landscape domestication can be explored by OSL (Bush and Feathers, 2003, Arnold and Roberts, 2009, Stockmann, et al., 2009, Kristensen, et al., 2015). Therefore, if landscape domestication activities do affect soil formation, it will affect soil formation processes, which changes the dosing environment of the samples relative to non-domesticated areas. This thesis will test the effect of landscape domestication on soils by comparing the overdispersion (OD) of the OSL. By detecting the evidence of landscape domestication through this examination, the answer to the first dependent research question on how past human activities affected soil formation processes will be explored.

When researchers utilize OSL to research the effects of pedogenesis and pedoturbation, the single-grain dating method is preferred to the multiple-grain dating method (Bush and Feathers, 2003, Stockmann, et al., 2013). This is due to that multiple-grain methods overestimate the low end of the D_e distributions from soils (Bush and Feathers, 2003). However, for this research, a simple comparison of the tendency of D_e dispersion between areas affected by landscape domestication and areas that have not is more suitable than quantifying the pedogenesis. Therefore, using a multiple-grain method is appropriate for this test.

Table 2. Sample number and information about OSL samples.

Sample Code	Sample Information	Context
BRA16-IBA1-OSL1	Grid coordinate UTM N9802323, E0451410; Extracted in layer 2 in the height of 470cm (105cm below the surface); July 4, 2016	ADE
BRA16-IBA1-OSL2	Grid coordinate UTM N9802323, E0451410; Extracted in layer 3 in the height of 530cm (45cm below the surface); July 4, 2016	ADE
BRA16-IBA5-OSL3	Grid coordinate UTM N9801305, E0452168; Extracted in Bw horizon (Layer 2), 23cm below surface, of an offsite soil located north of Forte site; July 7, 2016	Offsite
BRA16-FOR1-OSL5	Grid coordinate UTM N9800832, E0452308; Extracted in E1 horizon (Layer 2), 17cm below surface, of an offsite soil located south of the Forte site; This layer has weak iron precipitates forming; July 8, 2016	Offsite
BRA16-CAX1-OSL6	Grid coordinate UTM N9809166, E0449577; Extracted from the middle of ^A2 horizon (Layer 2) of CAX1 site, 21cm below surface; Ceramics and anthropogenic fill characterize this layer; July 11, 2016	ADE
BRA16-CAX2-OSL7	Grid coordinate UTM N9809166, E0449783; Extracted in Bt1 horizon (Layer 2), 14cm below the surface; Control sample for BRA16-CAX1 series samples; July 11, 2016	Offsite

BRA16-FOR2-OSL8	Grid coordinate UTM N9800887, E0452385; Extracted from South wall profile, 36cm below the surface in 2^ABb horizon (2AB, Layer 6); Inclusions in fill include burnt clay and charcoal; July 14, 2016	ADE
BRA16-FOR2-OSL9	Grid coordinate UTM N9800887, E0452385; Extracted from South wall profile, 9cm below the surface in ^A2 horizon (Layer 2, Archaeological Layer Ⅴ); Lots of shell Inclusions, *terra preta* soil; July 14, 2016	ADE
BRA16-IBA2-OSL10	Grid coordinate N998, E999 from site datum; Extracted from South wall profile of the excavated trench, 42cm below unit datum, 34cm below the surface in the 2AB horizon (Layer 6); July 16, 2016	ADE
BRA16-IBA2-OSL11	Grid coordinate N998, E999 from site datum; Extracted from South wall profile of the excavated trench, 33cm below unit datum, 25cm below the surface in the ^A3 horizon (Layer 5); July 16, 2016	ADE

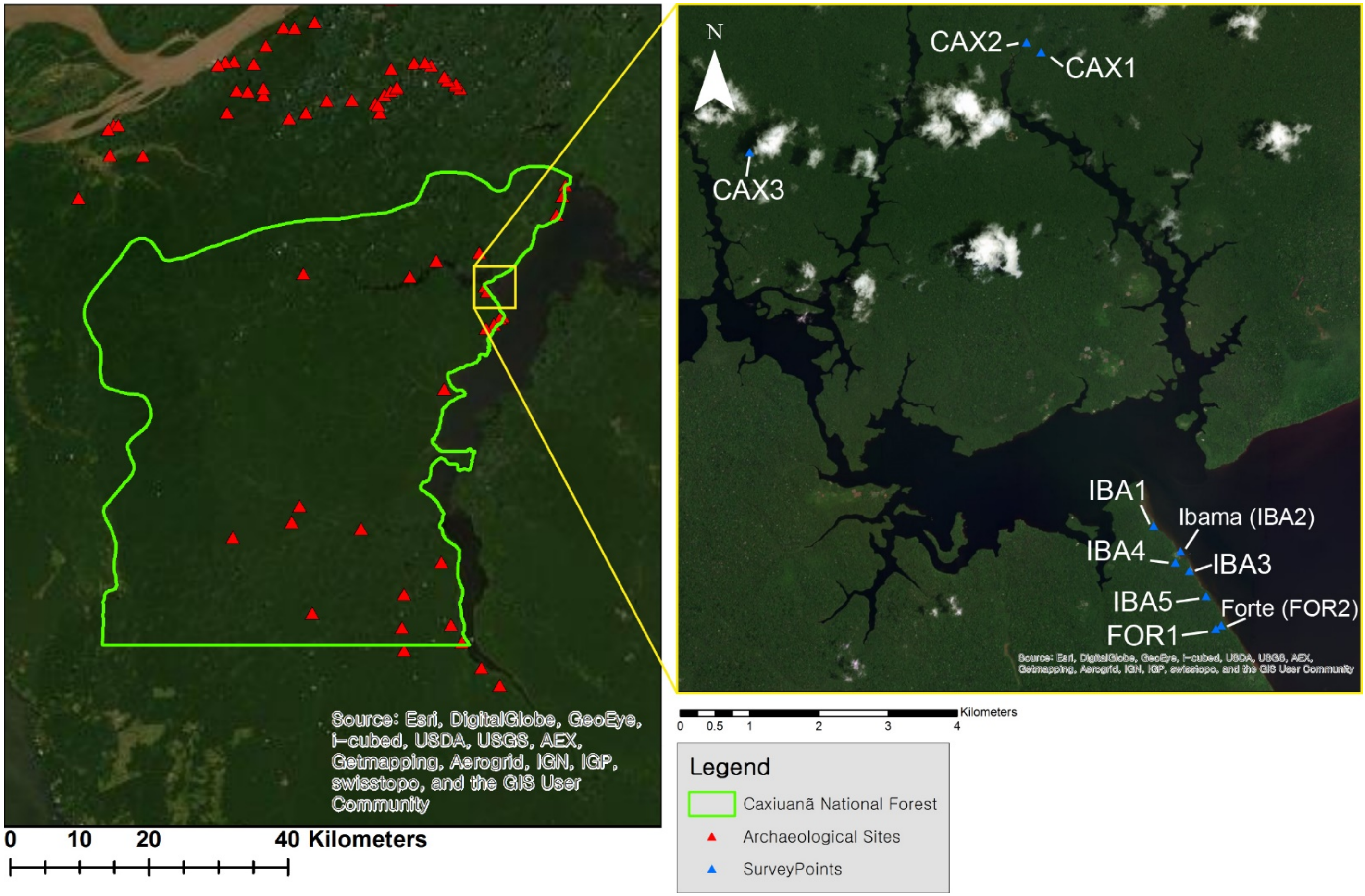

Figure 4. Location of the points where sampling, soil profiling, and pedestrian survey was undertaken.

Five OSL samples were collected from ADE contexts, which is the most obvious form of landscape domestication, and five samples from offsite contexts were collected to evaluate formation times and rates. All samples were collected by parallelly inserting a 5 cm diameter high carbon steel pipe into the sediment layer. After the collection of the samples, they were transported from Brazil to Korea and was stored at ordinary temperature for approximately three months before the analysis.

For the laboratory preparation, approximately 3-4 cm of both ends of the pipes were removed, since they have the possibility of being exposed to sunlight during sample collection. The removed parts were used to measure the D_r. While there are several methods to calculate the D_r, it was measured by Inductively Coupled Plasma Mass Spectrometer (ICP-MS) in the Korea Basic Science Institute (KBSI). Then 90-250 μm grains were extracted from the sampled sediments by sieving in a semi-darkened room using red light. The separated grains were cleaned in 10% H_2O_2 to remove organic material and 10% HCl to remove carbonate minerals. After the cleansing process, grains with a specific gravity between 2.62 $g{\cdot}cm^{-3}$ and 2.75 $g{\cdot}cm^{-3}$ were collected by using heavy liquid of sodium polytungstate. Of the collected grains, non-quartz was dissolved, and quartz grains were etched by approximately 10 μm by subjecting the sample to hydrofluoric acid for 45 minutes. The quartz grains were then made into a typical aliquot consisting of several thousand grains by fixing them to an aluminum disc with silicone spray. The OSL was measured using a Risø TL/OSL-DA-20 series reader equipped with seven clusters of LEDs with each cluster having two blue LEDs, two green LEDs, and three infrared LEDs. The blue LEDs, which are used in single-aliquot regeneration (SAR) protocol to measure OSL, applies energy up to 80 mW/cm^2.

The dating process followed the SAR protocol introduced by Murray and Wintle (2000). The SAR protocol was adopted since it provides an effective way to monitor sensitivity changes in both natural and regenerated signal in quartz grains during the analysis (Murray and Wintle, 2000, Choi, et al., 2004). In the first routine (i=0), which measures the

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natural OSL signal, D_0 is fixed to 0 Gy. After a preheat (step 2), the natural OSL signal, L_0, is measured (step 3). Then, a fixed test dose, D_t is given before heating to 160℃, which is a process to empty the TL trap. After that, the test dose luminescence signal, T_0, which is relevant to the natural OSL measurement, is measured (Murray and Wintle, 2000). Usually, the cycle is repeated three times (Choi, 2004).

Table 3. Generalized Single-Aliquot Regeneration sequence (from Murray and Wintle, 2000)

Step	Treatment[a]	Observed[d]
1	Give dose, D_i	-
2	Preheat[b] (160~300℃ for 10s)	-
3	Stimulate[c] for 100s at 125℃	L_i
4	Give test dose, D_t	-
5	Heat[b] to 160℃	-
6	Stimulate for 100s at 125℃	T_i
7	Return to 1	-

[a] For the natural sample, i = 0, and D_0 = 0Gy

[b] Aliquot cooled to <60℃ after heating. In step 5, the thermo luminescence (TL) signal from the test dose can be observed, but it is not made use of in routine applications.

[c] The stimulation time is dependent on the stimulation light intensity.

[d] L_i and T_i are derived from the initial OSL signal (0.3 or 0.8s) minus a background estimated from the last part of the stimulation curve.

The result of this process provides the age of the samples and the overdispersion (OD) of the samples. The grains or aliquots that are used for the analysis are very likely not to have experienced the same radiation dose in nature, even though they have been collected in the same environment (Galbraith and Roberts, 2012). There are several causes for the difference in the radiation dose, which include unequal partial bleaching, beta-dose heterogeneity after burial, and sediment mixing caused by various post-burial effects (Galbraith and Roberts, 2012). The soil formation process is one of the major events that can cause sediment mixing. The of the D_e between the aliquots caused by the heterogeneity in the radiation dose is reflected in the OD parameter (Galbraith, et al., 2005).

The OSL samples from the FNC were collected from similar environments besides the degree of landscape domestication. In this research, it was assumed that the effects of incomplete bleaching of grains and the beta-dose heterogeneity are small, and the greatest factor that influences the OD is the post-depositional sediment mixing by soil formation process. Therefore, by comparing the OD parameters between the samples from the highly domesticated landscape and less domesticated landscape, the effects of landscape domestication on soils were observed.

3.3. Testing the Effect of Soil on EVI

The second test in this thesis examines the effect of soil on EVI. It has been demonstrated that VIs are well-correlated with the increase of biomass (Ogaya, et al., 2015). It has also been presented that soil properties significantly affect the plant biomass (Nicholson and Farrar, 1994, Lehmann, et al., 2003). The research on the correlation between ADE sites and VIs were made based on this relationship between soils and VIs (Thayn, et al., 2011, Palace, et al., 2017). However, since this thesis aims to answer the question of how to trace and calibrate landscape domestication in general, an examination on the correlation between soil classes in Amazonia and VIs was required.

VIs include a large variety of types, and the researcher should select among such variation that well matches the purpose of research. Among the VIs, Normalized Differential Vegetation Index (NDVI) is one of the most frequently employed VI. Field and laboratory research have demonstrated that NDVI has a strong correlation with fractions of active photoabsorbent vegetation and leaf area index (Russell, 2005, Palace, et al., 2017). Due to such a correlation, NDVI is widely used among various disciplines and regions (Russel, 2005, Morton, et al., 2006, Alves, et al., 2015, Gandhi, et al., 2015, Palace, et al., 2017).

While NDVI is the most frequently used vegetation index, it contains potential deficiencies caused by atmospheric effects and background brightness (Yamamoto, et al., 2010). EVI was developed to overcome this weakness of NDVI. EVI is normally calculated by the following equation:

$$\mathbf{EVI} = \mathbf{2.5} * \frac{(\boldsymbol{NIR} - \boldsymbol{Red})}{(\boldsymbol{NIR} + \mathbf{6} * \boldsymbol{Red} - \mathbf{7.5} * \boldsymbol{Blue} + \mathbf{1})}$$

EVI is more sensitive in regions with high biomass, reduces the atmospheric effect in satellite images, and as a result, provides an enhanced vegetation signal (Jiang, et al., 2008, Yamamoto, et al., 2010). Amazonia is an area with dense vegetation cover and high moisture regime, which makes it appropriate to apply EVI for research (Jiang, et al., 2008).

The large scale of the research on landscape domestication in Amazonia makes it necessary to obtain I values through remote sensing as opposed to ground-based data collection. The remote sensing tool should be determined by the researcher, by the research objectives, since different remote sensing tools provide different spatial resolution, combinations of bands, and other information.

The spatial resolution of the remote sensing tool is one of the most important factors to be considered. A new generation of satellite-based sensors, such as Systéme Probatoire d’Observation de la Terre (SPOT), IKONOS, and Quickbird, provide the fine spatial resolution (15 m/pixel to less than 1 m/pixel) (Stefanov and Netzband, 2005). However, these data with the fine spatial resolution are provided by the commercial sector and therefore, often very costly and have limits in spatial and temporal coverage (Stefanov and Netzband, 2005). In contrast, data provided by national governments, such as satellite images provided by the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS), are relatively easy to access and provide larger coverage in space and time, though the spatial resolution may be generally coarser than those provided by commercial systems (Stefanov and Netzband, 2005).

Among the data provided by non-commercial satellite-based sensors, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) series products offer a spatial resolution of 15 m/pixel, which is relatively fine when compared to the spatial resolution of other products, such as the Landsat series (30 m/pixel) and Moderate Resolution Imaging Spectroradiometer (MODIS) series (250 m/pixel). Provided the Japanese Ministry of International Trade and Industry, ASTER was launched in 1999 mounted on the NASA EOS Terra spacecraft (United States Geological Survey, 2015). Among the three sensors that cover 14 frequency bands, three nadir-pointing bands, and an additional sensor duplicating the frequency of nadir band 3, comprise the ASTER (United States Geological Survey, 2015). The sensor that covers visible and near-infrared (VNIR) frequencies provides images at 15 m/pixel resolution (United States Geological Survey, 2015).

As with satellite images produced by other remote sensing tools, researchers attempted to obtain VI values from the ASTER. However, while there is no problem encountered when calculating the NDVI from ASTER dataset, EVI cannot be calculated with its original formula since ASTER does not collect blue frequency data, which covers the wavelength of 459-479 nm. However, researchers developed three alternative formulas to calculate EVI by using only NIR and red frequencies (Yamamoto, et al., 2010). However, one of the alternative formulas has been developed for application in snow-covered areas, and therefore, it is not applicable in this research.

One of the other two alternative methods to calculate EVI involves reflectance values from ASTER and MODIS sensors (Yamamoto, et al., 2010). This alternative method, named as EVI_C, is possible since the ASTER and MODIS sensors are both loaded on the same Terra platform and there are possibilities of simultaneous observation of a certain area (Yamamoto, et al., 2010). The formula involves NIR and red reflectance of the ASTER sensor, and blue reflectance of the MODIS sensor (Yamamoto, et al., 2010). The other method, named as EVI2, simply uses the NIR and visible red bands of ASTER (Jiang, et al., 2008).

EVI_C and EVI2 values were validated by comparison with EVI values calculated from MODIS data with the original formula. While EVI2 values showed a very close 1:1 correlation with the EVI data (Jiang, et al., 2008), EVI_C showed lower correlation (0.960) than EVI2, which seems to be a result of possible atmospheric effects in the MODIS blue reflectance values (Jiang, et al., 2008, Yamamoto, et al., 2010). Therefore, EVI was calculated by using the formula of EVI2.

$$\mathbf{EVI2} = \mathbf{2.5} * \frac{\boldsymbol{\rho}_{\boldsymbol{ASTER\,NIR}} - \boldsymbol{\rho}_{\boldsymbol{ASTER\,red}}}{\boldsymbol{\rho}_{\boldsymbol{ASTER\,NIR}} + \mathbf{2.4} * \boldsymbol{\rho}_{\boldsymbol{ASTER\,red}} + \mathbf{1}}$$

EVI values were extracted from two ASTER L1T satellite images covering the FNC, both taken on June 26, 2007. The images were obtained through the United States Geological Survey Earth Explorer website (https://earthexplorer.usgs.gov/), and EVI was calculated by processing the obtained dataset with ESRI's ArcGIS 10.2.2. The satellite images of June 26, 2007, were chosen for two reasons. First, the images contained the least amount of cloud cover relative to other images available in the data repository, while covering most of the area of FNC. Second, the variance between the VI values is the greatest between June and July throughout the year, with tropical rainforests demonstrating higher values than another type of land coverage, such as pastures, agricultural fields, or savannah (Arvor, et al., 2011).

To evaluate whether different soil types actually do affect the expression of EVI within the study area, analysis of variance (ANOVA) tests were executed using the soil survey result of Costa, et al. (2005). The soil map (Figure 2) presented in Costa, et al. (2005) was integrated into GIS by digitizing it into polygons with ArcGIS 10.2.2. Also, the EVI values were vectorized from raster using the 'Raster to Point' tool. The information from the soil types was then spatially joined to points, which contain the EVI values in 15 m intervals. For ANOVA tests, the soil classes were set as independent variables, and EVI values were designated as dependent variables. The null hypothesis of the ANOVA is that the population distribution of vegetation spectra is randomly distributed across the study area and that the variance of the values falls along a normal continuum (Pandit, 2010). If the F value, which indicates the influence of the effect, is significantly large and the significance of the result rejects the null hypothesis, it means that the conditions (in this case the soil class) (Pandit, 2010) non-randomly affect the distribution of vegetation spectra within different analytical zones with statistical significance determined by the p-value. The ANOVA between the independent and dependent variables, soil class and EVI values, was analyzed using IBM SPSS 23.

3.4. Examining the Relationship between Landscape Domestication, Soils and EVI

After the effects of landscape domestication on soils and soils on EVI are investigated, the relationship between landscape domestication and EVI is examined, which eventually leads to the discussion on the second dependent research question on how to trace and calibrate the pre-Columbian landscape domestication through the modern landscape of Amazonia. The examination is performed through the following steps, 1) visualization of EVI values into a map through spatial autocorrelation methods, 2) comparison between the created map with the ADE sites, 3) pedestrian survey according to the map and 4) comparison between the created map and areas of modern land use indicated in Figure 3.

The visualization of EVI values is performed by applying spatial autocorrelation methods using ArcGIS 10.2.2. The first spatial autocorrelation method that is applied is Getis-Ord's Gi*. Getis-Ord's Gi* is one variant in a family of spatial statistics called G, introduced by Getis and Ord (1992). Gi* allows identification of local clustering patterns, which may not appear in global statistics, G (Ord and Getis, 1995). As a result, Gi* can be applied more flexibly when compared to global statistics G, which cannot accommodate spatially variable clustering patterns. Getis-Ord's Gi* index is defined by the following equation (Ord and Getis, 1995):

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij}\, x_j - \bar{X} \sum_{j=1}^{n} w_{ij}}{S \sqrt{\frac{[n \sum_{j-1}^{n} w_{ij}^2 - (\sum_{j-1}^{n} wij)^2}{n-1}}}$$

where

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n}$$

and

$$\mathrm{S} = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2}$$

In this equation, x_j is the attribute value of feature *j*, *n* is the total number of features, $w_{ij}(d)$ is a binary spatial weighted matrix that defines w_{ij}. When locations of two features, *i* and *j* are within the defined distance *d*, w_{ij} is 1; otherwise, w_{ij} is 0. Calculated $\bar{X}$ is the simple mean, and S is the simple variance (Ord and Getis, 1995).

The Gi* value is compared with the z-score to examine whether clustering occurs (Getis and Ord, 1992). With a confidence level of 90%, the p-value, which indicates the probabilistic posterior distribution, should be smaller than 0.10. For the Gi* to be statistically significant, it is conventionally understood that the value should be larger than 1.65 or smaller than -1.65, which are the corresponding z-scores to p-values (ESRI, 2016).

Therefore, as a result of the Getis-Ord's Gi* analysis, each vectorized point of EVI will be given a z-score, p-value, and confidence level bin (Gi_Bin). The Gi_Bin, which is given as integer values between -3 to 3, is what indicates the statistically significant spatial clusters of high values (hot spots) and low values (cold spots). The degree of statistical significance is demonstrated through Gi_Bin as well. Features with the Gi_Bin value of +/-3 are statistically significant at a 99 percent confidence level; those with +/-2 Gi_Bin value are significant in at a 95 percent confidence level; +/-1 Gi_Bin indicate statistical significance at a 90 percent confidence level; and 0 indicates that clustering for features is not statistically significant (ESRI, 2016).

The second method that is applied is Anselin's Local Moran's I. While Getis-Ord's Gi* clarify areas characterized by very high values and very low values, Local Moran's I focuses more on expressing the clustering of similar attribute values (Coluzzi, et al., 2010). Local Moran's I index is defined by the following equation:

$$I_i = \frac{x_i - \bar{X}}{S_i^2} \sum_{j=1, j \neq 1}^{n} w_{i,j} (x_i - \bar{X})$$

In this equation, x_i is the attribute of *i*, $\bar{X}$ is the average of features, and $w_{i,j}$ is the spatial weight between feature *i* and *j* (Kim, 2012).

Anselin's Local Moran's I uses pseudo significance, which is expressed by pseudo p-values, which is a probabilistic statistic that examines the significance of statistics (Anselin, 1995). The pseudo p-values are generated by comparing the actual Local Moran's I value with the values produced by random permutations of points from spatially parameterized data (ESRI, 2016).

By executing Anselin's Local Moran's I analysis, z-score, pseudo p-value, and cluster/outlier type (C0Type) is given to each EVI points. The cluster/outlier type is determined by the z-score and p-value. When the z-score is a high positive value, it indicates that the point has similar values with neighboring points, demonstrating a clustering pattern. When the z-score is a low negative value, the analyzed feature can be classified as an outlier from its surrounding features. Therefore, the C0Type classifies the points into five classes, which are high-value cluster (HH), low-value cluster (LL), high-value outlier surrounded by low-values (HL), low value outlier surrounded by high values (LH), and features does not demonstrate any statistical significance (Not Significant). The confidence level of the statistical significance of the results of Anselin's Local Moran's I is fixed to 95% (ESRI, 2016).

A threshold distance needs to be set for the Getis-Ord's Gi*. A threshold distance indicates the range that features within it are acknowledged as neighboring to the target feature of analysis. For Getis-Ord's Gi*, the type of the threshold distance can be chosen between fixed distance band and inverse distance. While a default threshold distance can be computed, it is recommended to set a threshold distance that is appropriate for the research purpose (ESRI, 2016).

The analyses of Getis-Ord's Gi* and Anselin's Local Moran's I was executed with the threshold distance set as a fixed distance of 80 m. The threshold distance was set according to the size of the majority of ADE sites. For the size of ADE sites, there are a few large sites that exceed even 100 ha, but more than 80% of the sites are not larger than 2 ha (Kern, et al., 2003). Therefore, although there are sites that are smaller than 2 ha, this research postulated the size of the majority of ADE sites as 2 ha. The threshold distance of 80 m results in approximately 2 ha for the area of analyses.

After the maps that visualize the EVI are generated, the relationship between landscape domestication and EVI can be explored. The first method compared the distribution of EVI values between the ADE sites and the FNC. It utilized the location of the previously reported ADE sites in the FNC (Lisboa, et al., 2013). The location of the ADE sites was loaded into the GIS. Then buffers with the radius of 80 m were generated around the location of the ADE sites, according to the postulated site size. A histogram of the Gi_Bin and C0Type, which are collected from the EVI points that are within the 80 m radius, was generated to represent the clustering pattern of EVI values of the ADE sites. To represent the FNC, a total of 2,000 random points was generated. Buffers of 80 m radius were generated for the random points as well. Gi_Bin and C0Type from the EVI points within the 80 m radius were aggregated and used to create a histogram that displays the clustering pattern of EVI values of the FNC. The histograms of the Gi_Bin and C0Type of each ADE site and the FNC were compared. Through this comparison, the effect of ADE sites on EVI was observed.

The other method involved undertaking a pedestrian archaeological survey and shovel tests according to the map that visualizes the EVI clustering patterns. The points for pedestrian surveys were selected within the areas where ADE sites were not previously reported. For the pedestrian survey, the created map was loaded to a Garmin Montana 680t GPS device for navigation to the targeted location. Vegetation structure and composition were noted within the survey zones.

Although most of the FNC is protected by the Brazilian government, consideration of modern human disturbances in the FNC cannot be neglected (Lisboa, et al., 2013). Therefore, the effects of modern human land use on EVI should be analyzed as well. The location of the area of modern land use reported in Lisboa, et al. (2013) was employed for the analysis. The spots of terrestrial modern land use were input into the GIS as vector points, and the type of the land use was entered into the points. The types of terrestrial land use include nine classes, açai palm management area, brazil nut tree management area, cultivation area, secondary grassland, hunting area, timber area, area of diverse extractivism, and orchards. Of the nine classes of modern land use, eight classes, excluding timber area, were classified into two groups, which are activities that involve forest clearance and forest management activities. To analyze the EVI clustering patterns around the areas of modern land use, buffers with a radius of 80 m was generated around the inserted point features, as it has been done for ADE sites. Histograms of the Gi_Bin and C0Type were generated for activities that involve forest clearance and forest management activities. The created histograms were then compared with the histogram of the Gi_Bin and C0Type of the random points that represent the clustering patterns of EVI in the FNC.

3.5. Assessing the Contribution of Landscape Domestication to the Creation of Anthrome

The final analysis that was required in this research was assessing the contribution of landscape domestication to the creation of anthrome. Completing this objective directly addresses answering the main research question (How did pre-Columbian landscape domestication contribute to the formation of the modern Amazonian landscape?). The assessment was focused on areas that clearly demonstrate the attributes of the anthrome. The two areas that have been selected are archaeological sites, each named as Ibama (IBA2) and Forte (FOR2) (Figure 4). Tracing the process of anthrome construction by landscape domestication on Ibama and Forte involved two methods, which are (1) dating occurrences of landscape domestication following (2) archaeological and geologic excavations of ADE sites and offsite areas..

To obtain an idea of when the landscape domestication has occurred, radiocarbon dating was performed. Dates obtained by OSL dating was also considered to supplement the dates acquired through radiocarbon. However, dates acquired through radiocarbon was considered as the primary source of the timing of landscape domestication occurrence, since while OSL dates the time when the sediments were deposited, radiocarbon dates the age of the direct evidence of landscape domestication, such as shells and charcoal.

A total number of seven radiocarbon dating samples were collected. All of the samples were collected on-site; three from the Ibama site and four from the Forte site. All of the samples were mollusk samples, except one from the Ibama site, which is a charcoal sample. The contextual information for the samples is provided in Table 4.

The radiocarbon dating of the collected samples was carried out by Accelerator Mass Spectrometer (AMS) at the Korean Institute of Geoscience and Mineral Resources (KIGAM). The results were calibrated for atmospheric fractionation of ^{14}C using the IntCal13 calibration curve through OxCal 4.2 (Bronk Ramsey, et al., 2013).

Two screened archaeological excavations were conducted by digging a 1×5 m trench in the Ibama site, and a 2×2 m pit in the Forte site in 10 cm levels to sterile sediments. Descriptions of the soil profiles of the excavated sites were documented. For comparative purposes, non-screened shovel tests in various areas were performed within an area that measured approximately 50×50 cm. Soil profiles were documented for the shovel tests as well. The description of the soils was based on the Field Book for Describing and Sampling Soils from the United States Department of Agriculture (Schoeneberger, et al., 2012).

Table 4. Sample number and information on radiocarbon samples.

Sample Code	Sample Information
BRA16-IBA2-14C1	Freshwater mollusk shell recovered from auger test; Grid coordinate 980N, 1010E from datum; 93-100cm below the surface; Interpreted as a midden context below a 'Latosol'; July 9, 2016
BRA16-IBA2-14C2	Charcoal recovered from auger test; Grid coordinate 980N, 1010E from datum; 80-100cm below the surface; Interpreted as a midden and suprajacent to the midden in the 'Latosol'; July 9, 2016
BRA16-IBA2-14C3	Freshwater mollusk shell taken from the east wall profile of Excavation Unit 1(1×5m trench); Grid coordinate 998N, 998E from datum; Sample extracted 60cm south of the north wall(N998.60) and 20cm below the unit datum; Sample was not intact in the profile wall, so was flaked out using a small knife into aluminum foil; July 9, 2016
BRA16-FOR2-14C4	Grid coordinate UTM N9800887, E0452385; Extracted from East wall profile of excavation unit 1 at 25cm north of the southeast corner, 38cm below from site datum in ^A/C2 horizon (Layer 4); July 14, 2016
BRA16-FOR2-14C5	Grid coordinate UTM N9800887, E0452385; Extracted from the profile of excavation unit 1, 47cm below from site datum in ^C/A horizon (Layer 5); Bivalve shell and sediments matrix for radiocarbon dating; July 14, 2016
BRA16-FOR2-14C6	Grid coordinate UTM N9800887, E0452385; Extracted from 62cm West of East wall profile of excavation unit 1, 15cm below the surface in ^A/C1 horizon (Layer 3); Half of bivalve shell for radiocarbon dating; July 14, 2016
BRA16-FOR2-14C7	Grid coordinate UTM N9800887, E0452385; Extracted from South wall profile, 62cm West of East wall profile 29cm below the surface in ^C/A horizon (Layer 5); Fragmented bivalve shell for radiocarbon dating; July 14, 2016

Chapter 4. Results

4.1. Results of OSL

A general idea on the age of sedimentation of the ADE sites and survey points for comparison can be obtained from the OSL results (Table 5). Four samples were taken from the two previously reported sites of Ibama and Forte. The OSL age of the Ibama site is provided in the result of samples BRA16-IBA2-OSL10 and BRA16-IBA2-OSL11. The dates from Ibama demonstrate consistency between the age and depth since the sample collected from a greater age. The OSL dates of the Forte site are presented by the results of BRA16-FOR2-OSL8 and BRA16-FOR2-OSL9. The OSL dates from Forte are older than the dates from Ibama. The OSL age from a survey point, which turned out to be an ADE site, gives the age of 0.8±0.1, which is slightly older than that of Ibama.

When observing the OD (Table 5), it can be observed that ADE sites tend to have closer ranges of OD%, since four out of the five lowest values of the OD are from ADE sites. The samples taken from the Ibama site demonstrate the smallest value of OD. One sample from Forte and one sample form CAX1 are included in the group of samples that have small OD below 30%. Samples that have been taken from areas that have been less influenced by landscape domestication tends to provide greater OD values. This difference in the OD% can be visually observed by the dispersion pattern of the D_e of the samples (Figure 4). While the D_e of the samples from ADE sites tend to provide close to normal distributions, the dispersion of the D_e of the samples from less domesticated areas tend to be more skewed, or less normal. This indicates that sediment mixing by the soil formation process has less occurred in areas that have been highly affected by landscape domestication.

Table 5. OSL dates from the FNC, Pará, Brazil, 2016.

Sample	Depth† (cm)	Water Content※ (wt. %)	^{238}U ($Bq \cdot kg^{-1}$)	^{226}Ra ($Bq \cdot kg^{-1}$)	^{232}Th ($Bq \cdot kg^{-1}$)	^{40}K ($Bq \cdot kg^{-1}$)	Dry Beta ($Gy \cdot ka^{-1}$)	Dry Gamma ($Gy \cdot ka^{-1}$)	Cosmic Ray ($Gy \cdot ka^{-1}$)	Total Dose rate ($Gy \cdot ka^{-1}$)	D_e (Gy)	N	Age (ka)	OD (%)
BRA16-IBA1-OSL1	105	19.7	47.8±4.6	44.0±0.9	97.2±3.6	148.6±9.1	1.42±0.06	1.63±0.05	0.16±0.02	2.63±0.07	41.8±3.9	14	15.9±1.5	33.5
BRA16-IBA1-OSL2	45	19.8	54.0±3.2	41.9±0.5	98.0±3.0	84.0±4.8	1.04±0.04	1.29±0.04	0.18±0.02	2.50±0.06	5.6±0.3	15	2.3±0.1	21.0
BRA16-IBA5-OSL4	23	17.5	36.6±3.9	37.5±0.7	35.1±1.8	76.6±6.6	0.63±0.03	0.64±0.03	0.19±0.02	1.46±0.05	2.9±0.4	15	2.0±0.3	48.0
BRA16-FOR1-OSL5	17	21.5	41.6±3.8	41.2±0.7	32.2±1.7	51.8±5.6	0.57±0.03	0.59±0.03	0.19±0.02	1.35±0.05	1.3±0.2	16	0.9±0.2	64.4
BRA16-CAX1-OSL6	21	14.2	26.2±2.3	27.0±0.4	52.0±1.8	10.0±0.1	0.53±0.02	0.72±0.02	0.19±0.02	1.44±0.04	1.2±0.1	16	0.8±0.1	22.2
BRA16-CAX2-OSL7	14	17.1	23.4±2.6	18.4±0.4	45.2±1.7	10.0±0.1	0.43±0.02	0.58±0.02	0.19±0.02	1.21±0.03	1.6±0.3	16	1.3±0.2	62.5
BRA16-FOR2-OSL8	36	13.9	31.0±3.3	41.0±0.7	32.6±1.8	100.1±6.3	0.68±0.03	0.67±0.03	0.18±0.02	1.53±0.05	3.5±0.2	16	2.3±0.2	27.5
BRA16-FOR2-OSL9	9	22.9	37.1±1.9	39.5±0.4	34.2±1.3	109.6±4.0	0.71±0.03	0.63±0.03	0.19±0.02	1.53±0.04	0.4±0.1	16	0.3±0.1	34.0
BRA16-IBA2-OSL10	42	17.3	38.7±2.9	37.5±0.5	30.3±1.4	54.9±4.3	0.58±0.03	0.57±0.03	0.18±0.02	1.33±0.04	0.9±0.1	16	0.7±0.1	17.2
BRA16-IBA2-OSL11	25	19.6	34.8±3.8	37.8±0.7	31.3±1.8	69.4±5.9	0.58±0.03	0.58±0.03	0.19±0.02	1.35±0.05	0.7±0.1	16	0.5±0.1	11.2

†Depths of the samples are the vertical distance from the modern ground surface.
※Present water content.

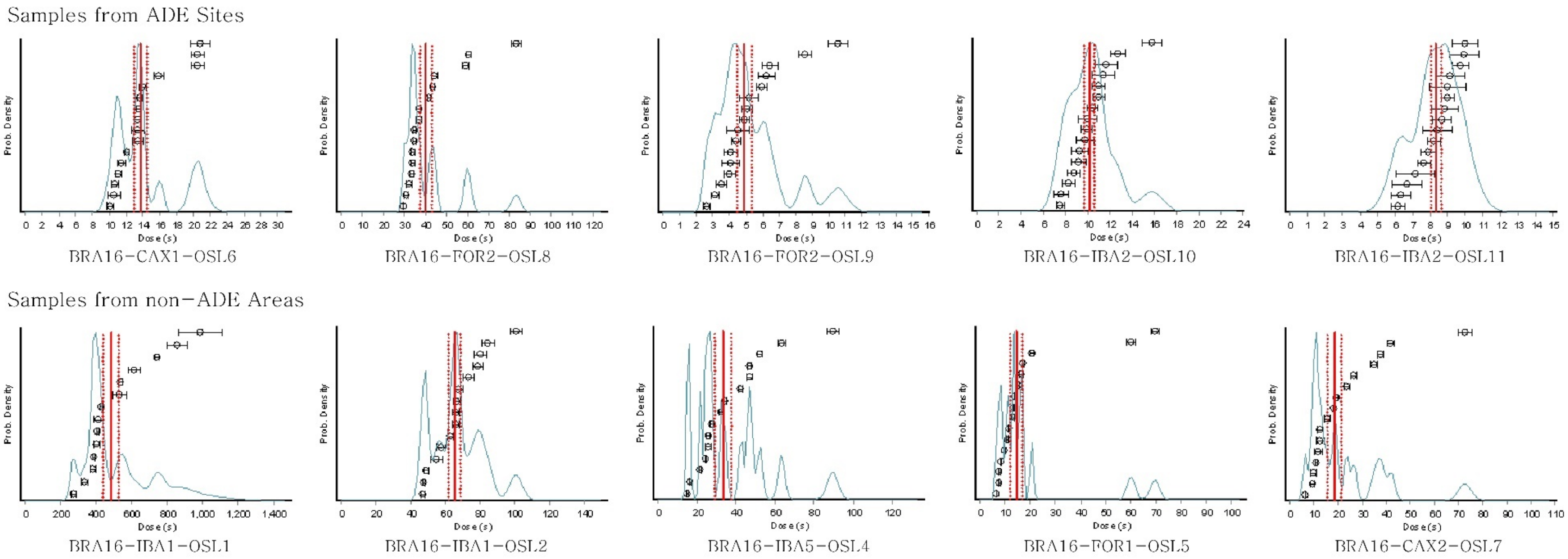

Figure 5. The dispersion pattern of the equivalent dose (D_e) of the samples from the FNC, Pará, Brazil, 2016.

4.2. Results of ANOVA using Soil Class an EVI

According to the summarized statistics of the EVI (Table 7), distinguished by the base soil type mapped in Costa, et al. (2005), it is evident that there is a difference in EVI values between different soil types. Even though the range of EVI values is limited since values smaller than 0.8753 were excluded, for explicit comparison between the forest environment, it is clear that there is a difference in the EVI values between soil types when observing the upper and lower bounds of the 95% confidence interval for the mean of the EVI values. The EVI values within the 95% confidence interval from the mean value do not overlap between soil types with high EVI values, such as Plinthosol (FTbd), and soil types with low EVI values, such as Latosol (LAd1). The summarized statistics present that EVI values do differ by soil types.

The F value result of the ANOVA test (Table 6) demonstrates that there is a statistically significant difference in the distribution of EVI values between the soil types such that the null hypothesis (there is a random relationship between soil class and EVI values) is rejected ($p<0.000$).

Table 6. Result of ANOVA on the effects of soil class to EVI.

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	116.711	8	14.589	4715.975	.000
Within Groups	1352.725	437279	.003		
Total	1469.436	437287			

Table 7. Summarized statistics of EVI distinguished by soil types. The description of the soil codes is presented in Table 1. Values smaller than 0.8753 were excluded from the analysis.

Soil Type	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
FTbd	17882	.9826	.0689	.0005	.9816	.9836	.8753	1.2352
GXbd1	33861	.9772	.0617	.0003	.9766	.9779	.8753	1.2500
GXbd2	37241	.9530	.0556	.0002	.9525	.9536	.8753	1.2678
LAd1	49438	.9412	.0462	.0002	.9408	.9416	.8753	1.1979
LAd2	160310	.9587	.0575	.0001	.9585	.9590	.8753	1.3121
LAd3	40304	.9910	.0608	.0003	.9904	.9916	.8753	1.2752
LAd4	79468	.9409	.0461	.0001	.9406	.9413	.8753	1.1813
PAd1	2063	.9421	.0476	.0010	.9400	.9441	.8753	1.1728
RUbd	16721	.9844	.0615	.0004	.9835	.9853	.8753	1.2752
Total (All Soil Types)	437288	.9593	.0579	.0000	.9591	.9595	.8753	1.3121

4.3. The Models and Comparisons with Previously Reported Sites

Based on the model created by the Getis-Ord's Gi* (Figure 6), 20 archaeological sites out of 29 were classified as sites with high EVI value clustering (Figure 7).

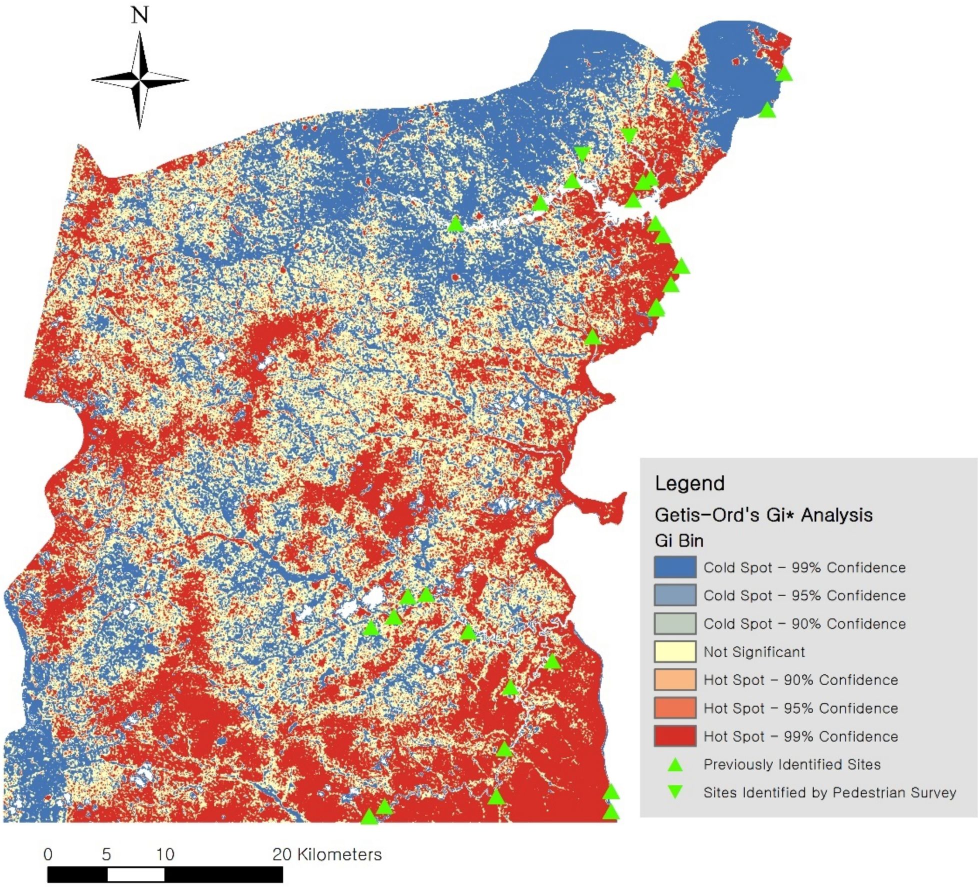

Figure 6. The model created through Getis-Ord's Gi* analysis.

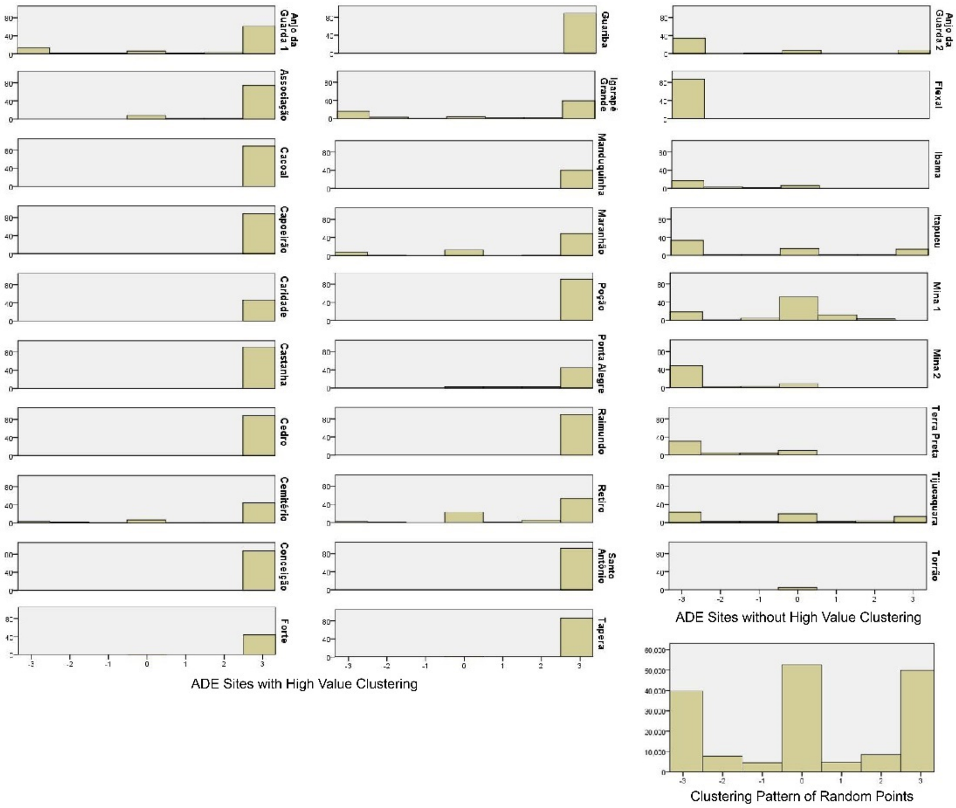

Figure 7. The classification of the sites into 'ADE Sites with High-Value Clustering' and 'ADE Sites without High-Value Clustering' according to the model created by Getis-Ord's Gi* analysis. The numbers of the x-axis indicate the Gi_Bin (-3=Cold Spot – 99% Confidence, -2=Cold Spot – 95% Confidence, -1=Cold Spot – 90% Confidence, 0=Not Significant, 1=Hot Spot – 90% Confidence, 2=Hot Spot – 95% Confidence, 3=Hot Spot – 99% Confidence). The y-axis indicates the number of points. The classification was made by comparing the percentage of the points classified with the Gi_Bin value 3. If the sites consisted of a higher percentage of points with the value of 3 than 2,000 randomly generated points that represent the FNC, they were classified as 'ADE Sites with High-Value Clustering.' If not, they were classified as 'ADE Sites without High-Value Clustering.'

According to the model generated by the Anselin's Local Moran's I (Figure 8), 22 archaeological sites out of 29 inside the FNC were classified as having a clustering of high EVI values (Figure 9).

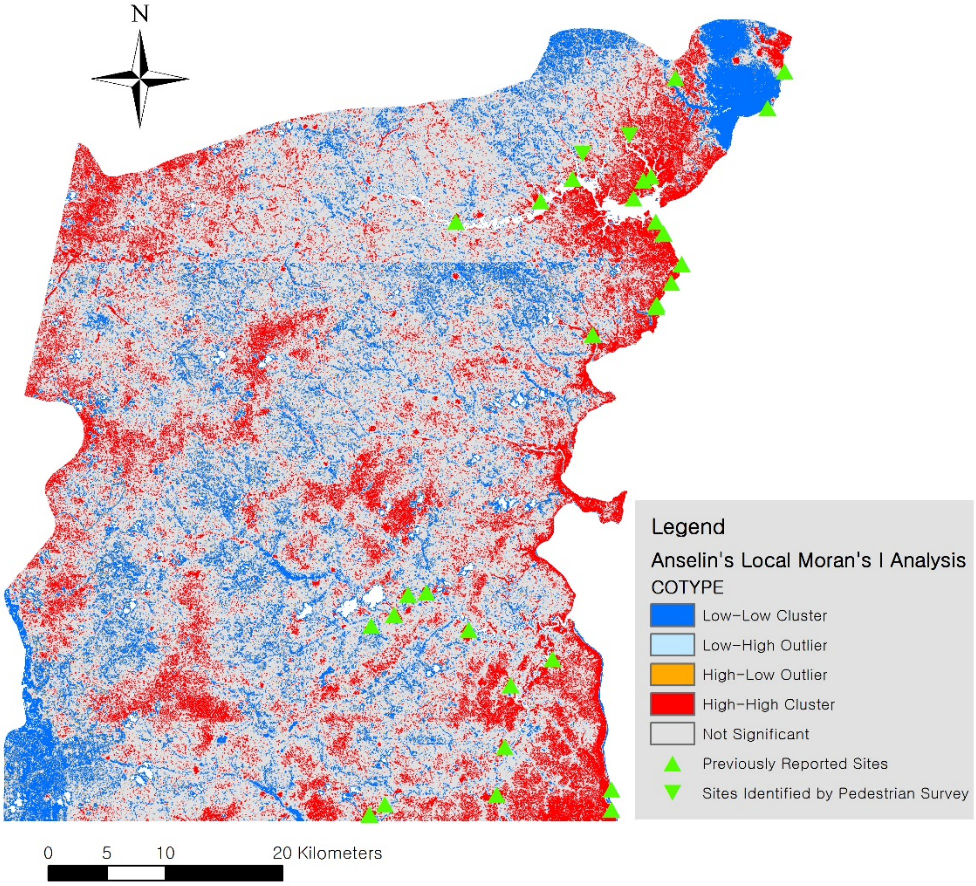

Figure 8. The model created through Anselin's Local Moran's I.

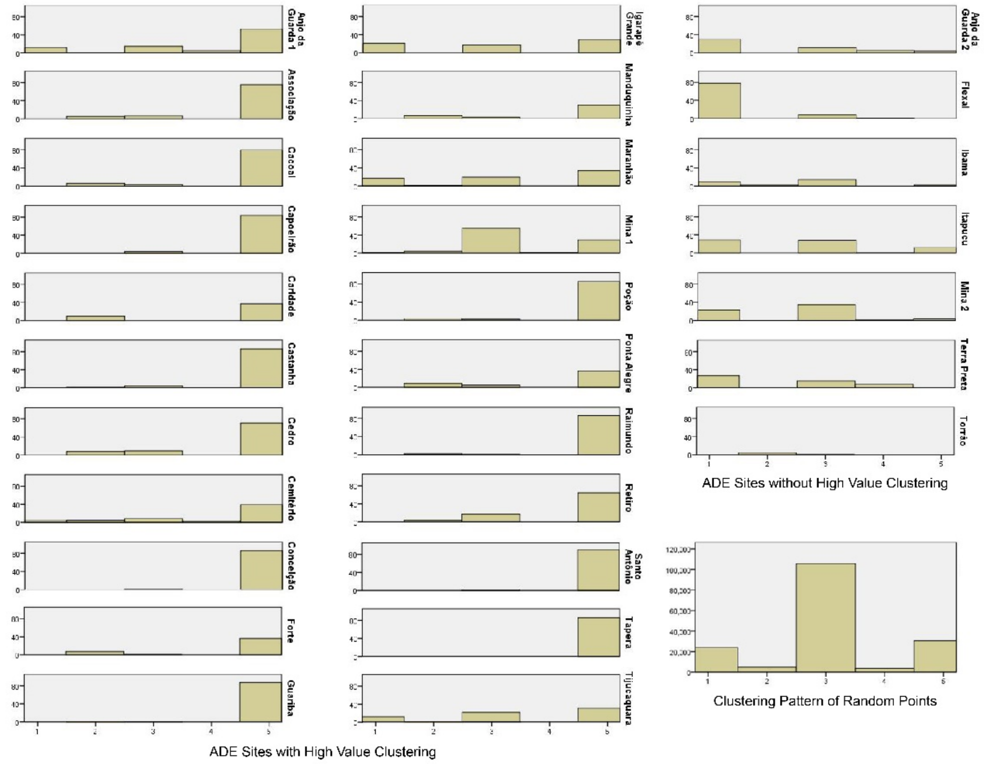

Figure 9. The classification of the sites into 'ADE Sites with High-Value Clustering' and 'ADE Sites without High-Value Clustering' according to the model created by Anselin's Local Moran's I analysis. The numbers of the x-axis indicate the C0Type (1=Low-Low Cluster, 2=Low-High Outlier, 3=Not Significant, 4=High-Low Outlier, 5=High-High Cluster). The classification was made by comparing the percentage of the points classified with the C0Type of High-High Cluster, indicated by the number 5. The y-axis indicates the number of points. If the sites consisted of a higher percentage of points with C0Type of High-High Cluster than 2,000 randomly generated points that represent the FNC, they were classified as 'ADE Sites with High Value Clustering.' If not, they were classified as 'ADE Sites without High Value Clustering.'

Out of the sites included in the analysis, two sites (Mina 1 and Tijucaquera) were classified differently by the models created by Getis-Ord's Gi* and Anselin's Local Moran's I. While Mina 1 and Tijucaquera sites were classified as ADE sites without high EVI value clustering by Getis-

Ord's Gi* analysis, they were classified as ADE sites with high EVI value clustering by Anselin's Local Moran's I analysis. Besides these two sites, the other 27 sites were classified the same by both spatial autocorrelation analysis of the EVI values.

4.4. Assessment of the Effects of Modern Human Activities on EVI

The effects of modern human activities on EVI values were explored by comparing the clustering patterns of EVI values between areas where land clearing activities are involved, areas of forest management, and the overall pattern of the FNC. The comparison was based on the model created by Getis-Ord's Gi* analysis (Figure 6) and the survey reported by Lisboa, et al. (2013) (Figure 3). The results presented that areas that are utilized for modern human activities, both areas that involve land clearing activities and areas of forest management, tend to a have higher proportion of points of high EVI value clustering when compared to the general EVI clustering pattern of the FNC (Figure 10). When the EVI clustering pattern between the areas involving land clearing activities and forest management areas are compared, areas involving land clearing activities demonstrated a higher ratio of high EVI value clustering (Figure 10).

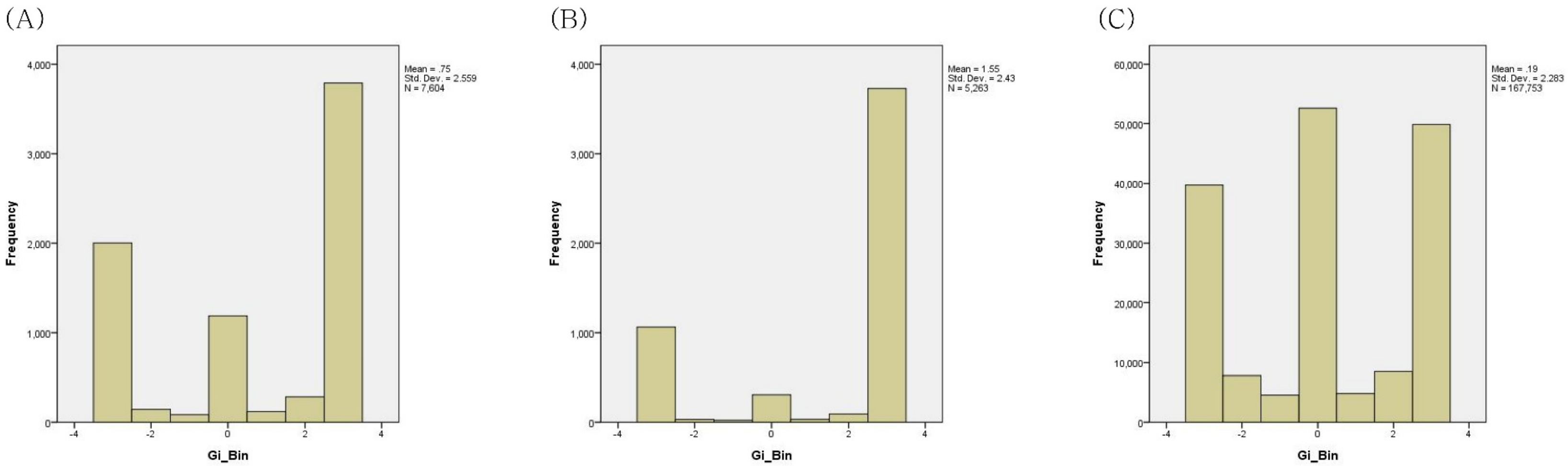

Figure 10. The comparison of EVI value clustering patterns between (A) modern forest management areas, (B) areas of modern human activities involving, and (C) the overall pattern of the FNC according to the model created by Getis-Ord's Gi* analysis. The numbers of the x-axis indicate the Gi_Bin (-3=Cold Spot – 99% Confidence, -2=Cold Spot – 95% Confidence, -1=Cold Spot – 90% Confidence, 0=Not Significant, 1=Hot Spot – 90% Confidence, 2=Hot Spot – 95% Confidence, 3=Hot Spot – 99% Confidence). The y-axis indicates the number of points.

4.5. Results of Pedestrian Surveys and Soil Profiling

Pedestrian surveys and soil profiling were carried out in July 2016. The soil profile was performed in eight points, and the pedestrian survey was performed during the navigation to the points of soil profiles. The soil profiles were documented in the locations marked in Figure 4. The areas demonstrated various degrees of influence of landscape domestication.

The site that showed the strongest influence of landscape domestication was the site labeled as CAX1. The topsoil of CAX1 has the color of 10YR2/1 (black), is a sandy clay loam with a very weak sub-angular blocky structure and has no preserved bedding or depositional features (Figure 11). The topsoil of CAX1 demonstrated obvious traits of ADE. Ceramic and charcoal inclusions were identified in the profile, indicating human activity on site. There were no trails in and around CAX1, suggesting the site had been abandoned for some time. The vegetation had the traits of a mature rainforest.

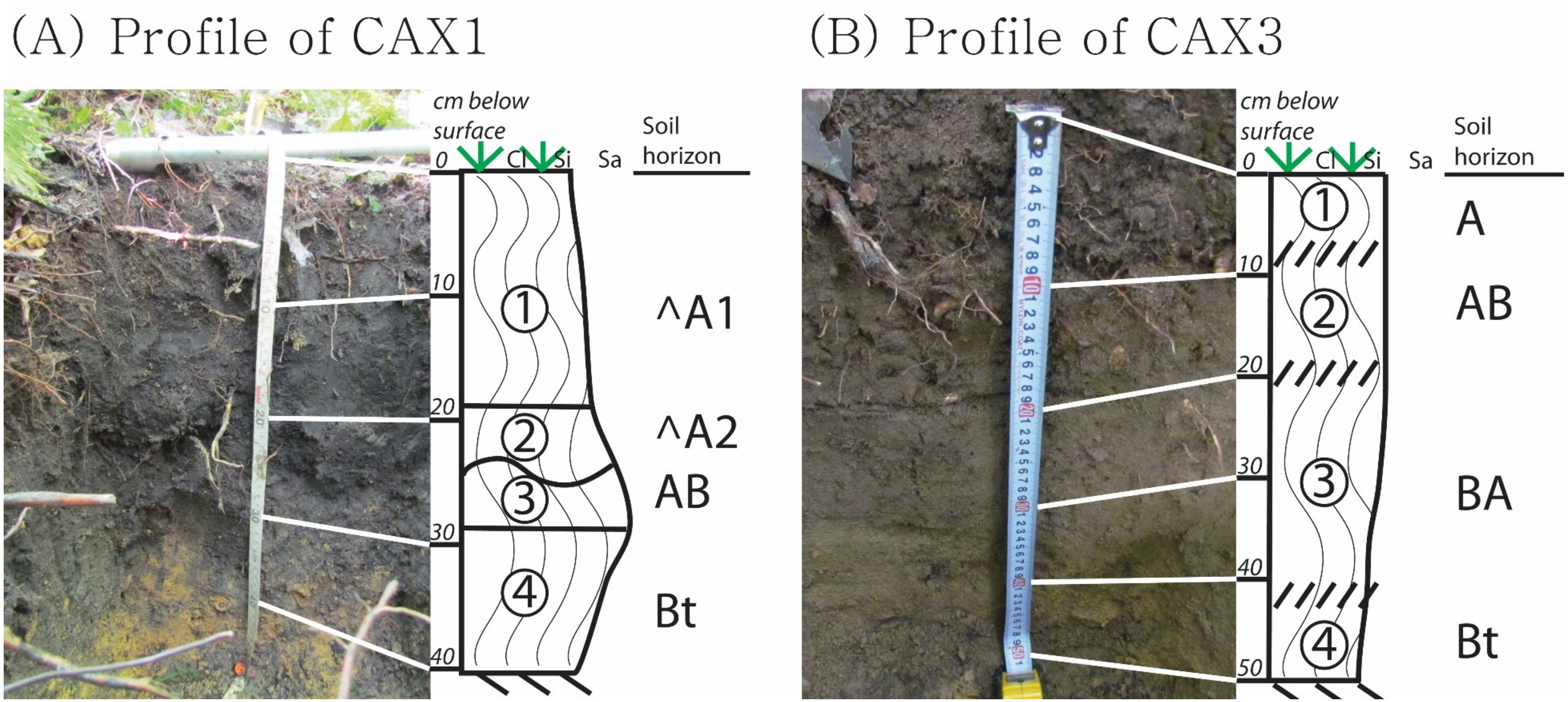

Figure 11. Profiles of (A) CAX1 and (B) CAX3 sites, which were identified during the pedestrian survey.

Table 8. Soil profile of CAX1. Descriptions follow protocols outlined in Schoeneberger, et al. (2012).

Site Code	Layer	Description
CAX1	1	0 - 18cm; ^A1; sandy clay loam; 10YR 2/1; soft, very weak subangular blocky; very friable, moderately plastic, non-sticky; clear, smooth boundary; ceramic inclusions found in abundance in fill; common root, common rootlet disturbances; *terra preta*
CAX1	2	18 - 25cm; ^A2; sandy clay loam; 10YR 3/1; soft, weak subangular blocky; very friable, moderately plastic, non-sticky; clear, wavy boundary; ceramic inclusions abundance in fill; rare rootlet disturbances; *terra preta*
CAX1	3	25 - 37cm; ^AB; sandy loam with high sand content compared to overlying deposits; soft, weak subangular blocky structure; very friable, moderately plastic, non-sticky; clear, smooth boundary; ceramic inclusions found in abundance; rare rootlet disturbances; nearly completely pedogenically modified *terra preta* soil
CAX1	4	37 - 50cm; Bt; silty clay; moderately hard, angular blocky; very friable, very plastic; ceramic inclusions found in fill, post mold feature present with ceramics and charcoal inclusion inside the feature; rare root, rare rootlet disturbances

The other point that had pertinence of landscape domestication evidence was IBA4. The topsoil of IBA4 also had the traits of ADE, but while CAX1 was an ADE site, IBA4 was located on a continuum of the Ibama site, which has been previously reported (Lisboa, et al., 2013). The color of the topsoil of IBA4 was less dark (10YR3/1) than that of the Ibama site (10YR2/1). Adjacent to the point, several trees that are present due to human activities were identified, including mango trees (*Mangifera indica*) and rubber trees.

Table 9. Soil profile of IBA4. Descriptions follow protocols outlined in Schoeneberger, et al. (2012).

Site Code	Layer	Description
IBA4	1	0 - 17cm; ^A1; silty clay; 10YR 3/1; soft, weak blocky; very friable, very plastic, moderately sticky; clear, smooth boundary; common rootlet, common root disturbances
IBA4	2	17 - 27cm; A2, silty clay, slightly clayer than the overlying deposit); 10YR 3/2; soft, weak subangular blocky; very friable, very plastic; clear, smooth boundary; common root, common rootlet disturbances
IBA4	3	27 - 36cm; BE; silty clay; 10YR 4/2; soft, weak subangular blocky; very friable, very plastic; clear, smooth boundary; modern material (tile, plastic) inclusions
IBA4	4	36 - 52cm; Bth; 2/5YR 5/8, 10YR 7/2; soft, angular blocky (cm-scale); very friable, very plastic; boundary unseen; clay films on ped faces, redox stage 1.5

CAX3 is another point that contained traits of an area influenced by landscape domestication. The topsoil was slightly darker than the natural rainforest soils, with the color of 10YR3/2 (strong brown). The topsoil is also a sandy clay loam with a moderate sub-angular blocky structure and also lacks bedding or depositional structure (Figure 7). CAX3 site lacks ceramics but has abundant charcoal inclusions in its profile.

Table 10. Soil profile of CAX3. Descriptions follow protocols outlined in Schoeneberger, et al. (2012).

Site Code	Layer	Description
CAX3	1	0 - 7cm; A; sandy clay loam; 10YR 3/2; slightly hard, moderate subangular blocky; friable, moderately plastic, non-sticky; clear smooth boundary; many roots, many rootlet disturbances; *terra mulata*
CAX3	2	7 - 20cm; AB; sandy clay; 10YR 4/3; soft, weak subangular blocky; very friable, moderately plastic, non-sticky; clear smooth boundary; common root, common rootlet disturbances
CAX3	3	20 - 41cm; BA; sandy clay (slightly more clay included than the overlying horizon); 10YR 5/4; soft, moderate subangular blocky; very friable, very plastic, slightly sticky; clear smooth boundary; common charcoal inclusions; rare root, rare rootlet disturbances
CAX3	4	41 - 50cm; Bt; silty clay; 10YR 5/6; slightly hard, moderate angular blocky; friable, very plastic, slightly sticky; common charcoal inclusions; rare rootlet disturbances

IBA3 was a point that was located on the trail linking the Ibama site and the Forte site. Although the topsoil of IBA3 did not demonstrate characteristics of ADE, the top layer of the soil was thickened, most likely by human activities. A remnant of a recently abandoned house and debris of modern human activity, such as plastic, were identified around the point. Also, trees that local people make of use, such as Brazil nut trees and açaí palms were identified near the point.

Table 11. Soil profile of IBA3. Descriptions follow protocols outlined in Schoeneberger, et al. (2012).

Site Code	Layer	Description
IBA3	1	0 - 20cm; ^A; sandy clay w/ very fine, subrounded sand; 10YR 4/3; soft, very weak subangular blocky; very friable, moderately plastic, non-sticky; very fine, inclusions; common root, common rootlet disturbances
IBA3	2	20 - 30cm; E; silty clay w/ very fine, subrounded sand; 10YR 6/4; soft, very weak angular blocky; very friable, moderately plastic, non-sticky; modern material inclusions; rare rootlet disturbances
IBA3	3	30 - 40cm; Bt; sandy clay; slightly hard; very friable; moderately plastic; clay films on ped faces, redox stage 1

FOR1 was a point that is several hundred meters away from the Forte site. The A horizon of the topsoil was slightly darker than typical rainforest soils. Although some plants that seemed to have been managed by humans, such as cacao (*Theobroma cacao*), were identified during the navigation, the impact of landscape domestication activity seemed relatively small.

Table 12. Soil profile of FOR1. Descriptions follow protocols outlined in Schoeneberger, et al. (2012).

Site Code	Layer	Description
FOR1	1	0 - 9cm; A; silty clay; 10YR 3/2; soft, weak subangular blocky; very friable, very plastic, slightly sticky; clear, smooth boundary; common root, common rootlet disturbances

FOR1	2	9 - 28cm; E1; silty clay loam; 10YR 4/3; soft, weak subangular blocky; very friable, very plastic, slightly sticky; abrupt, smooth boundary; iron precipitation; rare root, rare rootlet disturbances
FOR1	3	28 - 34cm; E2; silty clay loam; 10YR 5/2; soft, weak angular blocky; very friable, very plastic, slightly sticky; clear, wavy boundary; rare root, rare rootlet disturbances
FOR1	4	34 - 44cm; Bt; silty clay; 5YR 5/6, 5YR 6/2; slightly hard, weak angular blocky; very friable, very plastic; rare rootlet disturbances

IBA5 was located on an upper terrace from the passage that links the Ibama site and the Forte site. The A horizon was slightly darker than typical rainforest soils but had general traits of Latosols. The point where the soil profile was documented was sloped when compared to other points. The influence of landscape domestication seemed relatively low since there were no plants identified that the local people utilize. However, the density of the forest was relatively thick, which may indicate this point being a secondary forest.

Table 13. Soil profile of IBA5. Descriptions follow protocols outlined in Schoeneberger, et al. (2012).

Site Code	Layer	Description
IBA5	1	0 - 8cm; A; silty clay; 10YR 3/3; soft, weak subangular blocky; very friable, very plastic, moderately sticky; clear, wavy boundary; common root, common rootlet disturbances

IBA5	2	8 - 30cm; Bw; silty clay; 10YR 4/4; soft, weak angular blocky; very friable, very plastic, moderately sticky; clear, smooth boundary; rare root, rare rootlet disturbances
IBA5	3	30 - 45cm; Bt; silty clay; 7.5YR 4/4 soft, strong angular blocky; very friable, very plastic, moderately sticky; rare root, rare rootlet disturbances; mottled, very clayey sediments, possibility of some incipient redox formation

CAX2 was approximately 500 m away from CAX1. The soil was Latosol, which is common in the tropical rainforest. This point showed no evidence of human influence. The forest in this area had the greatest density among the forests near all survey points, being a fully mature rainforest.

Table 14. Soil profile of CAX2. Descriptions follow protocols outlined in Schoeneberger, et al. (2012).

Site Code	Layer	Description
CAX2	1	0 - 7cm; weak A; sandy loam; 10YR 4/2; soft, weak subangular blocky; very friable, moderately plastic, non-sticky; clear, smooth boundary; common root, common rootlet disturbances
CAX2	2	7 - 36cm; Bt1; sandy clay loam; soft, weak subangular blocky; very friable, moderately plastic, non-sticky; clear, smooth boundary; rare root, rare rootlet disturbances
CAX2	3	36 - 45cm; Btw2; sandy clay loam; 10YR 5/4; soft, weak angular blocky structure; very friable, moderately plastic, slightly sticky; rare root, rare rootlet disturbances

IBA1 was a profile that has been exposed due to erosion by the river. Thereby, it had to be approached by a boat. It was documented to get a general understanding of the geology of the area around the Ibama site. No evidence of human influence was observed. The top was covered with small bushes and trees.

Table 15. Soil profile of CAX2. Descriptions follow protocols outlined in Schoeneberger, et al. (2012).

Site Code	Layer	Description
IBA1	1	0 - 465cm (from bottom); silty clay; Mottled 5R 4/6, 5YR 8/1; slightly hard; very friable, strongly cemented, very sticky; no bedding features; very strong redoximorphic masses dm-m scale; rare root, rare rootlet disturbances
IBA1	2	465 - 476cm (from bottom); clay loam; 7.5YR 7/8; very hard; firm, slightly sticky; no bedding structures; very weak redoximorphic features, 1% redoximorphic nodules(gravels); common rootlet, common insect, rare root disturbances
IBA1	3	476 - 575cm (from bottom); clay loam; 5YR 7/8 - 7.5YR 5/3; very hard; very friable; diffuse lower boundary; no bedding structure; no redoximorphic features; common roots, common rootlet, common animal burrow, common insect disturbances

4.6. Archaeological Excavations in Ibama and Forte

Along with the soil profiles documented during the pedestrian survey, soil profiles for Ibama and Forte sites were documented as well (Table 16 and 17), through archaeological excavation.

Table 16. Soil profile of the Ibama site. Descriptions follow protocols outlined in Schoeneberger, et al. (2012).

Site Name	Layer	Description
Ibama	1	^A1; well-sorted silty clay; 10YR 2/1; slightly hard, weak subangular blocky; very friable, very plastic, slightly sticky; abrupt, wavy boundary; burnt clay inclusions; common grass rootlet disturbances; *terra preta*
Ibama	2	^A/C; very-poorly-sorted silty clay; 10YR 2/1 and white mollusk shell (not in Munsell book); soft, weak subangular blocky; very friable; non-plastic (too much shell), slightly sticky; very abrupt, wavy boundary; ceramic and burnt clay inclusions; common rootlet, common insect, rare root disturbances; matrix-supported *terra preta* sediments within a shell midden
Ibama	3	^A2; well-sorted silty clay; prominent mottled 2.5YR 5/8 and 10YR 2/1; slightly hard, weak subangular blocky; very friable, very plastic, slightly sticky; very abrupt, wavy boundary; burnt clay inclusions; common grass rootlet disturbances; a burnt clay lens within *terra preta*
Ibama	4	^C/A; very-poorly sorted silty clay; white mollusk shell (not in Munsell book) and 10YR 2/1; soft, weak subangular blocky; very friable, non-plastic (too much shell), slightly sticky; abrupt, discontinuous boundary; charcoal, ceramic and burnt clay inclusions; common rootlet, common insect, rare root disturbances; clast (shell)-supported *terra preta* sediments within a shell midden

Ibama	5	^A3; well-sorted silty clay; 10YR 2/2; soft, weak subangular blocky; very friable, very plastic, slightly sticky; abrupt, wavy boundary; burnt clay, charcoal, and ceramic inclusions; rare grass rootlet, rare root, rare insect disturbances; *terra preta* with dispersed burning features
Ibama	6	2AB; well-sorted silty clay; 10YR 3/2; soft, weak subangular blocky; very friable, very plastic, slightly sticky; clear, smooth boundary; charcoal, burnt clay and ceramic inclusions; common root, rare grass rootlet disturbances; human-occupied surface below *terra preta* but not primarily formed from anthropogenic processes (i.e., humans did not transport these sediments to the location, but the soil is an Anthrosol)
Ibama	7	2BA; well-sorted silty clay; 10YR 4/3; soft, weak subangular blocky; very friable, very plastic, slightly sticky; clear, smooth boundary; diffuse charcoal nodule and mass inclusions; rare root, rare grass rootlet disturbances; subsoil pedogenically modified by anthropogenic processes that preceded the formation of the *terra preta*
Ibama	8	2Bt; well-sorted silty clay; distinct mottled 10YR 6/6 and 5YR 5/8; slightly hard, strong subangular blocky; very friable, very plastic, slightly sticky; common, medium redox masses; boundary not seen (unexcavated); charcoal, burnt clay and ceramic inclusions; common root, rare grass rootlet disturbances; subsoil with increasing evidence of *in situ* redoximorphic weathering as a function of increasing distance below the ground surface

Table 17. Soil profile of the Ibama site. Descriptions follow protocols outlined in Schoeneberger, et al. (2012).

Site Name	Layer	Description
Forte	1	^A1; well-sorted silty clay loam; 10YR 2/2; soft, very weak subangular blocky; very friable, very plastic, slightly sticky; clear, wavy boundary; shell and ceramic inclusions; common root, common rootlet disturbances; *terra preta*
Forte	2	^A2; well-sorted silty clay loam; 10YR 2/2; slightly hard, weak subangular blocky, very friable, very plastic, slightly sticky; very abrupt, wavy boundary; shell and ceramic inclusions; common root and rootlet disturbances; *terra preta*
Forte	3	^A/C1; very poorly-sorted silty clay loam; 10YR 4/3 and white mollusk shell (not in Munsell book); soft, very weak subangular blocky; very friable, very plastic, slightly sticky; clear, wavy boundary; ceramic inclusions; common root and rootlet disturbances; matrix (*terra preta*)- supported shell midden deposits
Forte	4	^A/C2; very-poorly sorted silty clay loam; 10YR 4/3 and white mollusk shell (not in Munsell book); soft, very weak subangular blocky; very friable, very plastic, slightly sticky; clear wavy boundary; ceramic, burnt clay and charcoal inclusions; rare rootlet disturbances; matrix (*terra preta*)- supported shell midden deposits

Forte	5	^C/A; very poorly-sorted silty clay; white mollusk shell (not in Munsell book) and 10YR 5/4; soft, weak subangular blocky; very friable, very plastic, moderately sticky; abrupt, wavy boundary; burnt clay and charcoal inclusions; rare rootlet disturbances; clast (shell)- supported *terra preta* sediments within a shell midden
Forte	6	2AB; well-sorted silty clay; 10YR 5/4; soft, moderate subangular blocky; very friable, very plastic, moderately sticky; clear, smooth boundary; burnt clay, charcoal and ceramic inclusions; no disturbances observed; human-occupied surface below *terra preta* but not primarily formed from anthropogenic processes (i.e., humans did not transport these sediments to the location, but the soil is an Anthrosol)
Forte	7	2BA; well-sorted silty clay; 7.5YR 5/8; soft, moderate subangular blocky; very friable, very plastic, moderately sticky; few, medium redox masses; clear, smooth boundary; no inclusions observed; rare root disturbances; subsoil pedogenically modified by anthropogenic processes that preceded the formation of the *terra preta*
Forte	8	2Bt; well-sorted silty clay; distinct mottled 10YR 6/6 and 5YR 5/8; slightly hard, strong angular blocky; very friable, very plastic, slightly sticky; common, medium redox masses; boundary not seen (unexcavated); no inclusions observed; rare rootlet disturbances; subsoil with increasing evidence of *in situ* redoximorphic weathering as a function of increasing distance below the ground surface

4.7. Results of the Radiocarbon Dating

The results of the radiocarbon dating (Table 18) provides a general idea when the Ibama and Forte sites have been occupied. The Ibama site has been occupied from 900-550 cal. BP, just before the European colonization of Amazonia. The Forte site has been occupied earlier than the Ibama site, around 2000-1850 cal. BP.

Table 18. Results of radiocarbon dating. The dates were calibrated by IntCal13 calibration curve using OxCal 4.2 (Bronk Ramsey, et al., 2013).

Sample	Depth (cm) below surface	Material	$\delta^{13}C$‰	$\Delta^{14}C$‰	14C yr BP	cal. years BP (2-σ)
BRA16-IBA2-14C1	93-100	Mollusk	-16.4± 1.74	-101.48± 2.07	800± 20	780-820
BRA16-IBA2-14C2	80-100	Charcoal	-32.07± 1.15	-107.42± 4.16	850± 40	810-890
BRA16-IBA2-14C3	20	Mollusk	-19.22± 3.44	-76.54± 2.14	580± 20	560-600
BRA16-FOR2-14C4	38	Mollusk	-11.38± 0.96	-217.26± 1.81	1900± 20	1880-1920
BRA16-FOR2-14C5	47	Mollusk	-12.71± 1.72	-224.28± 1.88	1980± 20	1960-2000
BRA16-FOR2-14C6	15	Mollusk	-6.92± 1.48	-221.65± 1.74	1950± 20	1930-1970
BRA16-FOR2-14C7	29	Mollusk	-16.93± 3.43	-215.38± 1.93	1980± 20	1860-1920

Chapter 5. Discussion

The research questions that were presented in the introduction can be discussed from the vantage point of analyses of the two dependent research objectives, which are (1) how did pre-Columbian landscape domestication activities affect soil formation processes in the FNC, and (2) how can the pre-Columbian landscape domestication be traced and calibrated more generally across the modern landscape of Amazonia. By answering the two dependent research questions, the main research question on how the creation of anthromes by pre-Columbian landscape domestication affected the modern landscape of Amazonia can be discussed.

The focus on soils as evidence of pre-Columbian landscape domestication in Amazonian archaeology was due to the relative paucity of sites and artifacts in Amazonia when compared to other areas of South America (Goldberg, et al., 2016, McMichael and Bush, 2019). Especially, with the discovery of ADE, research of pre-Columbian landscape domestication based on soil analysis has been proposed (Sombroek, 1966, Smith, 1980, Woods and McCann, 1999, Hecht, 2003, Arroyo-Kalin, 2008). However, most of the research viewed ADE as an independent class of soil, split from its adjacent soils.

However, Fraser, et al. (2011) argued that ADE and its adjacent soils should be viewed as a continuum, rather than setting ADE as a separate category since ADE formation is based on the natural tropical soils. The results presented by Macedo, et al. (2017) demonstrate that landscape domestication activities affect the pedogenesis of the soils. Considering these results, the soils in general, rather than only ADE, should be considered as research material to study the landscape domestication in pre-Columbian Amazonia.

This thesis attempted to test the effects of landscape domestication to soils through OSL, especially by comparing the OD. OD of OSL demonstrates variation between samples. This difference in the OD in soils tested across the FNC is likely to have been caused by the pre-colonial human landscape domestication activities. OD tended to be lower in areas that have been more affected by landscape domestication. Samples from the Ibama site was the lowest among all samples. Ibama site was the area that underwent landscape domestication to the greatest degree among all the areas that have been surveyed in 2016. CAX1 demonstrated the second-lowest OD, and the soil profile of CAX1 included a thick layer of ADE. By contrast, samples from areas that had little evidence of landscape domestication, such as FOR1 and CAX2, demonstrated high OD.

Studies in other locations have determined that the high OD value in Amazonia is most likely to be caused by post-depositional mixing, especially by bioturbation (Araujo, et al., 2013). Therefore, it can be interpreted that pre-Columbian landscape domestication activities have affected the soils to be more resilient to pedoturbation and bioturbation. There are three possible explanations for this effect.

First is the addition of anthropogenic materials, such as potsherds and shells, to the soil matrix. For examination of the effect of potsherds or shells on the soil matrix, the effect of rock fragments on soils can be considered as a reference (Poesen and Lavee, 1994). The rock fragments help preserve the favorable soil structure by acting as a skeleton when included in the soil matrix, and by acting as a mulch when located on the soil surface (Poesen and Lavee, 1994). The inclusion of rock or gravel is extremely sparse in the FNC since none of the profiles included any rock or gravel inclusion (Table 8~17). The inclusion of hard materials, such as potsherds and shells, can have similar effects as rock fragments, and therefore, the soil matrix will be more stable and resistant to pedoturbation.

Second is the change in the root dynamics in Amazonia by the plant nutrient availability. It has been shown that vegetation in the Amazon tends to show higher above-ground productivity and lower below-ground productivity when growing on nutrient-rich soils but demonstrates the opposite result on nutrient-poor soils (Jiménez, et al., 2009). The formation ADE sites, which is a common form of landscape domestication in Amazonia, has higher nutrient availability for plants (Fraser, et al., 2011, Costa, et al., 2013) that will cause lower below-ground productivity, resulting in a lower rate of pedoturbation due to roots. The pre-Columbian forest management activities may also have the effect of enhancing plant nutrient availability. An ethnoarchaeological study presents an indigenous technique named as '*terra queimada*' (WinklerPrins, 2009). *Terra queimada* is a technique that places charred garden debris around vegetation, fruit trees in particular (WinklerPrins, 2009, Schmidt, et al., 2014). If a similar forest management technique were also practiced in the pre-Columbian period, it would have contributed to the enhancement of plant nutrient availability. Also, while the woody vegetation in the secondary forests do not demonstrate a significant difference in root depth from the vegetation in primary forests, the secondary vegetation, such as fruits and crops have significantly shallower roots when compared to the vegetation in primary forests (Sommer, et al., 2000). During the pedestrian survey, it has been observed that areas that have been highly affected by landscape domestication have a higher proportion of secondary vegetation. The higher proportion of the secondary vegetation with shallower roots will result in minimal vertical sediment mixing during soil formation processes relative to the more dominant horizontal mixing processes, which do not tend to affect OSL OD as much.

Finally, the speed of sediment aggregation should be considered. By simply dividing the depth that the sample was taken (Table 2) with the central age of the OSL (Table 5), a comparison between yearly aggregation of sediments can be made. While most of the samples demonstrate yearly sediment accumulation less than 0.2 mm, the sites that have been largely affected by landscape domestication showed exceptionally fast accumulation of sediments. CAX1 provided a result of 0.262 mm aggregation of sediments per year, and the yearly sediment accumulation of the Ibama site was 0.485 mm to 0.5 mm. This fast accumulation of sediments is most likely to have been occurred during the human occupation, and this fast accumulation of sediments in a short period would have resulted in low OD of the OSL samples.

The sample size in this research is not big enough for general application. Also, there is an exception in the samples that contradict the tendency of the rest of the samples. OSL sample BRA16-FOR2-OSL9, which was collected from the Forte site, provided high OD. This may have resulted from bioturbation and modern human activities. BRA16-FOR2-OSL9 was collected 9 cm below the surface, which is the shallowest sampling point among all samples and therefore most susceptible to bioturbation. Also, there was evidence of modern human activities identified during pedestrian surveys around the Forte site, including managed fruit trees, abandoned house, and modern garbage. These factors may have affected the OSL result of the sample.

Nonetheless, the OD of the OSL results demonstrates the possibility that landscape domestication activities have affected the pedogenesis and pedoturbation in various forms. Therefore, during the process to understand the pre-Columbian landscape domestication process, more evidence can be found when focusing on the general soil formation process in Amazonia, rather than separating out ADE from its adjacent soils.

The OSL results demonstrated that pre-Columbian landscape domestication activities affect the soils. The result of the ANOVA showed that the difference in soil characteristics is reflected in EVI. The results of the two analyses enabled the connection between the pre-Columbian landscape domestication activities and EVI. The comparison between the clustering patterns of EVI values of the centers of landscape domestication, which are ADE sites, and the general clustering pattern of EVI values of the FNC proposed that pre-Columbian landscape domestication enhances the EVI values. According to this result, to trace and calibrate pre-Columbian landscape domestication, researchers should focus on areas of high EVI value clusters.

However, this result contrasts with Thayn, et al. (2011) and Palace, et al. (2017). Their results showed that ADE sites tend to have lower average EVI values. This contrasting result may have been caused by modern land use. According to Thayn, et al. (2011), most of the ADE sites are currently used by local farmers, who recognize the productivity of these anthropic soils. This is also true in the case of the FNC as well. When comparing the location of modern human land use in the FNC (Figure 2) and the location of ADE sites, ten out of 31 sites are located within 500m of modern human activity areas. If modern human activities take place, which involves deforestation, such as agriculture or land clearance for residence, it will result in lower vegetation index values in the area (Morton, et al., 2006).

It is difficult to demonstrate that modern human activities affected the results since the land use of small farmers in Amazonia shows great variety between households by their conditions, such as available labor and their duration of stay (Marquette, 1998). Also, the planning of the small farmers of Amazonia is not established in a systematic manner, as modern industrialized farmers do (Summers, et al., 2004). Therefore, the type of land use in a certain area can be changed into various forms within a relatively short period (Fearnside, 1996). For instance, a fully cleared agricultural field may be transformed into a woody secondary forest within three years (Fearnside, 1996).

This complexity of modern land use is reflected in the current research, while forest management areas resulted in high EVI value clustering patterns as expected, areas that involve forest clearance resulted in high EVI value clustering as well (Figure 9). Since there is a temporal difference from the time when the satellite image was taken and when the modern land use survey was undertaken, it is difficult to verify whether the modern land use affected the spatial model. However, at least one site clearly shows that the land clearance by modern human activity results in the absence of high EVI value clustering. The Ibama site has been not classified as having high EVI value clustering and, a research station has been in operation by IBAMA since 1993. The land has been cleared since the establishment of the research station and, results in the low EVI value clustering pattern of the Ibama site.

The relationship between modern land clearance by small farmers and vegetation indices has not been fully explored in the FNC. However, it is evident that land clearance results in low VI values (Morton, et al., 2006, Alves, et al., 2015), and considering the case of the Ibama site, modern land clearance may be the main cause of the presence of sites without high EVI value clustering in the FNC, though there may be exceptions. Therefore, in general, it can be said that ADE sites tend to provide high EVI value clustering patterns, when they are located in a forest environment that is not subject to heavy commercial logging or ranching.

The attributes related to the research material, spatial resolution of the satellite images and the size of the majority of the ADE sites, may be factors that are contributing to the contradicting results with Thayn, et al. (2011) and Palace, et al. (2017). It has been reviewed that the majority of the size of the ADE sites is less than 2 ha in size (Kern, et al., 2003). The resolution of the MODIS series, the satellite images that Thayn, et al. (2011) and Palace, et al. (2017) utilized, is 250m per pixel, which each pixel covers an area greater than 6 ha. The model presented in this research and the results of a pedestrian survey also demonstrate that there are sites that cannot be detected with the 250 m/pixel resolution. For example, CAX1, which is an ADE site identified by the pedestrian survey, cannot be detected with 250 m/pixel resolution, since it is surrounded by low-value clustering. If the majority of the small sites are like CAX1, the location of ADE sites will not provide high EVI values.

The overall result present that EVI combined with spatial autocorrelation methods can be a useful tool in tracing and calibrating pre-Columbian landscape domestication in the modern landscape of Amazonia. However, modern landscape represented in VIs is susceptible to modern human land use. Therefore, before identifying landscape domestication through VIs, a firm understanding of the effects of modern land use on VIs is required. It is also important to select the proper tools, such as selecting satellite images with the spatial resolution that fits the research purpose.

The discussion on the two dependent research question leads to the discussion of the main research question on the contribution of landscape domestication and the creation of anthromes to modern landscapes. At the beginning of the thesis, landscape domestication was defined as 'the persistent process of mutual influence between human culture and natural environment on a certain space.' By focusing on the elements of persistence and mutuality, the process of the formation of anthrome in the FNC will be discussed. Understanding the process of the creation of anthromes will eventually lead to understanding how the anthrome creation formed the modern landscape of the FNC.

The Ibama site and the Forte site are the areas that have been influenced the most by landscape domestication, with thick development of ADE and numerous artifacts, which include potsherds, mollusk shells, and charcoal. However, although material records may only be identified in the actual site itself, the actual activity area of the occupants of the sites would have been more extensive than the site itself. Settlements, which are indicated by material remains, and ADE is only parts of the landscape domestication process (Erickson, 2008, Clement, et al., 2015). Landscape domestication involves other activities, such as anthropogenic burning and agroforestry, and these activities, unlike settlement and ADE formation, may not take place directly on-site nor leave obvious remains. However, when these activities were exerted as a long-term strategy, they have enhanced the biodiversity and productivity of the vegetation in the area (Erickson, 2008). During the pedestrian survey on the area that connects the Ibama site and the Forte site, a difference in the proportion of trees have been identified. Unlike other areas, such as the area around CAX1, the area adjacent to the Ibama and the Forte site have a higher proportion of plants that are useful to humans, such as açaí palms, Brazil nut trees, mango trees, and rubber trees. This variable distribution of trees that are useful to humans is the evidence of forest management activities

(Junqueira, et al., 2011, Shepard and Ramierez, 2011, Junqueira, et al., 2016, Levis, et al., 2017).

These patches of trees would have attracted pre-Columbians who used them for subsistence. When a certain group of pre-Columbian Amazonians migrates into the FNC, they would prefer to settle themselves near to these patches of plant resources. The radiocarbon dates demonstrate that there is a significant time difference between the Ibama site and the Forte site. While the Forte site was occupied around 2000-1800 cal. years BP, the Ibama site was formed around 900-500 cal. years BP (Table 18). Although there is no temporal overlap between the two sites, the effects of landscape domestication would have influenced the formation of the Ibama site.

The ADE site itself was an element that would have influenced the establishment of a new settlement. Ethnographic research has demonstrated that the local Amazonian farmers acknowledge and utilize ADE for various purposes, which include cultivation, forest management, and even for making pottery (Woods and McCann, 1999, Fraser, et al., 2011, Junqueira, et al., 2011, Thayn, et al., 2011). Archaeological excavations present that similar selection was made by pre-Columbian Amazonians as well, establishing settlements on or near ADE sites (Rebellato, et al., 2009).

Therefore, the persistent and mutual interaction between the humans and their surrounding environment aggregates from the initial arrival of humans in an area, which eventually leads to the creation of an anthrome (Ellis, 2011, 2014). Humans change the environment through ecosystem engineering, which transforms the environment with enhanced subsistence capacity. This transformed environment influences the behavior of humans of the following generations. This constant interaction between the humans and environment alter the environment from its fundamental elements of the terrestrial biosphere, such as soils and the microbial communities in the soils (Grossman, et al., 2010), to plants and animals that live on it (Junqueira, et al., 2011, Lins, et al., 2015).

The formation process of the anthrome demonstrates how the modern landscape of Amazonia, a mosaic of different forms of landscapes. The consequences of the initial landscape domestication activities, such as clusters of useful plant species and ADE, affect the landscape domestication activities of the succeeding generation. Domesticated landscapes are more likely to be a subject of future landscape domestication activities than non-domesticated landscapes. The result of this inequality in selection builds up in a long-term process, which eventually results in significantly different landscapes between areas, which are also reflected in the EVI values.

Chapter 6. Conclusion

This thesis has presented the results of the analyses and the interpretation of the relationship between soils, landscape domestication, EVI, and the creation of anthromes in the FNC. This research is one of the few regional level studies that involve remote sensing in Amazonia, while a majority of the preceding research has set the scale of the research at a continental or sub-continental level, covering the entire Amazonia. The results provided in this thesis is context-specific to the FNC, which cannot be directly applied to the general patterns of Amazonia.

Limiting the research area to the FNC is one of the most critical elements of this research. The heterogeneity of the natural and anthropic environment in Amazonia has been demonstrated several times in the preceding literature (Shepard and Ramirez, 2011, McMichael, et al., 2014). Therefore, the attempt to understand the aspect or the scale of landscape domestication in Amazonia as a whole cannot be achieved by a single research project, but by accumulating several regional scales research projects. Also, the characteristics of the FNC as protected by the national government from commercial logging, mining, and ranching, has created a semi-controlled research area. However, this is not the case for most of the other regions in Amazonia. Therefore, although the results that have been presented in this thesis may be further contextualized by future studies, it can provide a starting point for the studies that attempt to trace and calibrate landscape domestication in Amazonia on a regional scale.

Exploring the research question by pursuing the objectives addressed at the introduction of the thesis has led to the understanding of how pre-Columbian landscape domestication activities created the anthromes and eventually, created the modern landscape within the FNC. The research objective on how pre-Columbian landscape domestication activities affect soil formation processes provided the basis for a discussion on how to trace the landscape domestication. The relative scarcity of archaeological sites and artifacts in Amazonia (Goldberg, et al., 2016, McMichael and Bush, 2019) and that a large portion of landscape domestication activities may not leave direct material evidence to cause the difficulty in identifying the pre-Columbian landscape domestication. However, if the understanding on ADE, which is one of the major forms of landscape domestication in Amazonia, is broadened by thinking of it as a continuum from the natural soils (Fraser, et al., 2011), the possibility of Amazonian soils as sources of evidence of landscape domestication arises. The OSL results demonstrated that the landscape domestication activities could affect the pedogenesis and pedoturbation, which is a concurring result with that from Macedo, et al. (2017). In this way, the soils can be observed as a repository of evidence of pre-Columbian landscape domestication.

Subsequent geospatial analysis demonstrates that soils and landscape use affect EVI values. Therefore, a model to analyze the relationship between landscape domestication and EVI was created. The model showed that areas affected by human landscape domestication tend to be located within clusters of high EVI values, since approximately 70% of reported sites, which can be interpreted as focal points of landscape domestication, were located within the high-value clusters. The results also demonstrate that modern human land use can crucially affect remote sensing results. While modern land clearance activities, which are mostly related to farming and logging in Amazonia, clearly lowers the EVI values, modern forest management activities by residents, many of them involving açaí palms and Brazil nut trees, seem to increase EVI values in the affected area.

Finally, this thesis discussed how the creation of anthromes by pre-Columbian landscape domestication contributed to the formation of the modern landscape of the FNC. Various forms of landscape domestication, including ADE and anthropogenic forests, transformed the environment into a direction that increased its capacity to augment human subsistence. This transformed environment affected the behavior of humans. When this mutual and continuous interaction between humans and their surrounding environment accumulates, aspects of the biosphere, such as soils and vegetation, totally alter from their fundamental elements. The alteration of the terrestrial biosphere ultimately led to the creation of anthromes. The process of anthrome creation involves a concentration of landscape domestication activities into specific areas, which has yielded a mosaic landscape with areas of different degrees of landscape domestication.

To conclude, this research has demonstrated the potential of soils and vegetation structure as reflected in VI values that can be utilized as evidence of landscape domestication and presented a functioning model that can work as a powerful tool to trace and calibrate pre-Columbian landscape domestication in Amazonia. However, the results are provisional and context-specific, which thereby cannot yet be applied uncritically to other areas in Amazonia. Amazonia is more of a mosaic of diverse types of cultures (Neves, 2011) and landscapes (Erickson, 2008, McMichael, et al., 2014). Different areas of Amazonia have undergone different processes of landscape domestication and the scale of landscape domestication will significantly vary by region.

For the application of the results of the research in other landscapes of Amazonia, further research on the relationship between vegetation structure and other elements of landscapes should be explored. One of the elements that has proven to affect the VI values in this research is the modern human land use. Since the FNC is an exceptional type of landscape in Amazonia, where the effect of modern human land use is minimized, the results may vary in other regions of Amazonia where modern human land use has a more significant impact on the landscape. Therefore, how the vegetation reacts to modern human activities should be further explored by performing similar research on areas that are heavily influenced by modern humans.

Another relationship that should require further examination is the effect of soils on vegetation structures. It has been demonstrated in this research that landscape domestication activities affect the soil formation processes and thereby influence the vegetation. However, most of the examination performed in this research was based on Oxisols, which is the dominant soil class in the FNC. However, Amazonian soils include various classes of soils, including Alfisols, Ultisols, and Inceptisols, with different characteristics (Quesada, et al., 2011). To expand this research to other areas of Amazonia, how different classes of soils respond to landscape domestication activities should be explored.

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국문 초록

브라질 카슈아나 국립공원에서의 인공적 생물군계 형성이 토양과 식생 구조에 미친 영향에 대한 연구

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아마조니아는 과거 사람들이 생존을 위해 환경을 변화시킨 지역의 대표적인 사례로서 지난 수십년간 연구자들의 주목을 받았다. 인간에 의한 환경 변화의 과정은 오늘날 '경관 개변'이라는 개념으로 정리되었으며, 이 경관 개변의 개념에 바탕을 두고 역사생태학이 정립되었다. 유럽인들의 도래 이전에 아마조니아에 거주하던 사람들의 경관 개변 활동과 관련된 여러 문제들 중 경관 개변의 규모에 대한 문제는 아마조니아의 역사에 대한 여러 문제들과 연결된 중요한 주제다. 경관 개변의 규모를 연구하기 위해서 여러 연구자들은 현대의 경관을 해석하는 것을 통해 경관 개변의 규모를 측정할 수 있는 방법론을 개발하는 것에 주목하였다.

이 논문은 유럽인들의 도래 이전의 아마조니아에 거주하던 사람들의 경관 개변 활동을 추적하고 측정하며, 경관 개변 활동이 어떻게 인공적 생태군계(앤스롬)의 형성으로 이어졌는지 이해할 수 있는 연구방법론을 제시하기 위해 카슈아나 국립공원에서 진행된 지역적 연구의 결과를 제시한다. 카슈아나 국립공원과 위성사진을 통해서 얻은 자료를 바탕으로 하여 경관 개변과 토양의 관계, 토양과 개량식생지수(EVI) 사이의 관계, 그리고 경관 개변과 개량식생지수 사이의 관계가 제시될 것이다. 연구의 결과 (1) 토양 형성과 토양의 교란 활동은 경관 개변에 의해 영향을 받는다는 것, (2) 개량식생지수가 토양의 속성에 영향을 받는다는 것, 그리고 (3) 경관 개변 활동의 여부가 개량식생지수와 상관관계를 가진다는 것이 밝혀졌다. 또한 과거 인간들과 환경 사이의 상호적이고 지속적인 상호작용이 앤스롬이 형성되도록 하였고, 이러한 앤스롬의 형성은 현대의 아마조니아의 경관을 형성하는데 중요한 역할을 했다는 것이 제시될 것이다.

주제어 : 경관 개변; 토양 형성; 원격 탐사; 공간적 자기상관분석; 광여기루미네센스 연대측정; 아마조니아

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