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# *Terras pretas*: Approaches to formation processes in a new paradigm

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## Abstract

*Terras pretas* (Amazonian Dark Earths) are a remarkable kind of archaeological site found in the Amazon region. Rich in cultural artifacts and other occupational debris, these dark anthropogenic soil matrices are very fertile, presenting high levels of organic carbon, phosphorus, calcium, magnesium, zinc, and manganese. Their high nutrient levels come from decomposed organic matter, including remains of fish, shellfish, game, and other refuse, while their dark color has been linked to residual charcoal from intentional fires associated with daily activities and landscape management. Studies of anthropogenic earths in the Amazon have a deep history, as much in the geosciences as in archaeology and other historical sciences. *Terras pretas* have been studied as evidence of a major shift in human–environment relations, but also within the lens of environmental resiliency and sustainability. We review representative studies from various disciplinary fields and trace the development of knowledge about *terra preta*. We present a growing consensus with regard to the origin and significance of anthropogenic soils, concomitant with increased efforts toward interdisciplinary study. We argue that *terras pretas* constitute a genuinely interdisciplinary research topic that bridges scientific and traditional knowledge and applied contexts.

KEYWORDS
Amazonia, anthropogenic landscapes, interdisciplinary research, *terra preta*

## 1 | INTRODUCTION

The Amazonian environment presents abundant evidence of pre-Columbian human activities that significantly impacted natural resources. Evidence of these changes is found, among other places, in dark anthropogenic soil matrices common throughout various parts of the Amazon. Produced by human action, these soils, which present a darkened A horizon and archaeological remains, are known as archaeological black earth (*terra preta* arqueológica), Indian black earth (*terra preta* de índio), or black earth (*terra preta*). Interpreted as signs of dense or prolonged human occupation, these fertile soils are cultural markers of the past. Soils known as *terra mulata* have also been recorded. These soils, presumably resulting from pre-Columbian agricultural activity, are brown in color and contain more charcoal than adjacent soils, but have lower chemical fertility than *terras pretas* (Kern, Ruivo, & Frazão, 2009).

*Terras pretas* have an affinity with other archaeological and historic anthrosols including northern European plaggen soils, produced from the Bronze Age to the present through amendment of agricultural beds with litter from livestock stables (Blume & Leinweber, 2004), *terra preta australis*, a mounded "kitchen-midden" style soil created by Australian aborigines through accumulation of household waste (Downie et al., 2011), and European dark earths, produced by accumulations of urban waste since the Roman period (Davidson et al., 2006; Macphail et al., 2003).

Areas of *terra preta* range in size from a few hundred square meters to hundreds of hectares, where smaller areas correspond to isolated or small, autonomous villages and extensive areas to large, permanent or semipermanent settlements in pre-Columbian Amazonia. Areas of *terra preta* are thought to represent daily domestic activities including cultivation, while areas of *terra mulata* have been interpreted as zones of cultivation. Archaeological evidence seems to corroborate these hypotheses, but because these models are predicated on a Western model of an agricultural revolution that may not hold for Lowland South America (Neves, 2013), interpretive challenges remain. Regardless, Denevan (2001) has shown that soils on floodplains and riverine terraces, or *terras firmes*, have been affected by indigenous agriculture.

Recent evidence from extensive *terra preta* sites supports the existence of densely settled societies on *terras firmes* in the pre-Columbian Amazon (Heckenberger & Neves, 2009; McEwan et al., 2001; Moraes & Neves, 2012). These societies would have been dramatically reduced and destructured after European contact (Porro, 1994; Roosevelt, 1991). In this context, *terras pretas*, which are significantly enriched in nutrients compared to natural *terra firme* Amazonian soils, represent cultural activities and technologies through which humans altered their relationship with the environment. They also contradict the paradigm of scarcity proposed by environmental determinists, as outlined by Meggers (1971).

Because of their chemical fertility and/or location, *terras pretas* have been used in subsistence cropping for centuries, sometimes also mined as substrate for gardens. However, as archaeological sites, *terras pretas* are heritage preservation sites (under Brazilian law) and should be strictly protected. Today, *terras pretas* are under threat from commercial agriculture, extraction, and construction.

In recent years, *terra preta* research has received increasing interest from the scientific community, as exemplified by publications by Lehmann et al. (2003a), Glaser and Woods (2004), Woods et al. (2009), and Teixeira et al. (2009). This research boom is due as much to archaeological questions about people who once occupied the Amazon region as to the possibility of unraveling and reproducing the processes by which pre-Columbian peoples permanently transformed soils with low agricultural potential into areas of high chemical fertility and productivity. Thus, research on these ancient anthropogenic soils provides an opportunity to understand the past and may also yield knowledge for future sustainable agricultural development in the humid tropics.

In this overview essay, we consider representative studies from various disciplines to evaluate the advancement of knowledge regarding *terras pretas* within basic and applied contexts. In so doing, we aim to show how the construction of this knowledge is a predominantly interdisciplinary task. We also point to recent developments and future perspectives for *terra preta* research. Throughout, we use the term “anthropogenic” for Amazonian *terras pretas* over other terms to emphasize the importance of human action/activity in their genesis, while using “anthropic” as a qualitative designation; these terms do not necessarily refer to issues of intentionality (Holliday, 2004), as we will discuss next.

## 2 | HISTORICAL CONCEPTIONS OF *TERRA PRETA* AND *TERRA MULATA*

Given the heterogeneity of these Amazonian anthropogenic soils, the generic designations “Amazonian dark earths” (Lehmann et al., 2003; Woods & McCann, 1999) or “anthropogenic dark earths” (Glaser & Birk, 2012) were proposed. While useful for indicating the range of anthropogenic soils and sediments found across Amazonia, these terms confound distinctions, such as that between *terra preta* and *terra mulata*, which are soil matrices that differ in genesis and composition. While both present evidence of repeated burning (e.g., Arroyo Kalin et al., 2009; Costa et al., 2013), which is absent from Yellow Latosols, other characteristics, discussed next, help make a case for retaining this distinction. Figure 1 shows profiles from the Juruti area (Pará, Brazil) highlighting differences among these three soil types.

### 2.1 | *Terras pretas*

Travelers have been reporting highly fertile, dark-colored soils associated with archaeological remains in the Amazon since the second half of the 18th century (Costa et al., 2013; Kern, Ruivo et al., 2009). The first accounts, such as those by Hartt (1885) and Smith (1879), interpreted *terras pretas* as sites of ancient indigenous settlement. Conversely, Katzer (1944), a pioneer in the chemical analysis of *terras pretas*, concluded that these soils were similar to sediments found in Amazonian flooded forest areas (*igapós*). Between 1940 and 1970, other soil scientists attributed their genesis to natural causes, but the consensus view in the field of archeology has long been that these soils result from ancient human activity (Kern et al., 2004). The soil scientists Sombroek (1966), Ranzani and Kinjo (1970), and Falesi (1974) highlighted the high chemical fertility of *terras preta* soils in contrast with the generally low fertility of dominant soils in the region. Sombroek (1966) found enough similarity between textures, clay faction composition, and the depth of the C-horizon of *terra preta* profiles and adjacent soils, to conclude that the high chemical fertility of the former was a result of indigenous occupation.

Since 1948, the occurrence of *terra preta* has been a common criterion for the identification of archaeological sites in the field (Nimuendaju, 2004). In archaeology, there is a consensus that *terras pretas* are the result of prolonged human habitation, serving also as a source of evidence for understanding soil management and daily activities (Browne Ribeiro, 2011; Schmidt, 2010; Silva & Rebellato, 2004; Steiner et al., 2004). The anthropic origin of *terras pretas* has been confirmed by numerous other soil studies of archaeological sites and surrounding soils (Costa & Kern, 1999; Eden et al., 1984; Kern & Kämpf, 2005; Pabst, 1985). Currently, the role of past human activity in *terra preta* formation is widely accepted in the scientific community. As sites of ancient settlement, *terras pretas* are also the remains of activities performed by the past inhabitants of the Amazon (Petersen et al., 2001).

Researchers studying *terra preta* come from a variety of disciplines, which provides multiple kinds of data but can present interpretive challenges in the field and laboratory. From an archeological perspective, it comprises areas of soil that present dark surface layers (e.g., Munsell colors 7.5YR 2/1 to 3/2; 10YR 2/1 to 2/2, in moist soil) with varying thickness (usually 15–80 cm) that are associated with a qualitative and quantitative diversity of archaeological remains. However, color alone is not conclusive; Kern et al. (2015) have identified sites with A horizons too light to meet archaeological criteria for classification as *terra preta*, while still presenting abundant archaeological remains and high chemical fertility. Conversely, *terras pretas* with low chemical fertility also occur at the Caquetá River in Colombia (Andrade, 1986), in the southeastern region of Pará, and in the states of Amazonas and Rondônia in Brazil (Kern et al., 2015; Silva et al., 2012; Zimpel Neto, 2009). Soil chemical analyses can thus complement field observation of

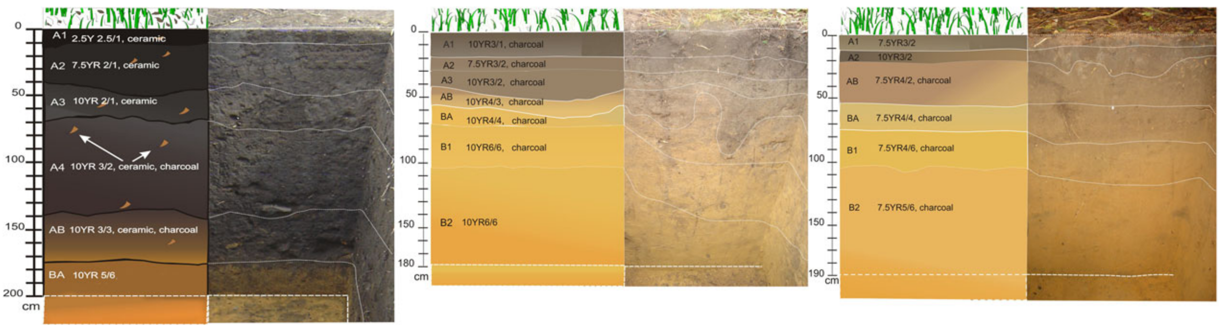


**FIGURE 1** Stratigraphic profiles of a *terra preta*, *terra mulata*, and Latosol from Juruti/Pará/Brazil (source: J. Costa, 2011) [Color figure can be viewed at wileyonlinelibrary.com]

anthropogenic soils. Studies that approach *terras pretas* from the pedological perspective usually focus on soil chemistry and present results in terms of available plant nutrients (e.g., Sombroek, 1966; Kern & Kämpf, 1989). In the geochemical approach, however, the emphasis is on the total content of elements (Costa & Kern, 1999; Costa et al., 2013; Schmidt, 2010; Schmidt et al., 2014). This difference in analytical approaches makes direct comparison of pedological and geochemical studies difficult. Hence, increasing interdisciplinarity in research teams can lead to more meaningful interpretation of sites.

## 2.2 | *Terras mulatas*

*Terras pretas* are sometimes surrounded by soils characterized by a slightly lighter (brownish gray) A-horizon with high organic matter (OM) content, including abundant charcoal. These often present lower levels of phosphorus and calcium and rare or absent archaeological remains. Known as *terras mulatas*, these are distinct from *terras pretas* and from adjacent natural soils, and some (Arroyo-Kalin, 2010; Sombroek, 1966; Woods & McCann, 1999) have proposed that they result from ancient permanent or semipermanent agricultural activity. Due to the scarcity or absence of archaeological remains, *terras mulatas* are rarely recognized as archaeological sites.

In the field, *terras pretas* and *terras mulatas* can be distinguished from each other by color and by the absence or rarity of archaeological artifacts in the latter. However, the diffuse gradation between these two soil types can hinder their differentiation. The morphological distinction between *terras mulatas* and natural soils can be difficult for similar reasons. Additionally, charcoal presence cannot serve as a *terra mulata* indicator because it also occurs in nonanthropogenic soils as a result of natural forest fires (Hammond et al., 2006; Sanford et al., 1985). Laboratory analyses, in conjunction with field observation, help isolate *terras mulatas*; however, even when color and chemical criteria are met, the identification of specific activities or anthropogenic formation processes is hampered due to the absence of archaeological structures (Costa et al., 2013; Sombroek, 1966; Woods et al., 2000). These challenges, along with the fact that greater attention has been paid to *terra preta* research, may explain the relative absence of more concrete information about *terras mulatas*.

Researchers have recently returned to the idea, proposed by Sombroek (1966), of *terra mulata* as evidence for permanent or semipermanent intensive prehistoric agricultural activity in the Amazon (Denevan, 2001, 2009; McCann et al., 2001; Woods & McCann, 1999; Woods et al., 2000). Sombroek suggested long-term prehistoric formation processes via cropping, which would have involved burning of standing vegetation in preparation for cultivation. Indeed, studies of *terras mulatas* have revealed signs of successive burning of organic matter (OM), transformation of minerals (maghemite to goethite), and refiring of ceramic artifacts in carbon-rich, non–*terra-preta* matrices (Arroyo-Kalin et al., 2009; Costa et al., 2013), corroborating this hypothesis. Palynological and phytolith evidence (Piperno, 2009) from the Araracuara sites in Colombia (Herrera et al., 1992; Mora et al., 1991) also point to the ancient use of *terras mulatas* for cultivation. In addition to the extensive areas of *terra mulata* reported by Sombroek (1966) in Belterra, Pará, they also have been reported in the region of Arapiuns, near Santarém (Woods & McCann, 1999), in Juruti (Costa et al., 2009, 2013), and in Araracuara, Colombia (Andrade, 1986; Mora et al., 1991).

# 3 | *TERRAS PRETAS*: CORE CHARACTERISTICS AND VARIABILITY

*Terras pretas* are found throughout most parts of Amazonia and are often considered a "Pan-Amazonian" phenomenon. Figure 2 shows the known zones of occurrence of *terra preta* sites in the Amazon region. Notably, the southwestern Amazon, which boasts monumental earthworks (e.g., ditched enclosures and geoglyphs) (Erickson, 2008; Pärssinen et al., 2009; Rostain 2013; Schaan et al., 2012), and large habitation mounds (Saunaluoma, 2013) indicative of intensive pre-Columbian occupations, lacks *terras pretas*. Their absence from this region indicates *terras pretas* are not pervasive across Amazonia, presenting challenges to generalizing models of human–environment interactions in the region (Bush et al., 2015; Clement et al., 2015; McMichael et al., 2012).

*Terras pretas* occur as isolated or overlapping patches or as large continuous areas. They present considerable variability in thickness and composition—both within and between sites—which is attributed to differences in the composition of refuse deposited, or to the intensity, duration, nature, and distribution of human activities. The internal variability of *terras pretas* is often significantly greater than that found in areas of adjacent natural soils of equivalent size.

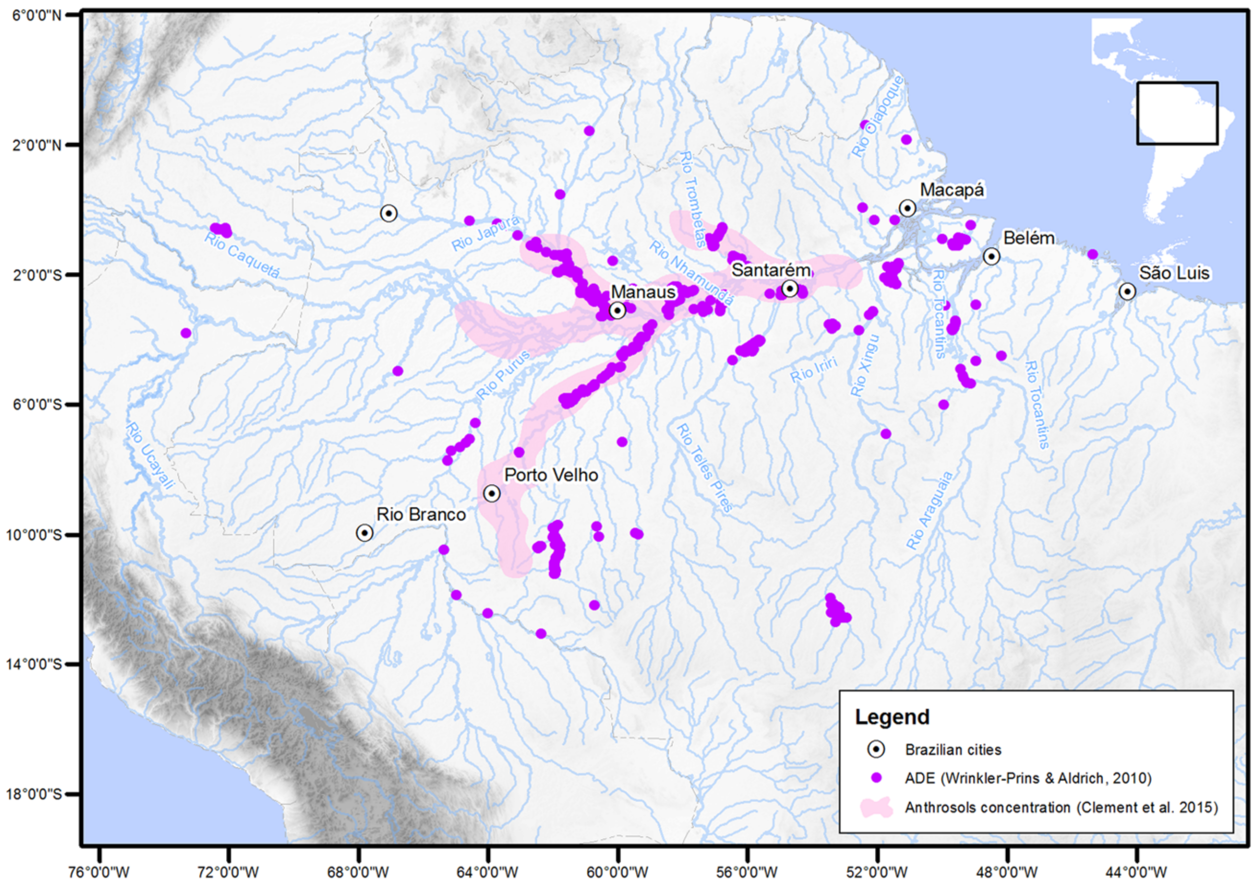


**FIGURE 2** Shaded relief imagery showing archaeological sites in lowland South America with concentrations of anthropogenic dark earths (ADE's or *terras pretas*) (adapted from Clement et al., 2015; WinklerPrins & Aldrich, 2010) [Color figure can be viewed at wileyonlinelibrary.com]

*Terras pretas* are generally described as deep, well-drained, soils with textures ranging from sandy to clay dominant and A horizons thicker (up to 2 m in thickness) and darker (black to very dark grayish brown: Munsell colors 5YR 2.5/1, 7.5 YR 2/0 to 3/1, 10YR 2/0 to 3/2) than adjacent soils. In addition, the A horizons of *terras pretas* differ from those of natural Amazonian Latosols and Argisols, presenting higher values for pH, OM, organic carbon (OC), available phosphorus, exchangeable calcium and magnesium, cation exchange capacity (CEC), and base saturation; they also contain higher levels of zinc and manganese than underlying horizons (Kern & Kämpf, 1989; Kern & Costa, 1997; Lima et al., 2002). These core chemical characteristics are generally taken as definitive evidence of anthropogenesis, although they do vary within and between sites.

For example, *terras pretas* are valued for their high chemical fertility by farmers in rural Amazonia, who opt to cultivate these soils over the naturally acidic and nutrient-deficient dominant *terra firme* soils (Rodrigues, 1996). However, folk soil taxonomies in Amazonia can be nuanced. German (2003) and German et al. (2009) find among farmers a widespread belief that loamy black earth is of higher quality than sandy dark earth. These two soil types are known as, respectively, "*terra preta legítima*" (legitimate black earth) and "*terra preta fraca*" (weak black earth). Indeed, *terras pretas* formed in sandier soils tend to have lower chemical fertility, including lower levels of OC, calcium, magnesium, and phosphorus, as well as lower CEC and base saturation. This has been observed in Araracuara, Colombia (Andrade, 1986), in the Brazilian states of Pará (Silva et al., 2012; Souza, 2007; Kern et al., 2015) and Rondônia (Zimpel Neto, 2009), at the Jiquitaia site in Rio Preto da Eva, Amazonas (Souza et al., 2009), as well as in horizons described by Smith (1980) and Kämpf et al. (2009). This distinction may hence be associated with local environmental factors and the pedogenic process.

*Terras pretas* also have higher microbial diversity than do adjacent soils (Glaser & Birk, 2012; Ruivo et al., 2009), which is understood to be a consequence, but not a cause, of *terra preta* soil conditions (Tsai et al., 2009). It has been argued that this microbial population can influence the dynamics of nutrients and carbon, promoting the stability of *terra preta*, which is important for understanding its persistence over time; however, the idea that it is self-propagating (Woods & McCann, 1999) has been discarded. These special conditions also favor intense activity by soil fauna that promote mixing and transport of materials, metabolization, and incorporation of OM into the soil, and contribute to the coating of soil grains and consequent darkening of mineral aggregates (Glaser & Birk, 2012; Lima et al., 2009; Topoliantz et al., 2006).

Such biogenic and pedogenic processes affect the physical structure, morphology, and composition of *terras pretas*. Past depositional processes, bioturbation, and particle migration can effect similar changes. Teixeira et al. (2009) have observed increased moisture retention in these soils compared to adjacent soils, which they attribute to the higher proportion of clay-sized particles and elevated OM content. The various forms of OM found in *terra preta*, including carbon and humified fractions, have been intensively researched. According to Cunha et al. (2009), humic acids from *terras pretas* have a different composition from humic acids of natural soils: there is a higher degree of humification due to the higher concentration of aromatic structures and organic free radicals. This is partially explained by the higher content of pyrogenic carbon incorporated during the process of formation of *terras pretas* (Glaser et al., 2001).

The ubiquitous presence of charcoal has been quantified by Glaser et al. (2002): the proportion of charcoal in the first 30 cm of *terra preta* profiles is up to 70 times higher than those of adjacent Latosols, while total OC stocks in *terras pretas* are more than double that of Latosols. High levels of pyrogenic carbon indicate intensive and prolonged addition of carbonized OM. Pyrogenic carbon is a by-product of vegetation clearing through controlled burns (Denevan, 2001), and is also produced throughout Amazonia in domestic burning contexts, such as hearths (Schmidt, 2010), garbage incineration (Silva, 2003), and other smoldering fires with a variety of applications (medicinal, cleansing, insect repellent, etc.).

Pyrogenic carbon is chemically and microbiologically stable due to its polycyclic aromatic structure; slow oxidation of pyrogenic carbon (biotic or abiotic) produces carboxylic groups on the edges of the aromatic ring, increasing CEC and the reactivity of carbon in the soil (Jorio et al., 2012). This micromolecular structure lends stability to OM found in *terras pretas* (Solomon et al., 2007). Pyrogenic carbon also contributes to a stable soil OM stock, with high nutrient retention capacity and a remarkable recalcitrance, such that it may persist in the environment for centuries (Cheng et al., 2006; Glaser et al., 2001; Liang et al., 2006; Novotny et al., 2009; Solomon et al., 2007).

As with other parameters discussed, OM found in *terras pretas* comes in a variety of forms, which indicates a diversity of sources and modes of incorporation (Glaser & Birk, 2012), such as food processing (hearth sweepings, animal and plant remains), tool or house manufacture or destruction (thatch, palm leaves, twine, fiber), mundane, ritual, or mortuary practices (clothing, hallucinogens, human remains, instruments), defecation and urination, and other activities (Costa et al., 2013; Glaser & Birk, 2012; Kern et al., 2004; Neves et al., 2003).

The morphological, physical, and chemical characteristics of *terras pretas* vary widely among and within sites. This requires a detailed and comprehensive analysis of known variants, an understanding of sources of enrichment, depositional and postdepositional practices, and covariance of factors. Thickness of the A horizon, phosphorus (available or total), calcium (exchangeable or total), and OC levels are among the most variable characteristics (Costa et al., 2013; Lemos et al., 2011; Kern & Kämpf, 2005). These may be most indicative of human activities and could be seen as a record of differences in cultural practices as well as timing and intensity of occupations. Other kinds of variability appear to be associated with environmental factors. The heterogeneity of these soils, and the number of processes and variables still under investigation, pose challenges to comprehending their formation and replicating their results.

## 4 | FORMATION OF *TERRAS PRETAS* AND *TERRAS MULATAS*

A variety of models for anthropogenic soil formation in Amazonia has been proposed, ranging from those that focus on environmental factors to those that focus on subsistence, political economies, and population growth. The wide range of variability among and within anthropogenic soils can be explained in terms of the interaction between local soil and environmental factors and cultural factors, the latter understood as spatial organization, patterns of land use, daily activities, and soil management. In understanding the cultural dimension of the problem, archaeologists speak of intensity of use. As a rule, permanent settlements produce more refuse, resulting in thicker deposits and, therefore, a thicker A horizon than temporary camps. Areas used for habitation or intensive use can accumulate refuse over time, forming midden-like mound deposits made up of perishable organic refuse and more durable waste, such as ceramic, lithic, faunal, and charred botanical remains. The question of intentionality, a long-time focus of debates, is increasingly understood as a matter of degree, rather than a binary issue. Instead, the focus has turned to understanding the structure of settlements and activity areas to assemble more precise chronologies and finer grained processes. At a minimum, it can be said that throughout most of the period of *terra preta* formation, there was an awareness of the impacts of human intervention in soil evolution, and it may be possible to argue for intentional production.

Both *terra preta* and *terra mulata* form as a result of the transformation of OM (from fresh to ashed or carbonized) and its concentration within a circumscribed area. Early understanding of *terras pretas* as cumulic soils led some to interpret its A horizon as a plaggen epipedon (e.g., Andrade, 1986; Ranzani et al., 1962). This attribution is problematic not only because it implies definitive intentionality in *terra preta* formation, but it also presumes a very specific source and process of enrichment. Plaggens are soils created through a dual process where OM is accumulated in one place (livestock enclosures) and later incorporated into managed soil beds (Blume & Leinweber, 2004). No evidence for accumulation and translocation of sediments has been found, and the lack of evidence for animal husbandry of any magnitude in pre-Columbian Amazonia requires a rejection of formation theories involving a plaggen-type process.

Formation processes that have received significant scholarly attention include agricultural and horticultural techniques involving controlled burning and/or soil amendment, long-term occupation of sites involving the formation of deeply stratified middens, repeated reoccupations or internal restructuring of habitation sites, and intentional charring of refuse in middens or subterranean pits.

One major model for *terra preta* formation recalls Sombroek's (1966) kitchen-midden hypothesis, so named because it combined the features of a household refuse collection area with combustion activities. The term "kitchen-midden" suggests areas of accumulation of domestic refuse, and indeed, most *terra preta* sites present a high frequency of ceramic, faunal, and charred botanical remains, albeit in varying proportions and degrees of fragmentation. A number of scholars (Petersen et al., 2001; Rebellato et al., 2009; Schmidt, 2010) have attributed *terra preta* formation to accumulation of domestic refuse. Indeed, microfragments of biogenic apatite from fish and animal bone are the primary source of phosphorus and calcium in *terras pretas* (Lima et al., 2009; Schaefer et al., 2004). Combustion activities, which would produce charred seeds other plant remains, may also be implicated in the formation of microaggregates in *terras pretas*, which are composed of mineral and OM particles and highly resistant to dispersion (Teixeira & Martins, 2003). Similarly, the occurrence of magnetite in these soils has been linked to fire (Lima et al., 2009).

*Terra preta* sites also often contain archaeological features that attest to house sites, such as remnant floors, terraces, and hearths as well as postholes and pits (Browne Ribeiro et al., 2016; Kern et al., 2015; Neves et al., 2003; Silveira et al., 2011; Tamanaha 2012). One specific version of this interpretation, articulated recently as part of the middenscapes model proposed by Schmidt et al. (2014), suggests *terra preta* formed around (behind, to the sides of) a dwelling, through the accumulation and decomposition of household waste. A consistent pattern of habitation would result in ring-shaped houses, or a honeycomb pattern of middens, as seen in the Trombetas, Central Amazon, and along the upper Xingu (Schmidt et al., 2014) and more recently, the lower Xingu (Browne Ribeiro et al., 2016). Erickson (2003) has suggested that shifting internal organization of habitation sites might result in overlapping patches of *terra preta*, wherein any such patterning would become obscured over time.

*Terras pretas* and *terras mulatas* have been linked to cultivation but neither form through contemporary slash-and-burn practices, which require a long fallow between cultivation periods (Heckenberger, 2005; Heckenberger et al., 1999; Pabst, 1991; Smith, 1980). *Terras mulatas* might be a result of some form of cultivation or soil management through targeted semipermanent intensive agriculture (Costa et al., 2013; Denevan, 2001; McCann et al., 2001; Sombroek, 1966; Woods & McCann, 1999). Their high levels of OC, lack of archaeological artifacts and *in situ* features, and lower phosphorus and calcium content than *terras pretas*, favor an agricultural explanation for their formation (e.g., Sombroek, 1966; Woods & McCann, 1999). Soil preparation practices of smallholder farmers, which involve successive burning of previously cultivated fallow fields and secondary growth forest, contribute charcoal to the present-day A horizon. A decades-long, semi-intensive program of cultivation, especially with smoldering, charcoal-producing fires (slash-and-char cultivation) is one potential explanation for such high levels of OC (Glaser et al., 2001; Lehmann et al., 2003b). Denevan suggests the creation of *terras mulatas* may have been be a long-term project, requiring management of burning with agricultural intentions (2004:135).

Because *terras mulatas* are adjacent to *terras pretas*, we may infer a connection between the two types of anthropogenic soils. In addition to the model in which *terras mulatas* served as the agricultural fields for villages (Sombroek, 1966), some have suggested the latter formed through soil amendment practices consisting of addition of nutrients derived from plant and animal waste, or even *terra preta* itself (Rebellato et al., 2009; Schmidt & Heckenberger, 2009; Sombroek et al., 2002).

Ethnographic studies have provided insights into the practical and experimental dimensions of *terra preta* and *terra mulata* formation. Ethnographic observations of many present-day indigenous villages along the upper Amazon show that household areas are kept clean through regular sweeping; refuse is then deposited, along with human and animal excrement, in zones surrounding activity areas or house/village sites (Myers, 2004). In an analogous fashion, Schmidt (2010) reports regular cleaning of domestic and plaza areas among the Kuikuro of the upper Xingu, with discard and burning of waste in peripheral zones. The resulting pattern is a large, circular, clean plaza encircled by a series of elongated mounds of *terra preta*. The mounds, which form behind the houses that line the village plaza, also serve as garden or orchard space (Schmidt, 2010). Management practices observed among the Asurini do Xingu (Silva, 2003) and the Kayapó (Hecht, 2009) also suggest structured deposition of household waste in middens, and some use of fire in the management of refuse on or off middens. These examples might help explain the formation and variability of *terras pretas*.

These observations suggest *terra preta* could have formed through a combination of practices that involve the maintenance of habitation areas, the production of garden soils, and perhaps even the intentional creation of compost for use in agricultural fields. Contemporary farmers understand that their clearing practices impact the soils, but also maintain that these are different from the processes that created *terra preta* (Silva, 2003). However, the contemporary agricultural management system used by the Kayapó (Hecht, 2003, 2009) and Kuikuro (Schmidt, 2010, 2013), in the form of low-intensity burns and the addition of ash to the soil and vegetation cover, may be similar to practices that have produced pre-Columbian *terra mulata*. These processes significantly elevate pH, phosphorus, calcium, magnesium, potassium, and carbon levels in the soils. Although we cannot extrapolate directly from any particular contemporary indigenous group to ancient Amerindian populations, the practical and experimental dimensions of these studies show possible routes to the formation of *terra preta* and *terra mulata*.

We may, in fact, need to consider that multiple models of *terra preta* formation existed in the past. The heterogeneity of sites and variation in the thickness, chemical and physical properties, morphology, and degree of stratification of soil matrices are a result of different spatial organization and/or different activities, such as food preparation, cultivation, dwelling construction, demolition and displacement, and refuse disposal (Kämpf & Kern, 2005; Kern, 1996; Mora et al., 1991; Schmidt, 2010). Equally, this range of variability in activities and cultural choices likely accounts for patchiness, differences in matrix color and texture, and surface morphology (mounds, ditches, ramps, etc.) of *terra preta* sites. Given the range of practices that could be hypothetically associated with its formation, and the lack of a fool-proof model, the choice, for the moment, is to embrace complexity.

Finally, the long chronologies exhibited by some *terra preta* sites, along with the widespread distribution of the phenomenon, suggests anthropogenic soils would have formed as part of intensive, multimodal, and integrated land-use systems involving burning, structured deposition, gardening, slash-and-char cultivation, and soil management. If *terra mulata* formation requires regulated, semi-intensive cultivation, it is difficult, as Myers (2004) and German et al. (2009) suggest, to imagine the formation of extensive, thick deposits of *terra preta* without some sort of intentional production process. Along a similar vein, Erickson (2008) concludes that *terra preta* represents soil engineering, rather than a by-product of intensive occupation; otherwise, it would be ubiquitous across Amazonia. The very fact that its occurrence is prevalent in some regions and absent from others suggests this phenomenon has true cultural significance.

## 5 | A SIGN OF DENSE OR LONG-TERM HUMAN OCCUPATION?

Smith (1980) proposed that the duration of occupation, the intensity of use, and/or population density could be correlated to thickness of anthropogenic soils. However, the diversity of activities (domestic, agricultural, etc.), the displacement and relocation of dwellings and sites, length of occupation, population density, and edaphic and other environmental conditions pose challenges to the formulation of reliable inferences regarding rates of accrual or soil formation (Kämpf & Kern, 2005; Kern, 1996; Mora et al., 1991; Schmidt, 2010). These challenges relate to the specific activities (the amount and frequency of input) that took place in a particular site or area as well as variability in the mobility of elements, particles, and organisms in the original soil (i.e., the latency of chemical and particulate inputs).

The high variability in ecological and cultural conditions complicates not only the interpretation of *terras pretas* as indices of population density or intensity of occupation, but also the long-standing debate surrounding the possibility of long-term, continuous occupation in the Amazonian hylaea. As an example, Meggers (2001) argued that large *terra preta* sites result from multiple re-occupations of the same areas over hundreds of years, rather than one extensive and permanent occupation. Conversely, several authors (Herrera et al., 1992; Heckenberger et al., 1999; Mora et al., 1991; Roosevelt, 1991; Roosevelt et al., 2002) suggest large, contiguous zones of *terra preta* were likely long-term permanent or semipermanent occupations, lasting for several centuries. Continuous occupation of *terra preta* sites has been recorded in several regions, including Central Amazonia (Arroyo-Kalin, 2008, 2010; Lima, 2008; Neves, 2012; Neves et al., 2014), the lower Amazon (Roosevelt, 1991; Guapindaia, 2008), the Madeira River region (Almeida, 2013; Suze, 2014), and Carajás (Magalhães, 2005; Silveira et al., 2009). However, detailed information about specific processes responsible for certain visible patterns (e.g., the formation of middens, mounds, deep "pockets" of *terra preta*) is necessary for the development of more robust theories of *terra preta* formation in terms of sociocultural processes.

Some researchers have tackled this problem by studying current *terra preta* formation, as observable in home gardens, where intensive management involving mixing of charred garden waste and decomposing plant remains results in fertile soil suitable for the cultivation of vegetables, fruits, and herbs (Fraser et al., 2009). The components and morphology of home gardens seem to correspond to that of archaeological habitation sites in terms of plant diversity (Lins et al., 2015), suggesting an analogous formation process. Fraser et al. (2009) also suggest that *terra mulata*–like soils are currently forming under long-term shifting cultivation, but more slowly than in Pre-Contact times.

Another approach, part of a growing interdisciplinary field of *terra preta* studies, involves combining methods from soil science, sedimentology, and archaeology to understand anthropogenic soils as the product of anthropic and natural processes. Such geoarchaeological studies can shed light on site-specific processes, such as periods of intensive deposition and the formation of occupation surfaces (such as plaza or domestic floors) as well as the subsequent alteration of these formations through pedogenic processes (Arroyo-Kalin, 2008; Arroyo-Kalin et al., 2009; Browne Ribeiro, 2011, 2014). Geoarchaeological approaches are site- and context-specific, and, when integrated within a comprehensive multidisciplinary research project, can be used to isolate specific moments of interaction between humans and the soil environment to identify and link natural and cultural causes and effects in anthropogenic soil matrices. Given the complexity of factors involved in *terra preta* formation and persistence, and the acknowledged diversity and internal variability of these soils, such detailed, process-oriented approaches are the ideal way to grasp the impact of particular behaviors on these complex soil matrices.

To date, these studies have provided key models and processes for understanding anthropogenic soil formation in Amazonia through the identification of specific soil structures, analysis of particle composition and migration, and the association of chemical indices with past human practices or events. Geoarchaeological studies have helped shed light on formation processes of middens, house sites, and *terra mulata* (Arroyo-Kalin et al., 2009; Schmidt et al., 2014). They have also shed light on the role of soil management in crop domestication (Arroyo-Kalin 2010), site morphologies along the lower and central Amazon River (Schmidt et al., 2014), and socioecological models for conceptualizing the *terra preta* phenomenon (Browne Ribeiro, 2014).

## 6 | INTERACTION OF PEDOGENIC AND ANTHROPOGENIC PROCESSES

*Terras pretas* on the lower Negro and upper Xingu rivers form through accretion, where gradual deposition of waste and sediments correlate with relatively continuous human occupation (Arroyo-Kalin, 2008; Heckenberger et al., 1999). Though thickening is a major formation process of the anthropic layer (A horizon), downward displacement of particles into lower horizons has been observed (Arroyo-Kalin, 2008).

Variability of chemical and particulate indices, which are signals of past human activities, can be preserved through accretion processes. Compaction surfaces (past habitation floors) or constructed features (house platforms) can prevent the down-mixing of fine material (Arroyo-Kalin 2012; Browne Ribeiro 2011). Similarly, the vertical distribution of phosphorus in the soil profile can be indicative of depositional processes (Browne Ribeiro 2011; Kern et al., 2015). However, the stratigraphic integrity of cultural layers and associated chemical indices may be disturbed by bioturbation, pedogenic processes, and subsequent use including cultivation and reoccupation (Kern et al., 2015; Lima et al., 2009).

Hence, the impact of human action is not limited to the surface horizons, but has been transmitted to lower horizons by pedogenic processes, including melanization, percolation, leaching, and bioturbation. Environmental factors favor the downward transport of small particles (sand, microartifacts) and elements (e.g., Ca and P) can be elevated in the underlying B horizons of *terras pretas* (Andrade, 1986; Costa & Kern, 1999; Kern & Kämpf, 1989; Kern et al., 2015; Pabst, 1985; Schmidt, 2010; Silveira et al., 2011). Arroyo-Kalin and colleagues working in the Central Amazon have noted the need to consider the volumetric contribution of durable material (e.g., microscopic bones, charcoal and ceramics) when analyzing the composition and inferring genesis of different *terra preta* soils (2008; also Arroyo-Kalin, 2012).

*Terras pretas* are thus the result of interactions between anthropic and pedogenic processes (Kern & Kämpf, 2005), which explains their variability within and between sites (Costa & Kern, 1999; Costa et al., 2013 Kern & Kämpf, 2005; Schmidt, 2010;). Hence, a dual approach, which considers archaeological sites as pedo-stratigraphic matrices, makes possible the untangling of such processes.

### 6.1 | *Terras pretas* as anthropogenic landscapes

The perspective of historical ecology, a paradigm shift in contemporary Amazonian research, has added to research agendas not only a different perspective on how landscapes change through interactions between humans and the environment, but also a new understanding of the enduring effects of these changes. The intensification of human occupation of the Amazon beginning in the first millennium B.C. has significantly altered the environment, producing the contemporary landscape. *Terras pretas* constitute dramatic evidence of anthropogenesis and are thus considered an important index of cultural development in pre-Columbian Amazonia (Neves, 2012 Neves et al., 2003; Petersen et al., 2001; Schmidt et al., 2014;).

At the same time, contemporary landscapes have emerged through a diachronic interplay of environmental and historical factors in which anthropogenic soils may be understood as a legacy from the past (Balée, 1994; Balée & Erickson, 2006; Clement et al., 2010; Fraser et al., 2009). Indeed, Petersen et al. (2001) once referred to *terra preta* as a “gift from the past.” This can be understood in various lights, including the advantageous agricultural properties of the soil, but also the wealth of information they carry for scientific and lay communities.

The anthropic landscape, in the present, contains multiple dimensions. In addition to landscape legacies, seen as the resilient outcomes of both deliberate and incidental landscape transformations, Arroyo-Kalin (2016) points to “landscaping” as a symbolic process of signification necessarily tied to cosmologies. The idea of landesque capital adds a dimension of knowledge or intentionality (Hackansson & Widgren, 2016). However, what constitutes deliberate human behavior and what constitutes the incidental effects of long-term, cumulative change, is yet to be understood. The extent to which particular *terras pretas* or *terras mulatas* were intentional agricultural soils or incidental anthrosols formed on substrates produced by former settlement activity is a function of the interplay of these various dimensions.

Historical ecology provides a framework for thinking about anthropogenic soils, and indeed, landscapes, as historically contingent results of the interaction of humans and nonhumans. In other words, distinct landscapes may evolve along independent trajectories that are nonetheless analogous. The study of local environmental/natural histories and their entanglements with human history demands a more particularistic and relational approach to *terra preta* studies, which asks “what human-animal-plant-abiotic interactions are associated with the genesis of these distinctive areas of cultivability?” (Graham, 2006, p. 74).

A close study of these processes and effects bring us to a better understanding of these soils as technological legacies with material and immaterial significance for the future of Amazonia. As Heckenberger and Neves propose, “The legacy of cultural landscapes, including contemporary practices, offers important clues to discussions of resource management in the future” (2009, p. 260).

### 6.2 | Sustainability? Lessons for modern agricultural soil management

Amazonian anthropogenic soils have great potential for developing sustainable strategies for current and future rural production systems, locally and globally. Smallholder farmers in the Amazon recognize the high fertility of these soils (German, 2003). Many researchers have found that “buried” *terras pretas* can aid in the development of appropriate modern agriculture in the Amazon and other tropical regions. In this context, several studies emphasize its reproduction (see Teixeira et al., 2009) such as the *Terra Preta Nova* Project (Kern et al., 2009; Lehmann, 2009; Sombroek et al., 2002), the application of biochar (pyrogenic carbon), or the substitution of slash-and-burn with slash-and-char (Falcão et al., 2009; Steiner et al., 2009;). Compared to slash-and-burn, the charring process generates lower $CO_2$ emissions and more biochar, thus contributing to carbon sequestration (Fearnside et al., 1999; Steiner et al., 2004).

The high variability in chemical and physical properties of these soils affects crops, showing the need for integrated studies to establish the relationship between causes and effects (Falcão et al., 2009). Agriculturally speaking, the most important aspect of *terras pretas* is their high nutrient availability and levels of OM.

Biochar the component of *terra preta* most often linked to its favorable morphological, physical, and chemical properties seems to offer the most promising conditions for sustainable soil management. As a result, biochar, as an industrially produced and marketed material under the label *terra preta*, has been recommended as a soil conditioner in agricultural cultivation. Although it has been criticized for serving agribusiness, the biochar initiative was designed for implementation by smallholders, who comprise most of the world's farmers (Woods et al., 2006).

However, recent research has shown that micrograins of charcoal from *terra preta* are different from those of fresh biochar. The former is characterized by irregularity and a high proportion of micropores; the increased surface area results in a significantly more adsorption sites than found in recently produced biochar (Jorio et al., 2012). It is this property that enhances CEC; hence, slash-and-char solutions may have limited applicability in contemporary agricultural settings. Additionally, the agricultural importance of *terras pretas* for riverine communities varies according to ecology, region, and family or community histories (Fraser et al., 2009; Kawa, 2016). These soils can thus represent opportunities or constraints to small landholders (Junqueira, 2015), which suggests sustainability initiatives need to be locally tailored.

From an agroecological perspective, *terras pretas* can be understood in terms of ancestral landscape management practices (Lins, 2015). Though these cannot be automatically or unproblematically reproduced today, the study of *terras pretas* makes visible the lessons of indigenous past peoples. *Terras pretas* teach us that understanding the ecological processes in relation to contemporary and ancestral management practices is highly relevant to the development of sustainable farming systems in the Amazon (Lins et al., 2015).

## 7 | FINAL REMARKS: *TERRAS PRETAS* AS A PARADIGMATIC INTERDISCIPLINARY RESEARCH TOPIC

Anthropogenic soils and landscapes result from a combination of multidimensional factors, which are temporally complex, regionally diverse, and culturally specific. They result from an awareness of the environmental impacts of environmental management by past and current populations. While an initial or occasional fortuitous formation of *terras pretas* or *terras mulatas* is conceivable, mounting evidence suggests intentional or conscious manipulation of resources, waste products, plants, animals, and soils. Importantly, the argument for intentionality does not necessarily imply agricultural use or intensification in the past or in the present, in strictly "landesque capital" terms; rather a multiplicity of factors and goals must be considered. Conceiving of *terras pretas* not just as soil, but as landscapes, requires a consideration of their role in the development of natural and cultural histories. This means thinking beyond agricultural or subsistence systems and incorporating the symbolic, phenomenological, relational, historical aspects of human–environment interactions.

While disciplinary approaches permit the discernment of geobiogenic (natural pedo-biogenic) and anthropogenic (cultural, historic) formation processes as a step toward deciphering the high diversity of *terras pretas* in terms of local coupled human/environmental histories, the framework presented here seeks to reconcile what are often treated as separate processes into a dialectical, integrated research agenda. Anthropogenic soils, which are at once evidence of past human behavior and an ecological resource, demand an interdisciplinary approach. In this sense, they comprise a paradigmatic research topic, capable of connecting past, present, and future.

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