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Amazonian dark earths in the fertile floodplains of the Amazon River, Brazil: an example of non-intentional formation of anthropic soils in the Central Amazon region

Terra Preta de Índio em várzeas eutróficas do rio Solimões, Brasil: um exemplo da não intencionalidade na formação de solos antrópicos na Amazônia Central

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Abstract: Amazonian dark earths (ADEs) are fertile soils created by pre-Columbian Amerindian societies of the Amazon Basin. However, it is still not clear whether these soils were produced intentionally to improve infertile Amazonian upland soils or if they resulted from the accumulation of organic matter from sedentary settlements. This study characterizes the ADEs found in the naturally fertile alluvial floodplains of the Amazon River in the Central Brazilian Amazon according to total, exchangeable, and available contents of elements and organic carbon in soil profiles. ADEs contained higher levels of available elements and total P, Ca, Zn, and Cu. High total Cr, Ni, Co, and V content in these soils indicate that mafic minerals contributed to their composition, while higher contents of P, Zn, Ba, and Sr indicate anthropic enrichment. The presence of ADEs in floodplain areas strongly indicates non-intentional anthropic fertilization of the alluvial soils, which naturally contain levels of P, Ca, Zn, and Cu higher than those needed to cultivate common plants. The presence of archaeological sites in the floodplains also shows that pre-Columbian populations lived in these regions as well as on bluffs above the Amazon River.

Keywords: Gleysols. Anthrosols. Amazonian Archaeology.

Resumo: Terras Pretas de Índio (TPI) são solos com elevada fertilidade criados pelas sociedades ameríndias pré-colombianas na bacia amazônica. Ainda não existe um consenso se esses solos foram formados intencionalmente para melhorar a fertilidade dos solos distróficos de terra firme da Amazônia ou se resultaram da acumulação de material orgânico em assentamentos sedentários. O objetivo desta pesquisa foi realizar uma caracterização pedogeoquímica de TPI localizadas em áreas de várzeas naturalmente férteis do rio Solimões na Amazônia Central brasileira. Foram analisados os teores totais, trocáveis e disponíveis de elementos e carbono nos solos. As TPI mostraram altos conteúdos trocáveis e disponíveis de P, Ca, Zn e Cu. Elevados conteúdos totais de Cr, Ni, Co e V indicam contribuição de minerais máficos na gênese dos solos, enquanto que teores elevados de P, Zn, Ba e Sr nas TPI indicam enriquecimento antrópico. A ocorrência de TPI em áreas de várzea é uma forte evidência da fertilização não intencional dos solos de várzea, os quais, em condições naturais, apresentam teores de P, Ca, Zn e Cu acima dos níveis críticos para muitas culturas. A presença de sítios arqueológicos em áreas de várzea mostra que as populações pré-colombianas habitaram as várzeas e os interflúvios do rio Solimões.

Palavras-chave: Gleissolos. Anthrossolos. Arqueologia amazônica.

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INTRODUCTION

The role pre-Columbian populations played in modifying the natural conditions of the Amazon Basin has been intensely debated (Barlow et al., 2012; Levis et al., 2012; Clement et al., 2015). This discussion includes suggestions by archaeologists, cultural anthropologists, and ecologists that the Amazon Basin was more densely occupied in pre-Columbian times than previously thought, and that these ancient populations actively altered their environments, leaving lasting features which are still recognizable today (Heckenberger et al., 2003; Heckenberger; Neves, 2009; McMichael et al., 2012). Amazonian dark earth soils (ADEs) are among the features indicated as supporting this hypothesis (Lehmann et al., 2003a; Teixeira et al., 2009; Clement et al., 2015). These horizon soils are found across the Amazon; they are highly fertile and normally associated with archaeological sites, with deposits reaching over 200 cm deep and several dozen hectares wide (Kern et al., 2009). Research in the last decade supports this claim, showing a strong correlation between the nutrients found in these sites and the human activities that produced these deposits (Neves et al., 2003; Arroyo-Kalin et al., 2009).

Yet there is no consensus as to whether these anthropic soil horizons were created intentionally (Arroyo-Kalin et al., 2009; Glaser; Birk, 2012). Did they result from management practices to improve the poor natural upland soils across much of the Amazon and make them suitable for agriculture? Conversely, were these soils formed around houses and other occupation areas such as trash middens, rather than former farming areas (Glaser; Birk, 2012; Schmidt et al., 2014)? This question is important because it address the long-standing debate on the role of environmental factors which limited the establishment of long-term, permanent, and sedentary settlements in the Amazon (Meggers, 1996; Roosevelt, 2013). Proving that ADEs were intentionally formed would also provide evidence of deliberate past human management to modify and overcome supposed environmental limitations on soil properties. Meanwhile, if ADEs are shown to have been formed unintentionally, this would cast doubt upon the supposed role of these limitations, since these soils are normally associated with large and permanent settlements in the Central Amazon and elsewhere (Neves, 2007; Schmidt et al., 2014). Studies of the chemical composition of ADEs are also important to clarify the mechanisms involved in these formations and potentially replicate this process for agricultural use; they could be used to develop waste management methods that create soil conditioners, halt land degradation, and act a model for sustainable agriculture in the humid tropics (Glaser et al., 2001).

To address these questions, we researched, sampled, and characterized naturally deposited soils from the fertile alluvial floodplain of the upper stretches of the Amazon River (also known as the Solimões River) in the Brazilian Central Amazon region, along with ADEs located in these same naturally fertile alluvial settings. Our goal was to compare the chemical properties of both soils to assess whether ADE formation implied a significant increase in soil fertility. Nearly all previous research on ADEs has been performed in archaeological sites located in non-fertile upland soils, with results showing a stark contrast between ADEs and the surrounding acidic Ferralsols and Acrisols in terms of soil fertility (Kern; Kämpf, 1989; Lima, H. et al., 2002; Aquino et al., 2016).

The predominant soils in the floodplains are eutrophic Gleysols and Fluvisols. The Amazon River and some of its major western tributaries were formed due to the recent uplift of the Andes during the early Paleogene (Potter, 1997), and their alluvial floodplains are enriched by the annual deposition of the suspended sediments typical of those rivers (Filizola; Guyout, 2009; Junk et al., 2011). Such Holocene floodplains often have eutrophic soils with high levels of exchangeable cations, mainly Ca^{2+} and Mg^{2+} (Lima, H. et al., 2007; Teixeira et al., 2006). Nevertheless, ADE studies in floodplains are scarce, since it is difficult to locate these horizons buried under several hundred centimeters of sediments deposited by periodical flooding. Moreover, intense erosion of riverbanks, a phenomenon known locally as *terras caídas* ['fallen land'], has destroyed many of these sites over the past centuries (Teixeira et al., 2006). Despite these challenges, we were able to locate buried ADE horizons in the floodplains in the Central Amazon.

Alluvial anthropic horizons (Au) show characteristics similar to Au horizons occurring in upland soils (Kämpf et al., 2003), namely dark coloration, high P, Ca, and Mg content (Lehmann et al., 2003b), and evidence of human occupation such as pottery and stone artifacts (Smith, 1980; Arroyo-Kalin et al., 2009). These anthropic horizons are typically buried and 'protected' by layers of sediments and typically represent paleosols in the stratigraphy (Sternberg, 1998; Teixeira et al., 2006; Silva et al., 2011).

The objective of this study was to quantify and compare the total, exchangeable, and available contents of mineral elements and organic carbon in non-anthropic and anthropic soil horizons of the floodplains of the Amazon River in the Brazilian Central Amazon region.

MATERIAL AND METHODS

The soils that are the target of this study are distributed across the floodplains of Holocene deposition on the banks of the Amazon River in the Central Amazon region. They were and still are formed by recent sedimentary depositions mainly composed of fragments of sandstones and siltstones containing quartz, kaolinite, K-feldspar, plagioclase, mica, hematite, schist, and volcanic and rare fragments of carbonate rocks (Franzinelli; Potter, 1989). The predominant climate in this region is tropical humid, with average annual temperatures exceeding 22 °C, annual rainfall of approximately 2,500 mm, intense sunlight, high air humidity, and low wind speeds.

We studied eight soil profiles where surface or buried anthropic soil horizons were present; they were located between the cities of Manacapuru and Coari in the state of Amazonas, Brazil (Figure 1). Soil profiles P1, P2, and P4 were located in bluffs on the Amazon River, while P3 was found in a trench and P6 and P7 were collected using a Dutch auger to a depth of 100 cm and P5 and P8 to a

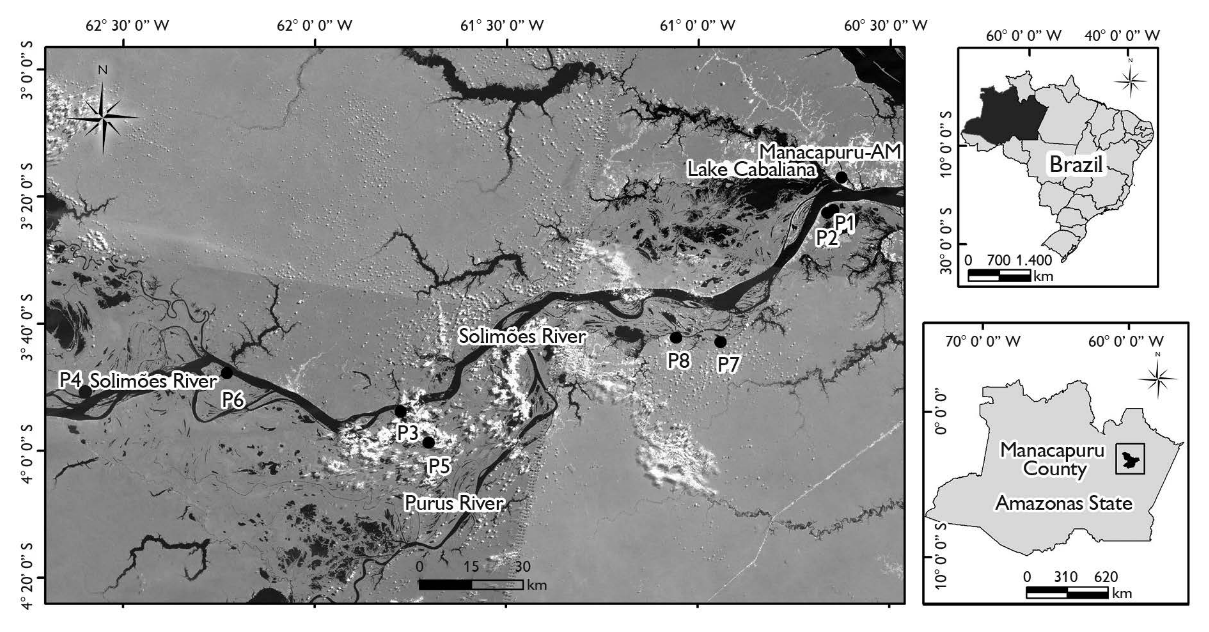

Figure 1. Location of the soil samples distributed in the fluvial Holocene floodplains on the banks of the Amazon River in the Central Amazon region, Amazonas, Brazil. Map: André Luiz de Souza Celerino (2018).

depth of 120 cm. The sites were selected in conjunction with the *Projeto Potenciais Impactos e Riscos Ambientais da Indústria do Petróleo e Gás Natural no Amazonas* group. This project has cataloged 86 archaeological sites between the cities of Iranduba and Coari (Lima, M.; Tamanaha, 2007).

The samples were analyzed at the EMBRAPA Western Amazon Soil and Plant Analysis Laboratory in Manaus, Brazil. The following parameters were analyzed: pH in water and in KCl; calcium, magnesium and aluminum (Ca^{2+}, Mg^{2+} and Al^{3+}) extracted in a solution of KCl 1 mol L^{-1}; potassium and sodium (K^{+} and Na^{+}) extracted in a solution of HCl 0.05 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}; exchangeable acidity (H + Al) extracted in a solution of calcium acetate 0.5 mol L^{-1} at pH 7.0; available phosphorous (P), Fe, Cu, Zn, and Mn extracted in Mehlich-1 and organic carbon using the Walkley-Black method (EMBRAPA, 2011).

The total contents of Ag, Al, As, B, Ba, Bi, Ca, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Sc, Sn, Sr, V, Y, Zn, Zr, and W were obtained using inductively coupled argon plasma atomic emission spectrometry (ICP-OES), after acid digestion with aqua regia (HCl-HNO_3, 3:1). TILL-2 and GBM997-9 were the reference samples used as quality control in chemical analysis. The profiles were described according to Santos et al. (2013) and Schoeneberger et al. (2012), and classified according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015).

RESULTS AND DISCUSSION

The profiles were classified as Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic) (P1, P2, and P4), Pretic Anthrosol (Hypereutric, Siltic, Fluvic, Oxyaquic) (P3) (Figure 2A-2D), Eutric Pantofluvic Fluvisol (Siltic, Oxyaquic) (P5 and P7), Gleyic Pantofluvic Fluvisol (Siltic, Ochric) (P6), and Pretic Anthrosol (Orthoeutric, Siltic, Fluvic, Oxyaquic) (P8). All profiles presented anthropic horizons (pretic horizon – Au) consisting of mineral material with thickness of ≥ 20 cm, a Munsell color value of ≤ 4 and a chroma of ≤ 3 (moist), > 1% organic carbon and ceramic artifacts, exchangeable $Ca^{2+} + Mg^{2+} \geq 2$ $cmol_c$ kg^{-1}, and > 30 mg kg^{-1} of extractable P. When the pretic horizon occurred within 100 cm of the mineral soil surface, the soils were classified as Anthrosols (IUSS Working Group WRB, 2015).

Table 1 shows that the anthropic horizons were brown (P1: 7.5 YR 4/2), dark gray (P6 and P7: 10YR 4/1), black (P8: 10YR 2/1), and very dark gray (P2, P3, P4, P5 10YR 3/1) (Table 1). Except for P1, all anthropic horizons demonstrated value 1 color, darker than non-anthropic horizons; this color is within the range commonly found for anthropic horizons among upland soils in the Amazon (Kämpf; Kern, 2005; Aquino et al., 2016). Small or very small (< 2 mm) charcoal pieces totaling 15-40% of the

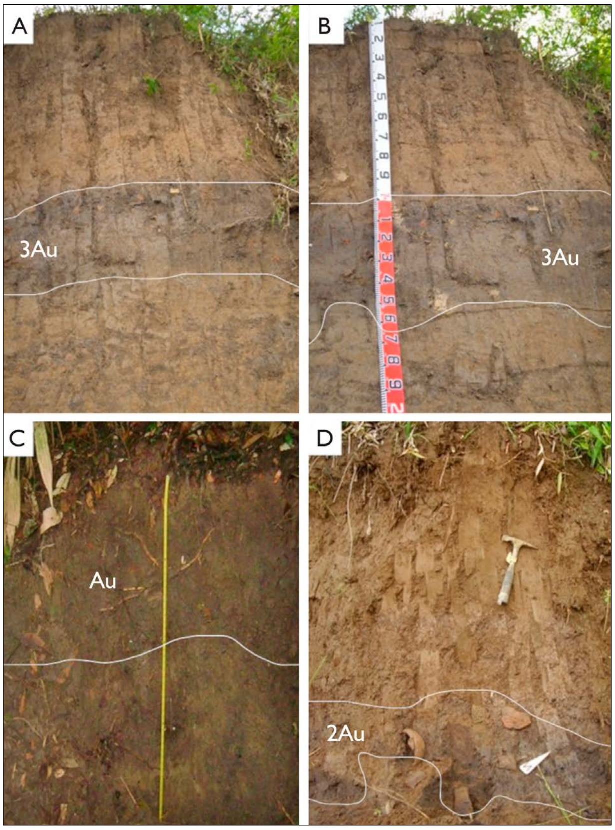

Figure 2. Soil profiles with the presence of surface or buried anthropic soil horizons (ADE) between the cities of Manacapuru and Coari in Amazonas state, Brazil: A) P1 Eutric Orthofluvic Fluvisol; B) P2 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic); C) P3 Pretic Anthrosol (Hypereutric, Siltic, Fluvic, Oxyaquic); D) P4 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic). Photos: Rodrigo Santana Macedo (2008).

sample were found in the anthropic soil horizons. Less carbon was found in the non-anthropic soil horizons, approximately 2-5%, and these were predominantly larger, between 5 and 10 mm. Charcoal pieces in ADEs were also found in association with biological channels, demonstrating significant bioturbation processes. Similar findings were also reported in other ADEs by Lima, H. et al. (2002). Charcoal pieces have also been found in archaeological excavations in ADEs in association with ceramics and bones, and later with cooking and burning ceramics (Arroyo-Kalin, 2008, 2012). Along with black carbon, the large quantities of millimeter-sized charcoal fragments result in the melanization of anthropic horizons (Macedo et al., 2017); in both cases, these substances do not degrade significantly because of the preferential links between polyaromatic groups and the mineral fraction of soils and because of the highly concentrated polyaromatic macromolecular structures they contain (Schellekens et al., 2017).

Ceramic artifacts were only found in the anthropic horizons, in quantities of 5-15%, with thickness ranging from 10 to 15 mm. The pretic horizon where P4 was sampled contained large ceramics artifacts and bowls (Figure 2D). These ceramics were related to the Guarita phase of the Polychrome tradition which appeared in the lower Solimões region around 1,000 AD, around 800 AD in its tributaries near the city of Coari, and even earlier during the fifth century AD in the Tefé area (Tamanaha; Neves, 2014; Belletti, 2015). The Guarita phase is characterized by ceramic artifacts including anthropomorphic urns (Figure 3A), and bowls with mesial flanges (Figure 3B) normally painted with red and black motifs covering a white slip (Moraes; Neves, 2012; Tamanaha; Neves, 2014; Belletti, 2015; Oliveira, E., 2016). The Polychrome tradition is found over a large area covering most of the Western Amazon, from the foothills of the Andes in Ecuador to the Upper Amazon River in Peru all the way down to the Central Amazon (Figure 4) near the city of Itacoatiara as well as the Upper Madeira River. The presence of this type of ceramics and thicker horizon layers of ADEs confirm occupation of the Central Amazon region, not only in dryland areas (Petersen et al., 2001; Neves et al., 2003) but also the floodplains, as noted by Sternberg on Careiro Island near Manaus (Sternberg, 1998).

Figure 3. Ceramic artifacts from the Guarita phase (Polychrome tradition) which appear in the lower Solimões River region: A) anthropomorphic urns; B) bowls with mesial flanges. Photos: Mauricio de Paiva (2009).

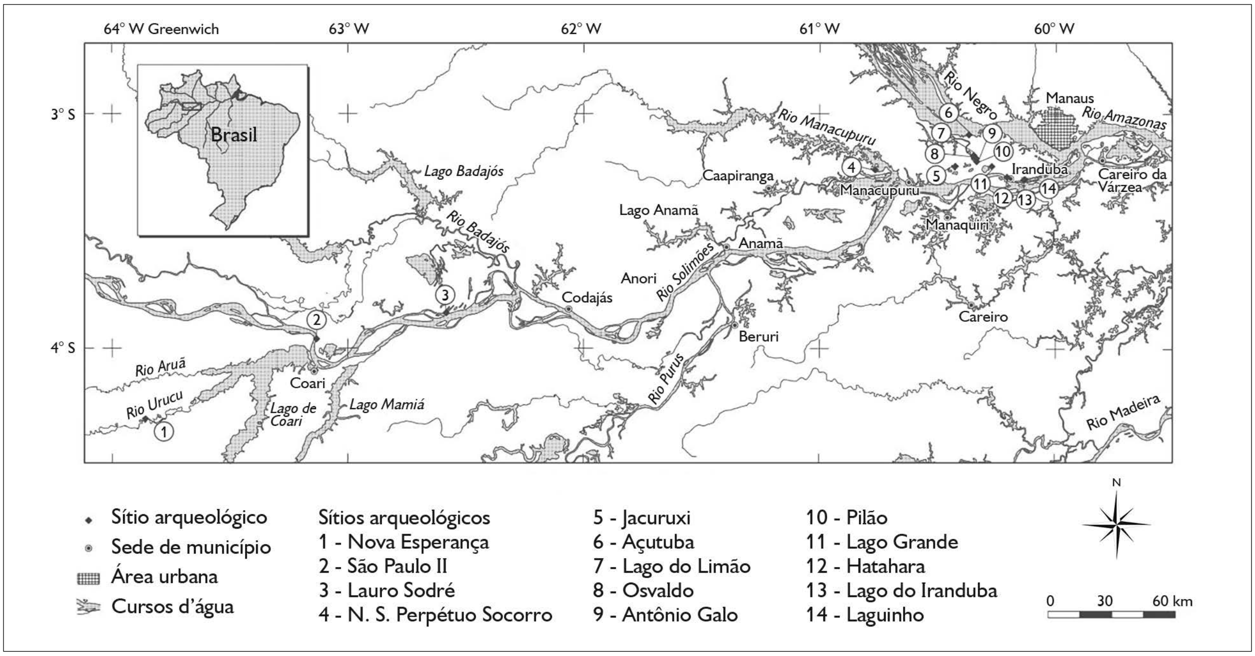

Figure 4. Location of excavated archaeological sites containing Guarita strata in the Central Amazon region. Note that the number of sites in the area is greater than the number excavated. Map: Projeto Amazônia Central (2009).

Silt particles predominated in all the samples, with an average value of 400 g kg^{-1}; this indicates the sedimentary nature of these soils as well as their low degree of pedogenetic development (Table 1). Except for P8 and subsurface P6 horizons, there was little coarse sand in the soil texture (not exceeding 80 g kg^{-1}), showing that during floods, the waterways are unable to transport coarser sediments to these positions in the landscape. Between anthropic and non-anthropic horizons, no differences in particle sizes were observed that could denote past human activities. This finding contrasts with studies that found higher sand fractions in anthropic horizons; this may result from fire, degradation, and illuviation of clay particles, and/or reduced scattering of organic mineral complexes in ADEs by traditional methods used to characterize soil particle content (Teixeira et al., 2006).

P3 Au featured angular blocks that crumbled into medium-to-large granules with low degree of development, while the buried anthropic horizons contained small-to-medium angular blocks with a moderate degree of development (Table 1). The predominantly granular structure of P3 shows the effects of higher organic matter contents and biological activity on the surface, while the presence of subangular blocks in buried ADEs reflects cycles of expansion and contraction due to the presence of high-active clays.

All the sampled horizons demonstrated a net negative surface charge, with the water pH ranging from highly acidic (4.82) in the A horizon of P2 to virtually neutral (7.12) in the $2C_2$ horizon of P6, while the pH variation in KCl was 4.04 in the A horizon of P5 and 5.61 in the $2C_2$ horizon of P6 (Table 2). Other studies on floodplain soils in the Central Amazon region (Oliveira, L. et al., 2000; Lima, H. et al., 2007) reported similar results. These values reflect the composition of the sediments in the Amazon River (Filizola; Guyout, 2009), which help maintain pH near neutral due to the dissolution of silicates in suspension via hydrolysis. The generally lower pH values in the surface horizons can be explained by the biological oxidation of organic compounds in the dry season, producing CO_2 that reacts with water to form carbonic acid, which in turn dissociates and releases H^+.

Table 1. Location, morphological characteristics, and particle composition of soils with an anthropic horizon (Amazonian dark earths) in floodplains of the Amazon River between the cities of Manacapuru and Coari, Amazonas state, Brazil. Legends: [1] = angular blocks, [2] = subangular blocks, [3] = granular, [4] = small, [5] = medium, [6] = large, [7] = weak, [8] = moderate.

(Continue)

Hz	Depth (cm)	Location	Coordinates	Color	Structure	Coarse sand	Fine sand	Silt	Clay
						g kg^{-1}			
P1 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic)									
A	0-15	Costa do Marrecão, Manacapuru	03° 21' 04" S 60° 40' 05" W	10YR 3/4	Ang. bl.[1], sm[4]/med[5], w[7]	4	510	367	118
AC	15-23			10YR 3/4	Ang. bl., sm/med, w	1	457	444	98
2C$_1$	23-70			10YR 3/4	Ang. bl., med/larg[6], w	1	190	618	191
2C$_2$	70-100			7.5YR 4/4	Ang. bl., med/larg, w	3	467	377	153
3Au	100-155			7.5YR 4/2	Ang. bl., sm/med, mod[8]	3	289	488	220
3C$_1$	155-180			10YR 4/3	Ang. bl., sm/med, mod	2	268	539	191
3C$_2$	-180+			10YR 4/3	Ang. bl., sm/med, mod	5	170	646	179
P2 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic)									
A	0-10	Costa do Marrecão, Manacapuru	03° 21' 32" S 60° 40' 40" W	10YR 3/3	Ang. bl./gran[3], med/larg, w	16	625	259	100
AC	10-25			10YR 3/3	Ang. bl., med/larg, w	2	500	370	128
2C$_1$	25-50			10YR 4/4	Subang. bl.[2], sm/med, mod	1	345	526	128
2C$_2$	50-100			10YR 4/4	Subang. bl., sm/med, w	1	354	481	163
3Au	100-150			10YR 3/1	Subang. bl., sm/med, mod	12	207	566	215
3C	150+			10YR 4/3	Subang. bl., sm/med, mod	13	255	560	172
P3 Pretic Anthrosol (Hypereutric, Siltic, Fluvic, Oxyaquic)									
Au	0-60	Comunidade São Lázaro, Anori	03° 53' 46" S 61° 46' 34" W	10YR 3/1	Ang. bl./gran, med/larg, w	32	104	547	318
CA	60-70			10YR 4/3	Ang. bl., med/larg, w	27	140	546	287
C$_1$	70-100			10YR 6/8	Ang. bl., med/larg, w	16	118	580	286
C$_2$	100+			10YR 7/8	Ang. bl., med/larg, mod	13	67	637	283
P4 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic)									
A	0-25	Comunidade Lauro Sodré, Coari	03° 51' 58" S 62° 35' 09" W	10YR 3/3	Subang. bl./gran, sm/med, w	1	266	532	200
C$_1$	25-80			10YR 3/4	Subang. bl., sm/med, w	0	445	447	108
C$_2$	80-110			10YR 4/4	Subang. bl., sm/med, mod	0	217	590	193
2Au	110-175			10YR 3/1	Subang. bl., sm/med, mod	6	340	449	206
3C	175+			10YR 4/3	Subang. bl., sm/med, mod	1	554	343	102
P5 Eutric Pantofluvic Fluvisol (Siltic, Oxyaquic)									
A	0-20	Comunidade São Lázaro, Anori	03° 58' 41" S 61° 42' 12" W	10YR 3/1	-	31	116	540	313
2C$_1$	20-40			10YR 4/3	-	32	99	519	350
2C$_2$	40-60			10YR 4/3	-	28	115	658	199
3Au	60-100			10YR 3/1	-	10	117	587	286
3C	100-120			10YR 4/3	-	13	114	617	256

Table 1. (Conclusion)

Hz	Depth (cm)	Location	Coordinates	Color	Structure	Coarse sand	Fine sand	Silt	Clay
						g kg^{-1}			
P6 Gleyic Pantofluvic Fluvisol (Siltic, Ochric)									
Au	0-20	Comunidade Matrinxã, Codajás	03° 47’ 19” S 62° 13’ 31” W	10YR 4/1	-	82	635	233	50
$2C_1$	20-40			10YR 5/3	-	7	336	542	115
$2C_2$	40-60			10YR 5/3	-	6	226	622	146
$3C_1$	60-80			10YR 5/3	-	168	715	90	27
$3C_2$	80-100			10YR 5/3	-	162	654	151	33
P7 Eutric Pantofluvic Fluvisol (Siltic, Oxyaquic)									
A	0-20	Costa do Paratati, Manacapuru	03° 42’ 45” S 60° 56’ 32” W	10YR 3/2	-	24	166	549	260
2Cg	20-60			2.5Y 8/8	-	20	98	528	353
3Au	60-80			10YR 4/1	-	22	159	577	241
3Cg	80-100			2.5Y 8/8	-	8	164	604	223
P8 Pretic Anthrosol (Orthoeutric, Siltic, Fluvic, Oxyaquic)									
Au	0-60	Comunidade Repartimento, Manacapuru	03° 42’ 06” S 61° 03’ 31” W	10YR 2/1	-	164	132	390	313
Cg_1	60-80			10YR 5/8	-	221	128	367	284
Cg_2	80-100			2.5Y 8/8	-	216	138	374	272
Cg_3	100-120			2.5Y 8/8	-	224	141	362	273

High organic carbon (OC) values are widely reported in the literature as characteristic of ADEs in the upland soils; these result from the accumulation of organic material caused by anthropogenic activity (Kern; Kämpf, 1989) and set fires (Smith, 1980), but because of the greater thickness of the anthropic horizon in relation to other non-anthropogenic soil horizons, many studies do not show high OC values but rather high stocks of carbon in ADEs (Teixeira et al., 2009). The anthropic horizons studied showed lower OC values than the surface A horizon (P1, P2, P4, P5 and P7) and some subsurface layers (P3 and P6) (Table 2). These findings concur with other studies investigating ADEs in floodplain soils (Silva et al., 2011) and are lower than values for other ADEs (Teixeira et al., 2006; Cunha et al., 2007). In these soils, OC may reflect the low average content of this component in fresh sediments deposited periodically in floodplain soils (Marques et al., 2002).

The available Ca^{2+} and Mg^{2+} contents are high in all horizons for all profiles. In terms of soil fertility classification (Ribeiro et al., 1999), the anthropic horizons showed Ca^{2+} values ranging from high (P6: 4.03 cmol$_c$ kg^{-1}) to very high (P3: 19.17 cmol$_c$ kg^{-1}), and Mg^{2+} values ranging from medium (P7: 0.49 cmol$_c$ kg^{-1}) to very high (P4: 2.83 cmol$_c$ kg^{-1}) (Table 2). In ADEs, Ca is associated with P, most likely under phosphates as well as through intermolecular association in oxidized nanometric carbon particles (Archanjo et al., 2014; Oliveira, N. et al., 2018). Although Ca^{2+} and Mg^{2+} are recognized as indicators of anthropic activity (Kämpf; Kern, 2005), in ADE floodplain soils these ions are poor indicators of anthropic activity since these elements naturally occur in this environment at high levels.

Because of the chemical richness of floodplains, K contents in anthropic horizons exceed those found in ADEs in the upland sites (Falcão et al., 2003; Lehmann et al., 2003b; Aquino et al., 2016), with levels ranging from adequate (P6: 41 mg dm^{-3}) to high (P5: 87 mg dm^{-3}) for plant cultivation (see Table 2). However, no difference was seen in the content of this element between non-anthropic and anthropic soil horizons in the floodplains. The considerable K content in the soils studied can mainly be attributed to the release of K from the crystal structure of clay minerals such as illite and micas. In some ADE sites in the floodplains of the Solimões River, potassium liberation from feldspars has also been identified (Corrêa, 2007). Along similar lines, enrichment of anthropic horizons with Na^+ was not seen. The low values for Na and minimal variation of this element in the profiles reflects its low total content in the soil samples (Table 2), as it is mainly released into the soil through the weathering of sodic plagioclase and illite.

Table 2. Chemical characteristics of soils with an anthropic horizon (Amazonian dark earths) in floodplains of the Amazon River between the cities of Manacapuru and Coari, Amazonas state, Brazil. Legends: [1] = sum of bases, [2] = cation exchange capacity, [3] = clay activity, [4] = base saturation.

(Continue)

Hz	pH H_2O	pH KCl	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	SB[1]	CEC[2]	T[3]	V[4]	Fe	Zn	Mn	Cu	OC
			mg dm^{-3}		cmol$_c$ kg^{-1}								%	mg kg^{-1}				g kg^{-1}
P1 Eutric Orthofluvic Fluvisol																		
A	5.83	5.12	96	199	14	6.43	2.07	0.00	1.65	9.07	10.72	91	85	306	8.1	98.0	2.1	11.88
AC	6.18	5.19	84	62	16	7.04	2.15	0.00	0.23	9.42	9.65	98	98	306	5.3	74.9	2.8	2.59
C_1	6.49	4.94	43	65	19	9.06	2.45	0.00	0.42	11.76	12.18	64	97	331	6.6	40.2	2.9	3.29
C_2	6.37	4.53	83	38	22	8.91	3.54	0.00	1.07	12.64	13.71	90	92	251	6.3	21.0	2.1	1.76
2Au	6.38	4.99	898	45	58	12.46	2.61	0.00	2.16	15.44	17.60	80	88	300	22.2	26.0	5.1	3.36
2C_1	6.70	4.83	215	48	40	12.42	2.71	0.00	1.43	15.43	16.85	88	92	299	11.6	32.0	3.9	2.01
2C_2	6.66	4.67	83	47	44	12.97	3.58	0.00	1.08	16.86	17.94	100	94	257	8.6	32.8	3.1	1.68
P2 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic)																		
A	4.82	4.09	101	45	26	4.57	1.52	0.46	3.10	6.32	9.42	94	67	326	5.1	40.9	1.8	9.12
AC	5.72	4.50	94	26	30	6.50	1.88	0.00	1.86	8.58	10.44	82	82	277	5.1	39.1	2.2	2.01
C_1	6.09	4.75	79	30	30	8.34	2.43	0.00	0.68	10.98	11.66	91	94	157	5.1	24.7	2.4	3.17
C_2	6.51	4.54	62	37	31	8.95	2.71	0.03	0.88	11.89	12.77	78	93	262	5.0	24.9	2.3	2.67
2Au	6.61	5.02	721	55	47	11.86	2.82	0.00	1.78	15.03	16.80	78	89	215	17.2	26.2	5.3	3.33
2C	6.52	4.90	191	58	38	12.20	2.71	0.00	1.44	15.22	16.66	97	91	207	10.0	23.1	4.5	2.70
P3 Pretic Anthrosol (Hypereutric, Siltic, Fluvic, Oxyaquic)																		
Au	5.97	4.59	814	55	70	19.17	1.34	0.00	5.69	20.96	26.64	84	79	257	33.5	46.8	11.1	10.94
CA	6.01	4.72	591	56	61	19.42	1.20	0.00	4.35	21.03	25.38	88	83	290	25.6	49.1	8.3	10.13
C_1	6.20	4.67	586	59	55	20.44	1.49	0.00	4.20	22.32	26.52	93	84	264	16.3	32.7	5.5	7.76
C_2	6.33	4.7	525	56	54	17.75	1.64	0.00	3.20	19.77	22.97	81	86	269	8.4	26.3	8.3	15.83
P4 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic)																		
A	6.28	5.38	81	82	17	8.34	4.00	0.00	1.63	12.59	14.22	71	88	458	13.7	201.6	2.9	9.86
C_1	6.35	4.62	93	66	27	6.56	2.30	0.04	0.86	9.10	9.96	92	91	323	6.2	36.2	3.3	1.96
C_2	6.11	4.51	90	86	44	11.22	4.43	0.04	1.60	15.98	17.58	91	91	338	10.4	36.5	4.3	4.71
2Au	6.26	4.84	379	78	39	8.98	2.83	0.00	1.67	12.11	13.78	67	88	276	23.1	29.2	5.7	3.94
2C	6.52	4.84	214	70	34	8.04	2.47	0.02	0.25	10.78	11.03	108	98	244	9.4	24.6	2.8	0.88

Table 2. (Conclusion)

Hz	pH H_2O	pH KCl	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	SB[1]	CEC[2]	T[3]	V[4]	Fe	Zn	Mn	Cu	OC
			mg dm^{-3}		$cmol_c$ kg^{-1}								%	mg kg^{-1}				g kg^{-1}
P5 Eutric Pantofluvic Fluvisol (Siltic, Oxyaquic)																		
A	5.08	4.04	99	55	35	12.19	0.88	0.86	6.64	13.36	20.00	64	67	227	9.2	47.6	7.4	11.90
C_1	5.64	4.34	505	62	71	15.36	1.13	0.00	7.49	16.96	24.44	70	69	265	39.3	45.8	7.0	11.75
C_2	5.98	4.65	543	67	78	17.60	1.35	0.00	6.39	19.46	25.85	130	75	259	66.2	35.8	5.5	8.16
2Au	6.16	4.78	599	87	68	17.24	1.04	0.00	3.44	18.80	22.24	78	85	265	28.0	36.1	6.0	5.10
2C	6.25	4.85	713	90	66	18.36	1.39	0.00	2.97	20.27	23.24	91	87	284	23.2	34.7	5.6	2.64
P6 Gleyic Pantofluvic Fluvisol (Siltic, Ochric)																		
Au	6.64	5.38	145	41	16	4.03	0.87	0.00	0.30	5.07	5.37	107	94	373	6.9	120.6	2.5	2.38
C_1	6.62	5.57	88	63	26	10.73	2.28	0.00	0.86	13.28	14.15	123	94	426	7.5	246.1	4.4	4.97
C_2	6.39	5.49	108	75	33	11.99	2.63	0.00	0.82	14.96	15.78	108	95	342	9.1	286.8	5.2	5.76
$2C_1$	6.81	5.44	132	40	15	4.00	0.82	0.00	0.04	4.99	4.95	183	101	194	3.7	54.0	0.8	0.93
$2C_2$	7.12	5.61	139	53	18	5.03	0.9	0.00	0.02	6.14	6.16	187	100	260	5.6	47.5	1.2	1.06
P7 Eutric Pantofluvic Fluvisol (Siltic, Oxyaquic)																		
A	6.19	5.46	270	60	22	15.07	2.58	0.00	3.65	17.90	21.55	83	83	106	49.7	123.2	2.0	32.27
Cg	5.70	4.37	396	46	19	12.94	1.45	0.00	4.95	14.59	19.54	55	75	238	13.4	26.6	3.6	3.90
2Au	6.99	4.76	826	44	38	10.73	0.49	0.00	4.63	11.50	16.13	67	71	305	21.5	24.1	3.5	5.46
2Cg	5.84	4.69	522	30	26	8.56	0.32	0.00	3.14	9.07	12.21	55	74	324	9.4	16.0	1.8	1.85
P8 Pretic Anthrosol (Orthoeutric, Siltic, Fluvic, Oxyaquic)																		
Au	5.25	4.63	113	69	11	11.10	0.76	0.05	6.39	12.08	18.47	59	65	264	28.4	123.9	5.3	34.14
Cg_1	5.75	4.24	156	33	12	6.24	0.38	0.00	5.18	6.76	11.94	42	57	453	8.8	10.1	3.6	8.32
Cg_2	5.62	4.13	147	32	11	5.92	0.34	0.00	5.93	6.39	12.32	45	52	458	9.1	9.7	4.1	8.69
Cg_3	5.65	4.15	137	36	10	2.09	0.13	0.00	5.51	2.36	7.87	29	30	453	13.1	8.9	3.7	7.80

The Al^{3+} contents were zero or very low (Table 2). At the pH values found in this study, hydrolysis and subsequent precipitation of this element in the form of $Al(OH)_3$ occurs, reducing its availability. The exchangeable acidity (H + Al) varied between the profiles and horizons, with the anthropic horizons in P1, P3, P4, and P8 showing higher values than the overlying or underlying non-anthropic layers; however, the absence of this pattern in the other profiles does not permit us to associate that content with anthropic activities (Table 2). Much of this acidity in the profiles comes from H^+ ions that dissociate from the organic compounds of OH groups on clay surfaces and Al polymers.

Although the floodplain soils studied are naturally high in P (Lima, H. et al., 2007; Guimarães et al., 2013), P content is markedly higher in anthropic horizons because of these activities, reaching values of 898 mg kg^{-1} in P1; this consequent increase in P in floodplain areas is corroborated by other authors (Lima, H. et al., 2002; Teixeira et al., 2006). High P contents in Amazonian Anthrosols are primarily attributed to the deposition of bones from fish and other animals (Schaefer et al., 2004), which change over time from stable crystalline forms to soluble forms of Ca-P (Sato et al., 2009). ADE floodplain soils also generally have higher Ca-P contents than other forms of P, as their humic and fulvic acids make a considerable contribution to the enrichment of P (Lima, H. et al., 2002). In ADEs located in the floodplains, the biogenic apatite present in bone fragments may be preserved because of pH-neutral or alkaline conditions, and the significant presence and apport of Ca and P from the rich alluvial sediments (Souza, 2011).

Furthermore, ceramics act as an additional major source of P, since they release this nutrient in weathering conditions resembling natural settings (Valente; Costa, 2017). As other authors have observed (Kern; Kämpf, 1989; Lima, H. et al., 2002), the higher P contents in the P8 profile were not observed in the superficial anthropic horizon, but rather at a greater depth, from the Cg_1 horizon. The greater P availability at this depth may result from mobility and subsequent retention in Fe and Al oxides. This mobility results from the negative precipitation of organic matter to reduce P adsorption, with adsorbed organic acids blocking adsorption sites and/or solubilizing Fe and Al oxides, in turn reducing their adsorption surface.

We found high values for micronutrients in all the profiles, and for the anthropic horizons these values (mg kg^{-1}) ranged from 215 to 373 (Fe), 6.9 to 33.5 (Zn), 24.1 to 120.6 (Mn), and from 2.5 to 11.1 (Cu), with the highest values seen for Fe (Table 2). The anthropic horizons generally exhibited significantly lower Fe content than non-anthropic horizons, especially in the P3 and P8 profiles. The waters of the Amazon River are naturally rich in Mn (Queiroz et al., 2009), and because of the overlap between anthropic and non-anthropic horizons this element cannot be used as an indicator of anthropogenic activities (Table 2). Higher Mn contents were observed in horizons with higher OC content.

Although the floodplains and the waters of the Amazon River naturally contain high levels of Zn (Queiroz et al., 2009), anthropic horizons generally tend to be rich in this element (Kern; Kämpf, 1989; Lima, H. et al., 2002). This study found higher contents of Mn and Zn in anthropic A-horizons compared to B-horizons of the same soils and A-B-horizons of adjacent soils (Lima, H. et al., 2002). It has recently been suggested that the organic material used to build walls and roofs of houses are one source of these elements (Costa, J. et al., 2009). Like Zn, Cu values increased significantly in anthropic horizons (Table 2); however, because this element is more mobile in the profile, high Cu contents were also observed in layers of non-anthropic soils. As with Zn, Ca, and P, high Cu contents can be found in bone fragments (Wilson et al., 2008) and/or associated with organic resources used as food (Parnell et al., 2002).

The total Fe_2O_3 contents were highest among the major elements analyzed (Table 3); there was no difference in total content of this element between the layers in non-anthropic and anthropic horizons, in contrast with the available form (which was significantly lower in the anthropic horizons).

The humified nature of organic matter in the anthropic horizons not only inhibits crystallinity but also contributes to the partial dissolution of Fe oxides, predominantly found as goethite (matrix 10YR), generating soluble organic-ferruginous complexes that were lost in leaching (Lemos et al., 2009). Given the similar contents of organic matter between the anthropic horizons and non-anthropic soil layers, this effect is related to the type of OM; in other words, in these cases ADEs can be richer in recalcitrant humified OM and simultaneously highly reactive, creating a favorable environment for the complexation of metallic cations.

Al and Fe account for at least 68% of the element load in white water rivers, and only Al (which has higher values in the Amazon River) helps differentiate this river from the others in the basin (Queiroz et al., 2009). In this study, the Al_2O_3 content ranged from 5.3 g kg^{-1} (P7) to 23.5 g kg^{-1} (P5), with similar concentrations in anthropic and non-anthropic horizons. The different sources of Al in the soil samples include oxides and their presence in the crystal structure of primary (quartz, mica, plagioclase) and secondary minerals (kaolinite, illite). Another possibility is the adsorption of this element in Fe oxides, which are found in considerable amounts in its amorphous fraction and present additional sites for Al adsorption.

A direct relationship was observed between the total contents of CaO, K_2O, MgO, and Na_2O with their respective contents in the exchangeable fraction (Tables 2 and 3). The source of these cations is related to their higher concentrations in muddy rivers such as the Amazon and their origin from the weathering of Andean soils, providing large quantities of ions in floodplain soils (Junk et al., 2011). Despite the rich chemistry of these areas, the total CaO and P_2O_5 contents are higher in anthropic horizons, indicating enrichment from human activities. The primary sources of Ca and P are attributed to an organic origin, namely feces, urine, and plant tissues (Smith, 1980) as well as biogenic apatite in the form of bones from fish and other animals which have been found in the soils (Schaefer et al., 2004). Moreover, the oxides K_2O, MgO and Na_2O showed no relationship to anthropogenic activity and their possible sources are attributed to the weathering of micas, feldspars, mafic minerals (pyroxene), and sodic plagioclase. Although it occurs in high levels in the Amazon River (Queiroz et al., 2009), the total MnO content was not associated with anthropic horizons, possibly because of its intense dynamics in sites which were significant influenced by pH as well as its redox potential.

Table 3. Total contents of major elements of soils with anthropic horizon (Amazonian dark earths) in floodplains of the Amazon River between the cities of Manacapuru and Coari, Amazonas state, Brazil.

(Continue)

Hz	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5
	g kg^{-1}							
P1 Eutric Orthofluvic Fluvisol								
A	10.5	3.7	26.8	1.0	3.9	0.3	0.1	0.7
AC	10.0	3.0	24.2	0.6	3.8	0.4	< 0.1	0.5
$2C_1$	12.2	2.7	23.5	0.7	4.0	0.5	< 0.1	0.3
$2C_2$	14.4	3.2	27.8	0.6	4.0	0.5	< 0.1	0.7
3Au	12.8	9.0	25.2	0.8	3.9	0.5	0.1	3.8
$3C_1$	13.4	4.4	25.8	0.9	4.2	0.4	0.1	1.5
$3C_2$	15.3	4.0	29.2	0.9	4.7	0.5	0.1	1.0
P2 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic)								
A	9.9	2.9	24.9	0.6	3.6	0.3	0.1	0.7
AC	10.0	2.9	23.3	0.5	3.8	0.4	0.1	0.5
$2C_1$	10.9	3.2	23.0	0.6	3.9	0.4	0.1	0.4
$2C_2$	12.0	2.9	23.8	0.6	3.9	0.4	< 0.1	0.4
3Au	15.2	7.4	26.7	1.2	4.3	0.5	0.1	2.7
3C	14.9	5.0	26.6	1.1	4.2	0.5	0.1	1.5
P3 Pretic Anthrosol (Hypereutric, Siltic, Fluvic, Oxyaquic)								
Au	20.7	15.7	27.9	1.3	4.2	0.5	0.1	7.5
CA	18.1	11.6	26.9	1.3	4.1	0.5	0.1	5.0
C_1	21.1	9.6	31.7	1.6	4.8	0.4	0.1	4.0
C_2	19.4	8.0	29.7	1.4	4.6	0.5	0.1	3.2
P4 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic)								
A	12.7	4.0	26.1	0.9	5.0	0.5	0.1	0.7

Table 3. (Conclusion)

Hz	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5
	g kg^{-1}							
C_1	11.7	2.9	24.8	0.7	4.3	0.4	0.1	0.5
C_2	18.2	3.9	34.6	1.0	5.8	0.8	0.1	0.6
2Au	15.4	4.9	29.8	1.0	4.9	0.7	0.1	1.7
3C	13.8	3.8	29.5	0.9	4.7	0.5	0.1	1.0
P5 Eutric Pantofluvic Fluvisol (Siltic, Oxyaquic)								
A	13.5	4.4	19.4	0.8	3.1	0.5	< 0.1	2.3
$2C_1$	23.5	14.0	30.4	1.5	4.3	0.7	0.1	8.0
$2C_2$	22.6	14.0	29.8	1.6	3.7	0.6	0.1	7.4
3Au	16.2	10.5	25.1	1.3	4.0	0.5	0.1	4.3
3C	17.0	10.2	28.2	1.4	2.9	0.5	0.1	4.2
P6 Gleyic Pantofluvic Fluvisol (Siltic, Ochric)								
Au	11.2	3.9	60.0	0.7	0.8	0.6	0.1	0.7
$2C_1$	14.1	4.3	30.3	0.9	0.1	0.6	0.2	0.6
$2C_2$	15.7	4.6	32.3	1.1	< 0.1	0.7	0.2	0.7
$3C_1$	11.0	3.7	32.5	0.7	< 0.1	0.5	0.2	0.7
$3C_2$	11.9	4.0	30.5	0.8	< 0.1	0.4	0.2	0.7
P7 Eutric Pantofluvic Fluvisol (Siltic, Oxyaquic)								
A	9.0	5.1	18.8	0.5	6.2	1.0	< 0.1	1.9
2Cg	11.2	4.3	26.7	0.5	< 0.1	0.4	< 0.1	2.4
3Au	7.3	4.8	13.9	0.4	0.6	0.1	< 0.1	3.6
3Cg	5.3	2.8	11.7	0.3	0.3	< 0.1	< 0.1	2.2
P8 Pretic Anthrosol (Orthoeutric, Siltic, Fluvic, Oxyaquic)								
Au	13.2	4.3	17.3	0.7	0.9	0.2	< 0.1	4.3
Cg_1	11.9	2.6	29.2	0.7	0.8	0.1	< 0.1	3.9
Cg_2	10.6	2.1	24.9	0.5	0.7	< 0.1	< 0.1	3.4
Cg_3	12.6	2.0	36.9	0.6	0.6	< 0.1	< 0.1	3.7

The values for the trace elements Ag, Mo, Sb, B, Bi, Sn, and W were below the detection limit (Table 4). The contents of Co, Cr, Li, Ni, Sc, Y, and Zr were below the average for the surface of the earth's crust, while Pb contents varied in relation to this average (Table 4); none of these elements were related to anthropic activities. Overall, the Ni content in Gleisols and Cr content in Fluvisols were similar to levels found elsewhere in Brazil (Paye et al., 2010). Higher contents of Cr, Ni, and Co show that mafic rocks contributed minerals to these soils, which have high natural contents of these elements.

Pb content far exceeded the content of this element for the surface of the earth's crust. These high values result from politic clastic rocks which are typical in the Amazon River basin and have average Pb content of 23 mg kg^{-1} (Guilherme et al., 2005). The low Zn contents associated with the low mobility of this element in the soils suggest low contents of this element in sediment depositions in floodplain soils, while Sc and Y were unevenly distributed among the horizons and are not related to human occupation.

Because V contents are high in anthropic as well as non-anthropic horizons, this element cannot be related to human activities. These levels reflect the contribution of minerals comprising volcanic and metamorphic rocks (schists), which rank among the geochemical sources of sediment depositions in the Amazon River (Guilherme et al., 2005).

Anthropic horizons generally have higher Cu, Zn, Sr, and Ba content, indicating the enrichment of these layers from human activities. Cu mostly contributed to the total trace elements analyzed, with contents exceeding those found elsewhere in Brazil (Biondi et al., 2011; Paye et al., 2010). As with its exchangeable form, the greater mobility of Cu also permits its presence in non-anthropic horizons. However, this element was seen in greater levels in the anthropic horizons of P1, P2, P3 and P8, showing its relationship with anthropogenic activities.

Table 4. Total contents of trace elements of soils with anthropic horizon (Amazonian dark earths) in floodplains of Amazon River between the cities of Manacapuru and Coari, Amazonas state, Brazil. Legends: Ag, Mo < 1; Sb < 5; B, Bi, Sn , W < 10.

(Continue)

Hz	As	Ba	Co	Cr	Cu	Li	Ni	Pb	Sc	Sr	V	Y	Zn	Zr
	mg kg^{-1}													
P1 Eutric Orthofluvic Fluvisol														
A	< 5	77	10	22	13	12	18	6	< 3	29	55	9	69	2
AC	< 5	81	10	18	12	12	18	6	< 3	24	44	8	58	1
2C$_1$	< 5	100	11	18	14	12	14	7	3	29	39	8	63	1
2C$_2$	< 5	113	12	22	16	13	17	8	4	33	51	12	73	2
3Au	< 5	184	9	19	24	12	17	8	4	71	38	10	109	3
3C$_1$	< 5	111	9	19	19	14	17	8	4	45	43	9	80	4
3C$_2$	< 5	114	10	22	21	15	19	8	5	39	47	11	80	5
P2 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic)														
A	< 5	6.8	9	22	11	11	15	6	< 3	25	54	8	63	< 1
AC	< 5	81	10	18	13	12	16	6	< 3	26	41	8	61	< 1
2C$_1$	< 5	101	11	18	14	12	18	6	< 3	31	41	9	72	< 1
2C$_2$	< 5	101	11	19	14	12	15	8	3	30	43	8	67	2
3Au	< 5	196	9	20	30	14	18	8	4	66	38	11	130	3
3C	< 5	144	9	20	23	13	17	7	4	51	42	10	99	3
P3 Pretic Anthrosol (Hypereutric, Siltic, Fluvic, Oxyaquic)														
Au	< 5	294	8	21	59	15	23	13	5	98	34	15	225	2
CA	< 5	190	8	20	40	14	20	11	5	78	39	11	165	2
C$_1$	< 5	190	9	24	41	17	23	11	6	77	49	13	154	3
C$_2$	< 5	178	9	23	37	16	21	12	6	63	48	13	134	2
P4 Eutric Orthofluvic Fluvisol (Siltic, Oxyaquic)														
A	< 5	99	11	19	15	14	17	9	3	37	43	8	76	1
C$_1$	< 5	86	10	19	16	13	16	6	3	30	44	9	59	2
C$_2$	5	138	14	24	26	18	20	10	6	41	55	12	80	4
2Au	< 5	169	12	22	25	17	20	9	4	46	48	11	91	1
3C	< 5	97	11	22	19	15	20	8	4	37	56	11	72	7

Table 4. (Conclusion)

Hz	As	Ba	Co	Cr	Cu	Li	Ni	Pb	Sc	Sr	V	Y	Zn	Zr
	mg kg^{-1}													
P5 Eutric Pantofluvic Fluvisol (Siltic, Oxyaquic)														
A	< 5	231	7	16	39	10	15	12	< 3	34	28	12	130	1
2C$_1$	< 5	397	9	23	69	17	26	14	6	104	40	16	245	2
2C$_2$	< 5	301	9	23	51	16	25	12	5	109	41	12	207	2
3Au	< 5	173	8	19	41	14	20	10	5	81	39	11	143	3
3C	< 5	177	10	21	36	15	20	11	5	77	44	12	129	3
P6 Gleyic Pantofluvic Fluvisol (Siltic, Ochric)														
Au	< 5	87.2	15	57	16	13	23	9	4	28	175	10	83	5
2C$_1$	6	145	12	21	21	17	19	9	4	32	47	10	76	4
2C$_2$	7	127	13	23	23	18	21	10	5	35	50	11	82	4
3C$_1$	< 5	91	13	27	11	14	21	6	3	28	72	9	78	6
3C$_2$	< 5	101	15	25	13	16	24	6	3	29	62	10	86	8
P7 Eutric Pantofluvic Fluvisol (Siltic, Oxyaquic)														
A	< 5	213	5	11	23	4	11	7	< 3	39	24	6	138	1
2Cg	< 5	144	< 3	15	21	4	7	8	< 3	34	40	5	77	1
3Au	< 5	153	< 3	8	16	3	6	4	< 3	45	18	4	60	< 1
3Cg	< 5	75	< 3	6	7	2	3	< 3	< 3	29	20	2	30	< 1
P8 Pretic Anthrosol (Orthoeutric, Siltic, Fluvic, Oxyaquic)														
Au	< 5	106	< 3	20	32	5	9	10	< 3	31	35	8	98	2
Cg$_1$	6	106	< 3	25	25	5	6	11	4	25	52	10	64	1
Cg$_2$	6	92	< 3	26	23	4	5	10	4	23	45	9	48	1
Cg$_3$	8	89	< 3	37	20	4	5	12	4	22	75	9	46	2
Crust average	2	580	25	100	50	30	75	10	13	300	150	30	80	150

Sr and Ba levels were high in all the soil samples, but they are higher in anthropic horizons. High Sr content in rivers loaded with Andean sediments is attributed to the weathering of carbonate, and silicate weathering contributes to 50% of its concentration in the Amazon River (Gaillardet et al., 1997). One explanation for the high Ba content in the soil samples may be its presence in the feldspar and biotite structure found in the soils analyzed as well as its presence in the composition of carbonate, considering that the Amazon River has calcic-bicarbonate waters (Wilson et al., 2008). Another reason may the high occurrence of this element in volcanic rocks, which contribute to the mineralogical composition of sediments deposited in floodplain soils. This fact, along with the low $^{87}Sr/^{86}Sr$ isotopic ratios calculated for the Amazon River (Gaillardet et al., 1997), highlights the influence of recent eruptive activity in the Amazon Basin, corroborating the hypothesis that mafic minerals contributed to the release of some elements into the soils. Nevertheless, Sr and Ba were strong indicators of anthropic activities and can be very useful in eutrophic soils with high natural levels of P and Ca. Research in the municipality of Cachoeira-Porteira in the Lower Amazon Basin showed that these elements were associated with shells (Costa, M.; Kern, 1999) and that barium is one of the most commonly found minerals in ceramic artifacts (Costa, M. et al., 2004). However, high concentrations of these elements where ceramic fragments are absent may indicate that organic waste of animal origin (skin and bones) or even human or animal excrement were deposited in these areas (Costa, J. et al., 2013).

Higher Ba, Sr, CaO, P_2O_5, and Zn content in anthropic horizons indicate similar sources of enrichment, probably due to the addition of organic plant and animal residues. In addition to this contribution, anthropic horizons rich in OC provided a favorable environment for the dissolution of Fe oxides, reducing the Ba and Sr content associated with these oxides and increasing the content of these elements in the soil. They reacted with the carbonates at higher contents in anthropic horizons (incorporated by the burning of OM) to form less mobile precipitates ($BaCO_3$ and $SrCO_3$). We should also consider that these elements which are still in the oxide form may have reacted with humic acids, forming precipitates with carbonate when exposed to air.

In general, all soil horizons featured high levels of the trace elements Cr, Ni, Co, V, while P, Zn, Ba and Sr were strong indicators of anthropic activities in the floodplains. This geochemical signature indicates the contribution of mafic minerals in the genesis of all horizons, and in anthropic horizons the addition of plant and animal material and its subsequent transformation in the pedogenetic process.

CONCLUSIONS

Early European chroniclers of the Amazon during the sixteenth and seventeenth centuries AD reported the presence of settlements on the floodplains of the Amazon and its tributaries. Despite such reports and the pioneering research by Sternberg (1998) on the alluvial plains of Careiro Island, most studies involving archaeological sites and ADEs in the Central Amazon have been restricted to upland settings on bluffs far above periodically inundated floodplains. This bias in archaeological representation may have skewed the knowledge available on the settlement patterns and economic strategies of the ancient societies that lived along the Amazon River. The prevailing hypothesis explaining ancient human occupations along the Amazonian floodplains maintains that the high bluffs which were spared from seasonal flooding were favored sites for large settlements, while ancient riverside settlements were not located on the floodplains but rather on these bluffs adjacent to the active river channels (Denevan, 1996). From this perspective, past economic patterns were comprised of multiple strategies involving seasonal utilization of the fertile and productive floodplains in combination with more permanent gardens on the edge of the bluffs and agroforestry. Although we still generally agree with this model, the results of this study show that the presence of deep anthropic soil horizons in the floodplain strongly indicate that these areas were also permanently inhabited by large populations, not only sporadically. This indicates that besides bluff regions, alluvial floodplains should also be targeted for future studies.

The typical soils in the floodplains of the Solimões River in the Central Amazon show high amounts of Ca^{2+} and Mg^{2+} and low amounts of available Al^{3+} because of rich sediments and periodical inputs from theses element which are dissolved and in suspension in the water (Corrêa, 2007; Souza, 2011; Guimarães et al., 2013). Despite the risk that agricultural crops in floodplains may be affected by high water, productivity in these areas is normally high, even for crops such as corn which have high nutrient requirements (Lima, H. et al., 2007; Fraser et al., 2010). Consequently, the presence of typical ADEs in fertile floodplains is strong evidence that the soil was not intentionally altered for agriculture, since these regions are naturally fertile and contain nutrient levels far above those needed for to cultivate the most common plants (Havlin et al., 2003). These findings show that the formation of ADEs, at least initially, was not intentional for agricultural practices, disproving hypotheses related to the role of limiting natural factors in the establishment of permanent and sedentary settlements in pre-Columbian Amazonia.

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