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Amazonian Dark Earths in Rondônia State: Soil properties, carbon dating and classification

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ABSTRACT: Throughout the Amazon region, dark-colored soils with increased fertility are identified and referred as Amazonian Dark Earths (ADE). These unique soils are characterized by an anthropic surface horizon with dark colors, presence of charcoal and artifacts, in contrast with surrounding non-ADE soils. The ADEs show extraordinary properties such as the capacity of maintaining the dark colors and high nutrient levels after years of farming, even under the highly favorable climatic conditions for oxidation of organic matter and weathering of nutrients of Amazon region. The ADE are considered islands of fertility in the Amazon biome, as well as very important models for research, in terms of agricultural and environmental sustainability, carbon sequestration, nutrient bioavailability, food security, and for anthropological studies. However, there are many unanswered questions regarding the extent of human alterations, how they were formed, and their classification in the taxonomic systems. Therefore, the objectives of this study were to identify, describe, and characterize soil profiles of ADEs, located in the Southern region of Rondônia State, Brazil, and to contribute to their classification according to the Brazilian Soil Classification System (SiBCS) and the World Reference Base (WRB). Five soil profiles were described and sampled; P1 to P3 were under grass pastures, P4 and P5 under forest and crops with no-till, respectively. The morphological, physical, and chemical attributes, as well as contents of Fe, Al, Si, and Ti oxides and extractable iron forms were characterized. The anthropic horizons exhibited dark colors, artifacts, charcoal, sandier textures, predominantly granular structures, abrupt or clear transitions, and mostly wavy and irregular boundaries. Values of pH, Ca^{2+}, Mg^{2+}, exchangeable bases (S), CEC, and C were high in all anthropic horizons. Compared to non-ADE soils in the Amazon region, phosphorus contents were superior in all anthropic horizons, with the highest values in surface horizons of P1, P2, and P3. According to SiBCS, P1 was classified as *Cambissolo,* P2 as *Argissolo*, and P3, P4, and P5 as *Latossolos.* Except for P4, where values of extractable P by Mehlich-1 are lower than 30 mg kg^{-1}, all soils fulfilled the requirements for the anthropic horizon in the SiBCS, and new classes at the subgroup level were proposed. In the WRB, P4 and P5 were classified as Ferralsols. The other profiles were classified as Anthrosols. The radiocarbon dates (C^{14}) of charcoal fragments, obtained using a mass accelerator, showed ages between 940 ± 40 and 1230 ± 60 years BP.

Keywords: *Terra Preta de Índio*, Anthrosols, Soil Taxonomy.

INTRODUCTION

The idea of an Amazon forest untouched by humans and little affected by anthropic activities has greatly changed over time. Throughout the Amazon basin, there are evidence of these activities such as the human-altered soils, internationally referred to as Amazonian Dark Earths (ADE), the presence of geoglyphs, terraces, pottery, the spreading patterns of plant species, human bones, and artifacts (McKey et al., 2010; Lombardo et al., 2013; Mcmichael et al., 2014; Schmidt et al., 2014; Levis et al., 2017). Among those evidence, the ADEs, locally identified as *Terras Pretas de Índio*, are dark-colored soils with improved fertility. They are referred as being formed as a result of ancient human activities in Amazon before the arrival of Europeans in South America (Clement et al., 2015). These same authors estimate that before the arrival of Pedro Álvares Cabral to Brazil, the Amazon was populated by over 8 million people, and these soils are the main records of these societies' existence.

The ages of ADEs vary from 500 to 8,000 years BP (Mangrich et al., 2011). These ages are estimated based on the contents of a naturally occurring radioactive isotope of carbon, the carbon 14 (^{14}C), also called radiocarbon. This isotope receives this number due to its molecular composition by six protons and eight neutrons, resulting in the mass number 14 (Francisco et al., 2002). The C^{14} is produced in the upper limits of the atmosphere by the action of cosmic rays. This carbon isotope is absorbed by plants during photosynthesis and enters the food chain of most living organisms. The contents of ^{14}C remain constant during all their lives. However, with the death of an organism, the ^{14}C counting begins to decay, and it is reduced to about half of the initial content after approximately 5,730 years, which is often referred as period of half-life (Alves, 2010). By using this concept of half-life, it is possible to estimate the approximated date of death of an organism or sample based on its initial and final ^{14}C contents or activities (Francisco et al., 2002). A standard of oxalic acid is used as a reference for the initial ^{14}C contents or activities, which are similar to the atmosphere in 1950 (Macario and Alves, 2018). This way, the results are expressed in years before present (BP), which refers to the year 1950, since in posterior years, thermonuclear bomb tests, pollution, and the burning of fossil fuels changed the natural concentration of some isotopes in the atmosphere (Turney et al., 2018).

The ADEs occur as irregular-shaped patches throughout the Amazon region, with sizes varying from 0.5 to 350 hectares (Costa et al., 2013); the majority of the reported sites are near rivers and roads, locations with easy access for researchers. Although the full extent of ADEs is still unknown, estimates are about 3.2 % (*ca* 154 063 km^2) of Amazon region (McMichael et al., 2014); but this number might be higher since most Amazon region has no detailed soil surveys. These soils are considered islands of fertility in the region, and although they represent a small percentage of the area, when compared to the total extent of the biome, the ADEs are highly relevant to local communities, for anthropological studies (Schmidt et al., 2014), and as proofs to develop sustainable agricultural practices in tropical environments (Glaser et al., 2001; Barbosa et al., 2020).

Humans can promote great changes in landscapes and ecosystems, which directly impact the intensity, action, and interaction among soil forming processes and, consequently, soil properties. The term "*Anthropic"* was first used to designate those changes related to humans' usage and occupation of the land. Nevertheless, other terminologies can be found in the literature such as - "*Anthropogenic*", which in theory differentiates from the first by the assumption of the intentionality of the alterations. In this way, the term "*Anthropic*" would characterize unintentional changes, while "*Anthropogenic*" is applied for those intentionally made (Barrow, 2012). Despite of this logical rationalization, the use of these concepts for distinguishing human-altered soils is complicated and sometimes inaccurate because the determination of intentionality requires profound archeological studies on a specific site. Thus, the intentionality of the creation of ADEs is still a theme of debates, where many controversial opinions are observed, and it may vary from site to site (Fraser and Clement, 2008; Balee, 2010). Therefore, in this study, the term Anthropic will be used in its ample definition to describe human alterations of soils, without taking into account whether the changes are intentional or unintentionally made for agricultural purposes.

In acknowledgment to the term Anthrosolization, proposed by Bockheim and Gennadiyev (2000) as an autonomous soil forming process, the World Reference Base (WRB, IUSS Working Group, 2015) introduced the reference group “Anthrosols” for identifying soils with strong human influence and evidence of long and intensive agricultural use. Whereas, in the Brazilian Soil Classification System (SiBCS), the Anthrosolization is not considered a primary pedogenesis process, comparable to other soil-forming processes that are recognized at a high level (order) in the taxonomy (Santos et al., 2018). A study by Macedo et al. (2017), in the Caldeirão archeological site in Central Amazonia, identified as processes contributing to ADE genesis: i) the addition of organic residues and ceramic artifacts (cumulization) with the use of fire; ii) mechanical action of humans, roots, and macrofauna (bioturbation); iii) melanization of deeper horizons as a result of bioturbation; and iv) argilluviation and degradation of iron nodules.

Anthropic soils or “Anthrosols” are characterized by seven distinct surface diagnostic horizons (anthraquic, hortic, hydragric, irrigric, plaggic, pretic, and terric) in the WRB (IUSS Working Group, 2015). In Europe, the most frequent human-altered soils resulted from activities starting in Medieval times, with additions of organic materials such as sods and other topsoil materials used for bedding livestock, which were mixed to animals’ excrements and later spread on fields. This led to the formation of the human-altered Plaggic horizon, which is general described as having an appreciably thickened horizon (in places >1.00 m thick), which is rich in soil organic carbon and the base saturation is typically low (IUSS Working Group, 2015). In the Amazon region, the ADEs show enrichment of carbon and macronutrients that are not associated with sod and manure, but with additions of carbonized residues of animal remains (such as shells, tissues, and bones) and plants along time. However, many of these soils were also classified as having a Plaggic horizon (Kämpf et al., 2003). The recognition that they have distinct properties from other human-altered soils led to the inclusion in the WRB (edition of 2014) of the Pretic Horizon (IUSS Working Group, 2015).

The Pretic Horizon is described in the WRB as: *“[...] a mineral surface horizon which results from human activities including the addition of charcoal. It is characterized by its dark colours, the presence of artefacts (ceramic fragments, lithic instruments, bones or shells, etc.), and high contents of organic carbon, phosphorus, calcium, magnesium, and micronutrients (mainly zinc and manganese), usually contrasting with natural soils in the surrounding area. It typically contains visible remnants of charcoal.*” (IUSS Working Group, 2015). In the SiBCS (Santos et al., 2018), human-altered soil horizons are registered as a distinctive attribute only in subordinate levels of the taxonomy, as subgroup, based on the presence of the Anthropic surface horizon. This horizon is described as: “*A horizon formed or modified by humans due to prolonged use of soil as a place of residence, disposal or agricultural exploration where there are evidences of additions of organic materials from varied sources with or without mixture to minerals, in which such human evidences can be proven by the presence of ceramic fragments and/or lithic artifacts, bones, shells or by-products of fire (charcoal and ashes).*” (Author’s translation). Up to the 5th edition of SiBCS (Santos et al., 2018), the Anthropic horizon was used to characterize a few subgroups of *Argissolos Amarelos, Argissolos Vermelhos,* and *Latossolos Amarelos* suborders.

It is possible that Anthropic horizons may occur in other soil orders than *Latossolos and Argissolos*, as they are identified in the SiBCS, since the full extent of human altered soils in Amazon and other Brazilian biomes is unknown. Despite the several studies with ADEs in the literature, there are many unanswered questions. Thus, the premises of this study are that, since studies on ADEs are mostly concentrated in Amazonas and Pará States, their identification in Rondônia, at a region near the boundary of Cerrado Biome, will add valuable information about their occurrence and further support the classification of these soils in a separate order, based on the influence of the human activities in their genesis.

The objectives of this study were to identify, describe, and characterize soil profiles of ADEs, located in the Southern region of Rondônia State, Brazil, and to contribute to their classification according to the Brazilian Soil Classification System (SiBCS) and the World Reference Base (WRB).

MATERIALS AND METHODS

Study area

The study area is located in Rondônia State, Brazil, municipalities of Cabixi, Pimenteiras do Oeste, and Cerejeiras (Figure 1), and the coordinates of the profiles are in table 1. The vegetation corresponds to the Amazon Biome, close to the boundary with the Cerrado Biome in the west. The climate is tropical rainy, Am type according to Köppen classification system (Alvares et al., 2014), with annual precipitation from 2,200 to 2,500 mm and mean annual temperature from 25 to 26 °C (Alvares et al., 2014).

Regarding geology and geomorphology, the formation is described as undifferentiated sedimentary coverages associated with alluvial environments, river channels, flood plains, and lakes, consisting of sediments from gravel to clay granulometries, with significant lateritization (CPRM, 1999). The study area is placed within the Amazon depression, in the fluvial plains of the Guaporé river (CPRM, 1999). All the soil profile sites are located on fluvial terrace systems, near water streams.

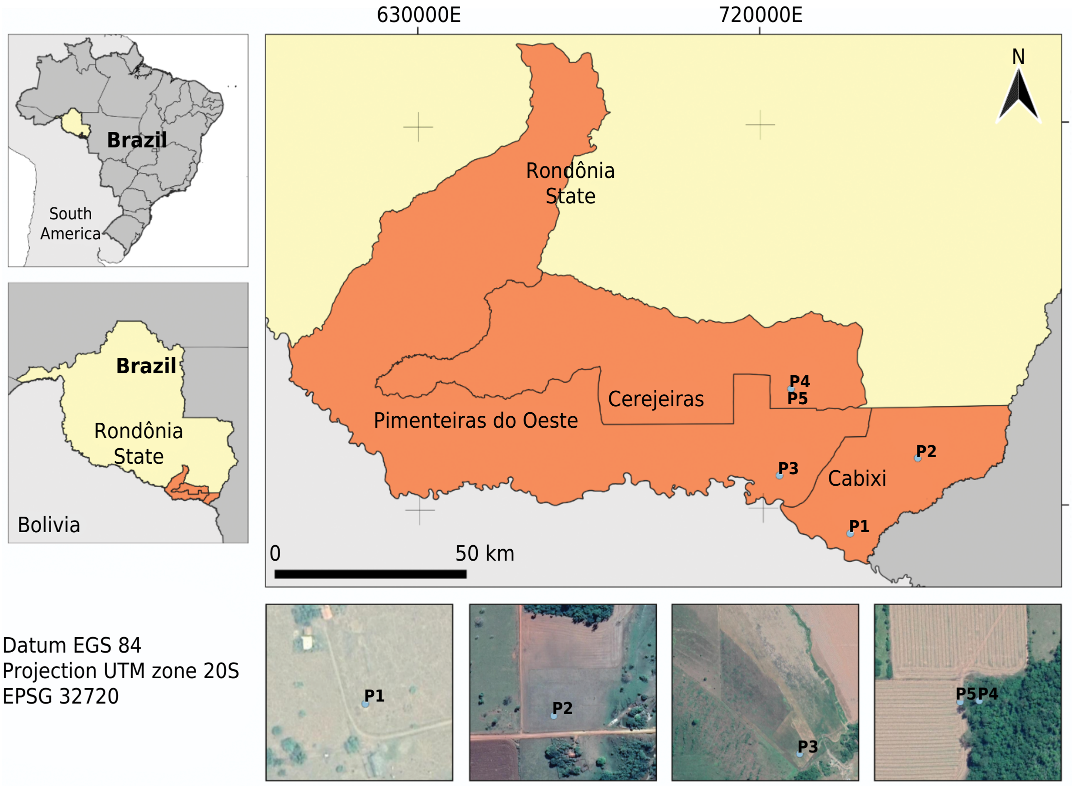

Figure 1. Location of ADE profiles evaluated in this study in Southern region of Rondônia State (Adapted from IBGE, 2014) and satellite view of profile locations from Google Earth Pro satellite images (Maxar Technologies, 2020).

Soil description and sampling

Four sites of ADEs were selected in the southern portion of the state of Rondônia, two in the municipality of Cabixi, one in Pimenteiras do Oeste, and one in Cerejeiras (Table 1). On the sites 1, 2, and 3, there was opened one soil trench per site (Figure 2), while in the fourth site two soil trenches (P4 and P5) were opened at the same patch of ADE but under different land coverages. The first one under forest (P4) and the second under no-till system (P5) of soybean and corn in succession for the last eight years (Figure 3). Previously this area was used with grass pasture for about 12 years.

The distribution of artifacts, mostly ceramic fragments and mottles of disperse charcoal in the profile walls, were marked by colored golf pins to provide an estimation of their quantities and distribution since no artifacts could be taken back to the laboratory. The soil horizons were described and collected according to the standard procedures of the Brazilian Society of Soil Science (Santos et al., 2015). Soil profiles were classified with the Brazilian Soil Classification System (SiBCS) (Santos et al., 2018) and with the international system, World Reference Base (WRB) (IUSS Working Group, 2015).

Samples for radiocarbon (^{14}C) dating were collected using clean tools, free of organic or mineral residues, avoiding contact with any source of external contaminations. Disposable vinyl gloves were used to prevent contamination of samples by carbon from human

Table 1. Location and land coverage of ADE profiles in the Southern region of Rondônia State

Site	Profile	Municipality	Elevation	Coordinates	Land coverage
			m	UTM	
1	P1	Cabixi	191	0742717/ 8493110	Pasture (*Urochla decumbens*)
2	P2	Cabixi	232	0760624/ 8512634	Pasture (*Urochla brizantha*)
3	P3	Pimenteiras do Oeste	185	0724293/ 8508400	Pasture (*Urochla decumbens*)
4	P4	Cerejeiras	226	0727572/ 8530859	Amazon forest
4	P5	Cerejeiras	226	0727527/ 8530895	No-till system (soybean/corn)

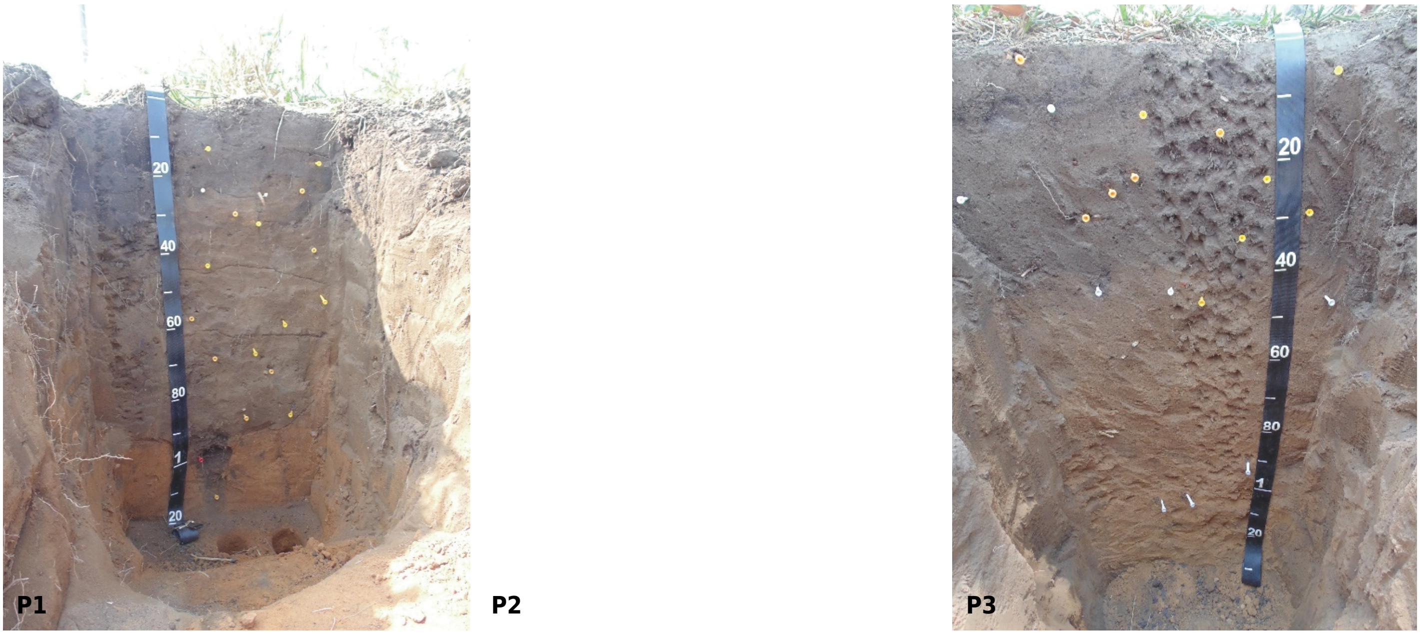

Figure 2. Soil profiles with anthropic horizons in the municipalities of Cabixi (P1 on the left, P2 center) and Pimenteiras do Oeste (P3 on the right), Rondônia State. P1: pins mark the distribution of artifacts and points of concentrated charcoal. P2 and P3: yellow and red pins mark the distribution of artifacts, and white pins mark points of concentrated charcoal.

Figure 3. Soil profiles with anthropic horizon in the municipality of Cerejeiras, Rondônia. Profile P4 on the left is under forest coverage, and P5 on the right is adjacent but under no-till crop system with soybean and corn. Yellow and red pins mark the distribution of artifacts, and white pins mark points of concentrated charcoal.

skin, which is a source of recent ^{14}C. The samples were collected in soil trenches, placed in clean new plastic bags, and sent to the laboratory of Soil Geneses Morphology and Classification (LGCS) at the Federal Rural University of Rio de Janeiro where charcoal fragments were picked using tweezers and magnifying glasses.

Profiles of ADE were graphically represented with R software (R Development Core Team, 2013) and plots generated through the package Algorithms for Quantitative Pedology (AQP) developed by Beaudette et al. (2013).

Analytical methods

Soil samples were air dried, ground, and sieved through a 2 mm stainless sieve. The fine fraction was used for chemical evaluations following the methodologies presented in the Manual for Chemical Analysis of Soils (Teixeira et al., 2017a). Soil texture was determined by the pipette method after dispersion with NaOH 1 mol L^{-1} and sand sieving (Donagemma et al., 2017). Soil bulk density (SBD) was calculated from the weight of the oven-dry mass and volume of the soil core using a volumetric cutting ring of 44 cm^3 for collecting one undeformed sample from each horizon (Almeida et al., 2017); the density of particles (Dp) was determined using volumetric balloon (Viana et al., 2017). Contents of soil organic carbon (C) were determined by wet oxidation with $K_2Cr_2O_7$ 0.0667 mol L^{-1} using a modified Walkley and Black method (Fontana and Campos, 2017). Soil pH was determined in water using a ratio 1:2.5 (soil:water) (Teixeira et al., 2017b). Contents of Ca^{2+}, Mg^{2+}, and exchangeable aluminium (Al^{3+}) were evaluated after extraction with KCl 1 mol L^{-1}. Exchangeable Ca and Mg^{2+} were quantified by complexometry and Al^{3+} was quantified by titration with diluted NaOH solution (Teixeira et al., 2017c). Available K^+ and Na^+ were extracted with double acid solution (HCl 0.05 mol L^{-1} + H_2SO_4 0.0125 mol L^{-1}) and determined by flame photometry (Teixeira et al., 2017c). Extractable acidity (Al+H) was extracted by using $Ca(OAc)_2$ 1 mol L^{-1} adjusted to pH 7.0 and determined by titration (Campos et al., 2017a). The results of chemical characterization were used for calculating the sum of bases (SB), cation exchange capacity (CEC), and base saturation (V) (Teixeira et al., 2017d). Phosphorus contents were determined by using Mehlich-1 (Teixeira et al., 2017e) and Olsen (Olsen et al., 1954).

For the determinations of oxides, 1 g of fine earth was treated with 20 mL of diluted sulfuric acid (H_2SO_4) in the proportion 1:1 (H_2O:H_2SO_4) and boiled using a condenser for 30 min (Teixeira et al., 2017c). The contents of Fe, Al, and Ti oxides in the acid extract were determined by atomic absorption spectrometry (AAS) (Teixeira et al., 2017d, e, f). Contents of Si were determined in UV-spectrophotometer after solubilization with NaOH and 12 h complexation with ammonium molybdate and ascorbic acid (Teixeira et al., 2017g). Results were used to calculate the molecular ratios Al_2O_3/Fe_2O_3, $(SiO_2/Al_2O_3)\times1.7$ (ki), and $(SiO_2 \times1.7)/Al_2O_3 + (0.64\times Fe_2 O_3)$ (kr) (Teixeira and Campos, 2017a, b).

The free iron (Fed) was extracted by dithionite-citrate-bicarbonate (DCB). Samples were heated in a tamponade complexing solution of citrate/bicarbonate to which sodium-dithionite powder was add as redox agent (Teixeira et al., 2017k). The amorphous iron (Feo) was extracted by ammonium oxalate solution after agitation for 4 h in the dark (Teixeira et al., 2017k). The contents of Fed and Feo in the extracts were determined by AAS and the ratios Feo/Fed and Feo/Fe_2O_3 were calculated.

For the determination of ^{14}C radiocarbon dates, charcoal fragments of 3 ADE sites were picked by using tweezers and magnifying glasses from the following locations, profiles and horizons: Cabixi (P2 Au3), Pimenteiras do Oeste (P3 AB), and Cerejeiras (P4 Au4). The collected charcoal fragments were subsequently sent to be threated and analyzed at the Laboratory of radiocarbon (LAC) of the University Federal Fluminense (UFF), where they were analyzed by mass accelerator spectroscopy (AMS). The calibrated results and graphs were obtained from the conventional radiocarbon dates using software OxCall and calibration curve SHCall113 (Scheel-Ybert, 1999; Hogg et al., 2013; Macario and Alves, 2018).

RESULTS

Morphological and physical attributes

All anthropic horizons of ADE in Rondônia display dark colors, the range goes from black, 5 YR 2.5/1 (P2 Aup), to dark brown, 10 YR 3/3(P3 AB). The thickness of anthropic horizons varied from 0.59 m in P3 (Aup to AB) to 1.00 m in P1 (Aup to Au4) (Table 2; Figure 4). The topography of boundaries between horizons are frequently wavy or irregular, and the width of boundary between anthropic and subsurface horizons are abrupt in P1 and P3, and clear in P2, P4, and P5, where the color change is the main aspect. Granular types of structure, in moderate and strong aggregation degrees predominate in all anthropic horizons. The consistence (moist) of anthropic horizons varied from friable to very friable mostly.

The textural classes (Table 3) for the ADE ranged from loamy sand to loam in P1, loam to clay in P2, loamy sand to sandy clay loam in P3, and sandy clay loam to sandy clay in P4 and P5. The Anthropic horizons have coarser textures than subsurface horizons (B). The contents of water dispersible clay were abundant in most of the horizons. The flocculation degree varied from 11 % in P5 AB to 83 % in P1 Au1. Soil bulk density (SBD) varied from 0.70 Mg m^{-3} (P4, Au1 under forest) to 1.36 g cm^{-3} (P5, AB under no-till agriculture). The density of particles (Dp) varied from 2.35 Mg m^{-3} (P2, Aup) to 2.74 g cm^{-3} (P4, Bw2). There was no clear pattern for the variation of densities in the surface and subsurface horizons, except for P2 and P4 where the lower values of SBD are found in the Au horizons.

Chemical properties

The values of soil pH(H_2O) (Table 4) in the Anthropic horizons range from 5.35 (P4, AB) to 7.97 (P2, BA). Profiles P1 and P2 show high values of pH in all the horizons (surface and subsurface) showing that the changes in soil pH by Anthrosolization (Bockheim and Gennadiyev, 2000) is not limited to the surface horizons. In P3, P4, and P5, the values of pH decrease in depth to 4.83 (P3 Bw3), 4.97 (P4 Bw2), and 5.15 (P5 Bw2) showing that in these profiles, the anthrosolization processes promoted in the soils were not enough

Table 2. Morphological attributes of ADE profiles in the Southern region of Rondônia State

Hor[(1)]	Layer	Munsell color Moist	Boundary topography[(2)]	Structure[(3)]	Consistence[(4)]		Plasticity/Stickiness[(5)]
					Dry	Moist	
	m						
			P1 – Cabixi				
Aup	0.00-0.13	7.5 YR 2.5/1	sm. gradual	mo., f., gr.	soft	v.fri.	n.pl./ n.st.
Au1	0.13-0.26	7.5 YR 2.5/1	wa. clear	mo., vf & f., gr.	soft	v.fri	n.pl./ n.st.
Au2	0.26-0.47	7.5 YR 2/2	wa. gradual	mo., vf. gr.	soft	v.fri	n.pl./ n.st.
Au3	0.47-0.65	7.5 YR 2.5/2	wa. diffuse	we., vf., gr.	loose	loose	n.pl./ n.st.
Au4	0.65-1.00	7.5 YR 3/1	irr. abrupt	we., vf., gr.	loose	v.fri	n.pl./ n.st.
Bi1	1.00-1.40	5 YR 4/6	sm. diffuse	mo., vf. & me., sab.	sl. hard	v.fri	n.pl./ n.st.
Bi2	1.40-1.60$^+$	5 YR 4/6	-	mo., f. & me., sab.	soft	v.fri	n.pl./ n.st.
			P2 - Cabixi				
Aup	0.00-0.14	5 YR 2.5/1	wa. clear	mo., f & me., gr.	soft	v.fri	n.pl./ n.st.
Au1	0.14-0.34	7.5 YR 3/2	wa. clear	mo., f & me., gr.	soft	v.fri	n.pl./ n.st.
Au2	0.34-0.47	7.5 YR 3/2	wa. clear	mo., vf., gr.	soft	v.fri	n.pl./ n.st.
Au3	0.47-0.63	5 YR 3/2	sm. clear	mo., vf & f., gr. & sab.	soft	v.fri	n.pl./ n.st.
AB	0.63-0.76	5 YR 4/3	sm. clear	mo., vf & f., gr./ mo., f., sab.	soft	v.fri	sl. pl./ sl. st.
BA	0.76-0.94	5 YR 5/6	sm. gradual	mo., f., sab.	sl. hard	fri.	pl./ st.
Bt1	0.94-1.34	2.5 YR 5/8	sm. gradual	mo., f., sab.	sl. hard	fri.	pl./ st.
Bt2	1.34-1.54$^+$	2.5 YR 5/8	-	-	-	-	pl./ st.
			P3 – Pimenteiras do Oeste				
Aup	0.00-0.09	10 YR 3/2	wa. clear	mo., f., gr.	soft	v.fri	n.pl./ n.st.
Au1	0.09-0.19	10 YR 3/1	wa. clear	mo., f & me., gr.	soft	v.fri	n.pl./ n.st.
Au2	0.19-0.47	10 YR 3/2	wa. abrupt	mo., vf & f., gr./ mo., vf., sab.	soft	v.fri	n.pl./ n.st.
AB	0.47-0.59	10 YR 3/3	wa. clear	mo., f., sab.	soft	v.fri	n.pl./ n.st.
BA	0.59-0.75	10 YR 5/4	sm. gradual	mo., f., sab.	sl. hard	v.fri	sl. pl./ sl. st.
Bw1	0.75-0.95	10 YR 6/6	sm. gradual	mo., f., sab.	sl. hard	v.fri	sl. pl./ sl. st.
Bw2	0.95-1.19	10 YR 6/8	sm., diffuse	mo., f., sab.	sl. hard	v.fri	sl. pl./ sl. st.
Bw3	1.19-1.36$^+$	10 YR 7/8	-	-	-	-	sl. pl./ sl. st.
			P4 – Cerejeiras (Forest)				
Au1	0.00-0.10	7.5 YR 2.5/1	sm. clear	str., me., gr.	sl. hard	v.fri	sl. pl./ sl. st.
Au2	0.10-0.26	10 YR 2/1	sm. clear	str., me., gr.	sl. hard	v.fri	sl. pl./ sl. st.
Au3	0.26-0.43	10 YR 2/1	wa. clear	str., me., gr.	sl. hard	v.fri	sl. pl./ sl. st.
Au4	0.43-0.55	10 YR 3/3	sm. clear	mo., f., gr.,	sl. hard	v.fri	sl. pl./ sl. st.
AB	0.55-0.71	7.5 YR 5/6	irr. clear	mo., vf & f., gr.	sl. hard	v.fri	sl. pl./ sl. st.
BA	0.71-0.85	7.5 YR 5/4	wa. gradual	mo., f., sab.	sl. hard	v.fri	sl. pl./ sl. st.
Bw1	0.85-1.21	7.5 YR 5/6	sm., diffuse	mo., f., sab.	sl. hard	fri	sl. pl./ sl. st.
Bw2	1.21-1.41$^+$	7.5 YR 5/6	-	-	sl. hard	fri	sl. pl./ sl. st.
			P5 – Cerejeiras (No-till system)				
Aup1	0.00-0.14	10 YR 2/1	sm. clear	str., vf., gr., mo., f., sab.	sl. hard	fri	sl. pl./ sl. st.
Aup2	0.14-0.27	10 YR 2/1	wa. clear	mo., vf., gr., mo., f., sab.	sl. hard	fri	sl. pl./ sl. st.

Continue

Continuation

Au	0.27-0.53	10 YR 3/2	wa. clear	mo., vf. & f., gr., mo., f., sab.	sl. hard	fri	sl. pl./ sl. st.
AB	0.53-0.60	7.5 YR 4/6	sm. gradual	mo., f., sab.	sl. hard	fri	sl. pl./ sl. st.
BA	0.60-0.76	7.5 YR 5/4	sm. gradual	mo., f., sab.	sl. hard	fri	sl. pl./ sl. st.
Bw1	0.76-1.19	7.5 YR 5/6	sm. diffuse	mo., f., sab.	sl. hard	fri	sl. pl./ sl. st.
Bw2	1.19-1.39$^+$	7.5 YR 5/8	-	mo., f., sab.	sl. hard	fri	sl. pl./ sl. st.

(1) Hor: horizon. (2) sm: smooth; wa: wavy; irr: irregular. (3) we: weak; mo: moderate; str: strong; vf: very fine; f: fine; me: medium; c: coarse; sab: sub-angular blocks; gr: granular. (4) sl. hard: slightly hard; v.fri: very friable; fri: friable. (5) n.pl: nonplastic; sl.pl: slightly plastic; pl: plastic; n.st: nonsticky; sl.st: slightly sticky; st.: sticky. Note: the w code in the B horizons is correspondent to the Ferralic horizon in the WRB field description manual.

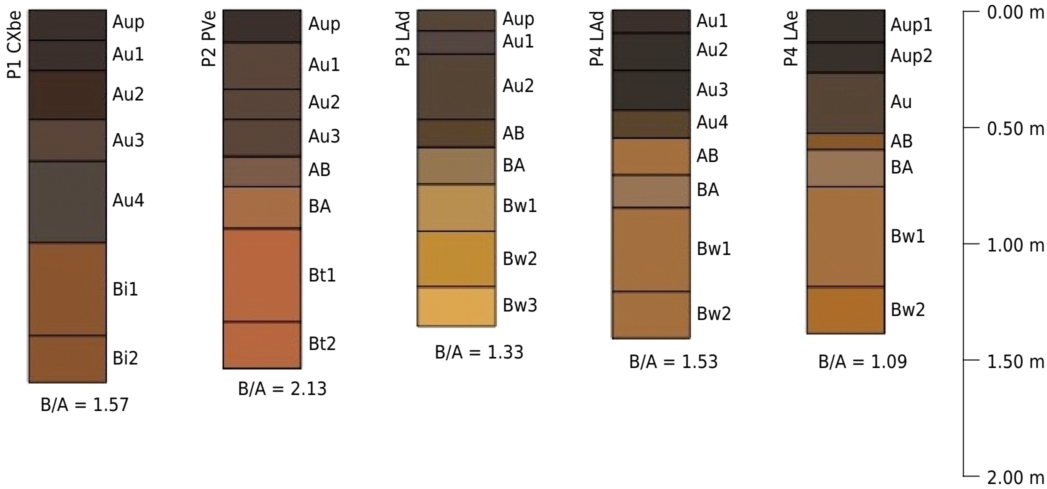

Figure 4. Graphical representation of horizons and depths of ADE profiles in Rondônia State. The codes of horizons and soil classes are according to SiBCS (Santos et al., 2018), in which Bw represents the Ferralic subsurface horizon.

to cause a large increase of pH(H_2O) in deeper horizons. In P5, the pH(H_2O) values in BA and Bw1 (6.97 and 7.06, respectively) are higher than in the upper horizons (Au).

High (P1) to very high (P2, P3, P4, and P5) contents of Ca^{2+} and Mg^{2+} were observed in all anthropic horizons, with values decreasing towards subsurface horizons. In the interpretation criteria values of Ca^{2+} + Mg^{2+} from 6.1 to 10 $cmol_c\ kg^{-1}$ are considered high and >10 $cmol_c\ kg^{-1}$ very high (Freire et al., 2013). The highest values of Ca^{2+} were observed in P2 (22.2 $cmol_c\ kg^{-1}$ in Au1) and the highest values of Mg^{2+} in P4 (4.4 $cmol_c\ kg^{-1}$ in Au1). Levels of K^+ and Na^+ were low in all profiles with values inferior to 0.14 $cmol_c\ kg^{-1}$ (P2, Aup) for K^+ and 0.01 $cmol_c\ kg^{-1}$ for Na^+. The anthropic horizons (Au) did not present detectable levels of Al^{3+} since the exchangeable aluminum in soil solution correlates negatively with higher pH values (Balee, 2010). The values of sum of basis (S) and cation exchange capacity (CEC) followed the distribution of the Ca^{2+} and Mg^{2+} ions, the predominant cations in the soils. The maximum values were 24.8 $cmol_c\ kg^{-1}$ (P2, Au1) for S, and 27.3 $cmol_c\ kg^{-1}$ for T (P2, Aup). The percentages of base saturation (V) are superior to 50 % in all Au horizons, but in P3 and P4, values of V are lower than 50 % in subsurface horizons which shows a dystrophic qualifier in the SiBCS.

The Mehlich-1 method, commonly used for phosphorus determination in tropical soils, provided higher results of P content than the Olsen method. The highest P values were observed in P1 Au3, 490.0 mg kg^{-1} by Mehlich-1 and 76.8 mg kg^{-1} by the Olsen method (Table 4). Phosphorous contents on anthropic horizons of P4 and P5, located in Cerejeiras, were inferior to those in other ADE sites (P1, P2, and P3). The higher P contents by

Table 3. Physical attributes of ADE profiles in the Southern region of Rondônia State

Hor[(1)]	Sand	Silt	Clay	WDC[(2)]	Soil texture	Silt/Clay	FD[(3)]	SBD[(4)]	Dp[(5)]
	g kg^{-1}						%	Mg m^{-3}	
					P1 – Cabixi				
Aup	754	145	101	30	Sandy Loam	1.44	70	1.22	2.50
Au1	735	95	170	29	Sandy Loam	0.56	83	1.20	2.50
Au2	730	164	106	23	Sandy Loam	1.55	78	1.30	2.60
Au3	825	91	84	25	Loamy Sand	1.08	70	1.28	2.60
Au4	810	90	100	39	Loamy Sand	0.90	61	1.11	2.60
Bi1	503	332	165	49	Loam	2.01	70	1.16	2.53
Bi2	679	133	188	49	Loamy Sand	0.71	74	-	2.63
					P2 - Cabixi				
Aup	420	404	176	68	Loam	2.30	61	0.97	2.35
Au1	466	374	160	110	Loam	2.30	31	0.85	2.50
Au2	515	323	162	75	Loam	2.00	54	0.97	2.47
Au3	618	251	131	76	Sandy Loam	1.90	42	1.08	2.47
AB	507	188	305	230	Sandy Clay Loam	0.60	25	1.23	2.63
BA	449	212	339	246	Clay Loam	0.60	27	1.25	2.56
Bt1	455	108	437	295	Clay	0.20	32	-	2.70
Bt2	431	153	416	270	Clay	0.40	35	-	2.56
					P3 – Pimenteiras do Oeste				
Aup	678	175	147	50	Loamy Sand	1.19	66	1.33	2.50
Au1	640	187	173	60	Loamy Sand	1.08	65	1.05	2.50
Au2	687	120	193	53	Loamy Sand	0.62	73	1.15	2.63
AB	695	106	199	107	Loamy Sand	0.53	46	1.25	2.70
BA	715	128	157	103	Loamy Sand	0.82	34	1.18	2.70
Bw1	664	136	200	138	Loamy Sand	0.68	31	1.21	2.53
Bw2	706	48	246	102	Sandy Clay Loam	0.20	59	1.20	2.70
Bw3	690	76	234	63	Sandy Clay Loam	0.32	73	-	2.70
					P4 - Cerejeiras				
Au1	538	225	237	50	Sandy Clay Loam	0.95	79	0.70	2.53
Au2	542	207	251	121	Sandy Clay Loam	0.82	52	1.04	2.53
Au3	593	233	174	21	Sandy Clay Loam	1.34	88	1.09	2.53
Au4	593	140	267	197	Sandy Clay Loam	0.52	26	1.14	2.38
AB	599	147	254	180	Sandy Clay Loam	0.58	29	1.18	2.63
BA	514	114	372	200	Sandy Clay	0.31	46	1.10	2.67
Bw1	527	99	374	177	Sandy Clay	0.26	71	1.14	2.67
Bw2	571	109	320	47	Sandy Clay Loam	0.34	85	1.24	2.74
					P5 - Cerejeiras				
Aup1	570	146	284	112	Sandy Clay Loam	0.51	61	1.27	2.50
Aup2	620	165	215	61	Sandy Clay Loam	0.77	72	1.13	2.53
Au	626	115	259	214	Sandy Clay Loam	0.44	17	1.34	2.67
AB	568	143	289	257	Sandy Clay Loam	0.49	11	1.36	2.60
BA	554	45	401	285	Sandy Clay	0.11	29	1.22	2.70
Bw1	546	95	359	108	Sandy Clay Loam	0.26	70	1.21	2.60
Bw2	544	129	327	92	Sandy Clay Loam	0.39	72	1.19	2.67

[(1)] Hor: horizon. [(2)] WDC: water dispersible clay. [(3)] FD: flocculation degree. [(4)] SBD: soil bulk density; [(5)] Dp: density of particle.

Mehlich-1 method was 10 mg kg^{-1} in P4 (Au3) and 79 mg kg^{-1} in P5 (Aup1). The levels of P extracted by Melich-1 are considered low 0–10 mg kg^{-1}; average from 11–20 mg kg^{-1}; high from 21 to 30 mg kg^{-1}; and very high >30 mg kg^{-1} (Freire et al., 2013).

The contents of organic carbon (C) (Table 4) in the anthropic horizons varied from 6.3 g kg^{-1}, in P1 Au4 (which is located in the layer from 0.65 to 1.00 m), to 42.4 g kg^{-1} in P2 Aup (0.00-0.14 m). These values are high when compared to well drained soils (non-anthropic soils) under similar climate conditions in the Amazon region.

The components extracted by the sulfuric acid attack method are expressed in the form of oxides (Table 5). Aluminium oxides (Al_2O_3) predominate in the fine earth fraction. Values of Al_2O_3 range between 43 g kg^{-1} (P1, Au5) and 184 g kg^{-1} (P5, Bw1). Silicon oxides (SiO_2) were the second most abundant, followed by iron oxides (Fe_2O_3) and titanium oxides (TiO_2). Overall, the contents of iron oxides (Fe_2O_3) by the sulphuric acid extraction were low, with values ranging from 9 g kg^{-1} (P1) to 50 g kg^{-1} (P2). Values of Fe_2O_3 are used in the SiBCS as a criterion to categorize soil classes. Thus, the contents of Fe_2O_2 inferior to 80 g kg^{-1} found in all the profiles correspond to the hypoferric class (Santos et al., 2018). Although the clay mineralogy was not evaluated, values of ki and kr indicate a non-oxidic kaolinite mineralogy (ki >0.75 and kr >0.75) for the profiles. Only in P3 (Au2) the values of ki and kr (ki >0.75 and kr ≤0.75) correspond to oxidic kaolinite mineralogy (Resende and Santana, 1988).

^{14}C radiocarbon dates

Radiocarbon dates for ADE sites in the municipalities of Cabixi (P2 Au3), Pimenteiras do Oeste (P3 AB), and Cerejeiras (P4 Au4) varied from 1074 ± 28 and 1323 ± 28 years before present (BP) (Table 6). The distribution of probabilities for calibrated dates (Figure 5) show slightly inferior results. In the figure 5a, the radiocarbon date for charcoal fragments in P2 (Au3), located in Cabixi municipality, is 1074 ± 28 years BP; however calibrated results are between 980- and 900-years BP with 90.8 % probability. For charcoal fragments collected from P4 (AB), in the municipality of Pimenteiras do Oeste, the radiocarbon date is 1247 ± 31 years BP, and the calibrated date is between 1190- and 1050-years BP with 89.5 % probability. For the last site located in the municipality of Cerejeiras (P4 Au4) the conventional date is 1323 ± 28 years BP and the calibrated date ranges between 1290- and 1170-years BP with 87.2 % probability. Figure 5d shows a comparison of calibrated dates among sites.

Soil classification

Based on the morphological, physical, and chemical attributes, the profiles were classified using the SiBCS (Santos et al., 2018) (Table 7). Due to the values of CEC higher than 17 $cmol_c$ kg^{-1}, the clay fraction in the B horizons, and absence of a textural gradient, P1 was classified, by exclusion from all other orders, as *Cambissolo.* Profile P2 was identified as *Argissolo* due to the presence of a textural B/A gradient, which characterizes the *B textural* horizon; and P3, P4, and P5 were classified as *Latossolos*. Profile P1 was identified in the sub-order *Háplicos*. Based on the colors of subsurface horizons, P3, P4, and P5 were identified in the sub-order *Amarelos* (Yellow), and P2 as *Vermelho* (Red). Regarding to base saturation of diagnostic subsurface horizons, the profiles P1, P2, and P5 are identified at the great group level as *eutróficos* (eutrophic), while P3 and P4 are *distróficos* (dystrophic). In addition, at the fifth level, P3 and P4 are *epieutróficos* (V higher than 50 % in the surface horizon).

According to WRB (IUSS Working Group, 2015) (Table 7), the profiles P1, P2, and P3 met the requirements for the Pretic horizon and are identified as Anthrosols. On the other hand, P4 and P5 in Cerejeiras, despite of presenting clear evidences of human's occupation by Pre-Colombian populations, in the form of artifacts, charcoal, and high C content, it did not meet the minimum requirement of P (30 mg kg^{-1}, Mehlich-1 method)

Table 4. Chemical attributes of ADE profiles in the Southern region of Rondônia State

Hor[1]	pH(H_2O)	Ca^{2+}	Mg^{2+}	Na^+	K^+	Al^{3+}	H^+	S[2]	CEC[3]	V[4]	P Meh[5]	P Ols[6]	C[7]
		cmol$_c$ kg^{-1}								%	mg kg^{-1}		g kg^{-1}
						P1 – Cabixi							
Aup	6.00	7.0	1.9	0.00	0.06	0.0	2.7	9.0	11.7	77	226	69	21.2
Au1	6.31	8.1	1.7	0.00	0.03	0.0	2.1	9.8	12.0	82	239	59	17.8
Au2	6.70	4.9	1.2	0.01	0.01	0.0	0.9	6.1	7.1	87	434	62	5.5
Au3	6.86	5.6	1.1	0.01	0.01	0.0	0.9	6.7	7.7	88	490	77	6.9
Au4	6.92	5.2	1.1	0.01	0.01	0.0	0.8	6.3	7.2	88	424	71	6.3
Bi1	6.74	3.4	0.7	0.00	0.01	0.0	0.7	4.1	4.9	85	77	37	1.1
Bi2	6.77	3.1	0.9	0.00	0.00	0.0	0.5	4.0	4.5	88	75	47	1.4
						P2 - Cabixi							
Aup	6.56	19.9	3.8	0.01	0.14	0.0	3.4	23.8	27.3	87	207	65	42.4
Au1	7.80	22.2	2.6	0.01	0.01	0.0	0.2	24.8	25.1	99	61	54	35.7
Au2	7.89	21.6	2.1	0.01	0.00	0.0	0.1	23.7	23.9	99	68	66	29.2
Au3	7.92	15.0	2.0	0.01	0.00	0.0	0.1	17.0	17.2	99	93	49	15.7
AB	7.94	10.0	1.9	0.00	0.01	0.0	0.1	11.9	12.1	99	134	65	8.4
BA	7.97	8.1	1.8	0.00	0.00	0.0	0.1	9.9	10.0	99	100	36	6.5
Bt1	7.95	7.3	1.2	0.00	0.00	0.0	0.0	8.5	8.5	99	82	36	3.8
Bt2	7.96	5.1	1.4	0.00	0.00	0.0	0.1	6.5	6.6	98	20	6	2.6
						P3 – Pimenteiras do Oeste							
Aup	5.91	7.4	3.2	0.00	0.06	0.0	3.9	10.6	14.6	73	102	38	23.4
Au1	6.16	11.2	2.1	0.00	0.01	0.0	3.3	13.3	16.7	80	37	13	28.4
Au2	6.04	4.7	1.7	0.00	0.00	0.0	3.5	6.4	9.9	64	55	17	13.0
AB	5.44	1.6	1.1	0.00	0.00	0.0	2.8	2.7	5.5	50	19	12	5.1
BA	5.04	0.8	0.8	0.00	0.00	0.0	2.6	1.6	4.2	38	15	7	4.0
Bw1	4.88	0.5	0.7	0.00	0.00	0.1	2.1	1.2	3.4	35	9	5	2.8
Bw2	4.84	0.5	0.5	0.00	0.00	0.0	2.0	1.0	3.0	33	2	3	2.3
Bw3	4.83	0.3	0.6	0.00	0.00	0.0	1.0	0.9	1.9	46	5	2	1.4
						P4 - Cerejeiras							
Au1	6.40	13.6	4.4	0.00	0.02	0.0	1.9	18.0	20.0	90	8	5	34.2
Au2	6.21	8.4	3.3	0.00	0.00	0.0	2.2	11.7	13.9	84	6	4	21.7
Au3	5.91	5.0	2.3	0.00	0.00	0.0	3.2	7.3	10.5	69	10	4	15.3
Au4	5.66	2.3	2.2	0.00	0.00	0.0	2.7	4.5	7.2	62	6	5	8.9
AB	5.35	1.5	1.3	0.00	0.00	0.0	2.5	2.8	5.3	52	4	3	6.0
BA	5.18	0.6	1.4	0.00	0.00	0.0	1.8	2.0	3.8	52	2	5	2.6
Bw1	4.98	0.6	0.8	0.00	0.00	0.1	1.5	1.4	3.0	46	2	4	3.4
Bw2	4.97	0.3	0.7	0.00	0.00	0.0	1.5	1.0	2.5	39	2	3	2.6
						P5 - Cerejeiras							
Aup1	5.99	9.2	2.8	0.00	0.04	0.0	3.8	12.0	15.9	76	79	36	27.6
Aup2	6.27	10.4	2.3	0.00	0.01	0.0	2.7	12.7	15.5	82	23	16	20.0
Au	6.02	4.0	1.3	0.00	0.00	0.0	2.1	5.3	7.4	71	26	14	7.6
AB	6.78	3.2	1.2	0.00	0.00	0.0	0.7	4.4	5.1	86	12	9	4.4
BA	6.97	2.6	1.0	0.00	0.00	0.0	0.4	3.6	4.0	89	3	3	3.3
Bw1	7.06	2.1	1.0	0.00	0.00	0.0	0.4	3.1	3.5	88	2	2	2.5
Bw2	5.14	1.0	0.7	0.00	0.00	0.0	0.6	1.7	2.3	73	2	3	2.2

[1] Hor: horizon; [2] S: sum of exchangeable bases; [3] CEC: cation exchange capacity; [4] V = (S/T) x 100; [5] Meh = P Mehlich-1; [6] Ols: P Olsen; [7] C: organic carbon.

Table 5. Pedogenetic oxides, Ki and Kr indexes, Al_2O_3/Fe_2O_3 ratio, iron extractable by dithionite-citrate-sodium bicarbonate (Fed), and by ammonium oxalate (Feo) and their ratios, from profiles of ADE profiles in the Southern region of Rondônia State

Hor[(1)]	Clay	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Ki[(2)]	Kr[(3)]	Al_2O_3/Fe_2O_3	Fed	Feo	Feo/Fed	Fed/Fet[(4)]
	g kg^{-1}								g kg^{-1}			
						P1 – Cabixi						
Aup	101	46	47	9	1.9	1.66	1.48	8.20	6.31	1.21	0.19	0.70
Au1	170	46	43	10	2.1	1.82	1.58	6.75	6.30	1.34	0.21	0.63
Au2	106	46	44	10	2.0	1.78	1.55	6.91	6.53	1.09	0.17	0.65
Au3	84	44	45	10	2.0	1.66	1.46	7.06	6.39	1.25	0.20	0.64
Au4	100	43	46	9	2.2	1.59	1.41	8.02	6.32	1.16	0.18	0.70
Bi1	165	72	76	16	3.1	1.61	1.42	7.46	9.24	0.86	0.09	0.58
Bi2	188	87	95	18	4.0	1.56	1.39	8.29	11.96	0.82	0.07	0.66
						P2 – Cabixi						
Aup	176	87	115	33	7.9	1.29	1.09	5.47	30.23	2.16	0.07	0.92
Au1	160	81	103	36	6.0	1.34	1.09	4.49	22.60	2.05	0.09	0.63
Au2	162	84	111	33	5.8	1.29	1.08	5.28	25.43	2.04	0.08	0.77
Au3	131	99	123	41	6.6	1.37	1.13	4.71	27.80	1.80	0.06	0.68
AB	305	114	150	40	7.6	1.29	1.10	5.89	30.34	1.75	0.06	0.76
BA	339	122	160	45	8.5	1.30	1.10	5.58	36.69	1.66	0.05	0.82
Bt1	437	130	179	49	8.6	1.23	1.05	5.74	35.22	1.67	0.05	0.72
Bt2	416	135	182	50	9.7	1.26	1.07	5.71	37.93	1.22	0.03	0.76
						P3 – Pimenteiras do Oeste						
Aup	147	59	86	13	3.9	1.17	1.06	10.39	9.24	1.05	0.11	0.71
Au1	173	56	77	11	3.9	1.24	1.13	10.99	6.49	1.18	0.18	0.59
Au2	193	61	131	22	6.1	0.79	0.71	9.35	7.67	0.82	0.11	0.35
AB	199	64	100	22	5.1	1.09	0.95	7.14	8.29	0.49	0.06	0.38
BA	157	63	106	15	5.1	1.01	0.93	11.09	8.36	0.45	0.05	0.56
Bw1	200	66	112	17	5.7	1.00	0.91	10.34	9.38	0.55	0.06	0.55
Bw2	246	65	115	18	5.5	1.00	0.91	10.03	10.19	0.42	0.04	0.57
Bw3	234	59	114	17	5.7	0.96	0.87	10.53	9.46	0.29	0.03	0.56
						P4 – Cerejeiras (Forest)						
Au1	237	84	122	18	5.9	1.17	1.07	10.64	11.25	1.07	0.10	0.63
Au2	251	93	137	21	6.9	1.15	1.05	10.24	11.15	1.12	0.10	0.53
Au3	174	89	131	25	6.4	1.15	1.03	8.23	10.15	1.10	0.11	0.41
Au4	267	85	130	22	6.5	1.11	1.00	9.28	11.36	1.02	0.09	0.52
AB	254	98	149	22	7.8	1.12	1.02	10.63	10.65	0.96	0.09	0.48
BA	372	107	168	24	7.9	1.08	0.99	10.99	12.81	0.76	0.06	0.53
Bw1	374	109	171	27	8.7	1.08	0.98	9.94	14.07	0.70	0.05	0.52
Bw2	320	109	175	30	8.0	1.06	0.95	9.16	12.18	0.69	0.06	0.41
						P5 – Cerejeiras (No-till system)						
Aup1	284	83	131	22	5.8	1.08	0.97	9.35	14.67	1.42	0.10	0.67
Aup2	215	83	123	23	6.1	1.15	1.02	8.40	14.44	1.19	0.08	0.63
Au	259	98	153	26	8.4	1.09	0.98	9.24	15.99	1.01	0.06	0.61
AB	289	104	162	30	8.4	1.09	0.98	8.48	17.22	0.87	0.05	0.57
BA	401	106	176	30	8.5	1.02	0.92	9.21	15.18	0.83	0.05	0.51
Bw1	359	108	184	30	8.7	1.00	0.90	9.63	14.55	0.70	0.05	0.49
Bw2	327	94	173	30	8.8	0.92	0.83	9.05	15.71	0.53	0.03	0.52

(1) Hor: horizon. (2) Ki= $(SiO_2/Al_2O_3) \times 1.7$; (3) Kr = $(SiO_2 \times 1.7)/Al_2O_3 + (0.64 \times Fe_2O_3)$; (4) Fet = Fe_2O_3.

Table 6. Radiocarbon dates and calibrated dates of charcoal fragments from ADE profiles located in Cabixi (P2), Pimenteiras do Oeste (P3), and Cerejeiras (P4) municipalities, Rondônia State

Sample	Horizon	Layer	^{14}C dates	Calibrated dates[(1)]	Calibrated dates[(2)]
		m	——— BP ———		AD
Charcoal P2	Au3	0.47-0.63	1074 ± 28	940 ± 40	900 - 1140
Charcoal P3	AB	0.47-0.59	1247 ± 31	1170 ± 20	690 - 960
Charcoal P4	Au4	0.43-0.55	1323 ± 28	1230 ± 60	660 - 860

[(1)] BP: before present which is based in the year of 1950. [(2)] AD = Anno Domini.

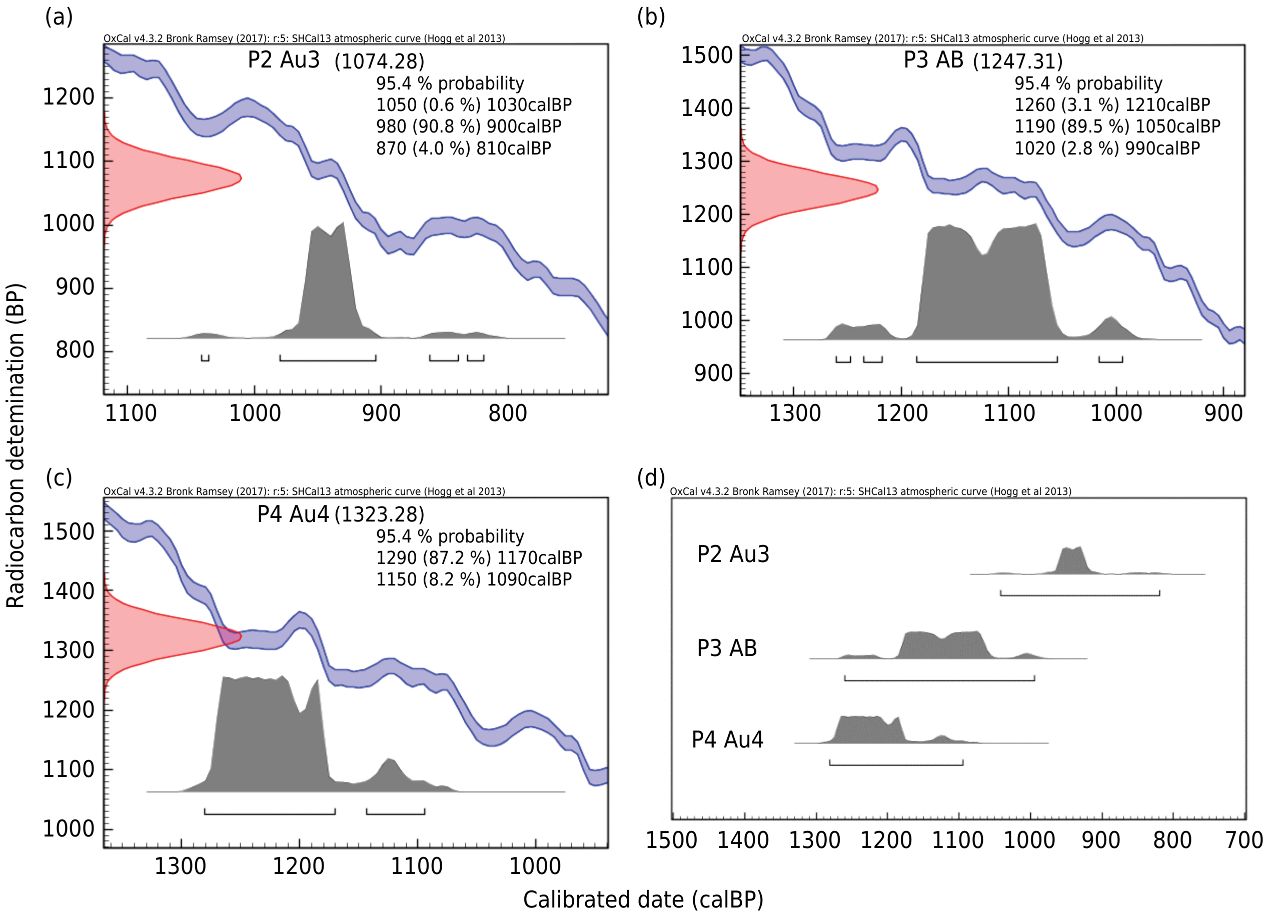

Figure 5. Calibrated radiocarbon dates and distribution of probabilities, using calibration curve SHCall113 and the software OxCall, of charcoal fragments from the deepest horizons of ADE profiles from Rondônia State municipalities (a - Cabixi; b - Pimenteiras do Oeste; c – Cerejeiras), with the comparison of ages and distribution of probabilities among sites (d).

Table 7. Soil classification of ADE profiles from Rondônia State according to the SiBCS and the WRB

Profile	SiBCS[(1)]	WRB[(2)]
P1	*CAMBISSOLO HÁPLICO Tb Eutrófico latossólico antrópico*	Pretic Anthrosol (Hypereutric, Loamic)
P2	*ARGISSOLO VERMELHO Eutrófico latossólico antrópico*	Pretic Anthrosol (Lixic Hypereutric, Ferralic, Loamic)
P3	*LATOSSOLO AMARELO Distrófico antrópico*	Pretic Anthrosol (Epiutric, Loamic)
P4	*LATOSSOLO AMARELO Distrófico argissólico*	Xanthic Ferralsol (Clayic, Eutric)
P5	*LATOSSOLO AMARELO Eutrófico antrópico*	Xanthic Ferralsol (Clayic, Eutric)

[(1)] Brazilian Soil Classification System, SiBCS (Santos et al., 2018). [(2)] WRB (WRB IUSS Working Group, 2015).

to characterize the Pretic horizon. Therefore, they were identified as Ferralsols, based on the characteristics of the subsurface horizons.

In the 4th edition of SiBCS (Santos et al., 2014), all the profiles of ADEs presented an Anthropic diagnostic horizon. However, by using the newer definition of "*A Antrópico*", modified in the 5th edition of SiBCS (Santos et al., 2018), all the profiles met the minimum depth criteria of 0.20 m, but P4 did not meet the minimum requirement of 30 mg kg^{-1} of P in at least one of the sub-horizons Au by the method of Mehlich-1. Therefore, the Anthropic horizon could not be identified in P4.

DISCUSSION

Soil color is an important indicator of anthropic activities, and it is extensively used in archeological studies (Woods, 2009). The dark colors are one of the most outstanding characteristics of the ADE in the field, contrasting with the surrounding predominantly yellow and red-colored soils of the Amazon basin. Therefore, color is an important indicator of Anthrosolization. In deforested areas, the dark colors of ADE can often be observed from satellite images (Figure 1). This tool can be used for finding ADE sites (Thayn et al., 2009) and it helps to build an idea of the size of a particular site, as well as the impact of human activities on these soils. The main source of the dark colors in ADE is charcoal, also referred as pyrogenic carbon or black carbon (Balee, 2010).

The smooth topography of boundaries between the first and second sub-horizons at most surficial horizons, in P1 and P5, is a consequence of plowing for agricultural use with pasture and crops, as well as due to bioturbation. In the P4, under forest, the smooth topography of the boundary between Au1 and Au2 is probably the result of bioturbation, especially by the macrofauna and plant roots which is intense in tropical areas. Bioturbation in archaeological sites under tropical climates is probably the major factor behind the vertical movement of pieces (Araujo, 2013). The type of structure and the friability are associated with high contents of OM and the presence of black carbon (charcoal, graphite, and soot) in the anthropic sub-horizons. Comparative studies of ADE and adjacent soils (non-Anthrosols) show that ADE present a much superior biological activity (Grossman et al., 2010; Navarrete et al., 2010). This explains the predominance of granular structures in the anthropic horizons.

The coarser textures observed in the anthropic horizons (Au) are related to the additions of external materials (charcoal, bones, pottery fragments, and others). The increasing clay content in depth is a result of dispersion and argilluviation, favored by anthropic activities on ADE sites (Macedo et al., 2017). This way, lower clay contents are found in the upper anthropic horizons (Au). In P2, the eluviation/illuviation processes led to forming a subsurface horizon with clay accumulation (Bt). The lighter textures in the anthropic horizons of ADE are also a consequence of fire management since phyllosilicates are broken down when heated, resulting in the fusion of clays and OM into sand-sized particles (Teixeira and Martins, 2003). These same authors observed that the course and especially the fine sand fractions of many ADEs are incrustations of charcoal and plant debris by inorganic materials. The low values of SBD in the Au horizons of P2 are associated with the lighter textures, high levels of soil OM, and carbonized materials which present low densities.

The friable and very friable moist consistencies in the anthropic horizons are associated with contents of charcoal and organic matter and also to the increased particle size (Teixeira and Martins, 2003). Therefore, improved friability is a characteristic of these ADE and an impact of Anthrosolization in these soils. The high contents of water-dispersible clay (WDC) in ADEs are explained by the high contents of dispersible ions as Ca^{2+} and Mg^{2+} on the sorption complex (Teixeira and Martins, 2003). The low flocculation degrees

(FD) found in most of the anthropic horizons are not coherent for the class of *Latossolos*/Ferralsols, which usually are associated with values close to 100 %.

In ADE's horizons, the high values of pH are related to the addition of carbonaceous materials from the pyrolysis process, especially ashes which have largely alkaline components such as calcium carbonate, calcium hydroxides, calcium sulfate, iron and magnesium salts and sodium and potassium carbonates and hydroxides (Woods, 2009). The increase in pH values in depth (P5 BA and Bw1) is because of ash translocation in the profile and accumulation in these subsurface horizons. Ash translocation is favored by the high rainfall associated with the sandier textures of the anthropic horizons, which confers greater water permeability. The different results of pH between P4 and P5, located at the same site, but under different coverages, are related to variations in the content of materials deposited on the soil by pre-Columbian populations (ashes, charcoal, and others). These variations are commonly observed between and inside ADE sites (Kern et al., 2009).

The high contents of Ca^{2+} and P in ADEs are attributed to the deposition of bones, ashes, human wastes, excrements, shells, among other materials (Kern et al., 2009; Monteiro et al., 2009). In addition, the high contents of Ca^{2+} in ADEs are preserved by the high adsorption capacity of this soils which is especially associated to functionalization of charcoal particles and also to the increased levels of stable OM compounds (Liang et al., 2006, 2013; Mao et al., 2012). The high affinity of Ca^{2+} for the exchange sites favors their accumulation in ADE. The low contents of K^+ and Na^+ are explained by their low valence (+1), low adsorption preference for the adsorption sites, which result in greater mobility of these ions in the soil. They are easily replaced by Ca^{2+} since it is available in high contents in ADE and have a higher preference for the adsorption sites. This way, K^+ and Na^+ stay in soil solution and are easily removed from the soil by leaching under the intense precipitation rates in the Amazon. The decreasing base saturation in depth for P3 and P4 corroborates with the assertion that the soil fertility in ADEs is not inherited from the mineral fraction (geological parent material), but from the anthropic activities specially the additions of the various materials (carbonized residues of plants and animals remains such as shells, tissues, and bones), oxidation of black carbon surfaces and increased organic matter contents.

The different P results, by Mehlich-1 and Olsen methods, are due to the acidic character of the Mehlich-1 extractor, which can promote the dissociation of P bounded to Ca ions in the form of calcium phosphates, allowing the quantification of non-labile P forms (Moreira et al., 2009). Thus, it is important to quantify phosphorus in ADEs by other methods. Studies by Kabala et al. (2018), in Anthropic horizons from Poland and in the same anthropic horizons of this study, indicate the Mehlich-3 method as the most suitable for quantifying P contents in human-altered soils.

The lower P contents in P4 and P5, compared to most of the ADE, is probably a consequence of the recurrent historic occurrence of floods in this area during certain years. Drainage ditches were recently opened for overcoming this problem, which affects farmers. The occurrence of floods during the rainy season still forces many Amazonian tribes move to a different location seeking dry land. These events probably reduced the occupation period of this site, resulting in lower organic matter additions. Also, P might have been uptake by plants, adsorbed by oxides, precipitated with Ca^{2+} or lost since it is mobile in solution. The P present in bones and organic tissues return to soils by phosphate solubilizing bacteria in the form of soluble compounds, which can be easily carried by water to the lower portions of the landscape (Teixeira, 2012). Therefore, we believe that previous floods in this area have also taken part in the low values of P observed and that other ADE subjected to floods may present low P contents. Low P contents (<9 mg kg^{-1}) were also reported by Moreira (2007) in the site of ADE named "*Terra Baixa*", which translates to low land, in the Manacapuru municipality, state of

Amazonas. The increase of P in P5 Aup1 is probably an effect of nowadays applications of P fertilizer since soybeans and corn can only be produced with the addition of large amounts of mineral fertilizes especially P in every sowing.

The high C contents in ADEs are explained by additions of pyrogenic carbon – PC (charcoal, graphite, soot), which have highly refractory polyaromatic structures of high stability and resistance to decomposition (González-Pérez et al., 2004; Solomon et al., 2007; Schellekens et al., 2017). Furthermore, some studies showed that PC causes enhanced retention of non-PC on soils (Liang et al., 2008, 2010, 2013). Charcoal particles in ADE have been proven to present electronically charged surfaces (Mao et al., 2012). Therefore, we believe that they can interact, protect, adsorb or sorb other organic compounds in soils.

The low contents of Fe_2O_2 extracted by the sulphuric acid attack method are related to the nature of the parent material, which is constituted by clastic materials poor in iron. In all profiles, higher values for Feo/Fed and Feo were observed in the surface horizons, which is due to the high levels of organic matter in the anthropic horizons, which favors dissolution and remobilization of iron oxides inhibiting oxide crystallization (Schwertmann, 1966). For this same reason, Fed contents show an increase in depth where the influence of soil OM is reduced. The Fed/Fes ratios, which indicate the amounts of iron associated with minerals that are not oxides (Pereira, 1996), presented values inferior to 0.92 (P2, Aup) and them decrease in depth. These results indicate greater alteration of minerals in the surface horizons, intensified by the high temperatures and humidity of the region.

The radiocarbon results show that the oldest occupation of sites initiated about 660–860 AD, 7 to 9 centuries before the arrival of Europeans to South America in the late 15 century AD. However, there are reports of much older anthropic sites in Rondônia. Studies carried out by Miller in pre-ceramist anthropic sites at the waterfalls of the "Madeira" river in the north portion of Rondônia state dates about 7000 years BP (Moraes and Neves, 2012). In this same region, sites of ceramist occupations studied during the PRONAPABA project (Miller, 1979/1973) date back at least 5200 years (Moraes and Neves, 2012). One of the three main proposed routes of entry of humans to South America is the rivers of the lower Amazon basin (Bueno and Dias, 2015). These rivers source at the Andean region and flow towards the Amazon basin, forming the Madeira river and later the Amazonas river. The Guaporé river, which surrounds the study area, is one of the main tributaries of the Madeira river. However, the Guaporé river sources in the state of Mato-Grosso, Brazil, and no other tributary rivers are coming from the southern portion until its intersection with the Mamoré river north of the state. So, having the Guaporé as the main river in the vicinity of the study area, we hypothesize the use of this river as the main route of access and that the occupation of this portion of the state may have happened up stream.

In the SiBCS (5th edition 2018), the sub-group "*Antrópico*" is not identified in the classes *Cambissolos Háplicos Tb Eutróficos Latossólicos, Argissolos Vermelhos Eutróficos latossólicos* and *Latossolos Amarelos Eutróficos*. This way, the profiles P1, P2, and P5 represent new classes in the Brazilian System of Soil Classification. To this end, it was taken into account the assumption that once the Anthropic subgroup is used in other classes, it can be applied to these profiles and later validated for definitive inclusion in the SiBCS. Therefore, it is suggested, for the consideration of the responsible committee for the SiBCS, the inclusion of anthropic subgroups in the orders and suborders identified in this study. The profiles P3 and P4 do not constitute new soils since there is already a class of *Latossolos Amarelos Distróficos antrópicos* in the SiBCS. However, their identification in Rondônia broadens the extension of ADEs in the Amazon region. It is also relevant to point that P1 was excluded from *Latossolos* and classified as *Cambissolos* due to the estimative of clay activity in the B horizons, which is influenced by the low amount of clay (165 and 188 g kg^{-1}) and the high amounts of cations (Ca+Mg) in the B horizons, which is certainly influenced by the anthropic upper horizon. Thus, this is significant for the proposal of creating a new order for these soils, since all the other characteristics of P1 do not fit in the general pedogenetic concept of the *Cambissolos*.

By using the WRB, the Pretic horizon was not identified in the profiles P4 and P5 because of its low values of extractable P. The first horizon of P5 (Aup1) meets the criteria of ≥30 mg kg^{-1} of extractable P (Mehlich-1); however, the requirement of ≥0.20 m thickness was not satisfied since the underlying sub-horizons have less than 30 mg kg^{-1} of extractable P, precluding it of being combined. Therefore, P4 and P5 were classified as Ferrosols based on the characteristics of the subsurface horizons. The errors obtained using this system are mainly associated with the stage of maturity of research with ADEs, which are not enough to support a meta-analysis yet. A meta-analysis in this stage would not be trustworthy since ADE is not yet well surveyed, and many ADEs with lighter colors as the "*Terras Mulatas*" have not yet received much attention by the soil science.

CONCLUSIONS

The ADE profiles were classified as *CAMBISSOLO HÁPLICO Tb Eutrófico latossólico antrópico* (P1), *LATOSSOLO AMARELO Distrófico antrópico* (P3), *LATOSSOLO AMARELO Distrófico argissólico* (P4) and *LATOSSOLO AMARELO Distrófico argissólico* (P5), and *ARGISSOLO VERMELHO Eutrófico latossólico antrópico* (P2), differing in the suborders by the colors of subsurface horizons, *Eutróficos* or *Distróficos* with *epieutrófico* qualifier at the fifth level. The profiles P1, P2, and P5 represent new classes for the SiBCS at the subgroup level. Regarding to the diagnostic surface horizon, by using the SiBCS' criteria in the 5th edition (Santos et al., 2018), P4 do not meet the requirements for the diagnostic horizon "*A antrópico*".

In the WRB, profiles P1, P2, and P3 were identified as Anthrosols; but P4 and P5 did not meet the requirements for the Pretic horizon, due to low P contents, being therefore classified as Ferrosols.

All soil profiles clearly show the influence of human activities from pre-Colombian populations, marked by dark colors, artifacts, charcoal particles, high OM content, and levels of nutrients that differ from other soils in the same environment. However, in the SiBCS, the main soil forming factor (humans) which marks the pedogenesis of ADE is not acknowledged at the highest level (order). Therefore, the characterization of these soils in Rondônia State further support the proposal of a new soil order in the SiBCS, such as in the WRB.

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