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First described over 120 years ago in Brazil, Amazonian Dark Earths (ADEs) are expanses of dark soil that are exceptionally fertile and contain large quantities of archaeological artefacts. The elevated fertility of the dark and often deep A horizon of ADEs is widely regarded as an outcome of pre-Columbian human influence. Controversially, in their recent paper Silva et al. argue that the higher fertility of ADEs is principally a result of fluvial deposition and pre-Columbian peoples just made use of these locales rather than contributing to their enhancement. Soil formation is inherently complex and often difficult to interpret, requiring a combination of geochemical data, stratigraphy, and dating. Although Silva et al. use this combination of methods to make their case, their study, based on the analysis of a single ADE site and its immediate surroundings, is too limited to distinguish among the possible mechanisms for ADE formation. Silva et al.'s conclusions contradict decades of research by archaeologists, soil scientists, geographers and anthropologists, who agree that ADEs are anthropic soils formed on land surfaces enriched by inputs resulting from pre-Columbian sedentary settlement. To be accepted, and be pertinent at a regional level, Silva et al.'s hypothesis would need to be supported by extremely solid evidence, which we demonstrate is lacking.

Geomorphological and Pedological considerations

There are several problems with reviving the argument that ADE fertility originates from deposited alluvium. First, with regards to the Caldeirão ADE site (Silva et al.'s case study): it is located on a Miocene plateau ~20 meters (~40 m asl) above the Solimões River floodplain, which in itself precludes significant flooding during the Holocene. Second, the parent material of the ADE and adjacent Ultisol shows analogous clay mineralogy and geogenic composition: both sites are characterized by the same 1:1 clays (as shown by Silva et al.'s Supp. Figure 3) and both lack the 2:1 clay minerals expected from fluvial origin. Moreover, no difference is observed in the geogenic elements (Al, Ti, Cr, V, Fe, As) (Figure 1A). Third, the overall mineral assemblage of the Caldeirão ADE is incompatible with the geochemistry of the sedimentary load of the Solimões River (Figure 1 A, B and D). Fourth, the lower content of clay in the anthropic ADE horizons at Caldeirão (erroneously described by Silva et al. as “sandy clay loam”) is not evidence of fluvial deposition but a partial outcome of argilluviation. Fifth, other well-studied ADE sites nearby contradict Silva et al.’s inference. At the Hatahara ADE site, located 4 km from Caldeirão on the same Miocene bluff, the dark ADE sediments are bulked up by sand and silt-sized particulate material resulting from anthropic activity (frammented charcoal and bone, pottery fragments, sponge spicules, etc.). The similarity in quartz sand grain morphology between the ADE A and B horizons excludes the inference of fluvial inputs into the A horizon. Moreover, a large number of ADE sites are found along black water rivers or inland, negating that alluvial deposition is relevant to the formation of many ADE expanses. Finally, if ADE were the result of alluvial processes, they would be continuous along rivers rather than patchy.

Elemental enrichment and isotopic ratios of ADE vs Ultisols (Acrisols)

The same group has elsewhere argued that the elemental composition of Caldeirão site “…can be used to unveil ADE sites and differentiate them from Amazonian soils without anthropic influence”. We agree with this assessment: enrichment of the ADE compared to the Ultisols profiles is consistent with inputs associated with human settlement. Among the latter are those related to burning, including K, Rb, Ba, Ca, Sr, P (from ash and charcoal); P, Ca, Sr, K, Zn, Cu (human waste); and Ca, P, Sr, Zn (bone debris) (Figure 1 B, C). Most of these, along with pyrogenic C, have been reported in ADEs. The most logical explanation for such an assemblage is anthropic inputs associated with settlement activity. How, then, can a fluvial input be surmised? The core of Silva et al.'s argument is that differences in Sr and Nd isotope ratios between ADE and Ultisols are best explained by fluvial inputs. However, both Sr and Nd
are found in plants\textsuperscript{11} and terrestrial and aquatic vertebrates \textsuperscript{12}. This makes it likely that these elements readily accumulate through deposition of food debris and ashed/charred plant waste. Silva et al. regard the difference in elemental stoichiometries of freshwater fish (Ca:P \textasciitilde 2.13) and human faeces (Ca:P \textasciitilde 2) with ADEs as further evidence of ADE being of fluvial origin. However, while the Ca:P ratio is highly variable in Caldeirão ADE (Figure 1C), the modern Ca:P ratio in ADEs is the result of differential preservation coupled with the specific tropical soil dynamics of Ca, which is easily leached, and P, which binds with soil Fe and Al oxides\textsuperscript{13}.

**High enrichment of P and Ca**

ADEs are widely recognized as evidence of population growth and landscape transformations in the late Holocene\textsuperscript{1}. However, elemental enrichment alone constitutes a poor demographic proxy. Soil enrichment with P and Ca and other anthropic indicators do not require large groups, let alone agricultural activity: virtually any long human occupation can result in soil enrichment \textsuperscript{14}. Silva et al.’s reference to improbably large agriculturalist populations as support for their argument of fluvial deposition, therefore, is artificial. ADE sites like Caldeirão are very rich in nutrients because they concentrate human debris and waste associated with resources gathered or produced in large areas. It is the concentration of resources in much smaller areas - settlements- that produce ADEs after hundreds or thousands of years. Put another way, a thousand people could extract resources produced from a 50 hectares’ catchment but concentrate debris and waste in a village of 0.1 hectares.

**Antiquity of microcharcoal and age of ADE formation**

Silva et al. report charcoal dated at >6.4 ky \textsuperscript{14}C BP from the B horizon of their ADE profile (https://doi.org/10.7264/9qdm-en61) and argue that >7.6 ky \textsuperscript{14}C BP charcoal collected from -90 cm in their Ultisol transect establishes the start of microcharcoal inputs to the Caldeirão ADE expanse. This interpretation is highly questionable on stratigraphic grounds alone. Middle Holocene charcoal fragments are commonly found stratified in Amazonian soil profiles\textsuperscript{15}, including the B horizons of ADE profiles\textsuperscript{16}. However, the relevant age to understand ADE formation (and whether it is consistent with human occupation) is that of the silt-sized charcoal making up the dark horizon of an ADE. At the nearby ADE site of Hatahara the age of this charcoal pool is consistent with a late first millennium AD Paredão phase settlement, albeit with older occupations starting around 500 BC\textsuperscript{17,18}. For Caldeirão, similar ages are reported by Schellekens et al.\textsuperscript{19}. Hence, mid-Holocene \textsuperscript{14}C dates from the B horizon of ADEs or Ultisols are largely irrelevant for understanding ADE formation.

To summarise, Silva et al.’s hypothesis is hardly new. Falesi \textsuperscript{3} famously argued that ADEs are soils of natural fertility that have black alluvial horizons, which would explain the high content of organic material. As we showed here, this hypothesis fails yet again.
Figure 1 Caldeirão’s soil compositional data compared with published data of Solimões River sediments and anthropogenic materials. Data is in supplementary table 1. A: Geogenic elements Al and Fe are similar in ADE and Ultisols, but different from Solimões sediments. B, C: Anthropogenic elements K, Ca and P fall in the range of anthropogenic materials. Solimões sediments have much lower Ca/K ratios and far higher K concentrations. D: Ca and Sr show strong correlations in ADE. The Ca/Sr ratio in Solimões sediments is higher than in ADE, suggesting an anthropogenic origin for Sr.

References


Table 1 Data used in Figure 1 based on Silva et al.\textsuperscript{2}, Viers et al.\textsuperscript{20}, Braadbaart et al.\textsuperscript{12}, Cílová and Woitsch\textsuperscript{22}, Vassilev et al.\textsuperscript{23}, Huisman et al.\textsuperscript{24}

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<th>Al (mg/kg)</th>
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References


