Evidence confirms an anthropic origin of Amazonian Dark Earths (Comment to Silva, L. C. R. et al. (2021). "A new hypothesis for the origin of Amazonian Dark Earths." Nature Communications 12(1): 127.)

Umberto Lombardo (umberto.lombardo@giub.unibe.ch)[1a], Manuel Arroyo-Kalin(m.arroyo-kalin@ucl.ac.uk)[2], Hans Huisman(hans.huisman@rug.nl)[3], Wenceslau Geraldes Teixeira(wenceslau.teixeira@embrapa.br)[4], Charles R Clement(cclement@inpa.gov.br)[5], Carlos Francisco Brazão Vieira Alho(carlos.brazaovieiraalho@wur.nl)[6], Fernando Almeida(fernando.ozorio.almeida@uerj.br)[7], Lucia Helena Cunha Anjos(lanjos@ufrrj.br)[7], Christopher Bronk Ramsey(christopher.ramsey@arch.ox.ac.uk)[8], George Brown(george.brown@embrapa.br)[9], Marcondes Costa(mlc@ufpa.br)[10], Luis Cunha(luis.cunha@uc.pt)[11], William M Denevan(williamdenevan@gmail.com)[12], Ademir Fontana(ademir.fontana@embrapa.br)[4], Bruno Glaser(bruno.glaser@landw.uni-halle.de)[13], Susanna Hecht(sbhecht@ucla.edu)[14], Klaus A Jarosch(klaus.jarosch@giub.unibe.ch)[1], André Braga Junqueira(Andre.junqueira@uab.cat)[15], Thiago Kater(kater@usp.br)[16], Thomas W Kuyper(thom.kuyper@wur.nl)[17], Johannes Lehmann(cl273@cornell.edu)[18], Helena Pinto Lima(helenalima@museu-goeldi.br)[19], Rodrigo Santana Macedo(rodrigo.macedo@insa.gov.br)[20], Marco Madella(marco.madella@upf.edu)[21], S. Yoshi Maezumi(s.y.maezumi@uva.nl)[22], Francis E Mayle(f.mayle@reading.ac.uk)[23], Doyle McKEY(doyle.mckey@cefe.cnrs.fr)[24], Claide de Paula Moraes(claide.moraes@ufopa.edu.br)[25], Gaspar Morcote-Ríos(hgmorcoter@unal.edu.co)[26], Eduardo Neves(edgneves@usp.br)[16], Francisco Pugliese(pugliesefrancisco@yahoo.com.br)[16], Fabiano Pupim(f.pupim@unifesp.br)[27], Marco F Raczka(m.f.raczka@reading.ac.uk)[23], Anne Rapp Py-Daniel(anne.daniel@ufopa.edu.br)[25], Philip Riris(priris@bournemouth.ac.uk)[28], Leonor Rodrigues(Leonormaria.gondimrodrigues@agroscope.admin.ch)[29], Stéphen Rostain(stephen.rostain@cnrs.fr)[30], Morgan Schmidt(morgansc@mit.edu)[31], Myrtle P Shock(myrtle.shock@ufopa.edu.br)[25], Tobias Sprafke(tobias.sprafke@bfh.ch)[32], Eduardo Kazuo Tamanaha(eduardo.tamanaha@mamiraua.org.br)[33], Pablo Vidal-Torrado(pvidal@usp.br)[34], Ximena S. Villagran(villagran@usp.br)[16], Jennifer Watling(jwatling@usp.br)[16], Sadie L Weber(sweber@fas.harvard.edu)[35].

[a] Corresponding Author @Umba_moxos Hallerstrasse 12, CH3012, Bern, Switzerland
[1] Institute of Geography, University of Bern
[2] Institute of Archaeology, University College London
[3] Groningen Institute of Archaeology, University of Groningen
[4] Embrapa Soils
[5] Instituto Nacional de Pesquisas da Amazonia
[6] Wageningen University & Research
[7] Soils Department, Federal Rural University of Rio de Janeiro (UFRRJ)
[8] School of Archaeology, University of Oxford
[9] Embrapa Forestry
[10] Geosciences Institute, Federal University of Pará
[11] Centre for Functional Ecology, Department of Life Sciences, University of Coimbra
[12] Department of Geography, University of Wisconsin-Madison
[13] Institute of Agricultural and Nutritional Sciences, Martin Luther University
[14] Institute of the Environment, University of California
[15] Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona
[16] Museu de Arqueologia e Etnologia, Universidade de São Paulo
[17] Soil Biology Group, Wageningen University
[18] School of Integrative Plant Science, Cornell University
[19] Museu Paraense Emílio Goeldi
[20] Instituto Nacional do Semiárido (INSA)
[21] ICREA, CaSEs Research Group, Department of Humanities, Universitat Pompeu Fabra
[22] Institute for Biodiversity & Ecosystem Dynamics, University of Amsterdam
[23] School of Archaeology, Geography & Environmental Science (SAGES), University of Reading
[24] Centre d'Écologie Fonctionnelle et Évolutive (CEFE), University of Montpellier
[25] Instituto de Ciências da Sociedade, Universidade Federal do Oeste do Pará
[26] Instituto de Ciencias Naturales, Universidad Nacional de Colombia
[27] Department of Environmental Science, Federal University of São Paulo
[28] Institute for Modelling Socio-Environmental Transitions, Bournemouth University
[29] Climate and Agriculture Group, Agroscope
[30] French National Centre for Scientific Research
[31] Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology
[32] Center of Competence for Soils, BFH-HAFL
[33] Instituto de Desenvolvimento Sustentável Mamirauá
[34] Soil Science Department, University of São Paulo
[35] Department of Anthropology, Harvard University

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[1]. Controversially, in their recent paper Silva *et al*.[2]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[3] 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[4]. 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)[2] and both lack the 2:1 clay minerals expected from fluvial origin[5]. 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[6]. 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.)[7]. The similarity in quartz sand grain morphology between the ADE A and B horizons excludes the inference of fluvial inputs into the A horizon[7]. Moreover, a large number of ADE sites are found along black water rivers or inland[1], 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"[8]. 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)[9]. Most of these, along with pyrogenic C, have been reported in ADEs[10]. The most logical explanation for such an assemblage is anthropic inputs associated with settlement activity[10]. 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[11] and terrestrial and aquatic vertebrates [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 ~2.13) and human faeces (Ca:P ~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[13].

High enrichment of P and Ca

ADEs are widely recognized as evidence of population growth and landscape transformations in the late Holocene[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 [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 ^{14}C BP from the B horizon of their ADE profile (https://doi.org/10.7264/9qdm-en61) and argue that >7.6 ky ^{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[15], including the B horizons of ADE profiles[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[17,18]. For Caldeirão, similar ages are reported by Schellekens et al.[19]. Hence, mid-Holocene ^{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 [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.

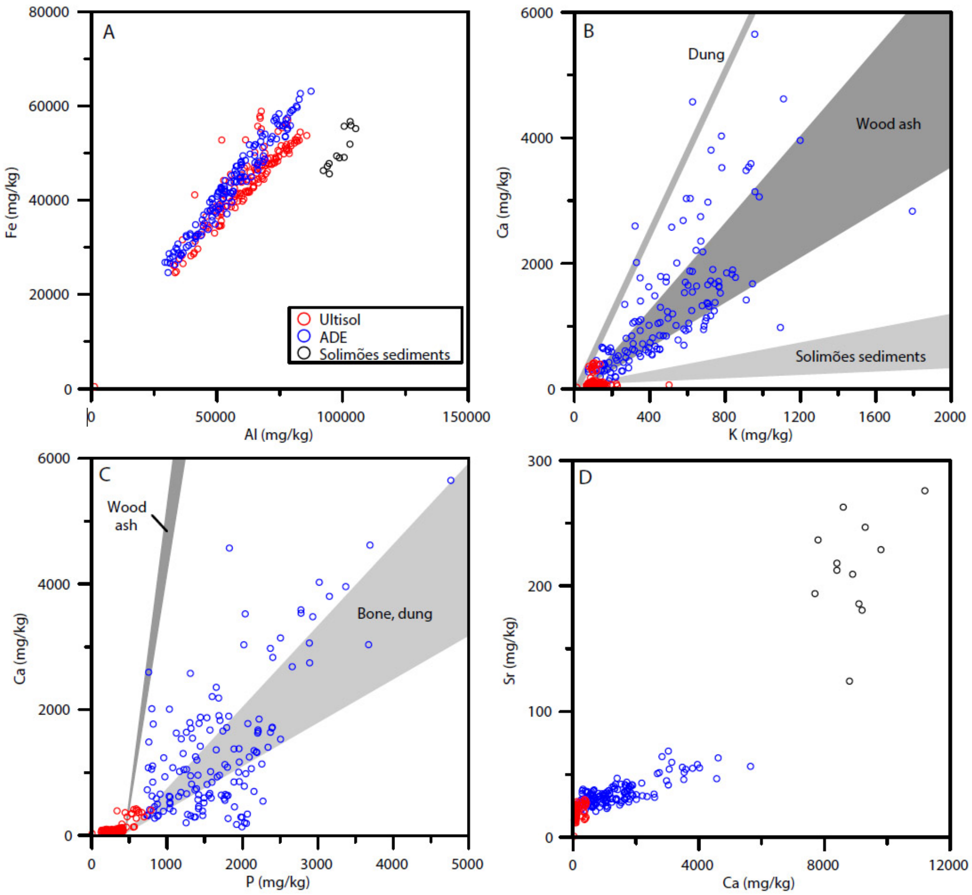

Figure 1 Caldeirão's soil compositional data compared with published data of Solimões River sediments and anthropogenic materials. Data is in supplementary table 1. A: Geogenic elements Al and Fe are similar in ADE and Ultisols, but different from Solimões sediments. B, C: Anthropogenic elements K, Ca 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

1 Clement, C. R. *et al.* The domestication of Amazonia before European conquest. *Proceedings of the Royal Society of London B: Biological Sciences* **282**, doi:10.1098/rspb.2015.0813 (2015).

2 Silva, L. C. R. *et al.* A new hypothesis for the origin of Amazonian Dark Earths. *Nat. Commun.* **12**, 127, doi:10.1038/s41467-020-20184-2 (2021).

3 Falesi, I. C. in *Man in the Amazon* (ed Charles Wagley) 201–229 (The University Presses of Florida, 1974).

4 Pupim, F. N. *et al.* Chronology of Terra Firme formation in Amazonian lowlands reveals a dynamic Quaternary landscape. *Quaternary Science Reviews* **210**, 154-163, doi: 10.1016/j.quascirev.2019.03.008 (2019).

5 Guyot, J. L. *et al.* Clay mineral composition of river sediments in the Amazon Basin. *Catena* **71**, 340-356, doi:10.1016/j.catena.2007.02.002 (2007).

6 Macedo, R. S., Teixeira, W. G., Corrêa, M. M., Martins, G. C. & Vidal-Torrado, P. Pedogenetic processes in anthrosols with pretic horizon (Amazonian Dark Earth) in Central Amazon, Brazil. *PLoS ONE* **12**, e0178038, doi:10.1371/journal.pone.0178038 (2017).

7 Arroyo-Kalin, M., Neves, E. & Woods, W. in *Amazonian Dark Earths: Wim Sombroek's Vision* (eds William I. Woods *et al.*) 99-125 (Springer Netherlands, 2009).

8 Barbosa, J. Z. *et al.* Elemental signatures of an Amazonian Dark Earth as result of its formation process. *Geoderma* **361**, 114085, doi: 10.1016/j.geoderma.2019.114085 (2020).

9 Oonk, S., Slomp, C. P. & Huisman, D. J. Geochemistry as an aid in archaeological prospection and site interpretation: current issues and research directions. **16**, 35-51, doi: 10.1002/arp.344 (2009).

10 Glaser, B. & Birk, J. J. State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). *Geochimica et Cosmochimica Acta* **82**, 39-51, doi: 10.1016/j.gca.2010.11.029 (2012).

11 Tyler, G. Rare earth elements in soil and plant systems - A review. *Plant and Soil* **267**, 191-206, doi:10.1007/s11104-005-4888-2 (2004).

12 Tütken, T., Vennemann, T. W. & Pfretzschner, H.-U. Nd and Sr isotope compositions in modern and fossil bones – Proxies for vertebrate provenance and taphonomy. *Geochimica et Cosmochimica Acta* **75**, 5951-5970, doi: 10.1016/j.gca.2011.07.024 (2011).

13 Sato, S., Neves, E. G., Solomon, D., Liang, B. Q. & Lehmann, J. Biogenic calcium phosphate transformation in soils over millennial time scales. *Journal of Soils and Sediments* **9**, 194-205, doi: 10.1007/s11368-009-0082-0 (2009).

14 Canti, M. & Huisman, D. J. Scientific advances in geoarchaeology during the last twenty years. *Journal of Archaeological Science* **56**, 96-108, doi: 10.1016/j.jas.2015.02.024 (2015).

15 Pessenda, L. C. R. *et al.* Vegetation dynamics during the late Pleistocene in the Barreirinhas region, Maranhão State, northeastern Brazil, based on carbon isotopes in soil organic matter. *Quaternary Research* **62**, 183-193, doi: 10.1016/j.yqres.2004.06.003 (2004).

16 Heckenberger, M. J., Petersen, J. B. & Neves, E. G. Village size and permanence in Amazonia: two archaeological examples from Brazil. *Latin American Antiquity* **10**, 353-376, doi: https://doi.org/10.2307/971962 (1999).

17 Arroyo-Kalin, M. Slash-burn-and-churn: Landscape history and crop cultivation in pre-Columbian Amazonia. *Quaternary International* **249**, 4-18, doi:10.1016/j.quaint.2011.08.004 (2012).

18 Neves, E. G., Petersen, J. B., Bartone, R. N. & Heckenberger, M. J. in *Amazonian Dark Earths: Explorations in Space and Time* (eds Bruno Glaser & William I. Woods) 125-134 (Springer Berlin Heidelberg, 2004).

19 Schelleken, J. *et al.* Molecular composition of several soil organic matter fractions from anthropogenic black soils (Terra Preta de Índio) in Amazonia — A pyrolysis-GC/MS study. *Geoderma* **288**, 154-165, doi: 10.1016/j.geoderma.2016.11.001 (2017).

Supplementary material

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

Material	K	Ca	P	Al	Fe	Sr	Source
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	
Beech ash	159480	281629	14408	4765	4895	NA	Cilova & Woitsch 2012 (table 2)
Beech ash	130883	330950	14408	14294	15383	NA	Cilova & Woitsch 2012 (table 2)
Spruce ash	63792	360971	10479	13235	11188	NA	Cilova & Woitsch 2012 (table 2)
Spruce ash	52793	390993	11789	19059	11188	NA	Cilova & Woitsch 2012 (table 2)
Wood ash s.l. (average)	59117	307576	15194	26947	24054	NA	Vassilev et al. 2013 (table 6)
Wood ash s.l.	33137	230164	26000	6000	4995	NA	Braadbaart et al. 2012 (table 3)
Ash of cow dung	7290	48034	45000	8000	4995	NA	Braadbaart et al. 2012 (table 3)
Unaltered bone (Stavanger, N)	0	145747	180366	16300	77000	NA	Huisman et al. (2017) (table 3)
Unaltered bone (Stavanger, N)	0	138384	178359	12900	81500	NA	Huisman et al. (2017) (table 3)
Unaltered bone (Stavanger, N)	0	103788	152401	16200	110600	NA	Huisman et al. (2017) (table 3)
Unaltered bone (Zug, CH)	0	282630	235493	0	33900	NA	Huisman et al. (2017) (table 3)
Unaltered bone (Zug, CH)	0	252108	206056	0	33900	NA	Huisman et al. (2017) (table 3)
Unaltered bone (Zug, CH)	0	267977	211676	3500	30900	NA	Huisman et al. (2017) (table 3)
Suspended sediment Solimoes river 2004	19800	8800	NA	98700	49000	124	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	21100	7800	NA	102900	51900	237	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	19900	9200	NA	94700	45600	181	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	18200	8400	NA	94600	47800	218	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	18800	7700	NA	93900	47200	194	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	20200	11200	NA	105200	55200	276	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	18600	9800	NA	103300	55900	229	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	19300	9300	NA	100600	55700	247	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	18400	8600	NA	103000	56700	263	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	17000	8900	NA	92300	46300	209	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	18600	8400	NA	100600	49100	213	Viers et al. (2008) (table 1a)
Suspended sediment Solimoes river 2004	18300	9100	NA	97600	49400	186	Viers et al. (2008) (table 1a)

References

20 Viers, J. *et al.* Seasonal and provenance controls on Nd–Sr isotopic compositions of Amazon rivers suspended sediments and implications for Nd and Sr fluxes exported to the Atlantic Ocean. *Earth and Planetary Science Letters* **274**, 511-523, doi: 10.1016/j.epsl.2008.08.011 (2008).

21 Braadbaart, F., Poole, I., Huisman, H. D. J. & van Os, B. Fuel, fire and heat: an experimental approach to highlight the potential of studying ash and char remains from archaeological contexts. *Journal of Archaeological Science* **39**, 836-847, doi: 10.1016/j.jas.2011.10.009 (2012).

22 Cílová, Z. & Woitsch, J. Potash – a key raw material of glass batch for Bohemian glasses from 14th–17th centuries? *Journal of Archaeological Science* **39**, 371-380, doi: 10.1016/j.jas.2011.09.023 (2012).

23 Vassilev, S. V., Baxter, D. & Vassileva, C. G. An overview of the behaviour of biomass during combustion: Part I. Phase-mineral transformations of organic and inorganic matter. *Fuel* **112**, 391-449, doi: 10.1016/j.fuel.2013.05.043 (2013).

24 Huisman, H., Ismail-Meyer, K., Sageidet, B. M. & Joosten, I. Micromorphological indicators for degradation processes in archaeological bone from temperate European wetland sites. *Journal of Archaeological Science* **85**, 13-29, doi: 10.1016/j.jas.2017.06.016 (2017).