Supplementary information

Early Holocene crop cultivation and landscape modification in Amazonia

In the format provided by the authors and unedited

Umberto Lombardo ✉, José Iriarte, Lautaro Hilbert, Javier Ruiz-Pérez, José M. Capriles & Heinz Veit

Supplementary Information

Study Area

Covering approximately 150,000 km^2, the LM is the third largest seasonal wetland in South America, after the Llanos del Orinoco and the Pantanal of Mato Grosso[1]. The LM belongs to the world's largest Ramsar site[2] and is key to the survival of a rich biodiversity including many endemic and threatened species[3,4]. Annual rainfall ranges from 1,200 mm to 3,500 mm and the average annual temperature is 25 ºC. The LM also hosts diverse and widely distributed pre-Columbian earthworks, attesting the anthropogenic contribution to its modern landscape[5]. The LM is also the area in Amazonia where forests contain the highest absolute and relative abundance of domesticated species[6]. The seasonally flooded savannahs of the LM are drained by three major rivers: the Beni, the Mamoré and the Iténez (or Guaporé). Together with the Madre de Díos, these rivers form the Madeira River, the largest tributary of the Amazon River. Savannah soils show different degrees of hydromorphism, with strong red mottling in the north-western LM and relatively more fertile sediments over the more recent (mid to late Holocene) alluvial deposits[7-9]. Soils under forest are mostly Cambisols and Luvisols[7,10]. Vegetation patterns are primarily controlled by the flooding regime, with forested areas relegated to the upper part of the landscape, mostly fluvial levees and crevasse splays[11,12]. Soil properties also contribute to vegetation patterns, especially in the northern part of the LM where lateritic soils are covered with cerrado-like savannah[11,13]. The landscape of the LM has undergone several changes during the Holocene. These changes have been caused by the combination of two independent factors, climate change and neotectonics, which have had a paramount effect on fluvial processes and the formation of many ria lakes[14-18]. Hundreds of geometric and oriented shallow lakes of controversial origins dot the LM[19,20].

Archaeological background

The LM is one of the Amazonian areas where the transformation of the landscape by pre-Columbians is most evident. In the central eastern LM, archaeological research has unveiled the presence of monumental mounds, large planned structures, with political and religious functions, covering up to 20 ha, reaching more than 20 meters in elevation, connected with canals, and often surrounded by polygonal causeways[21-24]. Thousands of hectares of pre-Columbian raised fields, artificial agricultural surfaces built in order to improve the drainage of otherwise flood-prone areas, cover the western part of the LM[25,26]. Fish weirs made of a combination of causeways in a zigzag fashion and small ponds that trapped the fish, are found in the north eastern LM[27,28]. Ring villages are found in the north eastern LM, built over tertiary uplands[21,25,29,30]. Hundreds of kilometers of canals and causeways cross the eastern LM[23,31]. All these earthworks have been built during the last 2000 years, it is only recently that some FIs have been discovered to be the earliest archaeological sites in the LM[32]. Systematic excavations in the LM anthropic forest islands has revealed a wealth of information about human occupation of south-western Amazonia prior to the adoption of pottery and agricultural intensification. Anthropic FI sites often contain deep stratigraphy consisting of overlapping layers of most likely seasonal occupations that include abundant food refuse, often dominated by apple snails of the genus *Pomacea*[32]. Other archaeological materials include abundant faunal remains of both terrestrial and aquatic taxa, burnt earth, and the remarkable presence of human burials, usually in extended position and generally completely covered by carbonates[33]. These sites are often associated with buried paleosols that confirm their great antiquity[34]. Many of these sites also have late Holocene ceramic

occupations but they also often have overlying sterile layers that suggest occupation hiatuses. Although no stone tools have been recovered from the early layers of these sites, mostly due to the absence of rock in the region, these bear evidence of intensive human use of the Llanos de Mojos landscape.

Implications of FIs' spatial characteristics over proposed theories for the formation of FIs

Apart from the evidence gathered during fieldwork, spatial analysis of FIs also support an anthropic and pre-ceramic origin for most of them. Previous studies have proposed three major mechanisms for FIs formation: FIs formed as termite mounds; 2) FIs derived from fluvial levees; and 3) FIs formed as late Holocene earthworks[10,14,35].

The average diameter of FIs is approximately 70 meters, which is much bigger than the termite mounds found today in Bolivia or in Brazil, where the *murundus* are about 10 m in diameter[36]. Even if we assumed that termite mounds were bigger in the past due to different environmental conditions, we would expect a negative correlation between the number of FIs and their size and this does not occur. The distribution shape of FIs diameters is almost normal centered around 70 m (Fig. ED5b). In addition, Brazilian *campos de murundus* are characterized by regularly spaced mounds elevated about 1 m above the surrounding savannah. This is not the case of the LM FIs, which can be as high as 3 m and are not regularly spaced. In Brazil, a type of macromound (*capões*), comparable in size to the LM FIs, has been described as resulting from differential sedimentation[37]. However, these mounds are elongated following the direction of the water current and this rarely true of the LM FIs, only 4% of which are elongated.

If FIs were the remains of eroded levees, we would expect most of them to be located along paleochannels and to be elongated. Our data show that only 934 FIs are located within 300 m of a paleochannel and only 437 of these have an irregular (381) or elongated (56) shape, with the majority of them (497) being perfectly circular (83) or almost circular (413). Furthermore, taking into account all the FIs that are located on naturally elevated surfaces (levees, crevasse splays and upland in general), they still only account for 1187, less than 18% of the total. Fig. S4 shows an example of FIs spatial distribution in the NW LM, the region with the highest density of FIs.

If the FIs had been built by the same people who built the late Holocene earthworks known today in the LM, it would be logical to expect a spatial relationship between the FIs and earthworks and this does not seem to be the case. We mapped all the earthworks visible on satellite imagery: agricultural fields, canals, causeways, circular ditches and added them to the dataset of known earthworks[23,26]. Only 867 FIs are within a distance of 500 m from the late Holocene earthworks we mapped, and only 1295 are within 1000 m (see also Fig. ED4).

Characteristics of "natural" FI vs early to mid-Holocene anthropic FI and potential misclassification of sites

A "natural" FI is made of organic-poor sediments, mostly of fluvial origin, covered by a thin organic topsoil (see for example Fig. ED5c). Anthropic FIs are entirely made with anthropic sediments (Figs ED5d and e). Throughout our extensive surveys and archaeological excavation of these sites, we have never found a "construction" layer of inorganic sediments actively transported from outside the site in order to artificially raise the platform. All the mineral fraction of the sediments forming the anthropic FIs has been deposited within a

cultural context and is made of food remains and fire derived materials. FIs are classified as anthropic when they are formed of thick layers of organic sediments and contain at least two archaeological materials, such as charcoal, burnt earth, animal bones or shells. FIs are classified as "natural" when the criteria we use to classify FIs as anthropic are not met. This does not mean that all the FIs classified as "natural" are actually resulting from natural processes. It could be that they have been built by late Holocene pre-Columbians by raising an earthen round platform (in which case the sediments immediately below the top soil would have a clear color and would not contain food remains or firer derived materials). The opposite case of natural sediments mistaken for anthropic ones is also possible, but far less likely. It could be that a FI was built over an aggradational soil, i.e. a soil that received a prolonged supply of sediments that where incorporated in its A horizon, as it can happen in a backswamp. In this situation, a thick layer of organic matter could accumulate. If such a thick soil then was exposed to redoximorphic conditions and the formation of red mottles and manganese oxides, when cored with an auger, that can easily crash the soil structure, it could be mistaken for an anthropic soil where red mottles look like burned earth and manganese oxides resemble charcoal fragments. However, no pedogenic process could mimic fragments of shells and bones.

Code used in OxCal:

```
#SM1_Burial
Options()
 {Curve="SHCal13.14c";};
 Plot()
 {P_Sequence("SM1_Burial",0.1,0,U(-2,2))
  {Boundary();
   Date("SM1-235") {z=235;};
   R_Date("D-AMS-032884",7447,37){z=225;};
   Date("SM1-215"){z=215;};
   R_Date("D-AMS-032885",7271,40){z=205;};
   Date("SM1-195"){z=195;};
   Date("SM1-175"){z=175;};
   Date("SM1-155"){z=155;};
   Date("SM1-135"){z=135;};
   R_Date("PSUAMS-4658",5565,20){z=120;};
   R_Date("D-AMS-1740",5502,30){z=117;};
   Date("SM1-102"){z=102;};
   Date("SM1-95"){z=95;};
   Date("SM1-65"){z=65;};
   Date("SM1-45"){z=45;};
   R_Date("youngest",3830,50){z=35;};
   Boundary();};
 };

#SM1_Central
Options()
 {Curve="SHCal13.14c"; };
 Plot()
 {P_Sequence("SM1_1",0.1,0.2,U(-2,2))
  {Boundary();
   R_Date("Poz-36135",9420,50){z=245;};
   R_Date("Poz-34301",9270,60){z=235;};
   R_Date("Poz-36136",5800,35){z=165;};
   R_Date("Poz-34232",5460,40){z=125;};
   R_Date("Poz-34231",5520,40){z=115;};
   R_Date("Poz-34230",4945,35){z=45;};
```

```
   R_Date("Poz-34229",3895,35){z=35;};
   Boundary();};
  };

#Manechi
Options(){Curve="SHCal13.14c";};
 Plot()
 {P_Sequence("Isla Manechi",0.1,0.2,U(-2,2))
  {Boundary();
   Date("BANR17-UE1-64"){z=155;};
   R_Date("D-AMS 029221",9346,41){z=145;};
   Date("BANR17-UE1-53"){z=125;};
   R_Date("BE-8259.1.1",9138,24){z=105;};
   R_Date("BE-8258.1.1",4491,23){z=85;};
   R_Date("BE-8257.1.1",4324,22){z=55;};
   R_Date("BE-8256.1.1",3017,25){z=25;};
   Boundary();};
  };

#SM3_Burial
 Options(){Curve="SHCal13.14c";};
 Plot()
 {P_Sequence("SM3_Burial",0.1,0,U(-2,2))
  {Boundary();
   Date("SM3-160-164"){z=162;};
   R_Date("PSUAMS- 1564",7930,30){z=155;};
   Date("SM3 140-145"){z=142;};
   R_Date("PSUAMS-1563",6650,30){z=121;};
   Date("SM3 108-113"){z=110;};
   R_Date("PSUAMS-1450",6030,30){z=100;};
   Date("SM3 80-84"){z=82;};
   Boundary();};
  };
#SM3_Core
 Options(){Curve="SHCal13.14c";};
 Plot(){P_Sequence("SM4_Burial",0.1,0,U(-2,2))
  {Boundary();
   R_Date("Poz-38866",7790,80){z=240;};
   R_Date("Poz-38865",7860,50){z=236;};
   R_Date("Poz-38862",5140,40){z=107;};
   Boundary();};
  };
```

1   Junk, W. Current state of knowledge regarding South American wetlands and their future under global climate change. *Aquatic Sciences - Research Across Boundaries* **75**, 113-131, doi:10.1007/s00027-012-0253-8 (2013).

2   Wittmann, F. *et al.* Implementation of the Ramsar convention on South American wetlands: an update. *Research and Reports in Biodiversity Studies* **4**, 47-58 (2015).

3   Herzog, S., Maillard Z, O., Embert, D., Caballero, P. & Quiroga, D. Range size estimates of Bolivian endemic bird species revisited: the importance of environmental data and national expert knowledge. *J Ornithol* **153**, 1189-1202, doi:10.1007/s10336-012-0850-2 (2012).

4   Wallace, R. *et al.* in *Primates in Fragments Developments in Primatology: Progress and Prospects* (eds Laura K. Marsh & Colin A. Chapman) Ch. 33, 493-501 (Springer New York, 2013).

5   Lombardo, U., Denier, S., May, J.-H., Rodrigues, L. & Veit, H. Human–environment interactions in pre-Columbian Amazonia: The case of the Llanos de Moxos, Bolivia. *Quaternary International* **312**, 109-119, doi:http://dx.doi.org/10.1016/j.quaint.2013.01.007 (2013).

6   Levis, C. *et al.* Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. *Science* **355**, 925-931, doi:10.1126/science.aal0157 (2017).

7   Lombardo, U., Denier, S. & Veit, H. Soil properties and pre-Columbian settlement patterns in the Monumental Mounds Region of the Llanos de Moxos, Bolivian Amazon. *SOIL* **1**, 65-81, doi:10.5194/soil-1-65-2015 (2015).

8   Rodrigues, L., Lombardo, U., Canal Beeby, E. & Veit, H. Linking soil properties and pre-Columbian agricultural strategies in the Bolivian lowlands: The case of raised fields in Exaltación. *Quaternary International* **Volume 437, Part B**, 143-155, doi:http://dx.doi.org/10.1016/j.quaint.2015.11.091 (2017).

9   Boixadera, J., Poch, R. M., García-González, M. T. & Vizcayno, C. Hydromorphic and clay-related processes in soils from the Llanos de Moxos (northern Bolivia). *Catena* **54**, 403-424, doi:10.1016/s0341-8162(03)00134-6 (2003).

10   Langstroth, R. P. *Forest islands in an Amazonian savanna of northeastern Bolivia*, University of Wisconsin-Madison, (1996).

11   Langstroth, R. P. Biogeography of the Llanos de Moxos: natural and anthropogenic determinants. *Geographica Helvetica* **66**, 183-192 (2011).

12   Mayle, F. E., Langstroth, R. P., Fisher, R. A. & Meir, P. Long-term forest-savannah dynamics in the Bolivian Amazon: implications for conservation. *Philosophical Transactions of the Royal Society B: Biological Sciences* **362**, 291-307, doi:10.1098/rstb.2006.1987 (2007).

13   Navarro, G. *Clasificación de la vegetación de Bolivia*. (Centro de ecología difusión fundación Simón I. Patiño, 2011).

14   Hanagarth, W. *Acerca de la geoecología de las sabanas del Beni en el noreste de Bolivia*. (Instituto de ecología, 1993).

15   Lombardo, U. Neotectonics, flooding patterns and landscape evolution in southern Amazonia. *Earth Surf. Dynam.* **2**, 493-511, doi:10.5194/esurf-2-493-2014 (2014).

16   Lombardo, U. Alluvial plain dynamics in the southern Amazonian foreland basin. *Earth Syst. Dynam.* **7**, 453-467, doi:10.5194/esd-7-453-2016 (2016).

17   Mayle, F. E., Burbridge, R. & Killeen, T. J. Millennial-scale dynamics of southern Amazonian rain forests. *Science* **290**, 2291-2294, doi:10.1126/science.290.5500.2291 (2000).

18   Dumont, J. F. & Fournier, M. Geodynamic environment of Quaternary morphostructures of the subandean foreland basins of Peru and Bolivia: Characteristics and study methods. *Quaternary International* **21**, 129-142, doi:10.1016/1040-6182(94)90027-2 (1994).

19   Lombardo, U. & Veit, H. The origin of oriented lakes: Evidence from the Bolivian Amazon. *Geomorphology* **204**, 502-509, doi:http://dx.doi.org/10.1016/j.geomorph.2013.08.029 (2014).

20   Plafker, G. Oriented lakes and lineaments of northeastern Bolivia. *Geological Society of America Bulletin* **75**, 503-522, doi:10.1130/0016-7606(1964)75[503:olalon]2.0.co;2 (1964).

21   Prümers, H. & Jaimes Betancourt, C. 100 años de investigación arqueológica en los Llanos de Mojos. *Arqueoantropológicas* **4**, 11-53 (2014).

22   Prümers, H. ¿«Charlatanocracia» en Mojos? investigaciones arqueológicas en la Loma Salvatierra, Beni, Bolivia. *Boletín de arqueología PUCP* **11**, 103-116 (2009).

23   Lombardo, U. & Prümers, H. Pre-Columbian human occupation patterns in the eastern plains of the Llanos de Moxos, Bolivian Amazonia. *Journal of Archaeological Science* **37**, 1875-1885, doi:10.1016/j.jas.2010.02.011 (2010).

24   Jaimes Betancourt, C. *La ceramica de la loma Salvatierra*. (Plural Editores, 2012).

25   Lombardo, U., Canal-Beeby, E., Fehr, S. & Veit, H. Raised fields in the Bolivian Amazonia: a prehistoric green revolution or a flood risk mitigation strategy? *Journal of Archaeological Science* **38**, 502-512, doi:10.1016/j.jas.2010.09.022 (2011).

26   Rodrigues, L., Lombardo, U. & Veit, H. Design of pre-Columbian raised fields in the Llanos de Moxos, Bolivian Amazon: Differential adaptations to the local environment? *Journal of Archaeological Science: Reports* (2018).

27   Erickson, C. L. An artificial landscape-scale fishery in the Bolivian Amazon. *Nature* **408**, 190-193 (2000).

28   Blatrix, R. *et al.* The unique functioning of a pre-Columbian Amazonian floodplain fishery. *Scientific Reports* **8**, 5998, doi:10.1038/s41598-018-24454-4 (2018).

29   Prümers, H., Jaimes Betancourt, C. & Plaza Martinez, R. Algunas tumbas prehispánica de Bella Vista, Prov. Iténez, Bolivia. *Zeitschrift für Archäologie Außereuropäischer Kulturen* **1**, 251-284 (2006).

30   Jaimes Betancourt, C. in *Cerâmicas Arqueologicas de Amazônia*   (eds C. Barreto, Helena Pinto Lima, & Carla Jaimes Betancourt) 435-447 (IPHAN - Ministério de Cultura, 2016).

31   Lombardo, U., Canal-Beeby, E. & Veit, H. Eco-archaeological regions in the Bolivian Amazon: Linking pre-Columbian earthworks and environmental diversity *Geographica Helvetica* **66**, 173-182 (2011).

32   Lombardo, U. *et al.* Early and Middle Holocene Hunter-Gatherer Occupations in Western Amazonia: The Hidden Shell Middens. *PLoS ONE* **8**, e72746, doi:10.1371/journal.pone.0072746 (2013).

33   Capriles, J. M. *et al.* Persistent Early to Middle Holocene tropical foraging in southwestern Amazonia. *Science Advances* **5**, eaav5449, doi:10.1126/sciadv.aav5449 %J Science Advances (2019).

34   Lombardo, U., Rodrigues, L. & Veit, H. Alluvial plain dynamics and human occupation in SW Amazonia during the Holocene: A paleosol-based reconstruction. *Quaternary Science Reviews* **180**, 30-41, doi:https://doi.org/10.1016/j.quascirev.2017.11.026 (2018).

35   Erickson, C. L. in *Handbook of South American archaeology*   (eds Helaine Silverman & William H. Isbell) Ch. 11, 157-183 (Springer, 2008).

36   Silva, L., Vale, G., Haidar, R. & da S. L. Sternberg, L. Deciphering earth mound origins in central Brazil. *Plant and Soil* **336**, 3-14, doi:10.1007/s11104-010-0329-y (2010).

37   Ponce, V. M. & da Cunha, C. N. Vegetated earthmounds in tropical savannas of central Brazil: a synthesis. *Journal of Biogeography* **20**, 219-225 (1993).