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CASE STUDY

Geometry by Design: Contribution of Lidar to the Understanding of Settlement Patterns of the Mound Villages in SW Amazonia

Jose Iriarte*, Mark Robinson*, Jonas de Souza†, Antonia Damasceno‡, Franciele da Silva*, Francisco Nakahara§, Alceu Ranzi|| and Luiz Aragao¶

Recent research has shown that the entire southern rim of Amazonia was inhabited by earth-building societies involving landscape engineering, landscape domestication and likely low-density urbanism during the Late Holocene. However, the scale, timing, and intensity of human settlement in this region remain unknown due to the dearth of archaeological work and the logistical difficulties associated with research in tropical forest environments. A case in point are the newly discovered Mound Villages (AD ~1000–1650) in the SE portion of Acre State, Brazil. Much of recent pioneering work on this new archaeological tradition has mainly focused on the excavation of single mounds within sites with little concern for the architectural layout and regional settlement patterns, thus preventing us from understanding how these societies were organised at the regional level. To address these shortcomings, we carried out the first Lidar survey with a RIEGL VUX-1 UAV Lidar sensor integrated into an MD 500 helicopter. Our novel results documented distinctive architectural features of Circular Mound Villages such as the presence of ranked, paired, cardinaly oriented, sunken roads interconnecting villages, the occurrence of a diversity of mound shapes within sites, as well as the exposure the superimposition of villages. Site size distribution analysis showed no apparent signs of settlement hierarchy. At the same time, it revealed that some small groups of villages positioned along streams exhibit regular distances of 2.5–3 km and 5–6 km between sites. Our data show that after the cessation of Geoglyph construction (~AD 950), this region of SW Amazonia was not abandoned, but occupied by a flourishing regional system of Mound Villages. The results continue to call into question traditional views that portray interfluvial areas and the western sector of Amazonia as sparsely inhabited. A brief discussion of our findings in the context with pre-Columbian settlement patterns across other regions of Amazonia is conducted.

Keywords: Amazon Archaeology; Lidar; Settlement Patterns; Circular Villages; Earthworks; Geoglyphs

1. Introduction

Earthen architecture featuring a wide variety of dimensions, architectural layout, chronology, functions, and distinct cultural affiliations was widespread across lowland South America from the Paraná River Delta to the Llanos de Venezuela extending up to the Andean piedmont (Bonomo Politis & Gianotti, 2011; Erickson & Balée 2006; Heckenberger et al. 2008; Iriarte et al. 2004; Iriarte et al. 2013; Prümers & Jaimes Betancourt 2014; Redmond & Spencer 2007; Schaan 2012; Walker 2018). Archaeological

research during the last two decades along the southern rim of the Amazon has begun to document a diversity of pre-Columbian earth-building traditions between the Upper Xingu and the Upper Purus rivers (**Figure 1**). It is now apparent that this region of Amazonia was inhabited by numerous earth-building societies involving landscape engineering, landscape domestication and likely low-density urbanism (Heckenberger et al. 2008; Levis et al. 2017; Pärssinen, Schaan & Ranzi 2009; Saunaluoma & Schaan 2012; Schaan 2012; Souza et al. 2018). Based on the extant data of earth-building cultures along the entire rim of the southern Amazon at the eve of European Encounter (AD 1250–1500), we predicted conservative figures of ~500 thousand to 1 million people living in this region of southern Amazonia (Souza et al. 2018). However, owing largely to the early stage of archaeological research in this vast region, the scale, timing, and intensity of human settlement for the most part remain unknown. Our study region, the south-eastern sector of Acre state in Brazil,

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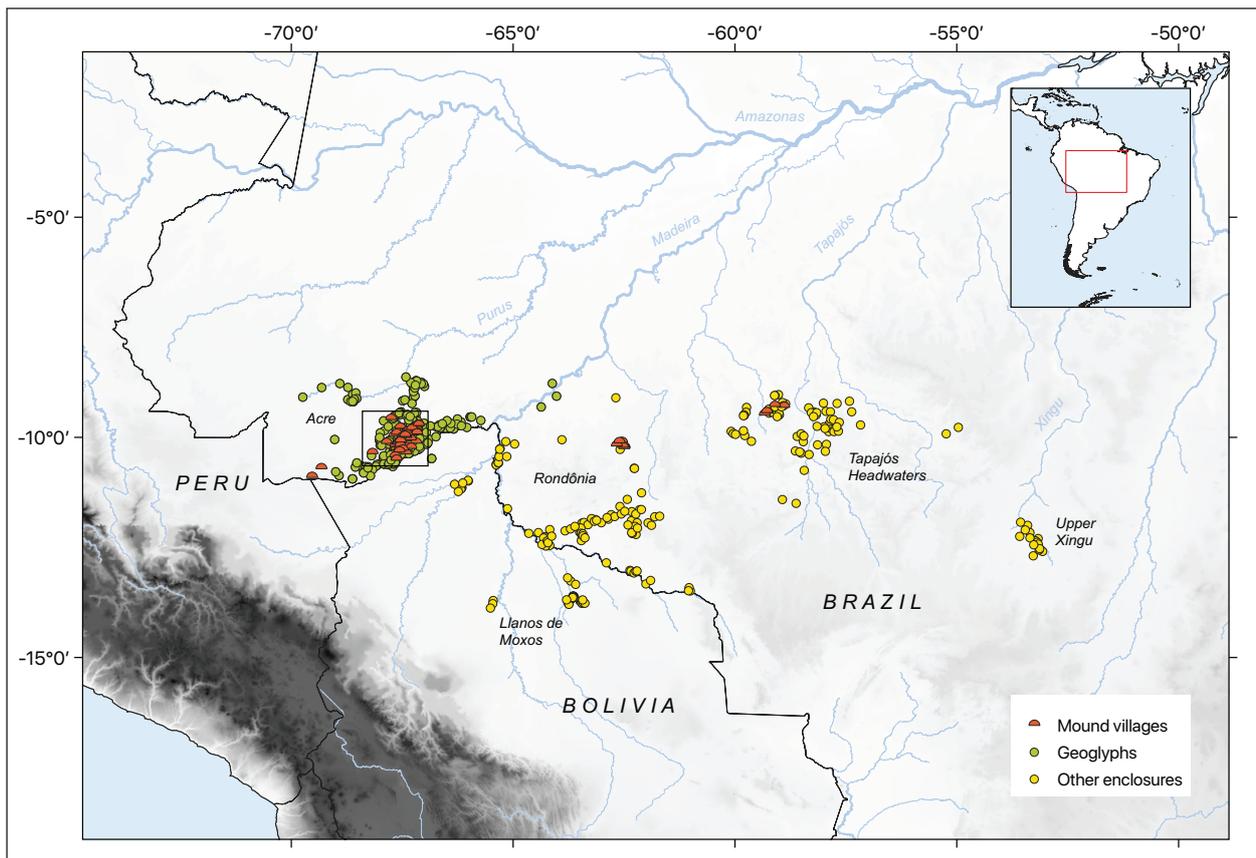


Figure 1: Map of earthworks across the southern rim of the Amazon showing spatial dispersion of mound villages. For the inset in the state of Acre, see Figure 2.

where the discovery of the geometrically perfect ditched geometric enclosures known as ‘Geoglyphs’ have captivated both archaeologists and the public imagination during the last decades (Mann 2005, 2008), are a case in point.

Importantly, in the last decade, a new archaeological tradition called Mound Villages has been discovered in this same region. The Mound Villages (~AD 1000–1650), locally known as ‘Sois,’ are constituted by circular or rectangular arrangements of mounds interconnected by radiating roads succeeded the Geoglyphs (400 BC–AD 950). Notwithstanding the discovery of more than five hundred earthen constructions due to deforestation for cattle grazing, there are still critical lacunae in our understanding of past settlement patterning due to the limited resolution of satellite images and the challenges of acquiring data in densely vegetated areas. Although largely cleared, southeastern Acre is still a patchwork of recently created pastures and forests preventing a clear landscape-scale picture of how these societies organised and interacted with their environment. Much work has been done on Geoglyph settlement patterns (e.g., Schaan 2012), yet, until now, most archaeological research related to the Mound Villages has mainly focused on the excavation of single mounds within sites with little concern for regional settlement patterns (Neves et al. 2016; Schaan 2012; Schaan et al. 2012; Saunaluoma & Schaan 2012; Saunaluoma, Pärssinen & Schaan 2018). To overcome these challenges, in the context of the ERC PAST (Pre-Columbian Amazon-Scale

Transformations) project, we conducted Lidar survey in selected areas of this region (Figure 2).

Lidar is allowing the discovery of archaeological sites covered by tropical forest in many regions of the world (Fisher et al. 2017) including Southeast Asia (e.g., Evans et al. 2013), Central America (e.g., Canuto et al. 2018; Chase et al. 2012), the Caribbean (Opitz et al. 2015), and Amazonia (Khan, Aragão & Iriarte 2017; Prümers & Betancourt 2014; Stenborg, Schaan & Figueiredo 2018). The technique is also providing archaeologists with higher resolution digital elevation models of archaeological sites in treeless environments (e.g., Bewley, Crutchley & Shell 2005; Brady et al. 2013; Henry, Shields & Kidder 2019) while acting as a cost-effective alternative to full coverage survey to detect earthen or masonry archaeological features that is generally time-consuming, expensive, and often impossible in remote tropical regions.

In this paper, we present the results of preliminary work carried out with a RIEGL VUX-1 UAV Lidar sensor integrated into an MD 500 helicopter. Unlike the majority of the papers in this volume that reflect on the two decades of Lidar use in different parts of the world, this article describes the results of the first Lidar application in Acre, Brazil, SW Amazonia to understand the settlement patterns and architectural grammar of the Mound Village tradition. We discuss the successes and challenges in identifying archaeological features. We carried out Lidar survey in three

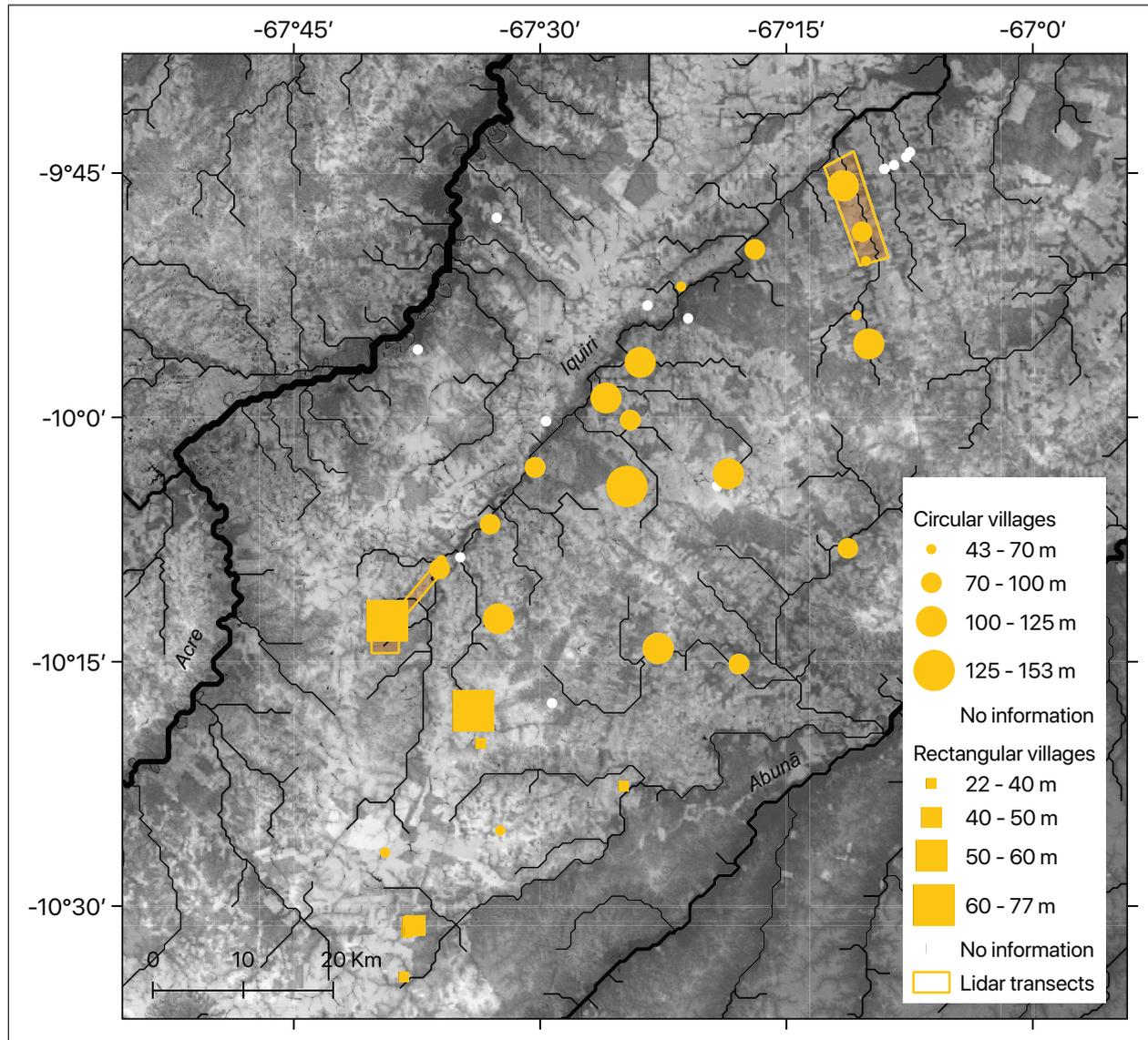


Figure 2: Map of our study region showing lidar transects and spatial distribution of Mound Villages.

selected small transects (Figure 2) due to our limited budget, and therefore, the Lidar data was complemented by satellite remote sensing to investigate regional settlement patterns. In addition, in order to compare our study region with other parts of Acre state, we include Lidar data from the Iracema-Cazumbá Extractive Reserve collected for the ERC FUTURES project (Figure 3b) and from previous tests of our UAV-Lidar system (Khan et al. 2017) that shed light on the Sanna Rectangular village (Figure 8a) and Geoglyphs sites (Figure 12). Since many of the Mound Village sites are near Geoglyph sites, we also briefly report some of the findings related to the Geoglyphs that appear in the Lidar maps. Based on the Lidar results, we conducted excavations in four Mound Village sites (Caboquim, Boa Esperança, Dois Circulos, and Tocantins), which are the subject of a manuscript in preparation (Robinson et al. in prep). The concluding section of the paper consists of a broader discussion of potential cultural affiliations, site construction histories, and research questions to move regional investigations forward.

2. Brief Archaeological Background

The nature and scale of Pre-Columbian land use and its modern legacy on Amazonian landscapes is a debate that remains largely unresolved because huge swaths of the rainforest are still unexplored (e.g., Souza et al. 2018) and because in many regions Amazonian archaeology is still in its infancy. The upland (*terra firme*) forests that account for ~95% of the Amazon are particularly uncharted. These areas have been archaeologically neglected following traditional views that Pre-Columbian people concentrated on resource-rich floodplains (Lathrap 1970; Meggers 1996). More recently, palaeoecologists (McMichael et al. 2012) have proposed that the western Amazon was sparsely populated based on inappropriate integration of palaeoecological records with incomplete archaeological records (see Watling et al. 2017). The unexpected discovery of hundreds of large-scale ditched geometric earthworks, known as Geoglyphs, among the upland *terra firme* rainforests of western Amazonia (Dias & Carvalho 1988; Pärssinen, Schaan & Ranzi 2009; Schaan 2012; Saunaluoma & Schaan 2012; Souza et al. 2018) has called into question

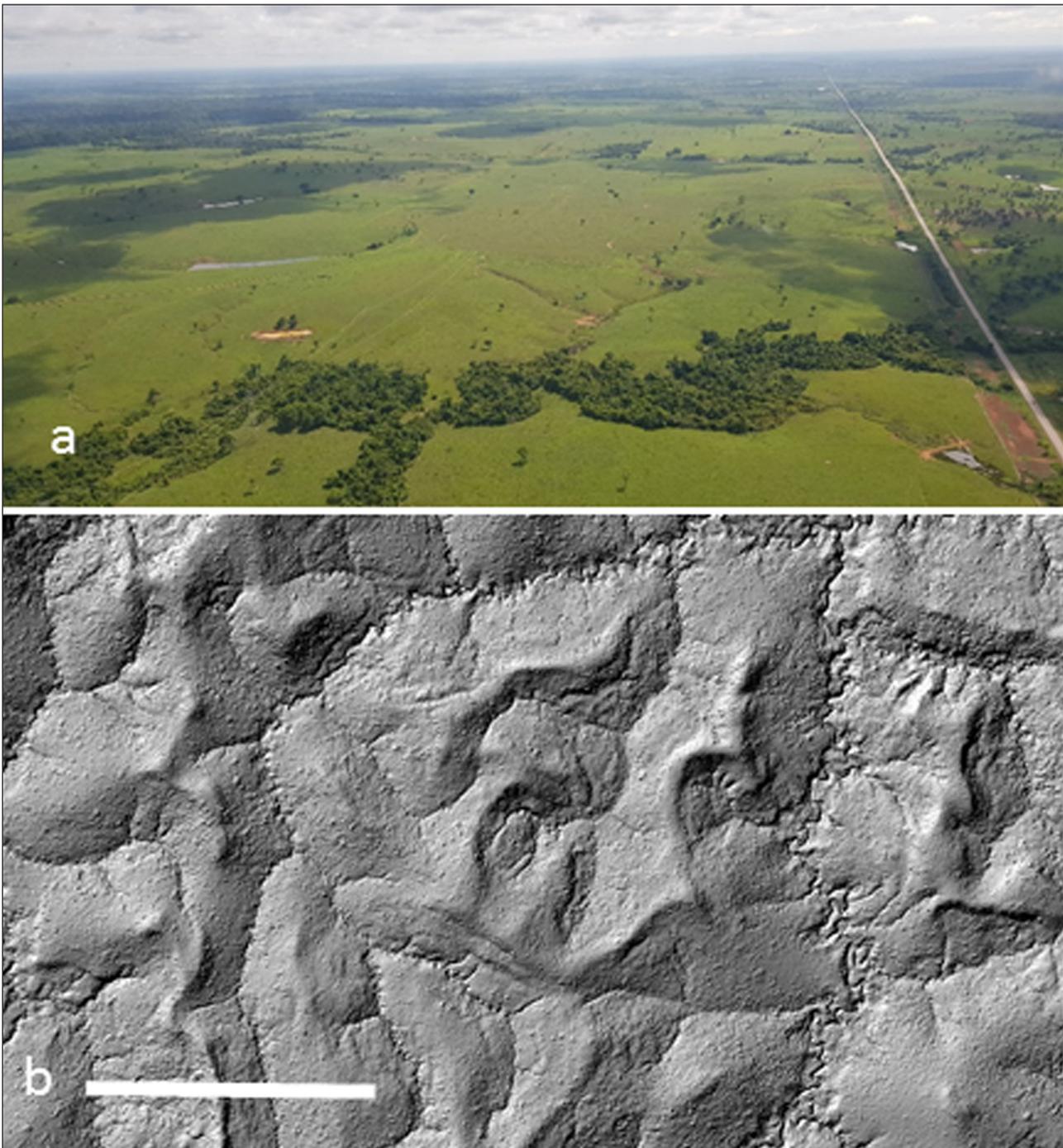


Figure 3: Topography of Acre state. **a.** Aerial view of area around Fazenda Iquiri circular mound village showing extensive plateaus on the SE portion of Acre state. **b.** Lidar image of dissected landscape at the Cazumbá-Iracema Extractive Reserve. Scale bar = 500 m.

traditional views of cultural development in interfluvial areas of Amazonia (Meggers 1996). Prior to the onset of large-scale deforestation in the 1980s, Acre state was completely blanketed by upland humid rainforest, assumed by most tropical ecologists to be pristine. It was only after large-scale deforestation that these previously hidden earthworks become visible. Although the region was initially known archaeologically for these massive geometric ditched enclosures, archaeological work has begun to document a diversity of earthen architecture (see Schaan 2012 for a history of the archaeology of the region). Notably, among the recent discoveries are the so-called Mound Village sites. Currently, three major distinct types

of earthworks have been described for SE Acre: i) geometric ditched enclosures, known as ‘Geoglyphs’, ii) Circular walled enclosures, and iii) Mound villages (Saunaluoma, Pärssinen & Schaan 2018). Below is a brief description of the three main types of earthworks present in the region.

Geometric ditched enclosures (Geoglyphs) consist of continuous ditches and banks of various shapes and are notable for their symmetry. They date from ~400 BC–AD 950 and are geographically restricted to the eastern sector of Acre, and adjacent parts of Amazonas and Rondônia states also in Brazil. The architecture of Geoglyph sites can be complex, juxtaposing square and circular ditches, walled enclosures, mounds and causeways, suggesting a

long history of construction and remodelling. The ditches are on average 11 m wide and up to 4 m deep, with external embankments up to 2 m high. The enclosures generally surround an area of 1–3 ha, although larger sites exist up to 15 ha. Avenues, delineated by low banks, frequently connect the separate enclosures and link them to streams carved in the upland soils. They are generally located on the edges of plateaus, 180–230 meters above sea level (masl), with good views of the surrounding landscape and ca. 1.5–8 km from navigable river courses. The low ceramic density, presence of votive deposits inside ditches, and the lack of Anthropogenic Dark Earth (ADE) or other signs of permanent occupation associated with the enclosures have led to their interpretation as public spaces for cyclical gatherings and communal feasting (Schaan 2012; Schaan et al. 2012; Saunaluoma, Pärssinen & Schaan 2018; Saunaluoma & Schaan 2012).

Circular walled enclosures are far less well known. They constitute circular embankments enclosing areas of 1–2 ha connected by a straight road leading to the entrance of the enclosure (Saunaluoma, Pärssinen & Schaan 2018). Excavations in circular walled enclosures recovered domestic debris, including large ceramic containers and grinding stones, but also funerary urns (Neves et al., 2016; Nícoli 2000; Saunaluoma, Pärssinen & Schaan 2018). The few available radiocarbon dates point to a later construction, from ~AD 1400 to colonial times.

Mound Villages consist of circular, rectangular, or elliptical arrangements of mounds surrounding a central plaza from which roads radiate in patterned directions. The Mound Villages represent a new architectural tradition that emerged when the ‘Geoglyph’ formative ceremonial network was dissolved ~1000 AD, a phenomenon that may be related to climate change during this time period (see de Souza et al. 2019). They spread from the Tapajós headwaters to the eastern and southern sectors of Acre, spanning over 1000 km (Saunaluoma, Anttiroiko & Moat 2019; Saunaluoma, Pärssinen & Schaan 2018; Souza et al. 2018; Virtanen & Saunaluoma 2017). Mound Villages include two distinct types: Circular/Elliptical types locally called ‘Sóis’ (Suns) (e.g., Sol de Iquiri, Sol de Campinas), due to their shape as seen from the sky, and Rectangular types. Thus far, only the circular/elliptical types have been excavated. They date to ~AD 1000–1650 with most dates falling between ~AD 1200–1500 (De Souza et al. 2019). Excavations at the mounds reveal clear occupational strata with domestic features and adjacent middens, confirming their function as settlements (Schaan et al. 2012; Neves et al. 2016; Saunaluoma, Pärssinen & Schaan 2018). Trench excavations in mounds have revealed discrete layers interpreted as alternating construction and occupation episodes. Construction layers are generally thicker, contain decomposed laterite, lack charcoal, ceramics, and macrobotanical remains, and are less compacted than occupation layers. The latter are more compact, thinner, darker, and contain larger quantities of artefacts and ecofacts (Neves et al. 2016). Mounds may contain more than 10 occupation layers intercalated with construction events with a 250-year temporal span (Robinson et al. in preparation). The ceramics associated with the Circular Mound Villages of Acre are generally

cruder than the ceramics of the Geoglyphs (Saunaluoma, Pärssinen & Schaan 2018). Since research on Mound Villages is still in its infancy, little is known about their portable material culture, but preliminary data show differences relative to the earlier ditches, such as the presence of red-painted geometric designs on a white-slipped surface (Saunaluoma 2010). Archaeobotanical analysis at Sol de Campinas documented maize (*Zea mays*), Brazil nut (*Bertholletia excelsa*), maracuja (*Passiflora edulis*), muruci (*Byrsonima cf. crassifolia*), palms including tucuma or murumuru (*Astrocaryum* sp.), and Chenopodiaceae seeds (Neves et al. 2016). Kistler et al. (2018) have proposed that Mound Villages could also be related to the second major west-to-east cultural expansion of maize traditions that appear to have taken place ~AD 800–1000 and afterwards with the spread of the Mound Villages and fortified villages throughout southern Amazonia, and ring villages in the central Brazilian savannas and along the Atlantic coast. Kistler et al. (2018) suggest that Arawak speakers likely brought non-local Andean/Pacific maize lineages into a landscape where maize was an established component of long-term land management and food production strategies. The site layout and regional settlement patterns of Mound Villages are the focus of this paper and will be described in more detail in the Results section below.

3. Study Region

Our study region is in the south-eastern portion of Acre (Figures 1 and 2). The climate is characterised by seasonal precipitation ranging from 1566 to 2425 mm/year (average 1944 mm/year) (Duarte 2005), with the east being drier than the west. Most rainfall occurs during the rainy season (October to April), while the dry season (June to August) can bring severe droughts (Aragao et al. 2007). The state is situated between two geological formations: the Andes to the west and the Brazilian shield to the southeast. The orogeny of the Andes continues to form the relief, soils, and hydrological basins through the uplift, deposition, and reworking of sediments (Silveira et al. 2008). Acre’s “eroded washboard” relief is gently undulating with close regularly spaced hills over most of the state, only becoming steeper upstream from the major rivers. The south-eastern sector of Acre where most geometric ditched enclosures and Mound Villages are located exhibits extensive plateaus (study area shown in Figure 2) compared to other portions of Acre like the Cazumbá-Iracema RESEX where Lidar has revealed a dissected landscape lacking earthen architecture (Figure 3b). The soils are mainly sandy clay sediments belonging to the Solimões Formation, which formed via Andean uplift between the end of the Miocene and Pliocene (Westaway 2006). Like most Amazonian soils, they are highly acidic, shallow, and poorly drained, which means that they have low agricultural potential when unmodified (Silveira et al. 2008). Many rivers drain the state in a northeasterly direction, the largest of which are the Juruá and the Purus, which carry heavy sediment loads due to their meandering forms. Floodplains and terraces comprised of more fertile alluvial soils flank the Juruá, Purus, and Acre rivers, but are either absent or very limited along the smaller rivers (Silveira et al. 2008). Botanical inventories conducted in eastern Acre have shown that its

forests have floristic similarities with drier formations of the Central Amazon. Although less diverse than forests near Manaus, their alpha diversity is higher than roughly half of the similar inventories throughout Amazonia (Silveira et al. 2008). In contrast to the dense forests present in the Central Amazon, most of Acre is covered by forms of open forest that allow greater light penetration to the understory and the growth of bamboo, palms, and other monocots (Silveira et al. 2008). The three polygons where Lidar survey was carried out (**Figure 2**) are characterised by bamboo forest, palm forests on alluvial soils, and palm dense humid evergreen forest (Watling et al. 2016).

4. Methods

4.1. Sample selection

Based on published data (Neves et al. 2016; Saunaluoma, Anttiroiko & Moat 2019; Saunaluoma, Pärssinen & Schaan 2018; Schaan et al. 2012) and our inventory of Mound Villages discovered using satellite remote sensing in deforested areas (Banco de Dados 2019) (**Figure 2**), we selected two areas for Lidar coverage. One exhibits known concentrations of Mound Villages along major streams (Dona Maria and Estrela do Norte transects) and another shows complex earthen architecture associated with Mound Villages (Dois Circulos transect).

4.2. Lidar data acquisition

Lidar data was collected using a Reigl VUX-1 UAV Lidar scanner, with an Applanix APX-15 IMU (Inertial Meas-

urement Unit), and an Antcom G5Ant-1AS1-RoHS GNSS designed for small, low altitude, aerial missions. UAV integration is described in Khan et al. (2017). To collect data in regions that were inaccessible for the UAV, a mount was constructed for integration onto a helicopter. For the missions discussed in this paper, the system was integrated with a MD 500 helicopter. We designed and constructed a portable pod to house the VUX-1 scanner, with a flexible attachment design for mounting on a range of helicopter models. The pod was constructed from an off-the-shelf lockable hard plastic box, measuring 30 × 25 × 18 cm. A removable stainless-steel base plate was fitted to the interior of the box, onto which the VUX-1 was attached. A stainless-steel plate was affixed to the exterior of the box to reduce vibration between the helicopter and the sensor. Two stainless steel U bolts were fitted to the plate to allow the pod to attach to a 6 cm diameter aluminium pole. The 3 m aluminium pole attached to the helicopter landing struts. The APX-15 GNSS receiver was attached to a stainless-steel plate extension off of the front of the attachment plate. The VUX-1 was powered from the helicopter battery and controlled via LAN to an onboard laptop using RiAcquire software (**Figure 4**).

The data were collected during three flights on 10–12 October 2018, at the end of the dry season in this part of Amazonia. The missions were planned to last approximately two hours each, which was optimal in terms of helicopter fuel load, area covered, and pilot fatigue. Each



Figure 4: VUX-1 integrated into the Bell 500M helicopter.

mission consisted of parallel flight lines, with a minimum of 40% overlap. Missions were flown at 150 m altitude at 40 knots with a scanner frequency of 200 khz. The area covered by each mission is as follows: Dois Circulos, 12.9 square km; Estrela do Norte, 9.81 square km; and Dona Maria, 42.9 square km totalling 65.61 square km.

4.3. Lidar data processing

POSPac UAV 8.3 was used for all trajectory processing. Due to the remote location of the research area, no ground control stations are available to calibrate GNSS data. As such, rectifying the trajectory relies on mobile satellite data. Initially, the only option available was the Precise Point Positioning (PPP) method. This method inherently has errors and imprecision. The results of this method were sub-optimal, creating a challenge for the accurate generation of a trajectory. As such, when the generated trajectory is combined with the laser data, there is a misalignment between scan lines that could reach up to 2 m. Manual processing to rectify this misalignment is highly time consuming and was unable to produce acceptable results. The misalignment ultimately did not allow the accurate identification of ground points, which precluded the creation of a Digital Elevation Model (DEM).

The release of the licensed extension PP-RTX within POSPac, using Trimble's RTX technology, provided a solution. While the annual license results in an additional cost, the processing enabled the generation of acceptably aligned data, with <10 cm error. The PP-RTX generated trajectory was subsequently combined with the laser data in RiProcess. Further processing in RiProcess refines the alignment of scan lines and removes noise from the dataset. This includes laser returns from airborne entities, such as birds or clouds, and outlying laser data. After testing export variations, a final processing step was added that trims each scanline to remove the outer edges of data, where point density is low. An automatic option to reduce the scan angle is available. However, the results were not as good as manual selection of the points. Manual selection allows direct assessment of the data and point density in every area of the scanline, whereas the automatic filter is non-discriminatory and would often keep areas of low-quality data, or conversely exclude areas of high-quality data.

4.4. Lidar data visualisation

The processed data are exported as .las or .laz (compressed) files for further analysis and visualisation. Due to the size of the files, separation of the data into smaller tiles was preferable to facilitate file manageability and further processing. The exported data includes all laser points (vegetation and ground). The exported data are further processed depending on the research question and desired output. The software Lastools and ArcGIS were primarily used for further processing. Lastools enables the classification of points based on automated detection processes. The process Lasground was used, with user defined parameters to classify and separate the ground data points from the vegetation data points. The classified ground points were converted to a DEM and saved as a georectified .tif. The

separated ground points were imported into ArcGIS as a DEM for analysis and visualisation.

4.5. Remote sensing and ground truthing

Deforested areas of our study region were systematically surveyed using free satellite imagery available in Google Earth v 7.1.8.3036 and <http://zoom.earth>. We conducted opportunistic ground-truthing and test excavations, and these results will be presented separately (Robinson et al. in prep).

5. Results

Combining satellite and Lidar data, we have documented 25 Circular Mound Villages and 11 Rectangular Mound Villages in our study region of Acre (**Table 1**). Another 15 Mound Villages cannot be assigned to either the circular or rectangular category using satellite remote sensing due to their poor preservation. Below we describe the settlement patterns and architectural grammar of Mound Villages with emphasis on the data visible within the Lidar coverage.

5.1. Mound Villages layout

The results of our Lidar and remote sensing survey show that there are two major types of Mound Villages: circular/elliptical villages (or Circular Mound Villages) (**Figures 5, 6, 7 and 9**) and rectangular villages (or Rectangular Mound Villages) (**Figure 8**). Circular Mound Villages are comparable to other circular villages across lowland South America, but they exhibit several idiosyncratic features that set them apart from other traditions. Their singular features include ranked, paired, cardinaly oriented, radial sunken roads exhibiting high banks and elongated mounds (among other mound shapes) positioned around the circle like the marks of a clock. These latter elongated mounds, when seen from above, look like the rays of the sun, which gives them the common name of 'Sóis.' They exhibit a strikingly uniform and consistent construction. The arrangements, shapes, and sizes of the mounds in conjunction with radial road structures are repetitive and remarkably similar. The diameter of Circular Mound Villages ranges from 40 m to 153 m (average of 86 m; $n = 23$) with the area enclosed by the central plaza ranging from ~0.12 to 1.8 ha. Site size variation does not show any trends toward a bimodal distribution of site size that could clearly indicate a hierarchical settlement pattern.

Mounds are arranged in clusters of 3 to 32 with the former cases most likely corresponding to sites that have been partly destroyed. They contain a diversity of mound shapes. Elongated dome-shape mounds are ca. 20–25 m long, 1.5 to 3 m high, and are oriented around the circle like the marks of a clock, with their major axis orientated to radiate outwards from the centre of the circle of mounds. The mound slopes are steeper towards the village plaza and gradually fade away from the circle, forming what appear to be access ramps to the top of mounds. Along with the elongated mounds, these sites also exhibit larger platform mounds and conical mounds. The latter need further investigation to understand their construction history and uses. Unlike ethnographic and

Table 1: Inventory of Mound Villages in the study area.

ID	Site Name	x (UTM 19S)	y (UTM 19S)	Classification	LIDAR	Number of mounds	Mound shape	Entrance shape	Paired	Main avenue directions	Diameter (m)	Associated features	Elevation (m)
1	Aparecida do Norte I	705710	8924021	Irregular	No				No			Square Geoglyph	140
2	Caboquim	700331	8915044	Circular	Yes	26	Elongated and square	L	Superimposed	North/South	84		140
3	Coqueiral	680928	8905338	Irregular	No	10	Elongated		No	North/South			160
4	Dois círculos IV	647270	8871232	Rectangular	Yes	16	Elongated and square		Twins		77	Circular Geoglyph	200
5	Dois círculos V	647803	8871561	Irregular	Yes	32	Elongated and square		Twin/Super-imposed		68	Circular Geoglyph	200
6	Dona Maria IV	698270	8920257	Circular	Yes	12			Twins		105	Square Geoglyph	160
7	Dona Maria V	697792	8919995	Circular	Yes	16	Elongated and square		Twins			Square Geoglyph	160
8	Estrela do Norte I	653169	8877129	Circular	Yes	12			Twins		84	Square Geoglyph	170
9	Estrela do Norte II	653379	8878115	Irregular	Yes	12			Twins		67	Square Geoglyph	160
10	Fazenda Boa Esperança	700753	8911712	Circular	Yes	14			No	North/South	55		160
11	Fazenda Iquiri II	674027	8886364	Circular	No	19	Elongated		No	East/West	153	Square Geoglyph	190
12	Fazenda Tocantins	699646	8905612	Circular	Yes	18		L	No	East/West	60		150
13	Fonte Boa II	684072	8886375	Circular	No				No			Square Geoglyph	210
14	Gavião VI	649260	8836229	Rectangular	No	5	Elongated		Twins	Sudeste	33		210
15	Gavião VII	649417	8836048	Rectangular	No	7	Elongated		Twins	North	35		210
16	Gavião VIII	650216	8836814	Rectangular	No	6	Elongated		No		50	Square Geoglyph	210
17	Independência	655462	8878437	Irregular	Yes				No	North/South			170

(Contd.)

ID	Site Name	x (UTM 19S)	y (UTM 19S)	Classification	LIDAR	Number of mounds	Mound shape	Entrance shape	Paired	Main avenue directions	Diameter (m)	Associated features	Elevation (m)
18	Karina	658805	8882164	Circular	Yes	11	Elongated and square		No	North/South	72		160
19	Lidar	676417	8906822	Irregular	Yes	3			No				170
20	Montículos Plácido	677412	8868019	Circular	No	20	Elongated		No	East/West	115		150
21	Nakahara 79	698560	8879231	Circular	No				No	North/South	77		160
22	Nakahara 88 II	673493	8852425	Rectangular	No	8	Elongated and square		No	North/South	33		180
23	Nakahara 104	657597	8857397	Rectangular	No	8	Elongated	L	No	East/West	34		200
24	Nakahara 136	590803	8853516	Rectangular	No	10	Elongated and square		No		55		210
25	Nakahara 166	649418	8837242	Rectangular	No	9	Elongated	L	No	North/South	35	Square Geoglyph	190
26	Nakahara 174	656854	8861015	Rectangular	No	7	Elongated	L	No	North/South	72	Circular Geoglyph	210
27	Nakahara 177	659686	8871460	Circular	No	7	Elongated		No	South/East	115		200
28	Nakahara 180	665065	8893773	Irregular	No				No	North			180
29	Nakahara 195 II	702868	8922127	Irregular	No				Twins	North/South		Square Geoglyph	140
30	Nakahara 195 III	703926	8922561	Irregular	No				Twins	North/South		Square Geoglyph	150
31	Nakahara AC 207	650843	8901952	Irregular	No				No				160
32	Nakahara AC 209	659674	8916810	Irregular	No				No				150
33	Nakahara 223	464778	8815609	Circular	No				No		40		270
34	Nakahara 225	648998	8831007	Rectangular	No				No	North	22		200
35	Nakahara 226	659757	8847511	Irregular	No	3	Elongated		No	North/South	66		220
36	Nakahara 227	665579	8861886	Irregular	No				No				190
37	Nakahara 228	663813	8888556	Circular	No	8	Elongated	L	Twins	South	80		160

(Contid.)

ID	Site Name	x (UTM 19S)	y (UTM 19S)	Classification	LIDAR	Number of mounds	Mound shape	Entrance shape	Paired	Main avenue directions	Diameter (m)	Associated features	Elevation (m)
38	Nakahara 229	686380	8866200	Circular	No	9			No		72		150
39	Nakahara 230 I	671748	8896379	Circular	No	10	Elongated		Twins	North/South	105		160
40	Nakahara 230 II	672121	8896351	Circular	No	9	Elongated	L	Twins	North/South	73		160
41	Peter 1	680162	8908938	Irregular	No	6	Elongated	L	No	Noroeste	43		160
42	Peter 2	688398	8913104	Circular	No	9	Elongated		No	Noroeste/sudeste	77		140
43	Peter 3	705294	8923462	Irregular	No				No				140
44	Ramal Nabor Junior I	701011	8902345	Circular		5		L	No	North/South	104		150
45	Sanna	672735	8906845	Rectangular	Yes	7	Elongated	L	No	South		Square Geoglyph	200
46	Sol do Alceu	441809	8793705	Circular	No	4			No		89		280
47	Sol do Iquiri	675577	8900386	Circular	No	16	Elongated and square	L	No	East/West	114		150
48	Sol de Campinas	685329	8887733	Circular	No	15	Elongated		No	North	106		170
49	Sol de Maio	674441	8893856	Circular	No	17			No	North	100		170
50	Sol do Nakahara I	663896	8888254	Circular	No	11	Elongated	L	Twins	North/South	50		160
51	Sol do Nakahara II	646957	8845072	Circular	No		Elongated		No		55		220

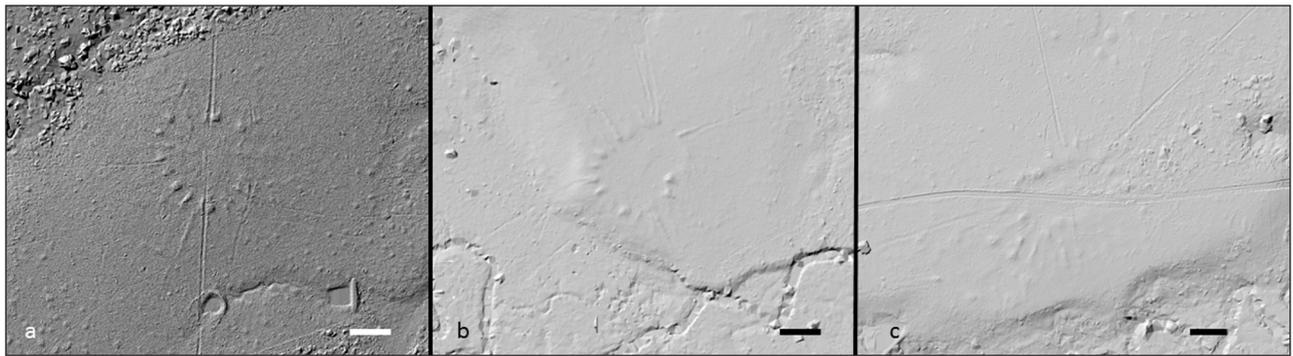


Figure 5: Example of Circular Mound Villages. **a.** Fazenda Boa Esperança. **b.** Karina. **c.** Estrela do Norte I. Scale Bar = 50 m.

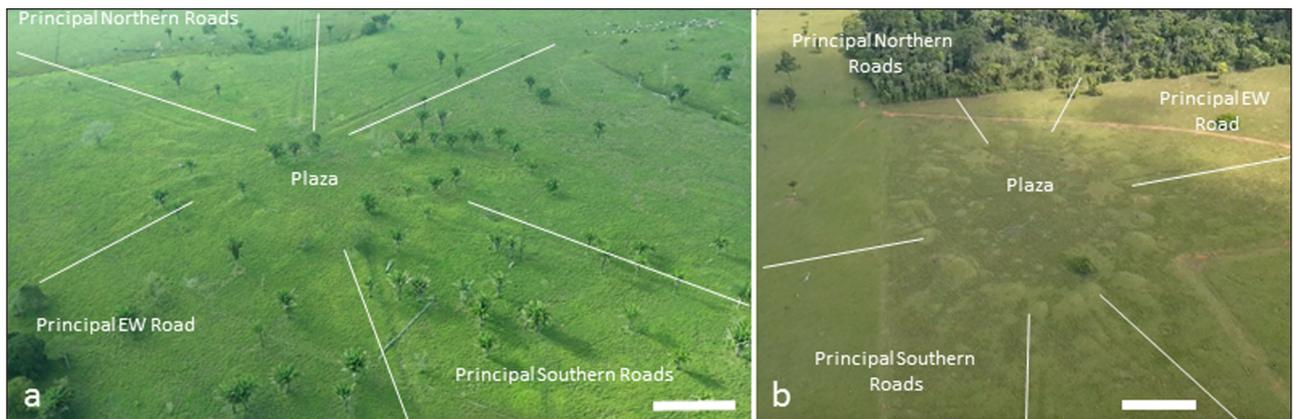


Figure 6: Examples of Circular Mound Villages highlighting Principal Roads and Plaza area. **a.** Sol de Camila. **b.** Sol de Iquiri. Scale Bar = 50 m.

archaeological circular villages, which usually exhibit more than one concentric ring of domestic units, like the Ring Villages of Central Brazil (Wüst & Barreto 1999) or a central formal sector surrounded by informal architecture like the mound villages of Uruguay (Iriarte 2006), the Circular Mound Villages of Acre only contain a single ring of mounds. The potential presence of structures, such as men's houses or cemeteries that are a common feature within the central plaza area in other circular plaza village tradition, need further archaeological testing.

Circular Mound Villages show a hierarchy of roads: Principal Roads and Minor Roads (Figure 6). Principal roads are deeper, wider (3–6 m), and exhibit higher banks. Most of them exhibit two principal roads leaving in a northward direction (Principal Northern Roads) and two principal roads leaving in a southward direction (Principal Southern Roads). They are generally situated at 310–320 to 30–40-degree angles. The roads come closer together without connecting to each other as they approach the village. Generally, when the roads contact the village the banks became higher and wider. They cut through the mounds producing a rather straight mound profile and/or creating a double-L-shaped feature as a prolongation of the banks. These mounded structures are generally taller than the rest. Circular Mound Villages are also often cut by a Principal East-West Road. Principal roads become narrower as they move away from the site. Although they run separately from the village, they can reconnect forming a single trail like in the case of Principal Southern

Roads connecting Dona Maria and Caboquim (Figure 10). Circular Mound Villages also usually exhibit minor roads that lead to streams nearby.

The distinct architectural layout of Rectangular Mound Villages places them into a category of their own. While preliminarily we call them villages, their uses will be determined with future archaeological excavations. Besides the rectangular shape, the most diagnostic features are their rectilinear elongated mounds that define the perimeter of the structure, forming a rectangular enclosure with openings, some of which connect to roads. The diameter of Rectangular Mound Villages ranges from 22 m to 77 m (average of 45 m; $n = 10$). The number of mounds ranges from 5 to 16 – with the former cases most likely corresponding to sites that have been partly destroyed.

Lidar data has allowed us to identify new features of Mound Villages including the discovery of new sites below the forest canopy, the exposure of superimposed villages, and the detection of roads clearly connecting villages. A new Circular Mound Village was discovered below a forested area 500 m to the east of the Dona Maria site which is connected by the Principal East-West road (Figure 7). Ground reconnaissance of Dona Maria II in October 2019 confirmed its nature as a Circular Mound Village. Paired Circular Mound Villages connected by a road, like the one reported here, are emerging as a common pattern in the region (e.g., Sol de Campinas and Fonte Boa, Nakahara 230 I and II, Sol de Nakahara and Nakahara 228) reminiscent of dual patterns of

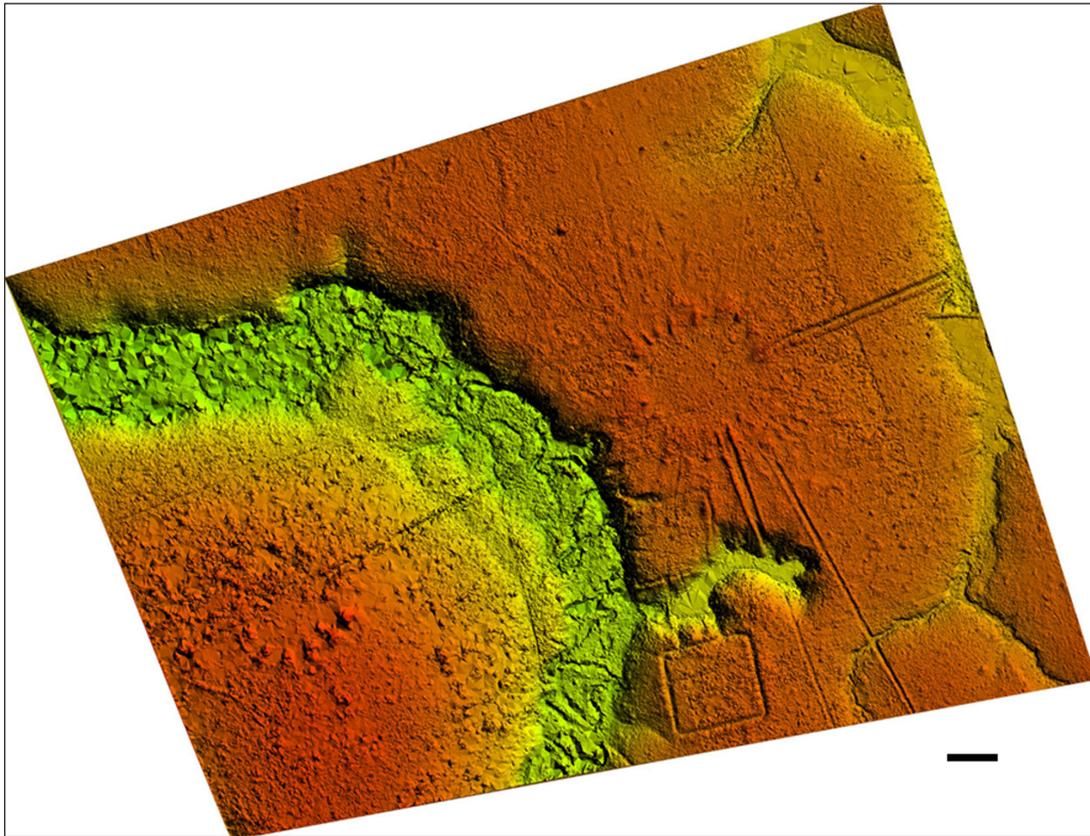


Figure 7: Detail of Dona Maria with 'twin' village. Scale Bar = 50 m.



Figure 8: Rectangular Mound Villages. **a.** Sanna. **b.** Dois Circulos. **c.** Estrela do Norte II. Scale bar = 50 m.

architecture in other regions of lowland South America (e.g., Iriarte et al. 2013; Iriarte et al. 2017). Lidar data from the Sanna Rectangular Mound Village (**Figure 8a**), partially covered by vegetation, reveals its rectangular structure. Lidar data also documents that in many cases, like in Estrela do Norte 2, these sites can be rather informal and asymmetrical (**Figure 8c**). Another interesting aspect that becomes clear with Lidar data is the superposition of Circular Mound Villages, like the ones shown at Caboquim and Dois Circulos (**Figure 9**). The mounds of the earlier village are flatter and are more distorted.

Roads connecting villages become clearly visible with Lidar. In the Dona Maria transect, Lidar data has allowed us to document roads that link Dona Maria to Boa Esperança, passing through Caboquim. These roads are more than 5 km long and show that these villages were interconnected (**Figure 10**). The road connecting Caboquim with Boa Esperança is also visible within

the Lidar coverage (**Figure 11**). Dated structures from Caboquim and Boa Esperança demonstrate that the two villages were broadly contemporaneous (Robinson et al. in prep).

5.2. Preliminary observations about regional settlement patterns of Mound Villages

Circular Mound Villages are generally located in small flat plateaus overlooking a stream to which they generally connect by a road. They are largely predominant in the north-eastern portion of our study area, while Rectangular Mound villages are in the south-eastern portion. Circular Mound Villages are significantly closer to rivers than Geoglyphs ($t = 3.376$, $df = 92.46$, $p < .01$), although the difference is not large (averages of 1.4 and 2.1 km, respectively). To further explore the role of river proximity for Mound Villages in contrast to Geoglyphs, we used flow accumulation as a proxy of river navigability. The closest

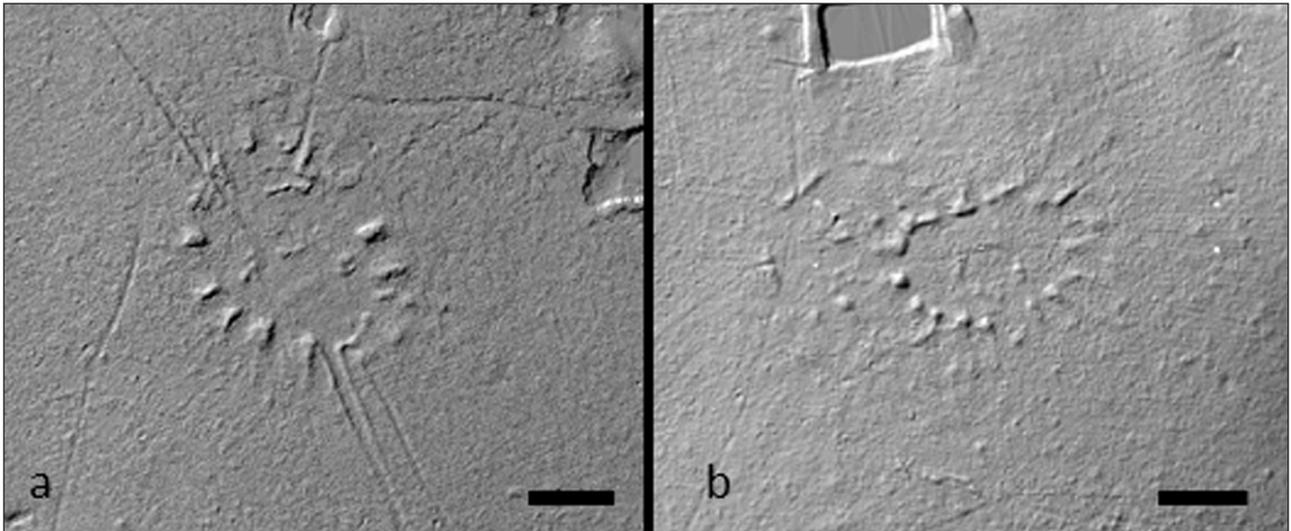


Figure 9: Lidar images illustrating superimposition of Circular Mound Villages: **a.** Caboquim. **b.** Dois Circulos. Scale Bar = 50m.

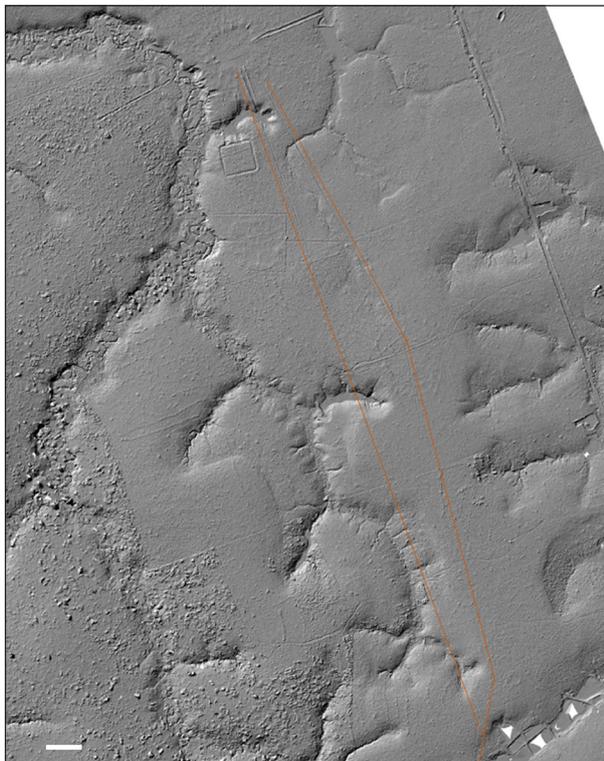


Figure 10: Fragment of Principal Southern Roads connecting Dona Maria with Caboquim. Scale bar = 100 m.

rivers to Mound Villages have a much higher flow accumulation than in the case of the Geoglyphs (averages of 3925 and 864 cells, respectively) and are, in theory, more navigable. However, this observation must be taken with caution, since the difference was not found to be significant ($t = 1.2623$, $df = 47.242$, $p = 0.213$). If confirmed, the preference for proximity to larger rivers would reinforce the domestic role of Mound Villages as opposed to the ceremonial function of Geoglyphs, for which water transportation was apparently less important. To what extent we can extrapolate today's estimations of flow accumulation to the Geoglyph and Mound Village periods in the past is uncertain. There are no local palaeoclimate records

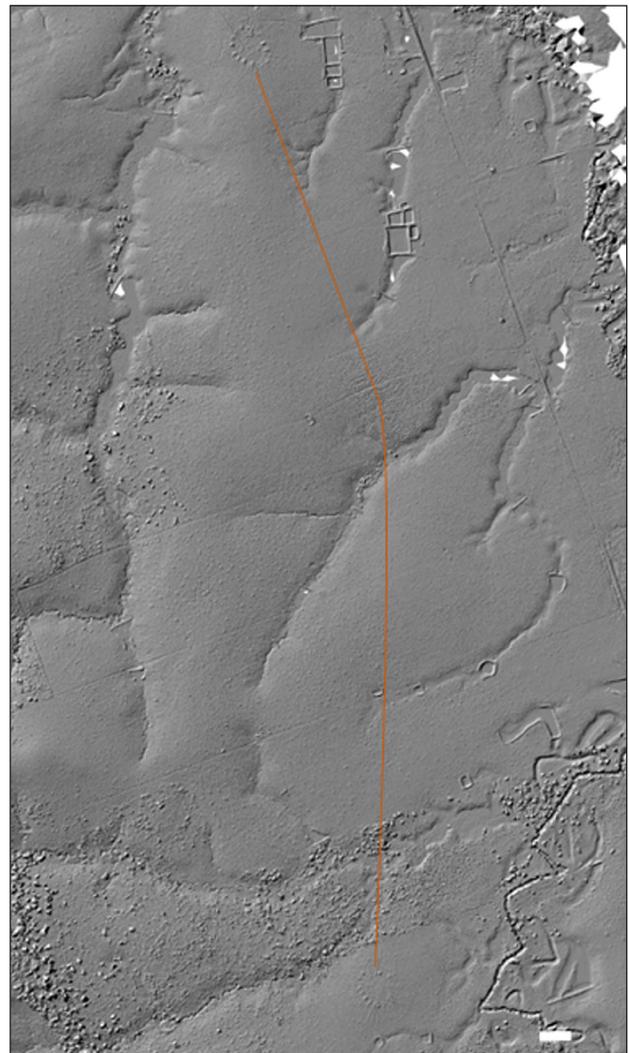


Figure 11: Principal Southern Road connecting Caboquim with Boa Esperança. Scale bar = 100 m.

from the region, but as we summarised in Souza et al. (2019), the end of Geoglyph construction coincides with decreased precipitation in the western Amazon, and in turn, Mound Village construction is coterminous with the

increase of precipitation in the region. How these changes in rainfall influenced flow accumulation, and consequently, river navigability, is a matter for future studies.

Mound Villages are separated, on average, by 4.35 km, but distances are irregular ($NNI = 1.04$, $p = 0.6$). In fact, some regions (e.g., Dona Maria to Boa Esperança) exhibit small distances of 2.5–3 km between sites, whereas others (e.g., Dois Círculos to Karina) have sites separated by around 5–6 km. However, Mound Villages are significantly clustered at small distances (between ca. 500 m and 3.5 km) but not at larger spatial scales (Ripley's K). We argue that the clustering of Mound Villages and the distances separating them are coherent with patterns created by ethnographic settlements (see below). In our study area, 28 out of 48 sites have a Geoglyph as their closest feature, at a mean distance of 1.6 km, whereas 20 sites have another Mound Village as their nearest neighbour, at a similar distance (1.7 km).

5.3. Geometric ditched enclosures

Lidar has been able to detect previously undocumented low-profile rectangular annexed enclosures with interconnected roads. Most of them are not visible within the best satellite data available. In some cases, like at the Chiquiho site, it is easy to distinguish an interior enclosure within the enclosure attached to the Geoglyphs (**Figure 12**). The Lidar acquisition of the Dois Circulos locality underscores the diverse and complex construction history of this location. There is an overlap between the ditched

circles, the low-profile enclosures, and the Mound Village that likely represent phased construction. However, it is impossible to distinguish the sequence, other than that the 'Geoglyph' is older than the Mound Village, without further ground investigation.

6. Conclusion and Discussion

The new data presented here contribute to the understanding of the architectural grammar and settlement patterns of the Mound Villages (~AD 1300–1700) and the geometric ditched enclosures (~400 BC–AD 1000) revealing a much richer and complex archaeology than previously known. Our study confirms that Lidar is a technology that provides a new opportunity to locate and document earthen sites in forested parts of Amazonia characterized by dense vegetation. As we discuss, Lidar can even document the smallest and surficial earthen features in the recently opened pasture areas.

The overall settlement patterns observed in the Circular Mound Villages of Acre have parallels to the archaeology in other parts of the southern rim of the Amazon, as well as clear correlates with ethnographic and archaeological circular villages. In lowland South America, circular villages have their beginnings during the mid-Holocene in disparate regions as far as Ecuador (Lathrap, Marcos & Zeidler 1977) and Uruguay (Iriarte et al. 2004). Ring villages along the southern rim of the Amazon during the late Holocene, mostly built by Arawak and Jê speakers but also by other

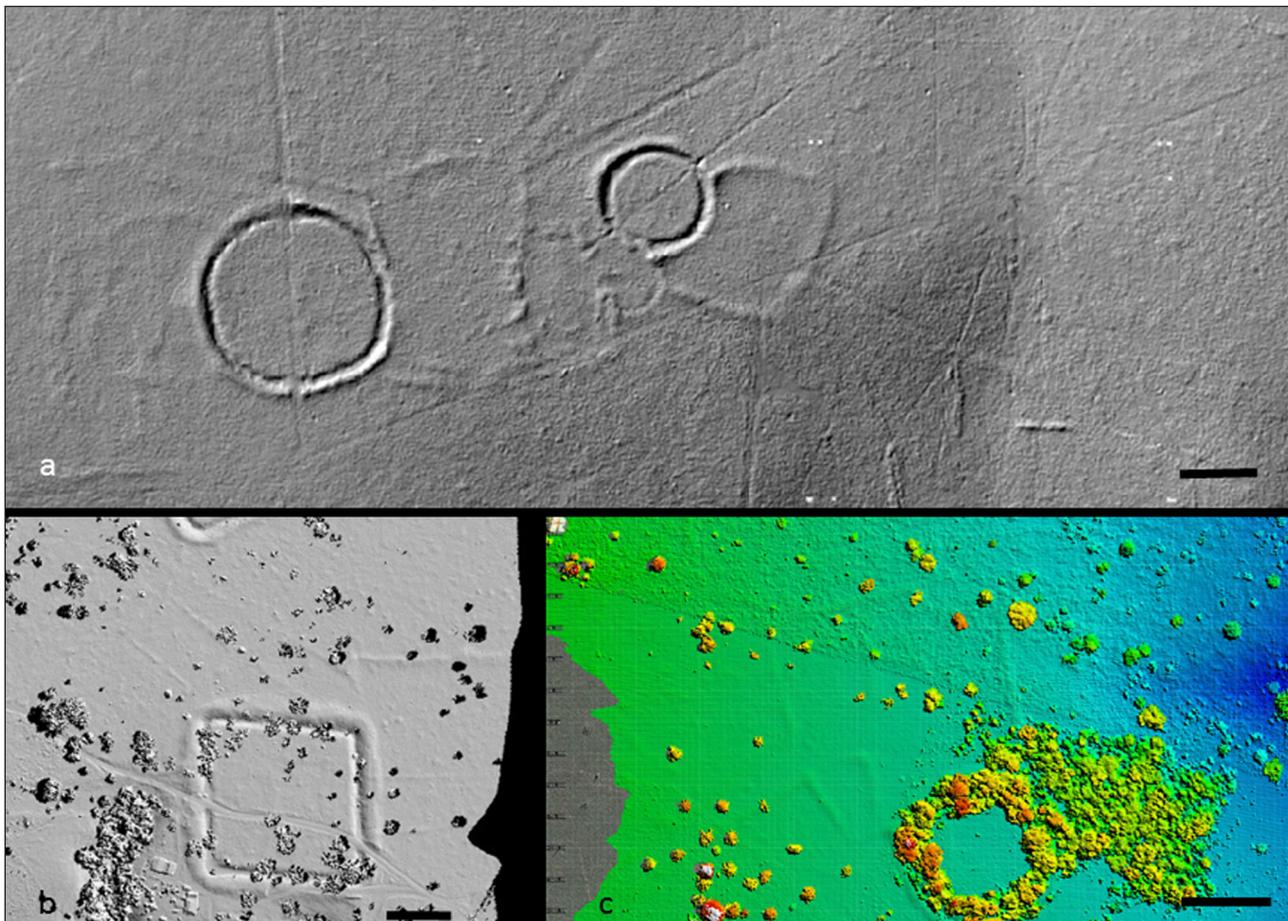


Figure 12: Geoglyph Annex enclosures. **a.** Dois Circulos. **b.** Jaco Sa. **c.** Chiquinho. Scale bar = 100 m.

populations influenced by them, are relatively permanent settlements (Heckenberger 2005; Hill and Santos Granero 2002; Hornborg 2005; Wüst and Barreto 1999). In the Upper Xingu, villages rarely move, except when fissioning – when they tend to remain within the catchment of the mother village (Heckenberger 2005). Archaeological settlements and ethnographic villages in the Upper Xingu are usually separated by distances of 5–10 km following rivers (Heckenberger 2005), matching the pattern found among the Mound Villages of Acre and reinforcing the hypothesis of their contemporaneous occupation. Similarly, road networks connecting villages that are found in the archaeology and ethnography of the Upper Xingu are also present in Acre with distinct characteristics. Contemporary village organisation can shed light on some of the patterns found in the archaeological settlement layouts. For example, Xinguano villages are reported to have their main entrances aligned with the cardinal directions, with chiefs' houses built next to the northern and southern roads (Heckenberger 2005). Distinct features are also apparent in the Circular Mound Villages when the major roads connect with the village: their banks became higher and wider, mounds are generally taller, and in many cases, they create a double-L-shaped feature as a prolongation of the banks. Although the Circular Mound Villages of Acre share many commonalities with the Upper Xingu and the basic circular village template (circle of domestic units around a clean plaza area), they do possess distinctive characteristics that set them apart from this and other archaeological traditions. For example, while they are reminiscent of the Upper Xingu settlements in terms of their standardized layout and formal road architecture connecting villages (Heckenberger et al. 2008), they are distinguished by their smaller size, idiosyncratic diversity of mounded architecture, and a distinct system of roads. The Mound Villages of Acre do not exhibit circular ditches around them, are only constituted by one ring of mounds, and do not display core and peripheral sectors within the site. They are also significantly smaller than the ring villages of central Brazil, which has average village areas of 3.8 ha (Uru Tradition) and 7.2 ha (Aratu Tradition) (Wüst and Barreto 1999). Unlike the historical Xinguano villages and central Brazilian ring villages, we found no evidence of centrally placed structures built in the plaza that may have functioned as ritual “men's houses” (Heckenberger 2005; Maybury-Lewis 1979). It is possible that the absence of such village-level integrative facilities (Adler and Wilshusen 1990) was due to the small size of the Acre settlements, or that the enclosures and/or abandoned Geoglyphs in the surrounding landscape fulfilled community-wide ceremonial purposes. Previous work (Saunaluoma, Anttiroiko & Moat 2019; Saunaluoma, Pärssinen & Schaan 2018) and our analysis shows that Mound Villages exhibit distinctive and rather consistent arrangements, suggesting that ancient Acreans had a very particular social model for how they viewed community layout and village organization. The uniform spatial layout of the mound villages, like many contemporaneous ring villages of the Neotropics, are likely to represent physical representations of the Native American cosmos (Heckenberger 2005; Siegel 1999).

The Circular Mound Villages do not appear to show a clear difference in site size that would suggest centralisation, hierarchy, or the concentration of population at sites. They tend to show continuous gradations pointing to rather fluid and occasional hierarchies. There is also no clear evidence of inter-site hierarchy shown as differential elaboration of mounded architecture, with most Circular Mound Villages showing a consistent pattern of architectural layout. In this regard, regional settlement patterns of the Circular Mound Villages are more like the Ring Villages of Central Brazil (Wüst and Barreto 1999) than the multi-centric pattern of the plaza villages and smaller hamlets arranged in a nested hierarchy characteristic of the Upper Xingu (Heckenberger et al. 2008). Importantly, the variation in size of the ring villages recorded in Central Brazil has been argued to result from cyclical processes of fission and fusion (Wüst 1983; Wüst and Barreto 1999), but even those dynamics are not evident in Acre, where fission and the consequent formation of “twin villages” appears to have been more common (see below). The extent to which some of the larger Circular Mound Villages that are associated with Geoglyphs could represent central sites of this social system warrants further exploration.

Some dynamics related to village movement may be reflected in the archaeological record exposed by Lidar at the Dois Circulos I and Caboquim site. This may be especially the case with “twin” or superimposed Mound Villages. Many Amazonian forest farmers relocate their settlements 500 m–1 km every couple of years in order to be closer to newly opened gardens, and distant from rotting of houses, frequent deaths, internal disputes, warfare, and/or sanitary conditions (Craig & Chagnon 2006; Gross 1983; Hames 1983a; Hames 1983b; Souza 2011). Longer movements happen every 10 years to one generation, often relocating to previously occupied spots. Both “micro” moves and returns to former territories may potentially account for archaeological superimposition of Mound Villages and/or settlements that are located in close proximity (“twin” villages). More work is needed to clarify these patterns.

One area where ethnography does not aid in the interpretation of the archaeological record is the formation of habitation mounds. Most Amazonian ethnographic ring villages, when abandoned, do leave a circle of mounds (and, in some cases, anthropogenic soil) created by the accumulation of middens behind the houses (Schmidt 2013; Souza 2011). Interestingly, the archaeological mounds in Acre are formed by superimposition of occupation floors and construction layers (Neves et al. 2016; Robinson in preparation), and in no way do they resemble the middens created by modern villages. Mounds supporting domestic structures, however, do have parallels in the archaeology of the central Amazon (de Paula, Moraes & Neves 2012).

Lidar data has also documented more clearly the road network. This is hardly a surprise for Amazonian archaeologists. Early historical accounts attest to the ubiquity of road networks across the Amazon. They are mentioned since the 16th-century account of Friar Gaspar de Carvajal, who observed wide roads leading from the riverine villages to the interior (Carvajal 1984). Later, the explorer

Antonio Pires de Campos, crossing the headwaters of the Tapajós River in the 18th century, described a vast population inhabiting the region, with villages connected by straight, wide roads that were constantly kept clean (Pires de Campos 1862). Numerous historical accounts in the Llanos de Mojos, Bolivia, describe elevated roads connecting villages and cultivated fields (Eder [1772] 1985). “Old Indian roads” were also reported by Nimuendajú in his work in the Santarem area of Brazil in 1925 (Nimuendajú 2004). Closer to our study area, the account of Colonel Antonio Labre, who travelled from the Madre de Dios River to Acre in the 19th century, is revealing. He mentions ‘[...] many very old abandoned villages, roads crossing each other in all directions, and small cultivated fields [...] a small temple with clean courtyard in a circular form [...]’ (Labre 1889: 496–502). The patterns described above comprising Northern and Southern Principal Roads and EW Minor Roads appear to be unique to these portions of Amazonia. Further investigation to understand how these roads connect at the regional level is needed.

The relationship of Circular and Rectangular Mound Villages poses a similar dilemma due to the lack of archaeological research and the fact that we are dealing with an occupational pattern that endured for nearly 700 years. Differences in site layout may well be part of a contemporaneous settlement system or have temporal significance. No doubt, as more information becomes available on the archaeology of Mound Villages, the relationship between these different types of sites will come into clearer focus.

Our preliminary results have also shown that Lidar has the capacity to transform our understanding of ditch and embankment enclosures. These sites are certainly architecturally more complex and have longer use life history than previously thought. Our Lidar data indicates that these annex enclosures appear to be more common than previously known, opening new ways of interpretation for these sites to be targeted with further investigation. Excavations of these annex enclosures are needed before we can begin to understand the functions that they may have fulfilled at these earthwork sites.

The new results point to some straightforward avenues for future research on the Mound Villages. Below we mention a few that seem more immediate to understand chronology and site uses. At the site level, community focused excavations should be carried out to understand the construction history, uses, and articulation of different forms of mounded architecture such as L-shaped structures, and elongated and conical mounds. Excavations should also occur in off-site areas. Similarly, excavations at the Rectangular Mound Villages can provide the primary chronological data to understand whether they are contemporaneous with the Circular Mound Villages. At the regional level, it is imperative to carry out Lidar acquisition to reconstruct the entire settlement systems.

In conclusion, our data show that after the cessation of Geoglyph construction (~AD 950), human occupation of this region of SW Amazonia was not discontinued, but rather extended with a flourishing regional system of distinct Mound Villages. The results contradict long-held views that envision interfluvial areas of the Amazon, and,

western Amazonia, as sparsely inhabited. The application of Lidar will be essential to have a complete picture of the archaeology of the Amazon. This is particularly so for the largest tropical forest on earth that is typically inaccessible and highly vulnerable to 21st Century earth system change and human impacts, including industrial agriculture and land-clearing for pasture.

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Competing Interests

The authors have no competing interests to declare.

References

- Adler, MA and Wilshusen, RH.** 1990. Large-Scale Integrative Facilities in Tribal Societies – Cross-Cultural and Southwestern United-States Examples. *World Archaeology*, 22(2): 133–46. DOI: <https://doi.org/10.1080/00438243.1990.9980136>
- Aragão, LEO, Malhi, Y, Roman-Cuesta, RM, Saatchi, S, Anderson, LO and Shimabukuro, YE.** 2007. Spatial patterns and fire response of recent Amazonian droughts. *Geophysical Research Letters*, 34(7): L07701. DOI: <https://doi.org/10.1029/2006GL028946>
- Banco de Dados do Grupo de Pesquisa Geoglifos da Amazônia.** 2019. Database on file. Rio Branco: Federal University of Acre.
- Bewley, RH, Crutchley, SP and Shell, CA.** 2005. New light on an ancient landscape: lidar survey in the Stonehenge World Heritage Site. *Antiquity*, 79(305): 636–647. DOI: <https://doi.org/10.1017/S0003598X00114577>
- Bonomo, M, Politis, G and Gianotti, C.** 2011. Montículos, jerarquía social y horticultura en las sociedades indígenas del Delta del Río Paraná (Argentina). *Latin American Antiquity*, 22(3): 297–333. DOI: <https://doi.org/10.7183/1045-6635.22.3.297>
- Brady, C, Davis, S, Megarry, W and Barton, K.** 2013. Lidar survey in the Brú na Bóinne World Heritage Site. In: Cowley, D and Opitz, R (eds.), *Interpreting Archaeological Topography: Airborne Laser Scanning, 3D Data and Ground Observation*, 225–239. Oxford: Oxbow Book. DOI: <https://doi.org/10.2307/j.ctvh1dqdz.23>
- Canuto, MA, Estrada-Belli, F, Garrison, TG, Houston, SD, Acuña, M, Kováč, M, Marken, D, Nondédéo, P, Auld-Thomas, L, Castanet, C, Chatelain, D, Chiriboga, CR, Drápela, T, Lieskovský, T,**

- Tokovinine, A, Velasquez, A, Fernández-Díaz, JC, and Shrestha, R.** 2018. Ancient lowland Maya complexity as revealed by airborne laser scanning of northern Guatemala. *Science*, 361(6409): eaau0137. DOI: <https://doi.org/10.1126/science.aau0137>
- Carvajal, GD.** 1984. *Descubrimiento Del Río de Las Amazonas*. Sevilla: Imprenta de E. Rasco.
- Chase, AF, Chase, DZ, Fisher, CT, Leisz, SJ and Weishampel, JF.** 2012. Geospatial revolution and remote sensing LiDAR in Mesoamerican archaeology. *Proceedings of the National Academy of Sciences*, 109(32): 12916–12921. DOI: <https://doi.org/10.1073/pnas.1205198109>
- Craig, N and Chagnon, N.** 2006. Locational analysis of Yanomamö Gardens and villages observed in satellite imagery. In: SEllet, F, Greaves, R and Yu, P-L. (eds.), *Archaeology and Ethnoarchaeology of Mobility*, 44–74. Gainesville: University of Florida Press.
- De Paula Moraes, C and Neves, EG.** 2012. O ano 1000: adensamento populacional, interação e conflito na Amazônia Central. *Amazônica-Revista de Antropologia*, 4(1): 122–148. DOI: <https://doi.org/10.18542/amazonica.v4i1.884>
- De Souza, JG, Robinson, M, Maezumi, SY, Capriles, J, Hoggarth, JA, Lombardo, U, Novello, VF, Apaéstegui, J, Whitney, B and Urrego, D.** 2019. Climate change and cultural resilience in late pre-Columbian Amazonia. *Nature Ecology & Evolution*, 3: 1007–1017. DOI: <https://doi.org/10.1038/s41559-019-0924-0>
- Dias, O and Carvalho, E.** 1988. As Estruturas de Terra na Arqueologia do Acre. *Arqueo-IAB*, 1: 14–28.
- Duarte, AF.** 2005. Variabilidade e tendência das chuvas em Rio Branco, Acre, Brasil. *Revista Brasileira de Meteorologia*, 20(1): 37–42.
- Eder, FJ.** [1772] 1985. *Breve Descripción de las Reducciones de Mojos*. Cochabamba: Historia Boliviana.
- Erickson, CL and Balée, W.** 2006. The historical ecology of a complex landscape in Bolivia. In: Balee, WL and Erickson, CL (eds.), *Time and Complexity in Historical Ecology: Studies in the Neotropical Lowlands*, 187–234. New York: Columbia University Press. DOI: <https://doi.org/10.7312/bale13562-010>
- Evans, DH, Fletcher, RJ, Pottier, C, Chevance, J-B, Soutif, D, Tan, BS, Im, S, Ea, D, Tin, T and Kim, S.** 2013. Uncovering archaeological landscapes at Angkor using lidar. *Proceedings of the National Academy of Sciences*, 110(31): 12595–12600. DOI: <https://doi.org/10.1073/pnas.1306539110>
- Fisher, CT, Cohen, AS, Fernández-Díaz, JC and Leisz, SJ.** 2017. The application of airborne mapping LiDAR for the documentation of ancient cities and regions in tropical regions. *Quaternary International*, 448: 129–138. DOI: <https://doi.org/10.1016/j.quaint.2016.08.050>
- Gross, DR.** 1983. Village movement in relation to resources in Amazonia. In: Hames, RB and Vickers, WT (eds.), *Adaptive Responses of Native Amazonians*, 429–449. New York: Academic Press. DOI: <https://doi.org/10.1016/B978-0-12-321250-4.50018-X>
- Hames, RB.** 1983a. Monoculture, polyculture, and polyvariety in tropical forest swidden cultivation. *Human Ecology*, 11(1): 13–34. DOI: <https://doi.org/10.1007/BF00891228>
- Hames, RB.** 1983b. The Settlement Pattern of a Ynomamö Population Bloc: A Behavioral Ecological Interpretation. In: Hames, RB and Vickers, WT (eds.), *Adaptive Responses of Native Amazonians*, 329–355. New York: Academic Press. DOI: <https://doi.org/10.1016/B978-0-12-321250-4.50017-8>
- Heckenberger, M.** 2005. *The Ecology of Power: Culture, Place, and Personhood in the Southern Amazon, AD 1000–2000*. New York/London: Routledge. DOI: <https://doi.org/10.4324/9780203486627>
- Heckenberger, MJ, Russell, JC, Fausto, C, Toney, JR, Schmidt, MJ, Pereira, E, Franchetto, B and Kuikuro, A.** 2008. Pre-Columbian urbanism, anthropogenic landscapes, and the future of the Amazon. *Science*, 321(5893): 1214. DOI: <https://doi.org/10.1126/science.1159769>
- Henry, ER, Shields, CR and Kidder, TR.** 2019. Mapping the Adena-Hopewell Landscape in the Middle Ohio Valley, USA: Multi-Scalar Approaches to LiDAR-Derived Imagery from Central Kentucky. *Journal of Archaeological Method and Theory*, 26(4): 1513–1555. DOI: <https://doi.org/10.1007/s10816-019-09420-2>
- Hill, JD and Santos-Granero, F.** 2002. Comparative Arawakan histories: rethinking language family and culture area in Amazonia. Champaign: University of Illinois Press.
- Hornborg, A, Gassn, R, Heckenberger, M, Hill, J, Neves, E, Santosgranero, F and Hornborg, A.** 2005. Ethnogenesis, regional integration, and ecology in prehistoric Amazonia: toward a system perspective 1. *Current Anthropology*, 46(4): 589–620. DOI: <https://doi.org/10.1086/431530>
- Iriarte, J.** 2006. Landscape transformation, mounded villages and adopted cultigens: the rise of early Formative communities in south-eastern Uruguay. *World Archaeology*, 38(4): 644–663. DOI: <https://doi.org/10.1080/00438240600963262>
- Iriarte, J, DeBlasis, P, De Souza, JG and Corteletti, R.** 2017. Emergent complexity, changing landscapes, and spheres of interaction in southeastern South America during the middle and late Holocene. *Journal of Archaeological Research*, 25: 251–313. DOI: <https://doi.org/10.1007/s10814-016-9100-0>
- Iriarte, J, Holst, I, Marozzi, O, Listopad, C, Alonso, E, Rinderknecht, A and Montana, J.** 2004. Evidence for cultivar adoption and emerging complexity during the mid-Holocene in the La Plata basin. *Nature*, 432(7017): 614–617. DOI: <https://doi.org/10.1038/nature02983>
- Iriarte, J, Moehlecke Copé, S, Fradley, M, Lockhart, JJ and Gillam, JC.** 2013. Sacred landscapes of the southern Brazilian highlands: Understanding southern proto-Jê mound and enclosure complexes. *Journal of Anthropological Archaeology*, 32(1): 74–96. DOI: <https://doi.org/10.1016/j.jaa.2012.10.003>

- Khan, S, Aragão, L and Iriarte, J.** 2017. A UAV–lidar system to map Amazonian rainforest and its ancient landscape transformations. *International Journal of Remote Sensing*, 38(8–10): 2313–2330. DOI: <https://doi.org/10.1080/01431161.2017.1295486>
- Kistler, L, Maezumi, SY, De Souza, JG, Przelomska, NA, Costa, FM, Smith, O, Loielle, H, Ramos-Madrugal, J, Wales, N and Ribeiro, ER.** 2018. Multiproxy evidence highlights a complex evolutionary legacy of maize in South America. *Science*, 362(6420): 1309–1313. DOI: <https://doi.org/10.1126/science.aav0207>
- Labre, A.** 1889. Colonel Labre's explorations in the region between the Beni and Madre de Dios rivers and the Purus. *Proceedings of the Royal Geographic Society and Monthly Record of Geography*, 11(18): 496–502. DOI: <https://doi.org/10.2307/1801328>
- Lathrap, DJ.** 1970. *The Upper Amazon*. Praeger: New York.
- Lathrap, DJ, Marcos, J and Zeidler, J.** 1977. Real Alto: an ancient ceremonial center. *Archaeology*, 30: 2–13.
- Levis, C, Costa, FR, Bongers, F, Peña-Claros, M, Clement, CR, Junqueira, AB, Neves, EG, Tamanaha, EK, Figueiredo, FO and Salomão, RP.** 2017. Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. *Science*, 355(6328): 925–931. DOI: <https://doi.org/10.1126/science.aal0157>
- Mann, CC.** 2005. *1491: New revelations of the Americas before Columbus*. New York: Alfred a Knopf Inc.
- Mann, CC.** 2008. Ancient earthmovers of the Amazon. *Science*, 321(5893): 1148–1152. DOI: <https://doi.org/10.1126/science.321.5893.1148>
- Maybury-Lewis, D.** 1979. *Dialectical Societies: The Gê and Bororo of Central Brazil*. Cambridge: Harvard University Press. DOI: <https://doi.org/10.4159/harvard.9780674180727>
- McMichael, C, Piperno, D, Bush, M, Silman, M, Zimmerman, A, Raczka, M and Lobato, L.** 2012. Sparse pre-Columbian human habitation in western Amazonia. *Science*, 336: 1429–1431. DOI: <https://doi.org/10.1126/science.1219982>
- Meggers, BJ.** 1996. *Amazonia: Man and Culture in a Counterferit Paradise. Revised Edition*. Washington, DC, Smithsonian Institution Press.
- Neves, EG, Pugliese, FA, Jr., Shock, MP, Furquim Pereira, L, Zimpel Neto, CA and Gibertoni Carneiro, C.** 2016. Pesquisa e Formação nos Sítios Arqueológicos Espinhara e Sol de Campinas do Acre – PESC – Relatório Final. University of Sao Paulo: IPHAN.
- Nícoli, I.** 2000. Estudo de Cerâmicas de Sítios Arqueológicos Circulares da Bacia Amazônica por Meio de Métodos Geoquímicos: Datação e Caracterização. Unpublished thesis (PhD), Universidade Federal Fluminense.
- Nimuendajú, C.** 2004. *In Pursuit of a Past Amazon: Archaeological Researches in the Brazilian Guyana and in the Amazon Region*. Gotenborg: Elanders Infologistik.
- Opitz, RS, Ryzewski, K, Cherry, JF and Moloney, B.** 2015. Using Airborne LiDAR Survey to explore Historic-era archaeological landscapes of Montserrat in the Eastern Caribbean. *Journal of Field Archaeology*, 40(5): 523–541. DOI: <https://doi.org/10.1179/2042458215Y.0000000016>
- Pärssinen, M, Schaan, D and Ranzi, A.** 2009. Pre-Columbian geometric earthworks in the upper Purús: a complex society in western Amazonia. *Antiquity*, 83(322): 1084–1095. DOI: <https://doi.org/10.1017/S0003598X00099373>
- Pires De Campos, F.** 1862. Breve notícia que dá o capitão Antônio Pires de Campos do gentio que há na derrota da viagem das minas do Cuyabá e seu recôncavo. *Revista trimestral do Instituto Histórico, Geográfico, e Etnográfico do Brasil*, 5: 437–449.
- Prümers, H and Jaimes Betancourt, C.** 2014. 100 años de investigación arqueológica en los Llanos de Mojós. *Arqueoantropológicas*, 4: 11–53.
- Redmond, E and Spencer, C.** 2007. *Archaeological Survey in the High Llanos and Andean Piedmont of Barinas Venezuela*. New York: Anthropological Papers of the American Museum of Natural History.
- Robinson, ME.** in prep. Excavations in the Circular Mound Villages of Acre. Manuscript on file. Exeter: Department of Archaeology, University of Exeter.
- Saunaluoma, S.** 2010. Pre-Columbian earthworks in the Riberalta region of the Bolivian Amazon. *Amazônica-Revista de Antropologia*, 2(1): 104–138. DOI: <https://doi.org/10.18542/amazonica.v2i1.347>
- Saunaluoma, S, Anttiroiko, N and Moat, J.** 2019. UAV survey at archaeological earthwork sites in the Brazilian state of Acre, southwestern Amazonia. *Archaeological Prospection*. DOI: <https://doi.org/10.1002/arp.1747>
- Saunaluoma, S, Pärssinen, M and Schaan, D.** 2018. Diversity of Pre-colonial Earthworks in the Brazilian State of Acre, Southwestern Amazonia. *Journal of Field Archaeology*, 43(5): 362–379. DOI: <https://doi.org/10.1080/00934690.2018.1483686>
- Saunaluoma, S and Schaan, D.** 2012. Monumentality in Western Amazonian formative societies: geometric ditched enclosures in the Brazilian state of Acre. *Antiqua*, 2(1): e1. DOI: <https://doi.org/10.4081/antiqua.2012.e1>
- Schaan, D, Pärssinen, M, Saunaluoma, S, Ranzi, A, Bueno, M and Barbosa, A.** 2012. New Radiometric Dates for Precolumbian (2000–700 bp) Earthworks in Western Amazonia, Brazil. *Journal of Field Archaeology*, 37(2): 132–142. DOI: <https://doi.org/10.1179/0093469012Z.00000000012>
- Schaan, DP.** 2012. *Sacred Geographies of Ancient Amazonia: Historical Ecology of Social Complexity*. Walnut Creek: Left Coast Press.
- Siegel, PE.** 1999. Contested places and places of contest: the evolution of social power and ceremonial space in prehistoric Puerto Rico. *Latin American Antiquity*, 10(3): 209–238. DOI: <https://doi.org/10.2307/972028>
- Silveira, M, Daly, D, Salimon, C, Wadt, P, Do Amaral, E, Pereira, M and Passos, V.** 2008. *First Catalogue of the Flora of Acre, Brazil. Physical environments and vegetation cover of Acre*. Rio Branco: Universidad Federal do Acre.

- Souza, ER.** 2011. Sociocosmologia Do Espaço Enawene-Nawe. Unpublished thesis (MA), Universidade Federal da Bahia.
- Souza, JG, Schaan, DP, Robinson, M, Barbosa, AD, Aragão, LE, Marimon, BH, Jr., Marimon, BS, Silva, IB, Khan, SS and Nakahara, FR.** 2018. Pre-Columbian earth-builders settled along the entire southern rim of the Amazon. *Nature Communications*, 9(1): 1125. DOI: <https://doi.org/10.1038/s41467-018-03510-7>
- Stenborg, P, Schaan, DP and Figueiredo, CG.** 2018. Contours of the past: lidar data expands the limits of late pre-columbian human settlement in the santarém region, lower amazon. *Journal of Field Archaeology*, 43(1): 44–57. DOI: <https://doi.org/10.1080/00934690.2017.1417198>
- Virtanen, PK and Saunaluoma, S.** 2017. Visualization and Movement as Configurations of Human–Nonhuman Engagements: Precolonial Geometric Earthwork Landscapes of the Upper Purus, Brazil. *American Anthropologist*, 119(4): 614–630. DOI: <https://doi.org/10.1111/aman.12923>
- Walker, JH.** 2018. *Island, River, and Field: Landscape Archaeology in the Llanos de Mojos*. Albuquerque: University of New Mexico Press.
- Watling, J, Iriarte, J, Mayle, FE, Schaan, D, Pessenda, LC, Loader, NJ, Street-Perrott, FA, Dickau, RE, Damasceno, A and Ranzi, A.** 2017. Reply to Piperno et al.: it is too soon to argue for localized, short-term human impacts in interfluvial Amazonia. *Proceedings of the National Academy of Sciences, USA*, 114: E4120–E4121. DOI: <https://doi.org/10.1073/pnas.1705697114>
- Watling, J, Iriarte, J, Whitney, B, Consuelo, E, Mayle, F, Castro, W, Schaan, D and Feldpausch, T.** 2016. Differentiation of neotropical ecosystems by modern soil phytolith assemblages and its implications for palaeoenvironmental and archaeological reconstructions II: Southwestern Amazonian forests. *Review of Palaeobotany and Palynology*, 226: 30–43. DOI: <https://doi.org/10.1016/j.revpalbo.2015.12.002>
- Westaway, R.** 2006. Late Cenozoic sedimentary sequences in Acre state, southwestern Amazonia: Fluvial or tidal? Deductions from the IGCP 449 fieldtrip. *Journal of South American Earth Sciences*, 21(1–2): 120–134. DOI: <https://doi.org/10.1016/j.jsames.2005.08.004>
- Wüst, I.** 1983. *Aspectos Da Ocupação Pré-Colonial Em Uma Área Do Mato Grosso de Goiás – Tentativa de Análise Espacial*. São Paulo: USP.
- Wüst, I and Barreto, C.** 1999. The ring villages of central Brazil: a challenge for Amazonian archaeology. *Latin American Antiquity*, 10(1): 3–23. DOI: <https://doi.org/10.2307/972208>

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