ACTA
AMAZONICA

http://dx.doi.org/10.1590/1809-4392202203511

HUMAN AND SOCIAL SCIENCES | ORIGINAL ARTICLE

Geography of ancient geometric earthworks and their builders in southwestern Amazonia

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ABSTRACT

Geometric earthworks are evidence of ancient human activity in western Brazilian Amazonia. We used a review of existing and new data to map earthworks across 27,569 km^2 of deforested areas in southwestern Amazonia using satellite imagery. We developed a conceptual basis for the classification of earthworks based on their structural characteristics using fuzzy sets. We recorded 1,279 structures with a distinctive core density zone. Most of the structures displayed geometric shapes, but they varied in construction accuracy. Geoglyphs accounted for 80% of all objects, with geographically variable shapes and enclosure areas. Other earthwork types included associated embankments, solitary embankments and mound sites. The abundance of earthworks provided evidence of strong pre-European human influence on the study area. A 10-km buffer around each earthwork included 75% of recent deforestation areas and 25.7% of standing forest, suggesting a significant potential for the presence of further earthworks in this ancient anthropogenic landscape and its possible far-reaching ecological legacy. The available radiocarbon data confirm a long-term anthropogenic impact in the study area, with ceremonial geoglyphs indicating activities over a thousand years old and other structures revealing more recent cultural transformations.

KEYWORDS: Acre, anthropogenic landscape, archaeology, geoglyph, mound village, radiocarbon dating

Geografia de antigas estruturas de terra geométricas e seus construtores na Amazônia Ocidental

RESUMO

Obras de terra com formatos geométricos são antigas evidências de atividades humanas na Amazônia ocidental brasileira. Utilizamos uma revisão de dados já existentes e também dados novos para mapear obras de terra em 27.569 km^2 de áreas desmatadas no sudoeste da Amazônia, usando imagens de satélite. Desenvolvemos uma base conceitual para a classificação dessas obras com base em suas características estruturais utilizando conjuntos fuzzy. Registramos 1.279 estruturas com uma zona de densidade central distinta. A maioria das estruturas apresenta formas geométricas, mas com níveis variáveis de precisão de construção. Os geoglifos representaram 80% de todas as estruturas, com formas e áreas delimitadas geograficamente variáveis. Outros tipos de obras incluíram aterros associados, aterros solitários e montículos. A abundância de terraplanagens forneceu evidências da forte influência humana pré-europeia na área de estudo. Uma zona tampão de 10 km em torno de cada obra de terra incluía 75% de áreas de desmatamento recente e 25,7% de floresta em pé, sugerindo um potencial significativo para a presença de mais terraplanagens nesta antiga paisagem antropogenica e no seu possível legado ecológico. Os dados radiocarbônicos disponíveis confirmam um impacto antropogênico de longo prazo na área de estudo, com geoglifos cerimoniais indicando atividades com mais de mil anos e outras estruturas revelando transformações culturais mais recentes.

PALAVRAS-CHAVE: Acre, paisagem antropogênica, arqueologia, geoglifo, vilarejo do monte, dados radiocarbônicos

INTRODUCTION

Deforestation in southwestern Amazonia has exposed geometric earthworks dating mainly from pre-European times (Schaan 2012; Ranzi and Pärssinen 2021). They usually include an excavated ditch alongside an earthen embankment extending generally between 60 and 400 m in size with a height difference of a few meters (Schaan et al. 2010; Pärssinen 2021). Earthworks might have once had associated wooden elements or vegetation, yet traces of these elements are rarely found because organic materials decay quickly in the warm and humid environment of the region. Archaeological excavations

CITE AS: Kalliola, R.; Pärssinen, M.; Ranzi, A.; Seppä, I.; Barbosa, A.D. 2024. Geography of ancient geometric earthworks and their builders in southwestern Amazonia. *Acta Amazonica* 54: e54hu22351.

have only revealed isolated marks of vertical postholes, and traces of horizontal wooden structures have been found in excavated ditches, likely utilized as wall supports (Schaan et al. 2012; Pärssinen and Ranzi 2020). The existence of palisades or stone constructions remains undocumented, although the subsoil sometimes contains a hard layer (hardpan) that could have served as rudimentary building material.

Various functions for these structures have been suggested, ranging from ceremonial centers and gathering places to water storage, fishponds, or defensive structures, all indicating the presence of regionally organized societies capable of environmental management (see Pärssinen et al. 2009; Schaan et al. 2012). Archaeological excavations indicate that numerous structures likely served as ceremonial centers, with the main population living in scattered areas with less clear archaeological evidence (Saunaluoma and Schaan 2012; Virtanen and Saunaluoma 2017; Ranzi and Pärssinen 2021). Another type of patterned earthwork in the region is mound villages with separate mounds surrounding a central plaza (Saunaluoma et al. 2018; Iriarte et al. 2021).

The region containing these earthworks features a rich human history, evidenced by increased burning activities documented from 4,500–4,000 BP (Before Present) onwards (Watling et al. 2017) and intermittent deposits of charcoal and ash dating back to the beginning of the Holocene era, around 12,000–10,000 BP (Pärssinen et al. 2020). Radiocarbon dating suggests that the active use period of many earthworks extended from at least ca. 2,500 BP to 1,050 BP, and, in some cases, the earthworks constructed in the first millennium were used until the 14th century (Ranzi et al. 2007; Pärssinen and Ranzi 2020; Pärssinen 2021). Ceramic residues, macrofossils, and diagnostic phytoliths offer further insights into early cultures (e.g., Pärssinen et al. 2003; Dias 2006; Saunaluoma 2012; Watling et al. 2015; Pärssinen et al. 2020). Pottery remains are often present in deposits, yet their quantity is typically small, except for sites like Tequinho, which yielded nearly 40,000 shards during excavations (Pärssinen 2021). The ceramics mainly correspond to the Quinari tradition, characterized by a variety of pottery forms and decorative incision techniques indicating multiculturalism and probable contacts with different ceramics traditions associated with Arawakan, Tupi-Guarani, and even Panoan language groups (Pärssinen 2021). The scarcity of cultural materials inside the enclosures suggests that people kept the central parts clean (Saunaluoma 2012).

The location and shape of these ancient earthworks can easily be determined on satellite images, such as Landsat Thematic Mapper and SPOT data (Santos et al. 2018). The documented number of earthworks in the northwestern Brazilian state of Acre and neighboring areas of the states of Amazonas and Rondônia, in the southwestern Brazilian Amazon, has shown a rapid increase. For example, the initial reported count of 60 earthworks (Ranzi 2003) surged to 450 (Watling et al. 2018) in just fifteen years. Around 1,000 structures were reported from a broader inventory area (Chouquer 2021), and ongoing surveys continue to reveal more new discoveries (Jacobs 2022). Recent studies utilizing Light Detection and Ranging (LIDAR) data offer deeper insights (Iriarte et al. 2020; Prümers et al. 2022; Peripato et al. 2023; Rostain et al. 2024), but their application is constrained by limited spatial coverage. Recognizing the uniqueness of the Acre geoglyphs, UNESCO included them in its tentative list of World Heritage Sites as early as 2015 (UNESCO 2015).

The geographic distribution and characteristics of earthworks provide information about the ancient cultures that built them. John Stuart Mill (Mill 1843) proposed an inductive working method that is well suited for this type of research. Three of his five methods form the basis of various disciplines that compare cultures and societies: agreement (similarity), difference, and multivariable analysis. Ragin (1987) distinguished between qualitative, case oriented, and quantitative, variable-oriented analysis, and suggested employing fuzzy sets that can take into account more options than simple "presence or absent dichotomies" (Ragin 2007). The absence of a reliable classification framework, however, has hindered the application of such a comparative approach in the study of Amazonian earthworks. A previous study mentioned that roundish earthworks are generally predominant in southern Acre (Pärssinen et al. 2009), but no formal and comprehensive classification of earthwork shapes has been proposed. Saunaluoma et al. (2018) used a combination of temporal, structural, and functional criteria to divide earthworks into three types – geoglyphs, circular walled enclosures, and mound sites – but even this classification allows for a more detailed approach.

This study seeked to deepen our understanding of the geography and structure of ancient geometric earthworks in southwestern Amazonia. With this aim, we present the first comprehensive, comparative geographic analysis of their distribution and characteristics within the region. Our specific research questions were 1) What does the comprehensive distribution mapping reveal about the geography of the ancient earthworks?; 2) How does a detailed classification of structural attributes of earthworks strengthen the analysis and contribute to cultural interpretation?; and 3) What is the likely extent, intensity, and duration of the anthropogenic impact by ancient earth builders?

MATERIAL AND METHODS

The study area comprised 134,400 km^2 in the southwestern Amazon, in the states of Acre, Amazonas and Rondônia (Brazil) (Figure 1). The topography is gently undulating lowland plains (100–350 m a.s.l.) with occasional river valleys. The climate is semiseasonal (Almeida et al. 2017). The natural vegetation is lowland evergreen to semideciduous

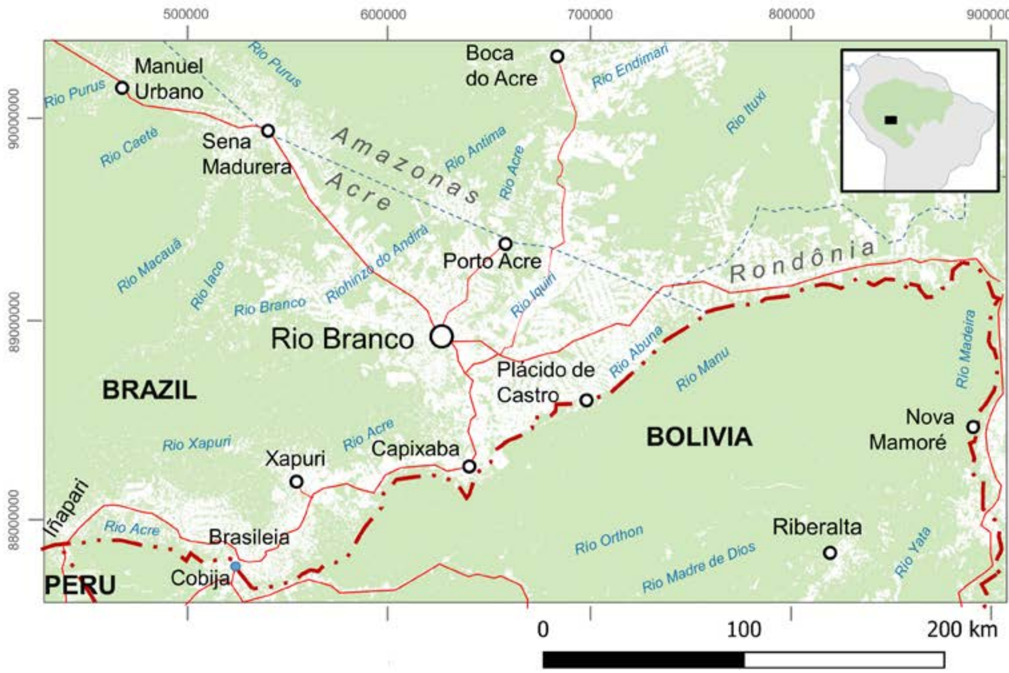

Figure 1. Map of the study area in the southwestern Amazon. Deforested areas are white, the solid lines are roads, the dashed lines are administrative boundaries, and the tick marks show WGS84 UTM Zone 19S projected coordinates. The inset displays the approximate location of the study area in the Amazon biome (in green). Deforestation areas are from RAISG (https://www.amazoniasocioambiental.org/en/maps/).

tropical forest, largely with semiscandent bamboos (Guadua spp.) (Ferreira et al. 2020). Earthworks were only visible on satellite images in areas where the forest has been cleared, corresponding to 27,569 km^2 (20.5%) of the study area.

We started by reviewing earthwork registers from prior studies, primarily drawing on the records compiled through collaborative research by Universidade Federal do Acre and Universidade Federal do Pará (Brazil), and the University of Helsinki (Finland) (Ranzi 2003; Schaan et al. 2008; Pärssinen et al. 2009; Schaan et al. 2010; Schaan 2012). Other sources were the data collected by Jacobs (2022) and the printed maps of Chouquer (2021). For verification, we used online satellite data via XYZ Tiles in QGIS (between 11 February 2021 and 12 August 2022), including the Google Earth Base Map (http://ecn.t3.tiles.virtualearth.net/tiles/a{q}.jpeg?g=1), Bing Virtual Earth (https://mt1.google.com/vt/lyrs=s&x={x}&y={y}&z={z}) and Esri World Imagery (https://server.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer/tile/{z}/{y}/{x}). We also used historical satellite images from Google Earth (https://earth.google.com/web/) and the Satellite HD layer of Zoom Earth (https://zoom.earth/). We occasionally consulted oblique-view aerial photographs (Supplementary Material, Figure S1), along with our available field notes. In some cases, we opportunistically used available LiDAR imagery from Iriarte et al. (2021) and from the Sustainable Landscapes Brazil Project (https://www.paisagenslidar.cnptia.embrapa.br/webgis/).

Comparisons across different sources and discussions among researchers were indispensable as some structural details of the earthworks appeared in only a few or a single source, and their interpretation was not always straightforward (Supplementary Material, Figure S2). To ensure that the interpretations were as thorough and consistent as possible, MP and RK conducted all visual interpretations of the earthworks collaboratively.

We digitized earthwork outlines by tracing along a ditch (when clearly visible) or along the top of a ridge (embankment), simultaneously evaluating their characteristics. We applied a novel conceptual framework for their classification, employing fuzzy set values. We focused on three general attributes, three elements of configuration, fourteen shape types in three shape groups, two descriptors of roundness, and four functional types (Table 1). Most of them were mechanistically descriptive, while the interpretation of functional types was rule-based and grounded in earlier scientific literature (Saunaluoma et al. 2018; Iriarte et al. 2020; Pärssinen and Ranzi 2020). The only modification here was the differentiation of embankments into two types based on their proximity to geoglyphs: associated embankments occurred in combination with nearby geoglyphs, often resembling an "atrium", whereas solitary embankments clearly were separate entities. We employed fuzzy memberships across various classes for earthworks exhibiting intermediate characteristics in specific classifications. For instance, we assigned the combination "somewhat circular" with "somewhat oval" to describe the

Table 1. Shape attributes of the earthwork classification proposed in this study. The goodness of fit levels of all classifications were: good fit, somewhat good fit, no fit/not applicable.

Column labels	Explanation
ID number	Running identification number for each earthwork
Name	Name of the earthwork in our records
General attributes	
Confidence	Confidence in our visual interpretation and digitization, as agreed upon
Hidden	Earthwork partly hidden by forest or other obstacle
Undamaged	Structure is mostly unaltered by modern human activity
Configuration	
Nested	Nested structure with a shape inside another
Enclosure	Structure digitized in polygon layer
With ancient roads	Earthwork associated with ancient roads
Shape type	
Roundish group	
Circular	Round to sub-round
Oval	Elliptical or egg-shaped
D-shaped	Closed structure with a strongly curved side
Drop-shaped	Mainly round but with a tapered tip
Quadrilateral group	
Square	Quadrilateral, equal sides and angles
Rectangle	Quadrilateral, parallel long and short sides
Rhombus	Quadrilateral; parallel sides, equal opposite angles
Trapezoid	Quadrilateral, only one pair of opposite parallel sides
Complex group	
Pentagon	Five angles (sides can be varyingly irregular)
Hexagon	Six angles (sides can be varyingly irregular)
Octagon	Eight angles (sides can be varyingly irregular)
Moon+sun	Shape of moon crescent with sun
U-shaped	Structure is probably built open (not an enclosure)
Unique-shaped	Unusual shape, often asymmetrical
Roundness (quadrilaterals only)	
Rounded corners	At least two noticeably rounded corners
Rounded sides	At least two noticeably rounded sides
Functional type	
Geoglyph	Enclosure or open shape featuring a constructed ditch and ridge
Associated embankment	Pattered embankment (no ditch) near or connected to geoglyph, like an "atrium"
Solitary embankment	Pattered embankment (no ditch) around 100 m or more from geoglyph
Mound site	Mounds framing a central space (no continuous ditch or embankment)

shape of an intermediate structure (Supplementary Material, Figures S3, S4).

We used numerical shape indices to supplement the visual shape classifications and assess their consistency. We computed the Roundness Index (RI) to facilitate comparison between circular and oval formations in the case of rounded structures, because their visual classification occasionally posed challenges:

$$RI = \frac{4\,\pi\,area}{perimeter^2}$$

For members of the quadrilateral group (square, rectangle, rhombus, trapezoid), we simplified their outlines into four straight lines using the Douglas–Peucker algorithm with a radial distance of 15 m. Because earthworks with specifications such as 'rounded corners' or 'rounded sides' often displayed misalignment of corner points, leading to inadequate representations of the ground structure, we excluded them from subsequent analyses. This left us with 375 quadrilateral earthworks for subsequent analyses, these including both those with a good fit and those with somewhat good fit to their respective shapes. The ratio of the longest and shortest sides of the simplified quadrilaterals served to distinguish perfect squares and rhombuses from other quadrilateral earthworks. Conversely, the ratio between the largest and smallest angles assisted in distinguishing visually classified squares and rectangles with right angles from rhombuses and trapezoids with varying angles.

We utilized a 10x10-km grid comprising 3,344 cells with different levels of deforestation to visualize geographical variations in earthwork density across the study area (Supplementary Material, Figure S5). The same grid also depicted the variability in the number of different shape types, with the fuzzy sets of good fit and somewhat good fit treated as separate entities for each shape type.

We applied distance-based buffering around all earthworks to gain plausible insight into the spatial extent of anthropogenic interaction, hereafter referred to as the anthropogenic landscape. Assuming high human activity near a structure, during both its construction and later use, and its decrease with increasing distance, we visualized the extent of a plausible anthropogenic landscape with varying intensities at 500-m intervals up to 10 km around each earthwork using QGIS batch processing.

We explored the temporal aspect of earthwork activities using both published radiocarbon data and compiled unpublished data. We obtained data from 131 samples associated with 33 earthworks, including geoglyphs, embankments, and mound sites (Supplementary Material, Table S1). We recalculated them into standardized radiocarbon years due to variations in age calibration methods across different sources, using the OxCal v4.4 program and the Atmospheric SHCal20 curve for the Southern Hemisphere (Hogg et al. 2020; Bronk Ramsey 2021). We denote the resulting calibrated datings as cal BP, which stands for calibrated years before the present ("present" is defined as AD 1950), and show the oldest and most recent ages as a likelihood of 95.4%, or 2-sigma.

RESULTS

We confirmed 1,279 distinct earthworks, 350 of which were previously unrecorded, and 75.4% were clearly visible on satellite images, making digitization confident (Table 2). Structures were partially obscured by trees in 17% of cases. A quarter of the earthworks (24.2%) displayed clear damage even after deforestation, including collapses due to cattle trampling, roads, off-road vehicle tracks, or agricultural land management. Of the total number of earthworks, 11.2% displayed a nested structure, 70.0% were enclosures, and 37.5% associated with ancient roads. Regarding their classification by functional type, the majority of the earthworks (80.5%) were geoglyphs.

Earthworks were mainly concentrated in the central parts of the study area, extending northeastward along the rivers in the region (Figure 2a,b). We henceforth designate this area, where earthwork density commonly exceeded 20 structures per 100 km^2, as the core density zone (Example: Supplementary Material, Figure S6). Elsewhere, earthworks were widely dispersed, with occasional local concentrations.

The most common shape types were trapezoid, rectangle, square, oval, and circular, which collectively accounted for 684 structures with a good fit to these shapes, representing 53% of all earthworks (Figure 2c). The need to employ the fuzzy classification varied among shape types in our dataset. For example, the U- and D-shaped earthworks were mostly categorized as somewhat good. When considering only shape classifications with a good fit, the most frequent shapes varied among functional types (Supplementary Material, Figure S7). Among geoglyphs, the five most common types were square, trapezoid, circular, rectangle, and rhombus. Associated embankments were most commonly uniquely shaped, and half of the solitary embankments were ovals or trapezoids.

Distinguishing between roundish and oval shapes was occasionally challenging. The roundness index (RI) confirmed that the majority of circular enclosures closely resembled near-

Table 2. Number (N) and relative frequency (RF) of earthworks (N = 1279) according to the structural attributes and goodness of fit of the classification proposed in here. The sum of the four functional types (1321) exceeds the number of earthworks as some structures exhibit characteristics of multiple categories. Percentages are relative to the number of distinct earthwork structures.

Attribute	Good fit		Somewhat good fit		Total	
	N	RF (%)	N	RF (%)	N	RF (%)
General attributes						
Confidence	964	75.4	315	24.6	0	0.0
Hidden	9	0.7	206	16.1	215	16.8
Undamaged	965	75.4	309	24.2	1274	99.6
Configuration						
Nested	106	8.3	44	3.4	150	11.2
Enclosure	895	70.0	0	0.0	895	70.0
With ancient roads	429	33.5	50	3.9	479	37.5
Functional type						
Geoglyph	990	77.4	40	3.1	1030	80.5
Associated embankment	72	5.6	20	1.6	92	7.2
Solitary embankment	73	5.8	20	1.6	93	7.3
Mound site	78	6.1	28	2.2	106	8.3

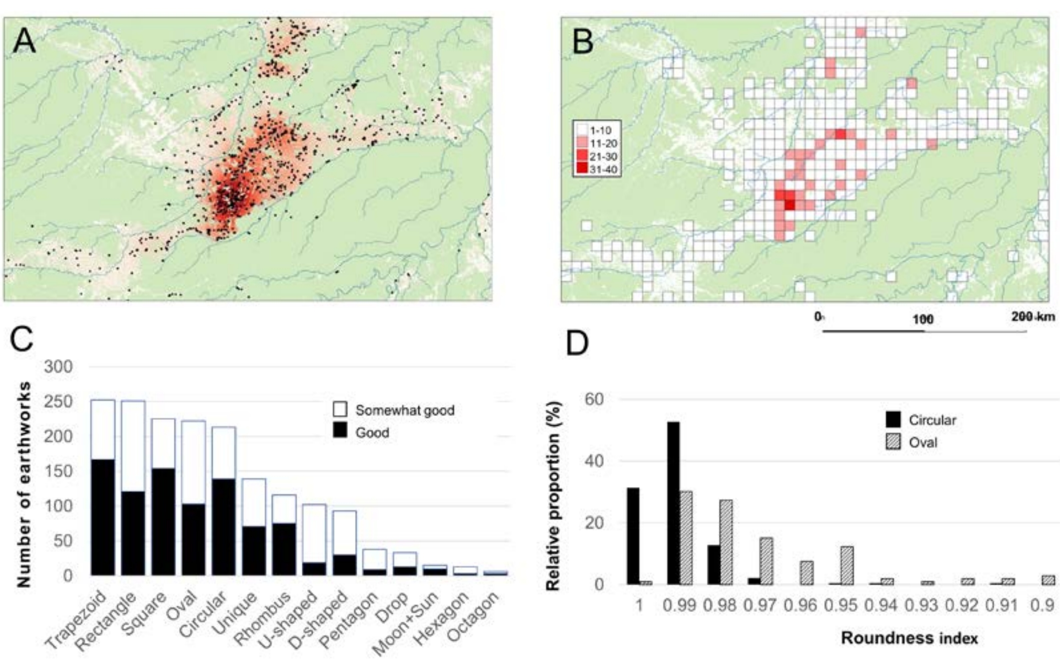

Figure 2. A – Earthwork locations (black dots) in the study area in the southwestern Amazon superimposed to their density heat map in red hues; **B** – Number of earthworks per 10x10-km grid cells; **C** – Goodness of fit of earthworks according to shape types (total N = 1,279); **D** – Distribution of roundness index (RI) values of circular and oval enclosures (both structures with good and somewhat good fit).

perfect circles (Figure 2d). These earthworks were primarily located in the central regions of the study area (Supplementary Material, Figure S8). The RI values for oval shapes exhibited a broader range, and the geographical distribution of structures with different RI values was widely dispersed throughout the study area. We observed that a notable number of roundish structures featured short, relatively straight segments along their perimeters (see Supplementary Material, Figure S3).

In the quadrilateral group, their side lengths showed less variation compared to their corner angles (Figure 3). Many squares and rhombuses displayed precisely equilateral sides extending up to nearly half a kilometer. The differences in side lengths for most rectangles and parallelograms were also relatively minor. Angle variation was generally moderate, showing a progressive shift from squares and rectangles with nearly right angles to increasingly tilted angles. Although fuzzy logic helped classify many intermediate structures, the most asymmetrical forms were clearly classified with a good fit as either rhombuses or trapezoids. The most tilted trapezoid in the study area had angles measuring 70 and 109 degrees. No distinct distribution pattern in side-length ratio or angle ratio was evident among the quadrilateral earthworks (Supplementary Material, Figure S9).

Common earthwork shapes were widespread, but rare and intricate shapes were often found in the core density zone and its vicinity (Supplementaty Material, Figures S10-S13). Nested earthworks were widespread but relatively sparse in the core density zone and western parts of the study area. Roundish shapes were more prevalent in the southwest, while quadrilaterals were commonly found in the northeast. The distribution of circular and square structures exhibited nearly complementary patterns, with an evident overlap zone (Figure 4).

The number of different shapes within the 10x10 km grid cells—or shape type variability—initially increased with the number of earthworks but soon leveled off, rarely exceeding 10 different shapes (Supplementary Material, Figure S14a). This pattern persisted even when fit levels categorized as "good" and "somewhat good" were considered as separate shapes. Geographically, the greatest shape type variability coincided with the core density zone previously identified (Figure 2a; Supplementary Material, Figure S14b).

Enclosure sizes, including all functional types, varied from 0.01 to 49.6 hectares; however, differently shaped earthworks did not vary equally in this respect. (Figure 5). Among the common shape types, squares and rhombuses were the largest, both with an average size of 2.6 ha (median = 1.8 and 2.1 ha, respectively). Circular earthworks were typically smaller than other shapes, but, notably, the largest earthworks were circular, including the largest one (Tumichucua). The core density zone exhibited numerous small structures, while the largest enclosures were dispersed in other parts of the study area and were often located near major rivers (Supplementary Material, Figure S15).

The ancient anthropogenic landscape covers a substantial area within the study area; however, its extent varied depending on the emphasized buffer distance (Figure 6). A 5-km buffer encompassed half of the presently deforested lands and a tenth of the current forests. A 10-km buffer covered 35.9% of the entire study area, including 75.0% of its recently deforested lands and 25.7% of present-day forests. Some areas in the northwest consistently remained outside the designated buffer zone, suggesting lesser impact from earthwork related activities.

All 16 geoglyphs among the 33 earthworks with radiocarbon data were dated to over 1,000 cal BP, with some datings

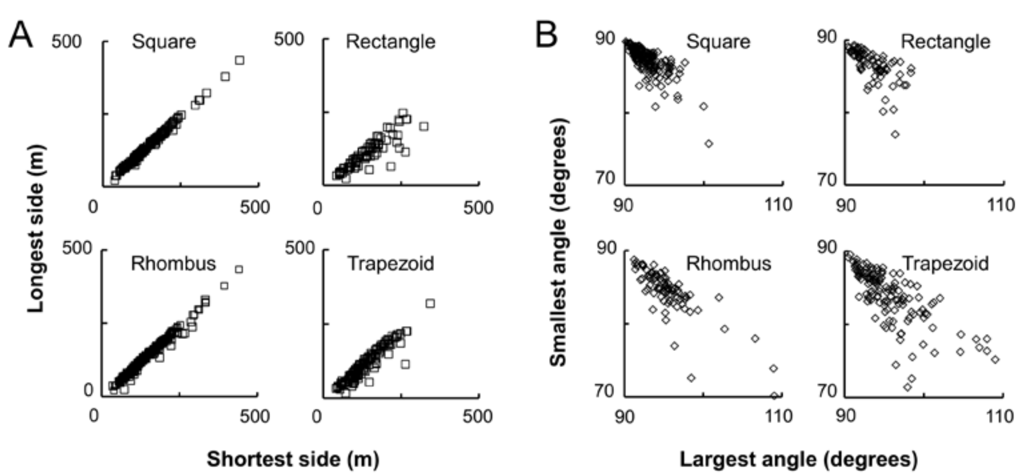

Figure 3. A – Relation between the longest and shortest side in each shape type of quadrilateral earthworks; **B** – Relation between the largest and smallest angle in each shape type of quadrilateral earthworks. N = 166 squares, 75 rectangles, 84 rhombuses and 128 trapezoids with good or somewhat good fit to their respective shapes (the data excludes structures with rounded corners or sides).

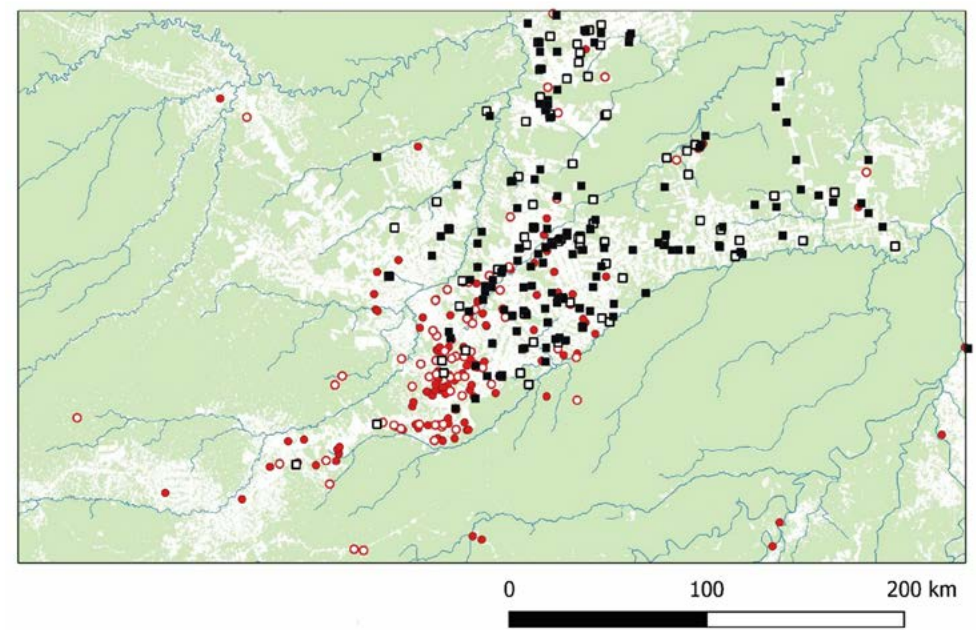

Figure 4. Distribution of circular (red) and square-shaped (black) earthworks in the study area. Filled symbols indicate good fit; open symbols indicate somewhat good fit.

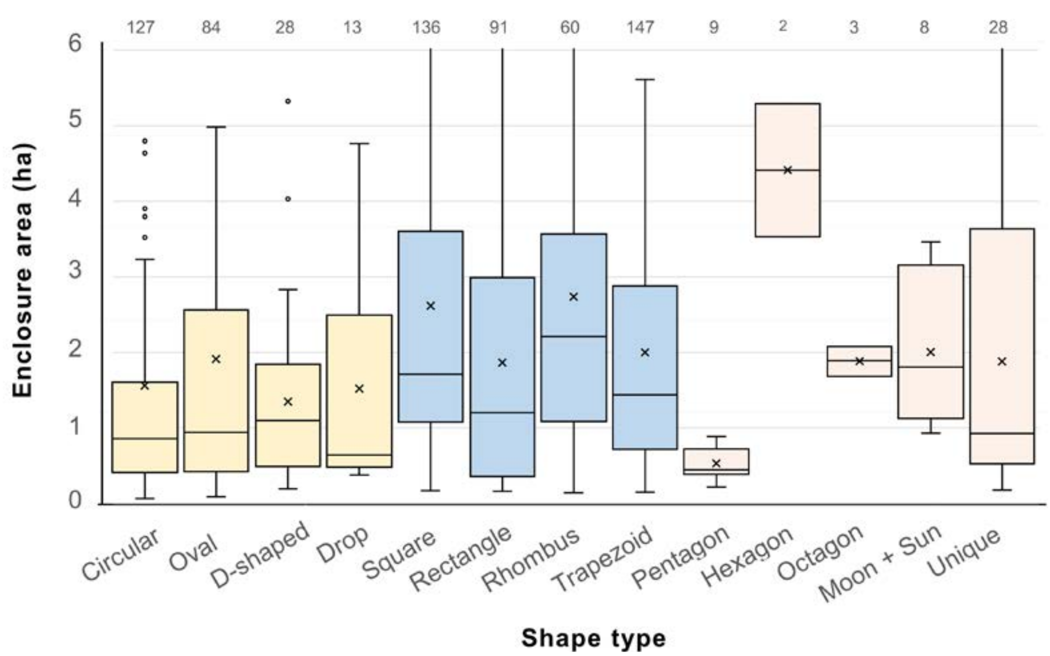

Figure 5. Enclosure sizes per shape type in the study area. Shape types are categorized as roundish (yellow), quadrilateral (blue) and other shapes (pink). The x in the boxplots indicates the mean, the horizontal line the median, the box the second and third quartiles, and the bars the first and fourth quartiles. Black dots indicate outliers. The y-axis is capped at 6 ha, resulting in the upper portions of certain fourth quartiles and outliers being excluded from the graph area. The numbers above the bars indicate the sample size, including only structures that exhibit a good fit to the specified shape (total N = 736).

extending back beyond 2,500 cal BP (Figure 7; (Supplementary Material, Figure S16; Table S1). The data shows that the duration of geoglyph use had exceeded 500 years in five instances. One sample from a solitary embankment was dated to over 1,500 cal BP, whereas three other embankments were dated to less than 700 cal BP. All mound settlements indicated relatively recent ages, ranging from 289 to 646 cal BP, although one sample in Sol de Campinas gave an age of 860 cal BP.

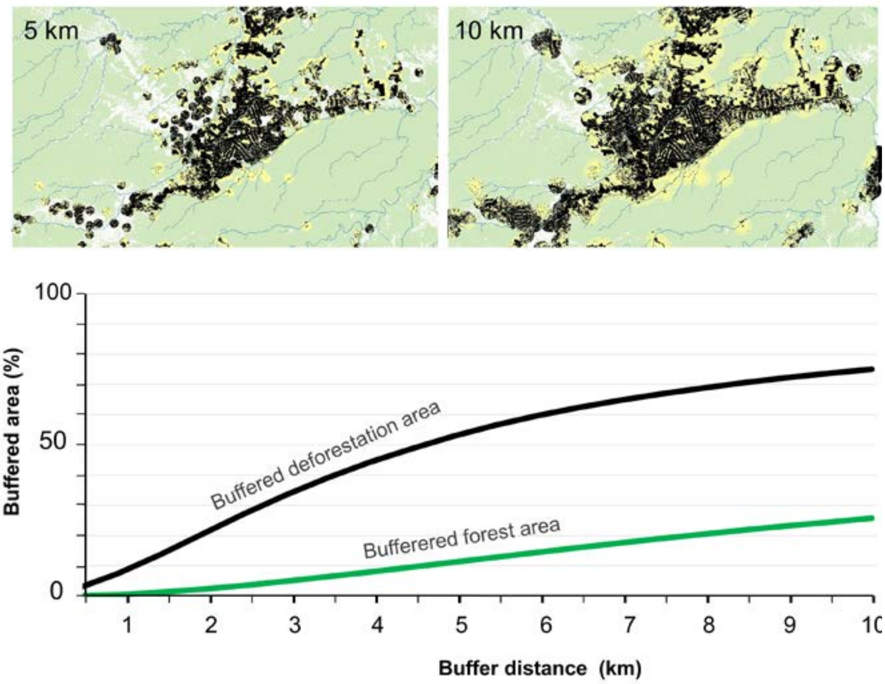

Figure 6. Influence of the buffer distance around earthworks (5 and 10 km in the maps) on the estimation of the extent of the ancient anthropogenic landscape within the study area. Black represents recently deforested areas, and light yellow represents present-day forested areas within the buffer zones. The graph estimates the area of ancient anthropogenic landscape in deforested and forested parts of the study area with 500-m increments in the buffer-zone diameter.

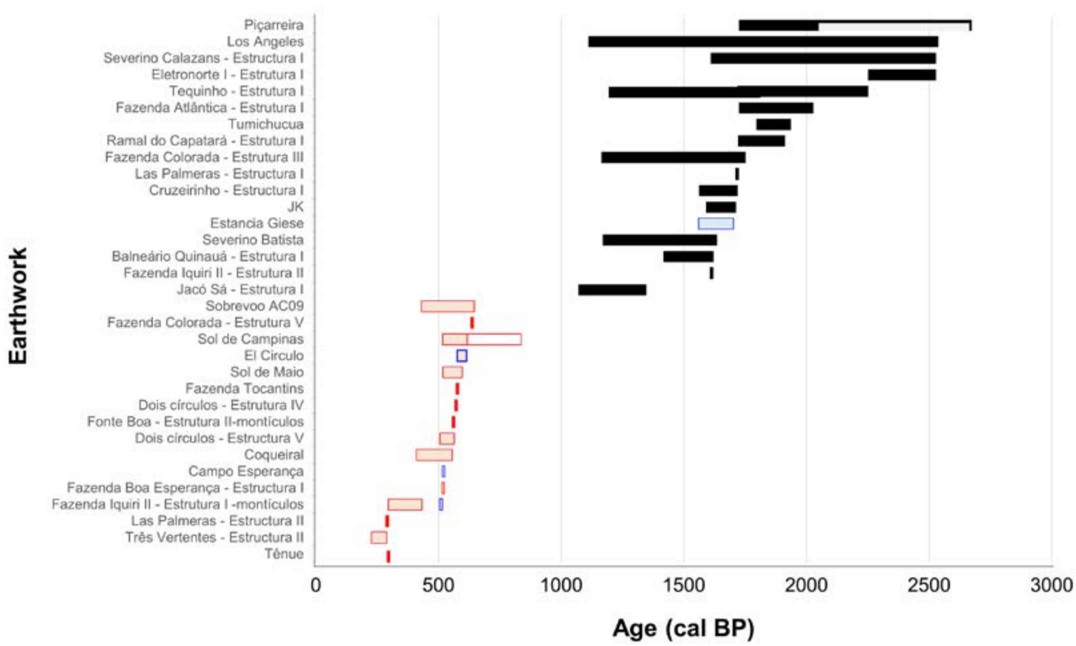

Figure 7. Radiocarbon data from 33 earthworks in the study area (for locations, number of available datings, and probability distributions see Supplementary Material, Figure S16, Table S1). Bars represent the range from oldest to most recent dating for each earthwork (when only one dating is available, the bar is slightly extended for visibility). The white portion in two bars (Piçarreira, Sol de Campinas) indicates that one sample was significantly older, introducing uncertainty. Earthworks are categorized as geoglyphs (black), solitary embankments (blue), and mound sites (red). One earthwork (El Circulo) has characteristics of both embankment and mound site, thus its bar is red with a blue outline. Fazenda Iquiri II – Estrutura Montículos has mound structures in near vicinity. Radiocarbon data calibrated for this study are from Pärssinen et al. (2003); Dias (2006); Saunaluoma (2010); Saunaluoma (2012); Schaan et al. (2012); Saunaluoma and Schaan (2012); Neves et al. (2016); Saunaluoma et al. (2018); Pärssinen et al. (2020); Iriarte et al. (2021); Pärssinen et al. (2021); and Saunaluoma et al. (2021), as well as 22 unpublished dates from Eletronorte I:1, Piçarreira, Três Vertentes, and Tequinho.

DISCUSSION

This study uncovered more earthworks and greater density variation in the study area than previously acknowledged. Furthermore, the structural characteristics of these earthworks suggested geographically diverse patterns. Table 3 summarizes our most important findings as answers to the proposed research questions.

The core density zone of the central study area confirms the significance of headwaters and interfluves for the region's ancient peoples (Schaan et al. 2012). Another aspect of spatial structure emerges as earthworks often form clusters, with geoglyphs merging with one another or with associated embankments, highlighting the significance of some sites over others. However, current knowledge does not suffice to determine if there was centralized control within the monumental landscape of Acre (Riris 2020). In numerous locations, mound villages constructed centuries later occurred in the same areas. A sparser distribution of earthworks extended eastwards from the core density zone towards Rondônia and Amazonas states. This distribution aligns with a nearly 2,000 km-long rim of ancient earthworks in southern Amazonia, suggesting a population of half a million to a million people (Souza et al. 2018). Unlike in our area, geoglyphs elsewhere in Amazonia often represent habitational settlements (Denevan 2012; Saunaluoma et al. 2018; Iriarte et al. 2020).

The prevalence of earthworks in small forest openings in northern Bolivia may indicate their high density under the forests of that region. If so, it could potentially alter the perception of a specific core density zone only in the central parts of our study area. A UAV-LIDAR system could help to validate this assumption by mapping archaeological landforms under vegetation (Saunaluoma et al. 2019; Iriarte et al. 2020; Prümers et al. 2022; Rostain et al. 2024). LIDAR could also reveal whether there were more earthworks in the forests west of the study area towards Peru and the Andes, possibly indicating an active Andean-Amazonian land use corridor (Loughin et al. 2018). Since earthworks were rare in the recently deforested northwestern portion of our study area, which features a hillier landscape, our data might instead reveal parts of the authentic western margin of this cultural tradition.

Literature commonly emphasizes the geometric shapes of earthworks in the southwestern Brazilian Amazon (Pärssinen et al. 2009; Saunaluoma and Schaan 2012; Carson et al. 2014). This generalization has certain basis, given the demonstrated familiarity with basic geometric concepts among present-day isolated indigenous peoples of the Amazon (Dehaene et al. 2006). Geometric images, such as circular or square patterns, help materialize non-humans like plants, animals, and ancestors, providing strength and resistance among the groups of Manchineri and Apurinã who live in the upper Purus (Virtanen and Saunaluoma 2017). These same shapes were common in our data. Triangular shapes were clearly and notably absent from our dataset, an intriguing detail worth mentioning.

Table 3. Summary of the major findings of this study with answers to the research questions.

Research question	Examined attribute	Findings	Interpretative relevance
What does the comprehensive distribution mapping reveal about the geography of the ancient earthworks?	Discernibility	Variable visibility	Construction methods and/or erosional ages differ
	Distribution	Occurrence in a wide range, but not everywhere	Widespread tradition, some areas preferred over others
	Density	Spatially variable with core density zone and many local centers	Builders' culture with core and peripheral areas and focal points
How does a detailed classification of structural attributes of earthworks strengthen the analysis and contribute to cultural interpretation?	Shape type	Varied geometric shapes, including intermediate or unique ones requiring fuzzy sets	Repeated but varying cultural traits that refer to collective ideologies and cosmologies
	Shape precision	Geometrically accurate shapes and diversely "sketch-like" shapes	Work quality differed or geometric accuracy was not always the goal
	Structural complexity	Nested constructions are relatively common	Intermittent/localized efforts for a more complex level
	Enclosure size	Great variation from a hectare to tens of hectares	Different earthwork sizes reflect essential but so far unknown cultural aspects
	Distribution of different shapes or sizes	Geographically distributed to varying degrees; mainly roundish and quadrilateral	Varied earthwork construction practices; potentially overlapping between neighboring populations, with distinct methods but shared cosmological beliefs.
	Functional types	90% of objects classify into one functional type; 80% are geoglyphs	Earthwork classification into different functional types is sensible; main use of geoglyphs was ceremonial
What is the likely extent, intensity, and duration of the anthropogenic impact by ancient earth builders?	Extent	A 10–km buffer zone covers 36% of the study area, yet earthworks could be mapped only on deforested lands	Earthwork building tradition was widespread; if forested areas were included, prevalence would likely be even greater
	Intensity	High-density and high-diversity areas contrast with sparse earthwork occurrence	Some places look almost urban, whereas in other areas, intensity inferred from the earthworks was lower
	Duration	Geoglyphs were built more than a thousand years ago; mound sites appeared later	Geoglyph building culture preceded mound-site culture; change points to unknown cultural events

The construction of both circular and quadrilateral shape groups often displays remarkable precision, even in structures of considerable size. However, many structures showed varying degrees of deviation from basic geometric shapes, challenging common assumptions about the strict adherence to geometry in pre-European engineering. For instance, some circular earthworks featured a short, relatively straight sector that appeared intentional, resembling the flat side of a ball against the floor. The reasons for these design choices remain unclear. These deviations may stem from challenges in accurate measurement during implementation, but they could also represent unknown manifestations of the builders' cosmology.

Many studies have reported evidence of landscape modification for food production in Acrean earthwork areas (Piperno et al. 2017; Watling et al. 2018; Pärssinen et al. 2021). Although Amazonian dark earth (McMichael et al. 2014; Kern et al. 2017) is not present in this area, there are reports of brown earth containing ash and charcoal fragments (Montoya et al. 2020; Pärssinen et al. 2020). Such studies suggest a dispersed population surrounding ceremonial sites (Ranzi and Pärssinen 2021; Saunaluoma and Schaan 2012; Virtanen and Saunaluoma 2017). The landscape presumably contained cultural forests enriched with useful plants and occasional clearings with semidomesticated species (Saunaluoma 2012; McMichael et al. 2014; Watling et al. 2015; Pärssinen et al. 2021). The Brazil nut tree (*Bertholletia exelsa* Humb. & Bonpl.) is an often-noted example of a plant still indicating an ancient anthropogenic footprint, with agreeing data from ecology, phytogeography, genetics, linguistics and archaeology (Shepard and Ramirez 2011; Pärssinen et al. 2021). Many researchers believe that that ancient indigenous Amazonians may have possessed the ability to manipulate large forest areas (e.g., Erickson 2010; Carson et al. 2014; Watling et al. 2017; Hill et al. 2023; Peripato et al. 2023).

The spatial extent and intensity of such pre-European human activity in southwestern Amazonia is a prominent subject of scientific research (Heckenberger and Neves 2009; McMichael et al. 2014; Bush et al. 2015; Souza et al. 2018; Montoya et al. 2020; WinklerPrins et al. 2020; Peripato et al. 2023; Walker et al. 2023). Pärssinen et al. (2009) estimated that 300 people were needed in Acre for 100 days just to excavate one geometric structure with a diameter of 200 m. It is reasonable to assume the immediate working area was kept as open as possible at the time, perhaps taking advantage of the time window when low-density forest followed bamboo die-off (Watling et al. 2017; Van doninck et al. 2020). The subsequent use of earthworks likely involved periodic gatherings of large groups for communal festivities in these areas. Assemblies of people require significant food resources and participants likely dispersed into areas surrounding central hubs. We demonstrated that over one-third of the study area lies within 10 km from the nearest earthwork, which may provide a feasible estimate of the influence area. This estimate is likely to grow as each new earthwork discovery expands the areas covered by the buffer. Given that the available data indicates many earthworks were in use for centuries, anthropogenic influence on the landscape has not only been widespread but also long-lasting, at least periodically.

Significant shifts in the nature and intensity of human activity appear to have occurred over the past millennium. Geoglyph activities ceased around 1,100 years ago, followed by a gap of centuries before the emergence of the first dated mound sites. This transition suggests a fundamental ideological shift in societal organization. The sudden emergence of mound village culture appears to have been dramatic; however, the proximity of many mound sites to older ceremonial centers suggests that they may have retained some significance in community life. Mound sites were utilized for well over 500 years (Iriarte et al. 2021; Saunaluoma et al. 2021), yet their small size and geographically limited distribution may suggest a population decline, or at the very least, a considerable reduction in the visible traces of their presence. We do not fully understand these aspects at the moment, and they need to be studied carefully in the future.

CONCLUSIONS

The distribution of 1,279 earthworks in the study area in southwestern Amazonia revealed variable densities, including a core density zone aligned with upstream rivers, suggesting that certain areas were more significant than others. The variable shapes and sizes of these structures suggested a rich cultural heritage in the region, with shared cosmology and complex social organization. Rigorously constructed earthworks highlighted ancient peoples' skill in measuring straight distances accurately, though achieving precise angle measurements may have been challenging. Circular and square earthworks showed nearly complementary distributions suggesting a potential interface between two prevalent peoples who may have coexisted. The abundance and widespread distribution of earthworks in the region suggests considerable human impact with available radiocarbon data indicating its lasting influence. While all of the oldest constructions were ceremonial geoglyphs, with their use ceasing around or before 1,000 years ago, they were followed for a few centuries later by a relatively short-lived mound village culture.

ACKNOWLEDGMENTS

We extend our gratitude to our collaborators at our home institutions, James Q. Jacobs, Francisco R Nakahara, and the other discoverers of ancient earthwork sites. We also acknowledge the Academy of Finland for funding research projects 296406 (RK) and 297161 (MP). In Brazil, the research was authorized by the Instituto do Patrimônio Histórico e Artístico Nacional (IPHAN license # 01423000336/2017-11). Our heartfelt thanks go to our long-term close collaborators Denise Schaan and Heli Pärssinen, and we dedicate this research to their memory.

REFERENCES

Almeida, C.T.; Oliveira-Júnior, J.F.; Delgado, R.C.; Cubo, P.; Ramos, M.C. 2017. Spatiotemporal rainfall and temperature trends throughout the Brazilian Legal Amazon, 1973–2013. *International Journal of Climatology* 37: 2013–2026.

Bronk Ramsey, C. 2021. OxCal 4.4. (http://c14.arch.ox.ac.uk/oxcal). Accessed on 16 Jul 2022.

Bush, M.B.; McMichael, C.H.; Piperno, D.R.; Silman, M.R.; Barlow, J.; Peres, C.A.; et al. 2015. Anthropogenic influence on Amazonian forests in pre-history: an ecological perspective. *Journal of Biogeography* 42: 2277–2288.

Carson, J.F.; Whitney, B.S.; Mayle, F.E.; Iriarte, J.; Prümers, H.; Soto J.D.; et al. 2014. Environmental impact of geometric earthwork construction in pre-Columbian Amazonia. *Proceedings of the National Academy of Sciences* 111: 10497–10502.

Chouquer, G. 2021. L'ancienne morphologie agraire de l'Amazonie occidentale, des Llanos et du Chaco (Brésil - Bolivie - Pérou). Éditions PublinTopex, Paris, 242p.

Dehaene, S.; Izard, V.; Pica, P.; Spelke E. 2006. Core knowledge of geometry in an Amazonian indigene group. *Science*, 311: 381–384.

Denevan, W.M. 2012. Rewriting the late pre-European history of Amazonia. *Journal of Latin American Geography*11: 9–24.

Dias, O. 2006. As estructuras arqueológicas de terra no Estado do Acre - Amazônia Ocidental, Brasil. Um caso de resiliência? In: Dias, O.; Carvalho, E.; Zimmermann, M. (Ed.). *Estudos Contemporâneos de Arqueologia*, Unitins, IAB, Palmas, p. 59-168.

Erickson, C.L. 2010. The transformation of environment into landscape: The historical ecology of monumental earthwork construction in the Bolivian Amazon. *Diversity* 2: 618–652.

Ferreira, E.; Kalliola, R.; Ruokolainen, K. 2020. Bamboo, climate change and forest use: A critical combination for southwestern Amazonian forests? *Ambio* 49: 1353–1363.

Heckenberger, M.; Neves, E.G. 2009. Amazonian archaeology. *Annual Review of Anthropology* 38: 251–266.

Hill, J.; Black, S.; Araujo-Murakami, A.; Boot, R.; Brienen, R.; Feldpausch, T.; et al. 2023. An assessment of soil phytolith analysis as a palaeoecological tool for identifying pre-Columbian land use in Amazonian rainforests. *Quaternary* 6: 33. doi: org/10.3390/quat6020033.

Hogg, A.G.; Heaton, T.J.; Hua, Q. Palmer, J.G.; Turney, C.SM.; Southon, J.; *et al.* 2020. SHCal20 Southern Hemisphere Calibration, 0–50,000 Years cal BP. *Radiocarbon* 62: 759–778.

Iriarte, J.; Robinson, M.; de Souza, J.G.; Damasceno, A.; da Silva, F.; Nakahara, F.; et al. 2020. Geometry by design: contribution of Lidar to the understanding of settlement patterns of the mound villages in SW Amazonia. *Journal of Computer Applications in Archaeology* 3: 151–169.

Iriarte, J.; de Souza, J.G.; Robinson, M.E.; Barbosa, A.D.; da Silva F. 2021. Refining the chronology and occupation dynamics of the mound villages of south-eastern Acre, Brazil. *Amazônica - Revista de Antropologia* 13: 153–176.

Jacobs, J.Q. 2022. Hundreds of geoglyphs discovered in the Amazon. (http://www.jqjacobs.net/archaeology/geoglyph.html). Accessed on 23 May 2022.

Kern, D.C.; Lima, H.P.; da Costa, J.A.; de Lima, H.V.; Browne Ribeiro, A.; Moraes, B.M.; et al. 2017. Terras pretas: Approaches to formation processes in a new paradigm. *Geoarchaeology,* 32: 694-706.

Loughlin, N.J.; Gosling, W.D.; Mothes, P.; Montoya, E. 2018. Ecological consequences of post-Columbian indigenous depopulation in the Andean–Amazonian corridor. *Nature Ecology & Evolution*, 2: 1233-1236.

McMichael, C.H.; Palace, M.W.; Bush, M.B.; Braswell, B.; Hagen, S.; Neves, E.G.; et al. 2014. Predicting pre-Columbian anthropogenic soils in Amazonia. *Proceedings of the Royal Society B: Biological Sciences* 281: 20132475.

Mill, J.S. 1843. Of the laws of the mind. In: Robson, J.M. (Ed.) *Collected Works of John Stuart Mill.* v. VII, University of Toronto Press, Toronto, p.24–36.

Montoya, E.; Lombardo, U.; Levis, C.; Aymard, G.A.; Mayle F.E. 2020. Human contribution to Amazonian plant diversity: Legacy of pre-Columbian land use in modern plant communities. In: Rull, V.; Carnaval, A. (Ed.). *Neotropical Diversification: Patterns and Processes. Fascinating Life Sciences.* Springer, Berlin, p.495-520.

Neves, E.G.; Pugliese Jr., F.A.; Shock, M.P.; Furquim, L.P. ;Neto, C.A.Z.; Carneiro, C.G. 2016. Pesquisa e Formação nos Sítios Arqueológicos Espinhara e Sol de Campinas do Acre – PESC. Portaria Iphan n° 48/2014: Relatório Final. Universidade de São Paulo, unpublished technical report.

Peripato, V.; Levis, C.; Moreira, G.A.; Gamerman, D.; Ter Steege, H.; Pitman, N.C.; et al. 2023. More than 10,000 pre-Columbian earthworks are still hidden throughout Amazonia. *Science* 382: 103-109.

Pärssinen, M. 2021. Tequinho geoglyph site and early polychrome horizon BC 300-AD 300/500 in the Brazilian state of Acre. *Amazônica - Revista de Antropologia* 13: 177–220.

Pärssinen, M.; Alceu, A.; Saunaluoma, S.; Siiriäinen, A. 2003. Geometrically patterned ancient earthworks in the Rio Branco Region of Acre, Brazil: New evidence of ancient chiefdom formations in Amazonian interfluvial *terra firme environment, In: Pärssinen, M.; Korpisaari, A. (Ed.). Western Amazonia - Amazônia Ocidental. Multidisciplinary Studies on Ancient Expansionistic Movements, Fortifications and Sedentary Life.* Renvall Institute Publications 14, University of Helsinki, Helsinki, p.97-133.

Pärssinen, M.; Schaan, D.; Ranzi, A. 2009. Pre-Columbian geometric earthworks in the upper Purús: a complex society in western Amazonia. *Antiquity* 83: 1084–1095.

Pärssinen, M; Balée, W.; Ranzi, A.; Barbosa, A.D. 2020. The geoglyph sites of Acre, Brazil: 10 000-year-old land-use practices and climate change in Amazonia, Antiquity 94*: 1538-1556.*

Pärssinen, M.; Ranzi, A. 2020. Mobilidade cerimonial e a emergência do poder político com as primeiras estradas conhecidas do oeste amazônico (2000 A.P.). In: Vilaça, R.; Simas de Aguiar, R. (Ed.). (I)Mobilidades na Pré-história: Pessoas, Recursos, Objetos, Sítios e Territórios. Coimbra University Press, Coimbra, p.307–349.

Pärssinen, M.; Ferreira, E.; Virtanen, K; Ranzi, A. 2021. Domestication in motion: Macrofossils of pre-colonial Brazilian nuts, palms and other Amazonian planted tree species found in the upper Purus, Environmental Archaeology 26: 309–322.

Piperno, D.R.; McMichael, C.; Bush, M.B. 2017. Further evidence for localized, short-term anthropogenic forest alterations across pre-Columbian Amazonia. *Proceedings of the National Academy of Sciences* 114: E4118–E4119.

Prümers, H.; Betancourt, C.J.; Iriarte, J.; Robinson, M.; Schaich M. 2022. Lidar reveals pre-Hispanic low-density urbanism in the Bolivian Amazon. *Nature* 606: 325–358.

Ragin, C.C. 1987. *The Comparative Method: Moving Beyond Qualitative and Quantitative Strategies*. University of California Press, Berkeley, p.185.

Ragin, C.C. 2007. Fuzzy sets: Calibration versus measurement. In: Boc-Steffensmeier, J.M.; Brady, H.E.; Collier, D. (Ed.). *The Handbook of Political Methodology.* Oxford University Press, Oxford, p.174–198.

Ranzi, A. 2003. Geoglifos: Patrimônio cultural do Acre. In: Pärssinen, M.; Korpisaari, A. (Ed.). *Western Amazonia - Amazônia Ocidental. Multidisciplinary Studies on Ancient Expansionistic Movements, Fortifications and Sedentary Life.* Renvall Institute Publications 14, University of Helsinki, Helsinki, p.135–172.

Ranzi, A.; Feres, R.; Brown, F. 2007. Internet software programs aid in search for Amazonian geoglyphs. *Eos* 88: 226–229.

Ranzi, A.; Pärssinen, M. 2021. Amazônia: Os Geoglifos e a Civilização Aquiry. Officio and Fundação Ibero-Americana da Finlândia/Instituto Ibero-Americano da Finlândia. *Acta Ibero-Americana Fennica*, *Series Lusitano-Brasiliensis* 1: 1-203.

Riris, P. 2020. Spatial structure among the geometric earthworks of western Amazonia (Acre, Brazil). *Journal of Anthropological Archaeology* 59: 101177.

Rostain, S.; Dorison, A.; De Saulieu, G.; Prümers, H.; Le Pennec, J.L.; Mejía Mejía, F.; et al. 2024. Two thousand years of garden urbanism in the Upper Amazon. *Science* 383: 183–189.

Santos, M.J.; Disney, M.; Chave, J. 2018. Detecting human presence and influence on neotropical forests with remote sensing. *Remote Sensing* 10: 1593. doi.org/10.3390/rs10101593.

Saunaluoma, S. 2010. Pre-Columbian earthworks in the Riberalta region of the Bolivian Amazon. *Amazônica-Revista de Antropologia, 2: 104-138.*

Saunaluoma, S. 2012. Geometric earthworks in the state of Acre, Brazil: excavations at the Fazenda Atlântica and Quinauá Sites. *Latin American Antiquity* 23: 565–583.

Saunaluoma, S.; Schaan, D. 2012. Monumentality in Western Amazonian formative societies: geometric ditched enclosures in the Brazilian state of Acre. *Antiqua* 2. doi:10.4081/antiqua.2012.e1.

Saunaluoma, S.; Pärssinen, M.; Schaan, D. 2018. Diversity of precolonial earthworks in the Brazilian state of Acre, southwestern Amazonia. *Journal of Field Archaeology* 43: 362–379.

Saunaluoma, S.; Anttiroiko, N.; Moat, J. 2019. UAV survey at archaeological earthwork sites in the Brazilian state of Acre, southwestern Amazonia. *Archaeological Prospection* 26: 325–331.

Saunaluoma, S.; Moat, J.; Pugliese, F.; Neves, E. G. 2021 Patterned villagescapes and road networks in ancient southwestern Amazonia. *Latin American Antiquity* 32: 173–187.

Schaan, D. 2012. *Sacred Geographies of Ancient Amazonia: Historical Ecology of Social Complexity*. Left Coast Press, Walnut Creek, 233p.

Schaan, D.; Ranzi, A.; Pärssinen, M. (Ed.). 2008. Arqueologia da Amazônia Ocidental: Os Geoglifos do Acre. Editora Universitária EDUFPA, Belém, 192p.

Schaan, D.; Ranzi, A.; Barbosa, A.D. 2010. Geoglifos do Acre (Janeiro 2008-Deziembro 2009). Universidade Federal do Pará, unpublished technical report, 76p.

Schaan, D.; Pärssinen, M.; Saunaluoma, S.; Ranzi, A.; Bueno, M.; Barbosa, A. 2012. New radiometric dates for precolumbian (2000–700 BP) earthworks in western Amazonia, Brazil. *Journal of Field Archaeology* 37: 132–142.

Shepard, G.H.; Ramirez, H. 2011. “Made in Brazil”: Human dispersal of the Brazil Nut (*Bertholletia excelsa*, Lecythidaceae) in ancient Amazonia 1. *Economic Botany* 65: 44–65.

Souza, J.G.; Schaan, D.P.; Robinson, M.; Barbosa, A.D.; Aragão, L.E.; Marimon Jr, B.H.; et al. 2018. Pre-Columbian earth-builders settled along the entire southern rim of the Amazon. *Nature Communications* 9: 1125. doi:10.1038/s41467-018-03510-7.

UNESCO. 2015. Geoglyphs of Acre. (https://whc.unesco.org/en/tentativelists/5999/). Accessed on 28 Feb 2024.

Van doninck, J.; Westerholm, J.; Ruokolainen, K.; Tuomisto, H.; Kalliola R. 2020. Dating flowering cycles of Amazonian bamboo-dominated forests by supervised Landsat time series segmentation. *International Journal of Applied Earth Observation and Geoinformation 93: 102196.*

Virtanen, P.K.; Saunaluoma, S. 2017. Visualization and movement as configurations of human–nonhuman engagements: precolonial geometric earthwork landscapes of the upper Purus, Brazil. *American Anthropologist* 119: 614–630.

Walker, R.S.; Ferguson, J.R.; Olmeda, A.; Hamilton, M.J.; Elghammer, J.; Buchanan, B. 2023. Predicting the geographic distribution of ancient Amazonian archaeological sites with machine learning. *PeerJ* 11: e15137

Watling, J., Saunaluoma, S.; Pärssinen, M.; Schaan, D. 2015. Subsistence practices among earthwork builders: phytolith evidence from archaeological sites in the southwest Amazonian interfluves. *Journal of Archaeological Science: Reports* 4: 541–551.

Watling, J.; Iriarte, J.; Mayle, F.E.; Schaan, D.; Pessenda, L.C.; Loader, N.J.; et al. 2017. Impact of pre-Columbian “geoglyph” builders on Amazonian forests. *Proceedings of the National Academy of Sciences* 114: 1868–1873.

Watling, J.; Mayle, F.E.; Schaan, D. 2018. Historical ecology, human niche construction and landscape in pre-Columbian Amazonia: A case study of the geoglyph builders of Acre, Brazil. *Journal of Anthropological Archaeology* 50: 128–139.

WinklerPrins, A.M.A.; Levis, C. 2020. Reframing pre-European Amazonia through an Anthropocene lens. *Annals of the American Association of Geographers* 111: 858-868.

RECEIVED: 23/02/2023
ACCEPTED: 11/08/2024
ASSOCIATE EDITOR: Guilherme Mongeló
DATA AVAILABILITY: A list with names and coordinates of all earthworks considered in this study is available at: https://doi.org/10.23729/31c411bf-5d94-4cfc-be06-006c16a5c309.

SUPPLEMENTARY MATERIAL

Kalliola *et al*. Geography of ancient geometric earthworks and their builders in southwestern Amazonia

Table S1. Range of oldest and most recent ^{14}C ages of earthworks in the study area. Dated samples refer to the number of available dating data from the referred structure/structures. Calibrated radiocarbon ages before present (cal BP) reported as a likelihood of 95.4% (2-sigma). Data sources in Figure 7.

Earthwork	Functional type	Dated samples	Calibrated age cal BP	
			Oldest	Most recent
Balneário Quinauá - Estruturas I,II	geoglyph	4	1703-1539	1520-1315
Campo Esperança	solitary embankment	1	550-500	550-500
Coqueiral	mound site	3	621-490	497-322
Cruzeirinho - Estructura I	geoglyph	4	1830-1610	1698-1427
Dois Circulos: Estrutura IV	mound site	1	623-505	542-470
Dois Circulos: Estrutura V	mound site	3	632-499	632-499
El Circulo	solitary embankment	7	671-559	653-501
Eletronorte I - Estrutura I	geoglyph	6	2702-2352	1402-1285
Estancia Giese	solitary embankment	2	1824-1580	1696-1425
Fazenda Boa Esperança - Estructura I	mound site	1	549-499	549-499
Fazenda Atlântica - Estruturas I,II	geoglyph	3	2127-1929	1827-1621
Fazenda Colorada – Estrutura V	mound site	1	722-562	722-562
Fazenda Colorada - Estrutura III	geoglyph	5	1918-1585	1263-1065
Fazenda Iquiri II - Estrutura I -montículos	mound site	2	528-338	441-150
Fazenda Iquiri II - Estrutura II	geoglyph	1	1700-1535	1700-1535
Fazenda Tocantins	mound site	1	638-525	638-525
Fonte Boa - Estrutura II-montículos	mound site	1	624-508	624-508
Jacó Sá - Estruturas I,II	geoglyph	3	1405-1290	1178-961
JK	geoglyph	2	1816-1610	1698-1484
Las Palmeras - Estructura I	geoglyph	1	1833-1610	1833-1610
Las Palmeras – Estructure II	mound site	1	442-150	442-150
Los Angeles	geoglyph	3	2717-2357	1263-960
Piçarreira	geoglyph	4	2844-2501	1829-1620
Ramal do Capatará - Estrutura I	geoglyph	2	1996-1830	1833-1610
Severino Batista	geoglyph	2	1705-1564	1698-1070
Severino Calazans - Estructura I	geoglyph	13	2703-2352	1698-1520
Sobrevoo AC09	mound site	9	724-568	525-336
Sol de Campinas	mound site	4	680-561	542-491
Sol de Maio	mound site	4	653-540	542-493
Tênue	solitary embankment	1	289-0	289-0
Tequinho – Estrutura I	geoglyph	16	2353-2149	1402-1285
Três Vertentes - Estructura II	mound site	2	433-144	314-140
Tumichucua	geoglyph	2	2120-1753	1887-1704

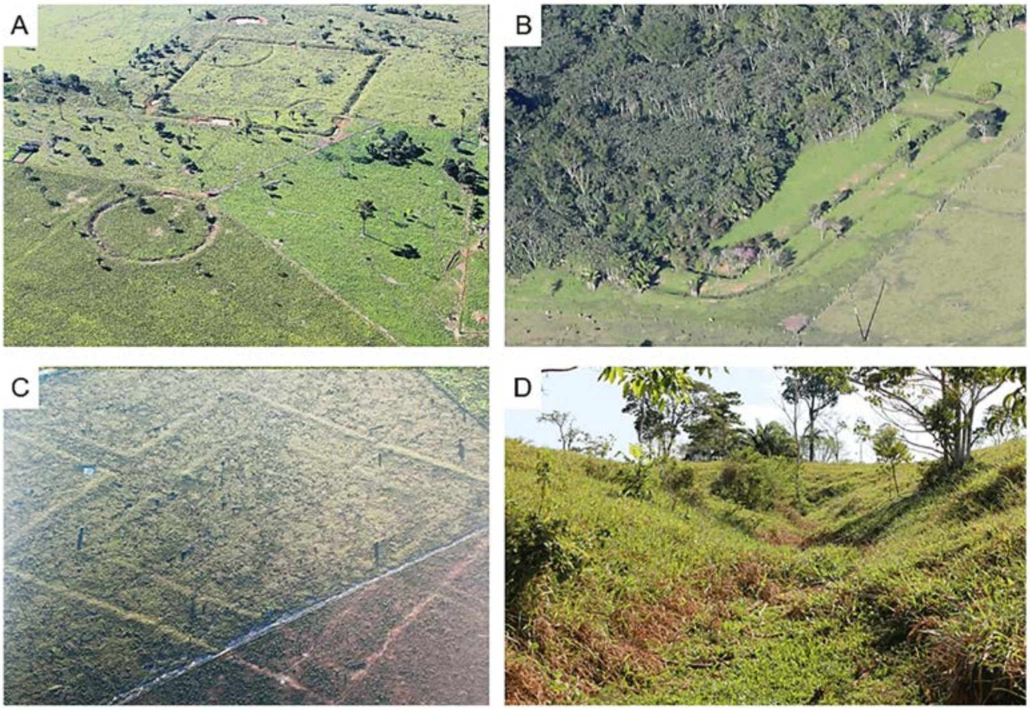

Figure S1. Aerial photographs of earthworks in the study area from oblique perspectives. **A** – Circular (site Fazenda Atlântica – Estrutura I) and square (site Fazenda Atlàntica – Estrutura II) geoglyphs; **B** – Somewhat square nested geoglyph with rounded corners and a wide ancient road (site JK); **C** – Nested rhombus embankment with two ancient roads (site Amapa); **D** – Approximately 3-m deep ditch on the side of an earthwork (site Jacó Sá - Estrutura I). Credit: Martti Pärssinen, Alceu Ranzi and Diego Gurgel.

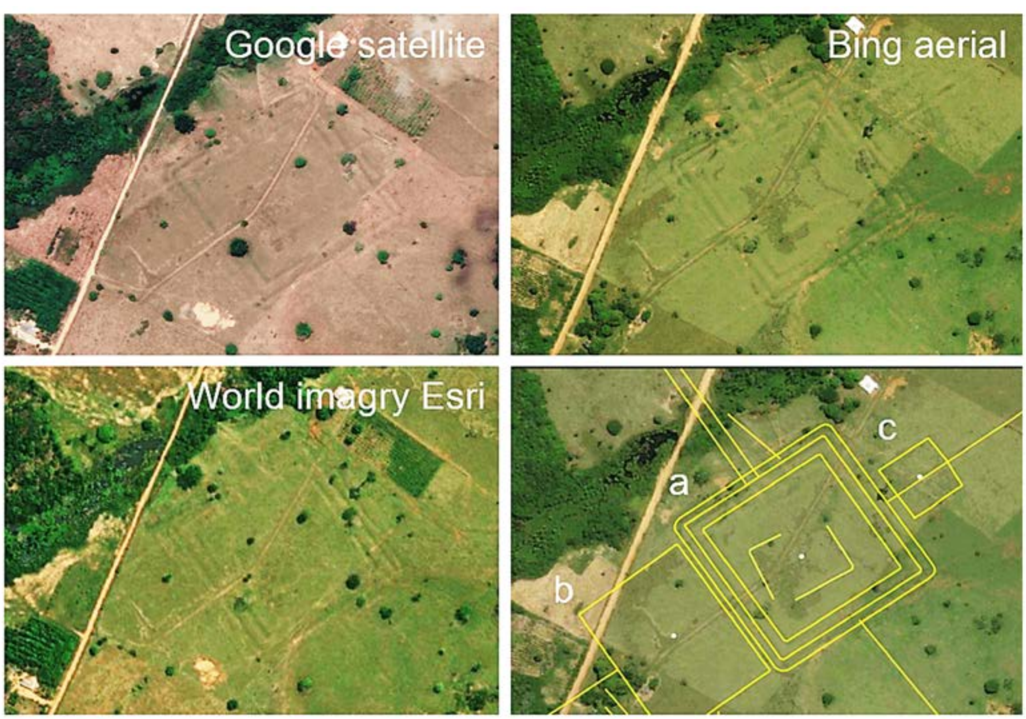

Figure S2. Examples of the visual depiction of the same earthworks on satellite images of the study area from different sources. In the lower right image, interpreted earthworks and ancient roads are highlighted in yellow. The three earthworks are Tequinho – Estrutura I (a), Tequinho – Estrutura III (b) and Tequinho – Estrutura IV (c).

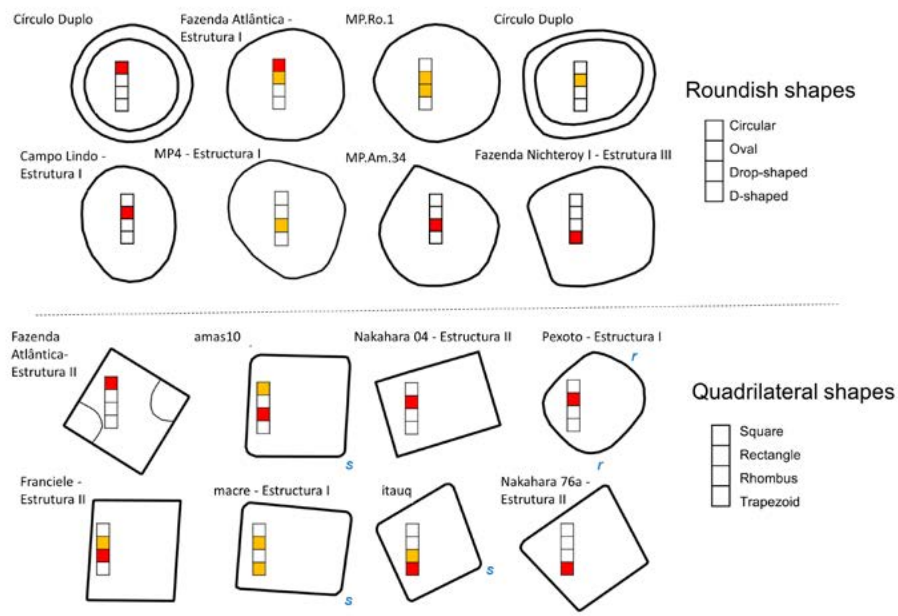

Figure S3. Examples of shape classification within groups of roundish and quadrilateral earthworks in the study area (site names are informed). Good fit of classification is shown in red, somewhat good in yellow, and no fit in white. The blue letters indicate corner or sides of some quadrilateral structures as rounded (r) or somewhat rounded (s).

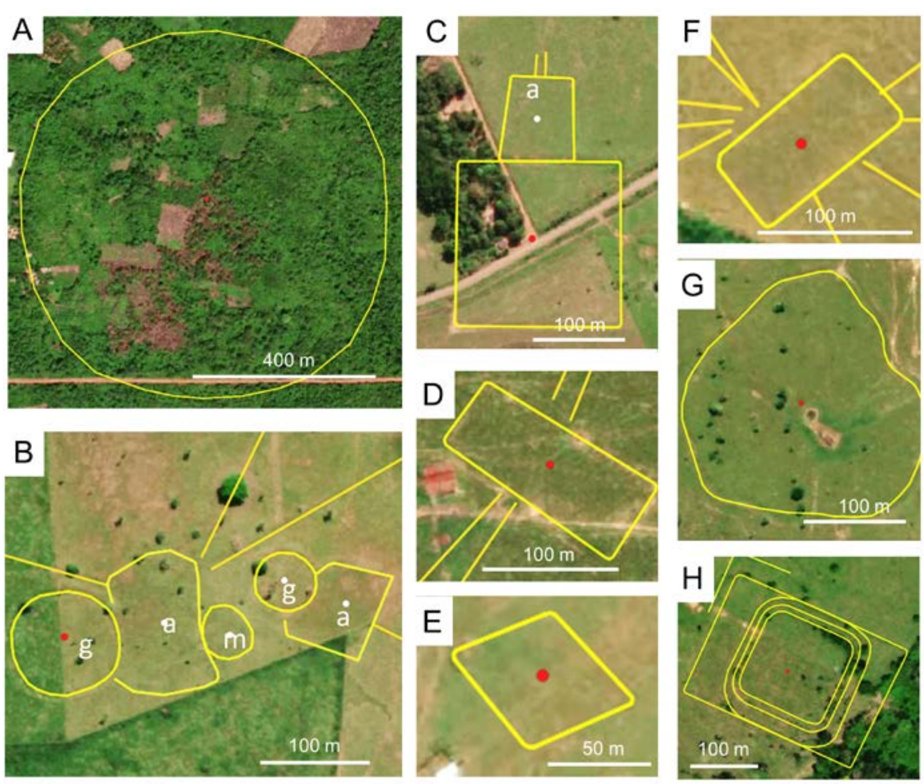

Figure S4. Examples of earthwork shapes. **A** – Giant circular geoglyph (site Tumichucua); **B** – Composed earthwork complex (site Dois círculos - Estrutura I) consisting of two circular geoglyphs (g), two unique-shaped associated embankments (a), and an oval mound site (m); **C** – Square geoglyph (site Severino Calazans - Estructura I) with a trapezoid associated embankment (a); **D** – Trapezoid to somewhat rectangle geoglyph with uneven side lengths (site ronr3); **E** – Strongly leaning parallelogram geoglyph (site Nakahara 111 - Estructura I); **F** – Rectangular mound site with many narrow roads (site Sol de Alceu); **G** – Uniquely-shaped geoglyph with curved outline (site Nakahara 130); **H** – Rectangular nested geoglyph with three inner squares and one incomplete outer structure. (site: D. Schaan).

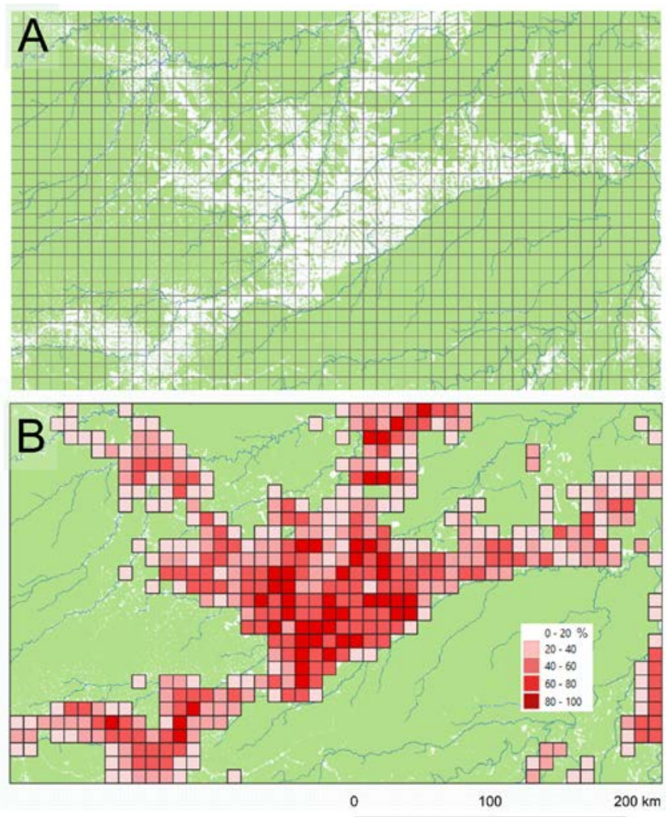

Figure S5. A – Map of the study area displaying the forested (green) and deforested (white) parts with the superimposed 10×10-km cell grid; **B** – Deforestation percentage within the grid cells.

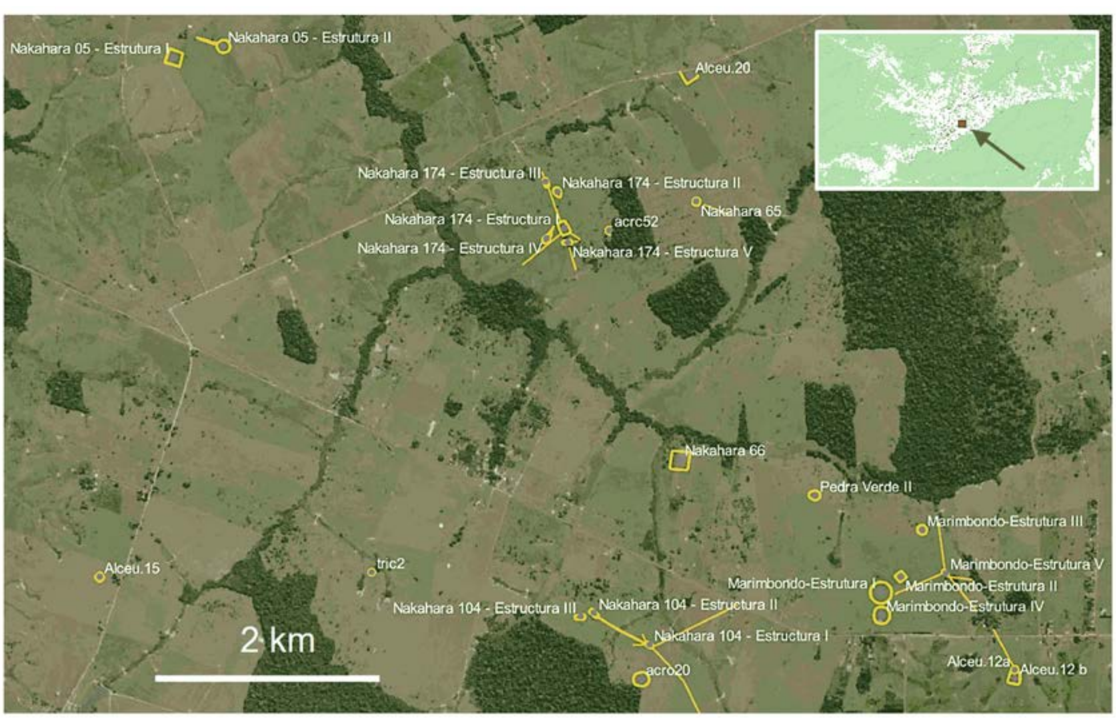

Figure S6. Example of the distribution of earthworks within the core density zone of the study area (red square in the inset map). Interpreted earthworks and ancient roads are highlighted in yellow.

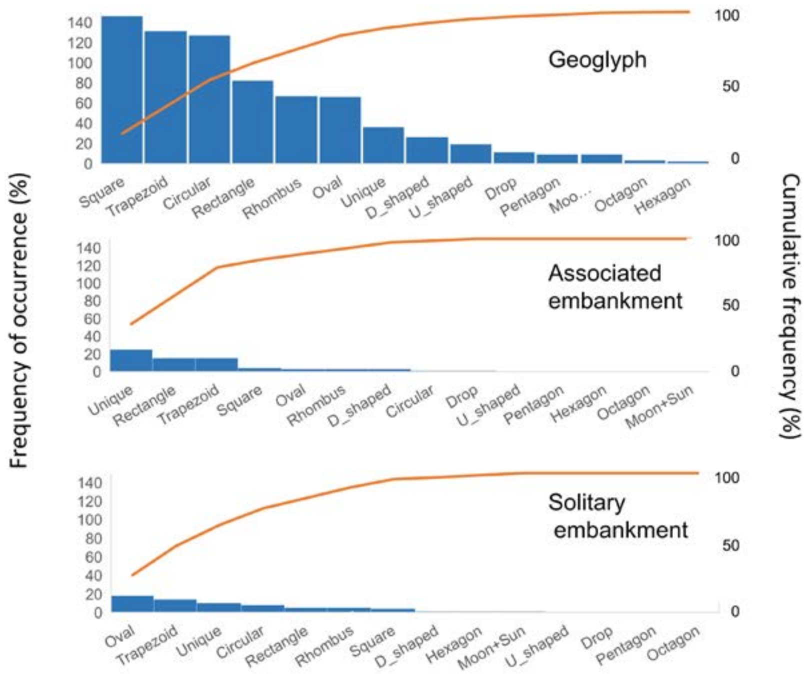

Figure S7. Pareto histograms for southwestern Amazonian earthwork shape types in three functional categories. Only earthworks with good fit shape classification are included. The red curve represents the cumulative total percentage.

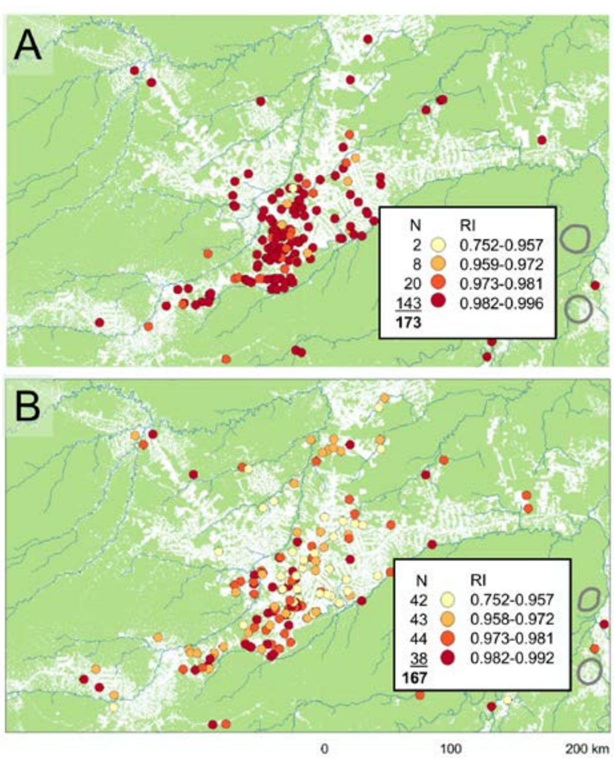

Figure S8. Roundness index (RI) of circular (**A**) and oval (**B**) enclosures in the study area. The RI range for each color code is based on the RI quantiles of the oval structures. The gray outlines right of the map legends examplify the type of roundness of the extreme quantiles. Both datasets comprise structures with both good and somewhat good fit for their respective shapes. N = number of earthworks.

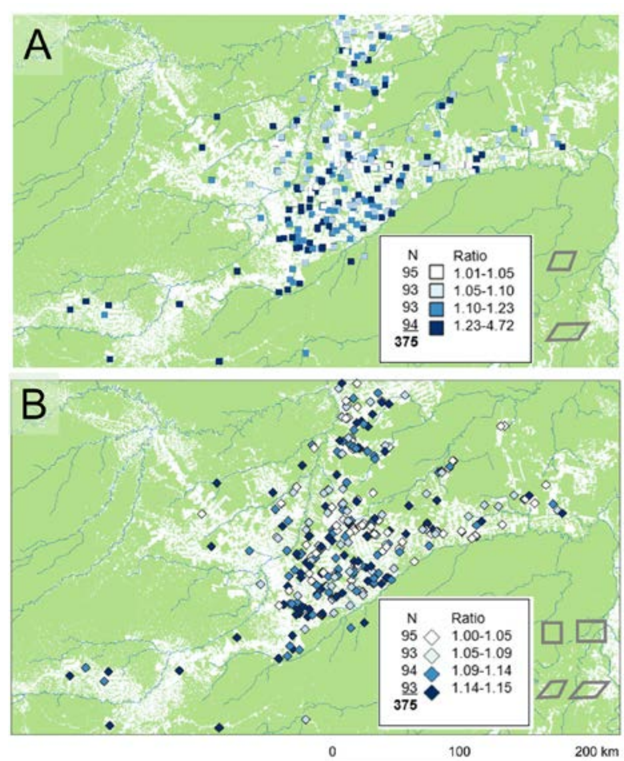

Figure S9. Categorization (in quantiles) of 375 quadrilateral earthworks in the study area based on the ratio between their longest and shortest side (**A**) and the ratio between the largest and smallest angle (**B**). The gray outlines right of the map legends exemplify the shapes of the extreme quartiles. Shapes with both good and somewhat good are included.

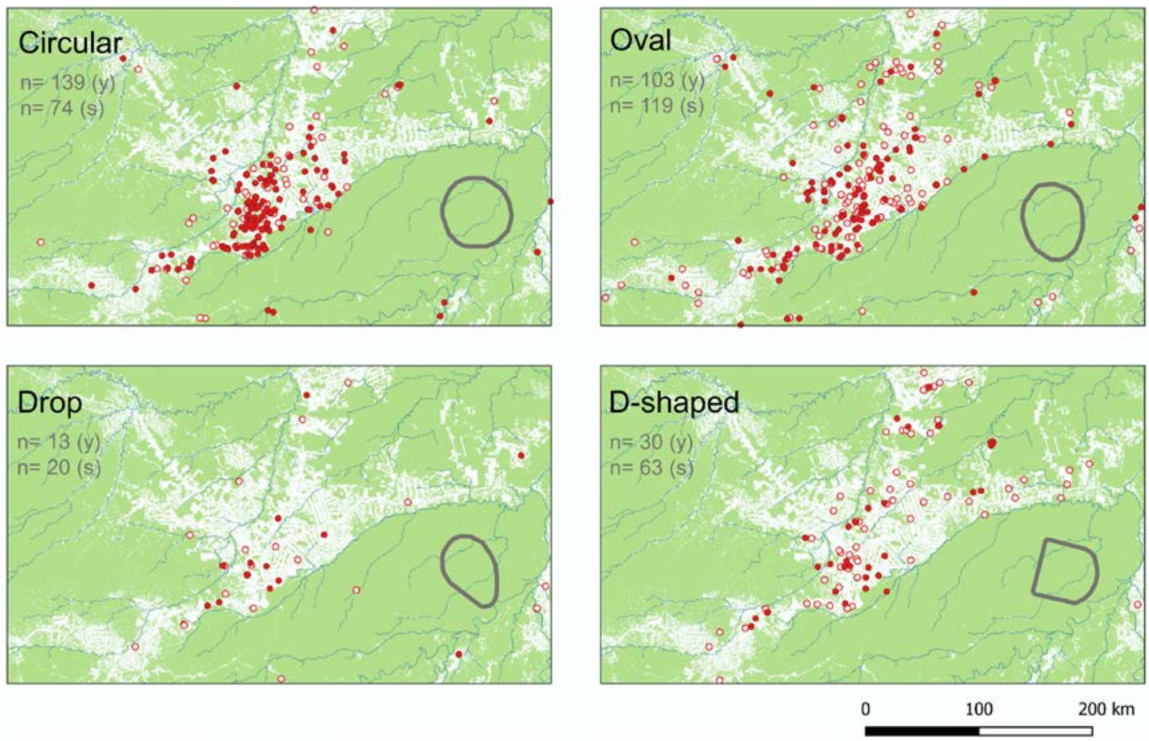

Figure S10. Distribution of roundish earthworks in the study area (shape-type example in gray outline). Red-filled circles indicate good fit and open circles somewhat good fit in shape classification. N = sample size corresponding to earthworks with good fit (y) and somewhat good fit (s).

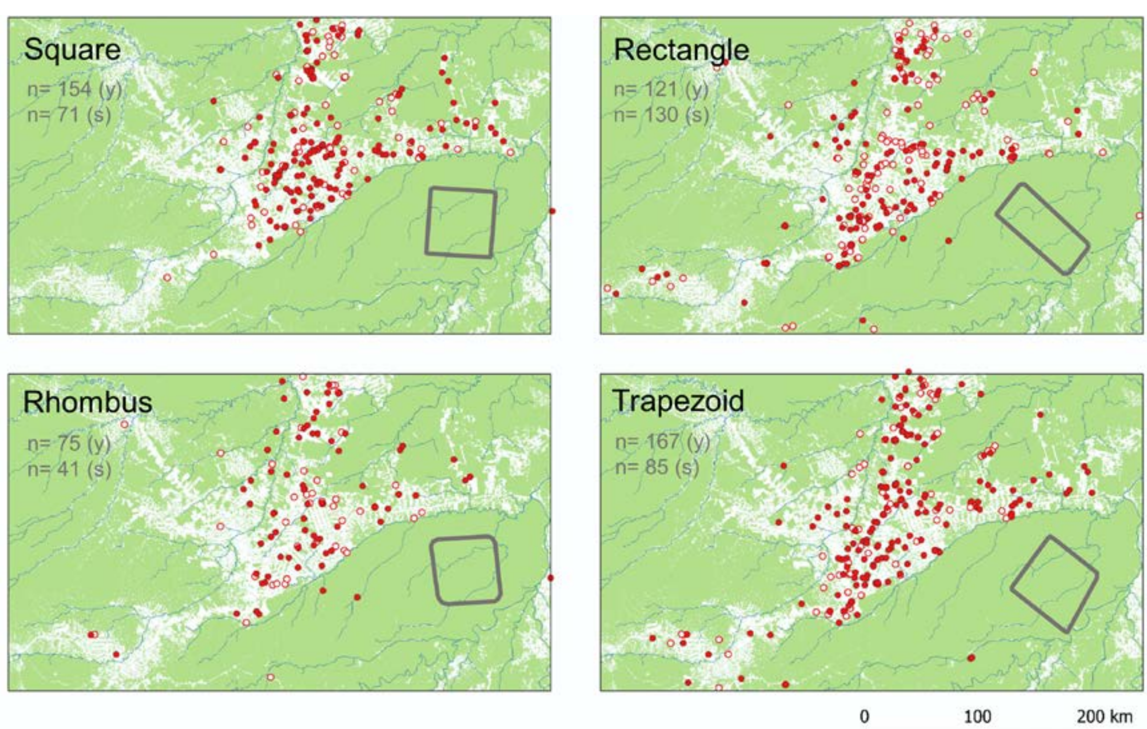

Figure S11. Distribution of quadrilateral earthworks in the study area (shape-type example in gray outline). Red-filled circles indicate good fit and open circles somewhat good fit in shape classification. N = sample size corresponding to earthworks with good fit (y) and somewhat good fit (s).

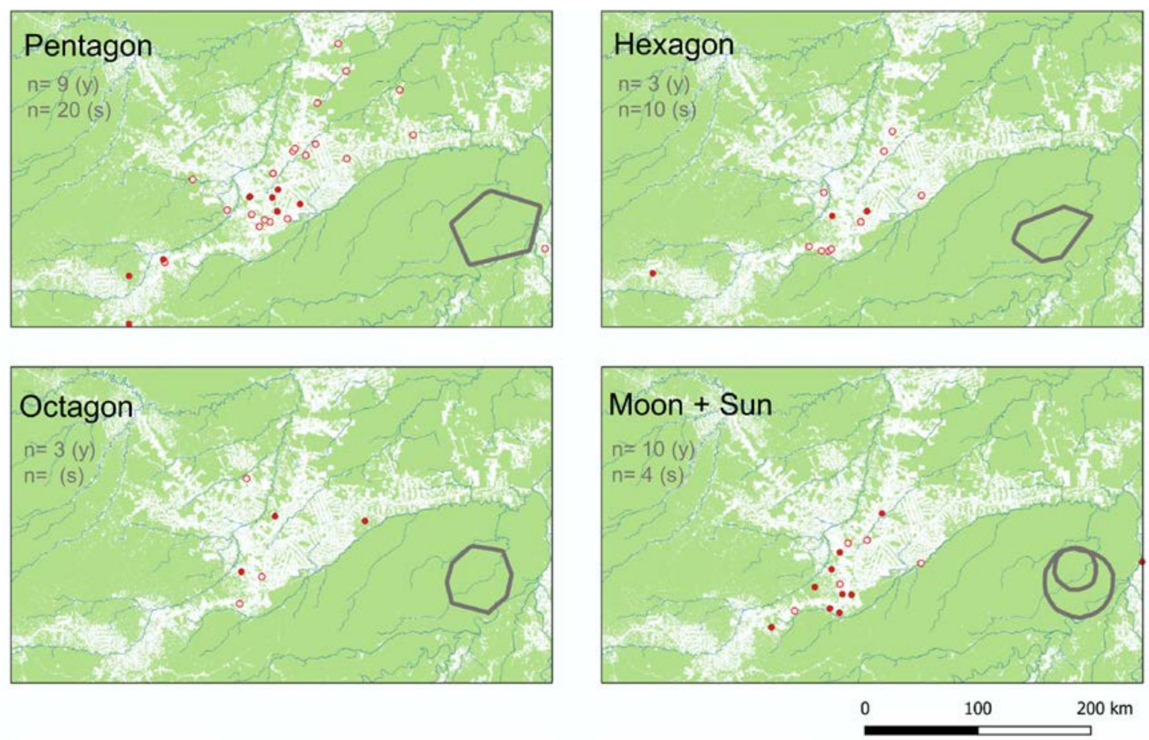

Figure S12. Distribution of multilateral earthworks and the shape type Moon+Sun in the study area (shape-type example in gray outline). Red-filled circles indicate good fit and open circles somewhat good fit in shape classification. N = sample size corresponding to earthworks with good fit (y) and somewhat good fit (s).

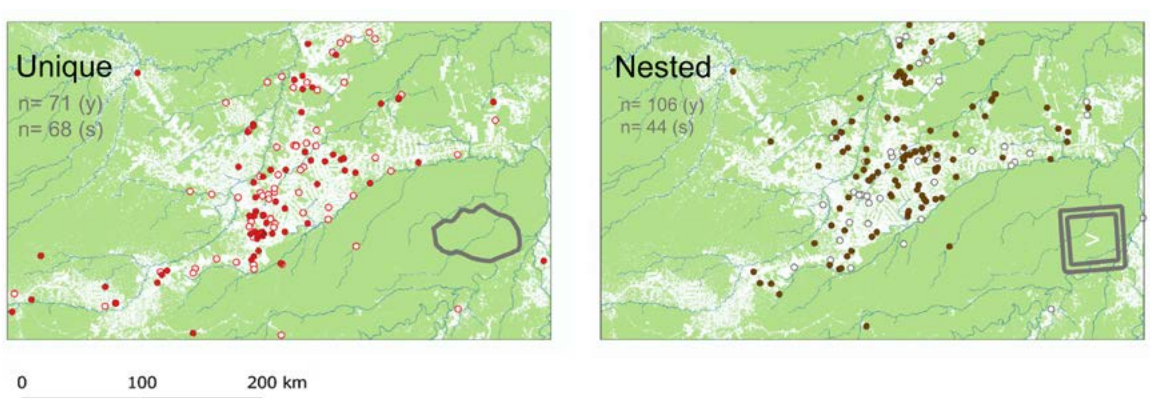

Figure S13. Distribution of uniquely-shaped and nested earthworks in the study area (shape-type example in gray outline). Filled circles indicate good fit and open circles somewhat good fit in shape classification. N = sample size corresponding to earthworks with good fit (y) and somewhat good fit (s).

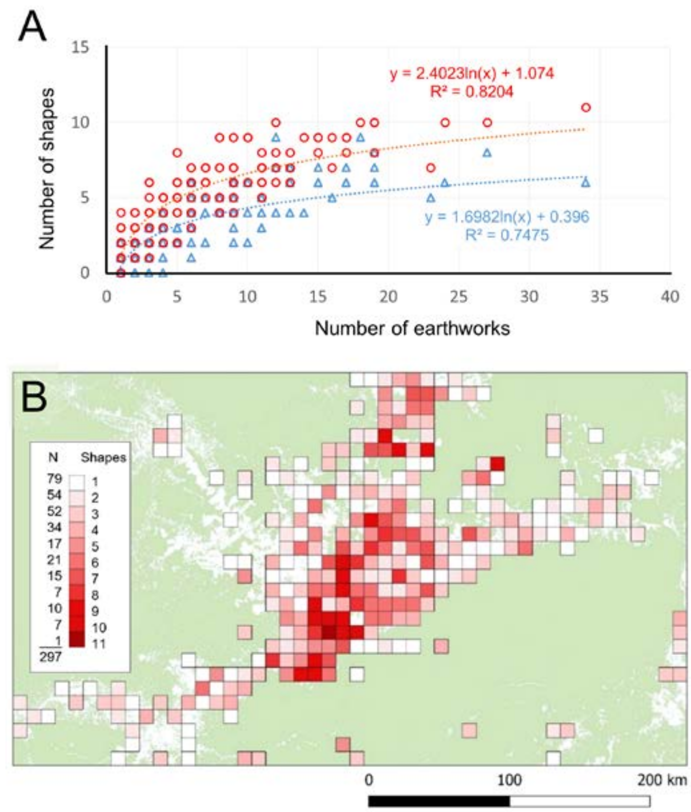

Figure S14. **A** – Relationship between the number of earthworks and the number of different shape classifications per 10x10-km grid cell in the study area. Blue triangles represent earthworks classified as having a good fit only, while red circles include earthworks with a somewhat good fit as well, allowing for the treatment of intermediate structures as distinct shapes. Logarithmic fit curves for both data sets are also shown; **B** – Distribution of the number of shape classifications, or shape variability, across a 10x10-km-cell grid within the study area (including good fit and somewhat good fit). N = number of grid cells; Shapes = number of different shape classifications within the grid.

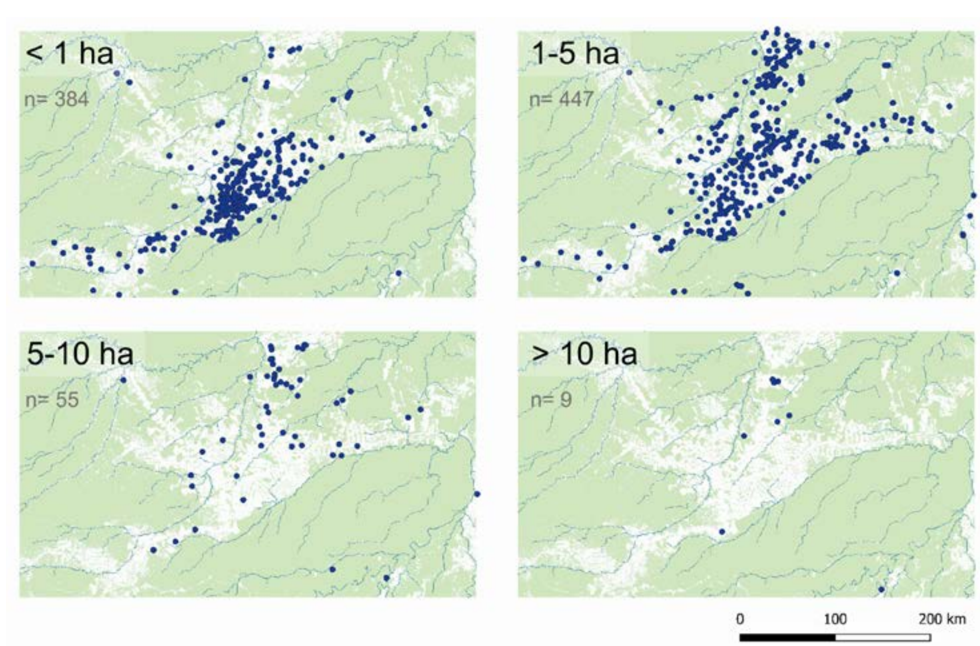

Figure S15. Distribution of earthworks of different size categories in the study area. N = number of earthworks.

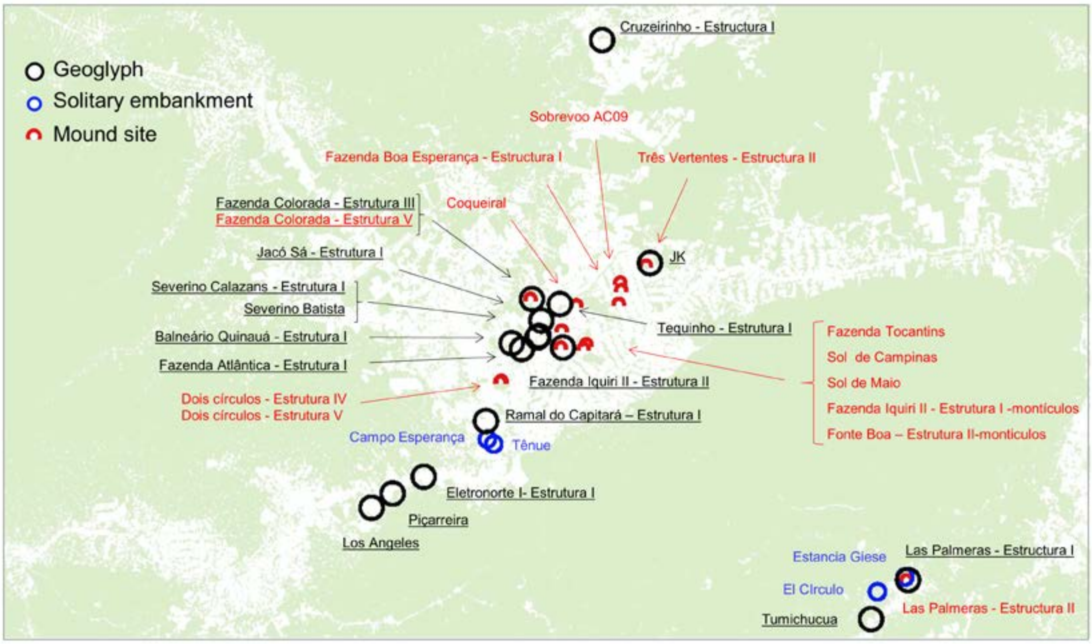

Figure S16. Distribution of 33 earthworks with radiocarbon data in the study area, identified by name and functional category. The estimated radiocarbon ages are available in Figure 7 and Table S1.