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Title: Over 10,000 Pre-Columbian earthworks are still hidden throughout Amazonia

Authors: Vinicius Peripato^{1*†}, Carolina Levis^{2†}, Guido A. Moreira³, Dani Gamerman⁴, Hans ter Steege⁵, Nigel C.A. Pitman⁶, Jonas G. de Souza⁷, José Iriarte⁸, Mark Robinson⁸, André Braga Junqueira⁹, Thiago B. Trindade¹⁰, Fernando O. de Almeida¹¹, Claide de Paula Moraes¹², Umberto Lombardo¹³, Eduardo K. Tamanaha¹⁴, Shira Y. Maezumi¹⁵, Jean P. H. B. Ometto¹, José R.G. Braga¹, Wesley A. Campanharo¹, Henrique L. G. Cassol¹, Philipe R. Leal¹, Mauro L. R. de Assis¹, Adriana M. da Silva¹⁶, Oliver L. Phillips¹⁷, Flávia R.C. Costa¹⁸, Bernardo Monteiro Flores², Bruce Hoffman¹⁹, Terry W. Henkel²⁰, Maria Natalia Umaña²¹, William E. Magnusson¹⁸, Elvis H. Valderrama Sandoval^{22,23}, Jos Barlow²⁴, William Milliken²⁵, Maria Aparecida Lopes²⁶, Marcelo Fragomeni Simon²⁷, Tinde R. van Andel^{5,28}, Susan G.W. Laurance²⁹, William F. Laurance²⁹, Armando Torres-Lezama³⁰, Rafael L. Assis³¹, Jean-François Molino³², Mickaël Mestre³³, Michelle Hamblin³⁴, Luiz de Souza Coelho³⁵, Diogenes de Andrade Lima Filho³⁵, Florian Wittmann^{36,37}, Rafael P. Salomão^{38,39}, Iêda Leão Amaral³⁵, Juan Ernesto Guevara^{40,41}, Francisca Dionízia de Almeida Matos³⁵, Carolina V. Castilho⁴², Marcelo de Jesus Veiga Carim⁴³, Dairon Cárdenas López^{44#}, Daniel Sabatier³², Mariana Victória Irumé³⁵, Maria Pires Martins³⁵, José Renan da Silva Guimarães⁴⁵, Olaf S. Bánki⁵, Maria Teresa Fernandez Piedade³⁷, José Ferreira Ramos³⁵, Bruno Garcia Luize⁴⁶, Evlyn Márcia Moraes de Leão Novo¹, Percy Núñez Vargas⁴⁷, Thiago Sanna Freire Silva⁴⁸, Eduardo Martins Venticinque⁴⁹, Angelo Gilberto Manzatto⁵⁰, Neidiane Farias Costa Reis⁵¹, John Terborgh^{52,29}, Katia Regina Casula⁵¹, Layon O. Demarchi³⁷, Euridice N. Honorio Coronado^{53,54}, Abel Monteagudo Mendoza^{47,55}, Juan Carlos Montero^{56,35}, Jochen Schöngart³⁷, Ted R. Feldpausch^{57,17}, Adriano Costa Quaresma^{36,37}, Gerardo A. Aymard C.⁵⁸, Chris Baraloto⁵⁹, Nicolás Castaño Arboleda⁴⁴, Julien Engel^{32,59}, Pascal Petronelli⁶⁰, Charles Eugene Zartman³⁵, Timothy J. Killeen⁶¹, Beatriz S. Marimon⁶², Ben Hur Marimon-Junior⁶², Juliana Schietti³⁵, Thaiane R. Sousa⁶³, Rodolfo Vasquez⁵⁵, Lorena M. Rincón³⁵, Erika Berenguer^{64,24}, Joice Ferreira⁶⁵, Bonifacio Mostacedo⁶⁶, Dário Dantas do Amaral³⁹, Hernán Castellanos⁶⁷, Marcelo Brilhante de Medeiros²⁷, Ana Andrade⁶⁸, José Luís Camargo⁶⁸, Emanuelle de Sousa Farias^{69,70}, José Leonardo Lima Magalhães^{71,65}, Henrique Eduardo Mendonça Nascimento³⁵, Helder Lima de Queiroz⁷², Roel Brienén¹⁷, Juan David Cardenas Revilla³⁵, Pablo R. Stevenson⁷³, Alejandro Araujo-Murakami⁷⁴, Bruno Barçante Ladvoat Cintra⁷⁵, Yuri Oliveira Feitosa⁷⁶, Flávia Rodrigues Barbosa⁷⁷, Rainiellen de Sá Carpanedo⁷⁷, Joost F. Duivenvoorden⁷⁸, Janaína Costa Noronha⁷⁷, Domingos de Jesus Rodrigues⁷⁷, Hugo F. Mogollón⁷⁹, Leandro Valle Ferreira³⁹, John Ethan Householder³⁶, José Rafael Lozada⁸⁰, James A. Comiskey^{81,82}, Freddie C. Draper⁸³, José Julio de Toledo⁸⁴, Gabriel Damasco⁸⁵, Nállarett Dávila^{46,##}, Roosevelt García-Villacorta^{86,87}, Aline Lopes⁸⁸, Fernando Cornejo Valverde⁸⁹, Alfonso Alonso⁸², Francisco Dallmeier⁸², Vitor H.F. Gomes^{90,91}, Eliana M. Jimenez⁹², David Neill⁹³, Maria Cristina Peñuela Mora⁹⁴, Daniel P. P. de Aguiar^{95,96}, Luzmila Arroyo⁷⁴, Fernanda Antunes Carvalho^{18,97}, Fernanda Coelho de Souza^{18,17}, Kenneth J. Feeley^{98,99}, Rogerio Gribel³⁵, Marcelo Petratti Pansonato^{35,100}, Marcos Ríos Paredes¹⁰¹, Izaías Brasil da Silva¹⁰², Maria Julia Ferreira¹⁰³, Paul V.A. Fine¹⁰⁴, Émile Fonty^{105,32}, Marcelino Carneiro Guedes¹⁰⁶, Juan Carlos Licona⁵⁶, Toby Pennington^{57,107}, Carlos A. Peres¹⁰⁸, Boris Eduardo Villa Zegarra¹⁰⁹, Germaine Alexander Parada⁷⁴, Guido¹¹⁰, Vincent Antoine Vos¹¹⁰, Carlos Cerón¹¹¹, Paul Maas⁵, Marcos Silveira¹¹², Juliana Stropp¹¹³, Raquel Thomas¹¹⁴, Tim R. Baker¹⁷, Doug Daly¹¹⁵, Isau Huamantupa-Chuquimaco¹¹⁶, Ima Célia Guimarães Vieira³⁹, Bianca Weiss

Albuquerque³⁷, Alfredo Fuentes^{117,118}, Bente Klitgaard¹¹⁹, José Luis Marcelo Pena¹²⁰, Miles R. Silman¹²¹, J. Sebastián Tello¹¹⁸, Corine Vriesendorp⁶, Jerome Chave¹²², Anthony Di Fiore^{123,124}, Renato Richard Hilário⁸⁴, Juan Fernando Phillips¹²⁵, Gonzalo Rivas-Torres^{124,126}, Patricio von Hildebrand¹²⁷, Luciana de Oliveira Pereira⁵⁷, Edelcilio Marques Barbosa³⁵, Luiz Carlos de Matos Bonates³⁵, Hilda Paulette Dávila Doza¹⁰¹, Ricardo Zárate Gómez¹²⁸, George Pepe Gallardo Gonzales¹⁰¹, Therany Gonzales¹²⁹, Yadvinder Malhi¹³⁰, Ires Paula de Andrade Miranda³⁵, Linder Felipe Mozombite Pinto¹⁰¹, Adriana Prieto¹³¹, Agustín Rudas¹³¹, Ademir R. Ruschel⁶⁵, Natalino Silva¹³², César I.A. Vela¹³³, Egleé L. Zent¹³⁴, Stanford Zent¹³⁴, Angela Cano^{73,135}, Yrma Andreina Carrero Márquez¹³⁶, Diego F. Correa^{73,137}, Janaina Barbosa Pedrosa Costa¹⁰⁶, David Galbraith¹⁷, Milena Holmgren¹³⁸, Michelle Kalamandeen¹³⁹, Guilherme Lobo³⁷, Marcelo Trindade Nascimento¹⁴⁰, Alexandre A. Oliveira¹⁰⁰, Hirma Ramirez-Angulo³⁰, Maira Rocha³⁷, Veridiana Vizoni Scudeller¹⁴¹, Rodrigo Sierra¹⁴², Milton Tirado¹⁴², Geertje van der Heijden¹⁴³, Emilio Vilanova Torre^{30,144}, Manuel Augusto Ahuite Reategui¹⁴⁵, Cláudia Baider^{146,100}, Henrik Balslev¹⁴⁷, Sasha Cárdenas⁷³, Luisa Fernanda Casas⁷³, William Farfan-Rios^{47,118,148}, Cid Ferreira³⁵, Reynaldo Linares-Palomino⁸², Casimiro Mendoza^{149,150}, Italo Mesones¹⁰⁴, Ligia Estela Urrego Giraldo¹⁵¹, Daniel Villarroel^{74,152}, Roderick Zagt¹⁵³, Miguel N. Alexiades¹⁵⁴, Edmar Almeida de Oliveira⁶², Karina Garcia-Cabrera¹²¹, Lionel Hernandez⁶⁷, Walter Palacios Cuenca¹⁵⁵, Susamar Pansini⁵¹, Daniela Pauletto¹⁵⁶, Freddy Ramirez Arevalo²³, Adeilza Felipe Sampaio⁵¹, Luis Valenzuela Gamarra⁵⁵, Luiz E. O. C. Aragão^{1,57*}

*Corresponding authors. Email: vinicius.peripato@gmail.com; luz.aragao@inpe.br

†These authors contributed equally to this work;

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Abstract:

Indigenous societies are known to have occupied the Amazon basin for over 12,000 years, but the scale of their influence on Amazonian forests remains uncertain. Using Light Detection and Ranging information from across the basin, we report the discovery of 24 previously undetected pre-Columbian earthworks beneath the forest canopy. Modeled distribution and abundance of large-scale archaeological sites across Amazonia suggest that 10,272–23,640 sites remain to be discovered, and that most will be found in the southwest. We also identified 53 domesticated tree species significantly associated with earthwork occurrence probability, likely suggesting past management practices. Closed-canopy forests across Amazonia are likely to contain thousands of new archaeological sites around which pre-Columbian societies actively modified forests, a discovery that opens new opportunities for understanding the magnitude of ancient human influence on Amazonia and its current functioning.

One-Sentence Summary:

Amazon-wide LiDAR surveys and predictive models suggest thousands of undocumented archaeological sites across the basin.

Main Text

During the pre-Columbian era, Amazonia was home to dense and complex societies throughout its vast forested area spanning 6.7 million km² (1). These ancient Indigenous societies had a profound knowledge of earthmoving, riverine dynamics, soil enrichment, and plant and animal ecology, which allowed them to create domesticated landscapes that were more productive for humans (2–4). With earthmoving techniques, Indigenous peoples created a wide variety of earthworks (i.e., ring ditches, geoglyphs, ponds and wells) mostly between 1500 and 500 years Before Present with social, ceremonial, and defensive functions (5). Around these earthworks they also managed hundreds of tree species, some of which show evidence of domestication (6–9), and effected long-lasting changes in forest composition (10–13). The scale and intensity of that landscape transformation remain unknown, in part because there has never been a comprehensive inventory of pre-Columbian sites across the basin.

Domesticated landscapes in Amazonia have mostly been discovered via evidence from on-the-ground surveys (5, 14). Earthworks can be detected by orbital optical satellites with very high spatial resolution (15), but that technique is mostly suitable for deforested areas (16). Airborne Light Detection and Ranging (LiDAR) data – a remote sensing technique that can map micro-topography beneath the forest canopy – has substantially changed our understanding of the magnitude of pre-Columbian urbanism in Mesoamerica (17, 18) and South America (19). Over the last decade, the use of LiDAR data has revealed the complexity of Mayan civilization by indicating a regionally integrated urban-rural community network in Mesoamerica (17). More recently, LiDAR enabled the detailed mapping of two monumental pre-Columbian settlements in an intensively domesticated landscape hidden under forest in southwestern Amazonia (19).

Although Mesoamerican archaeological sites feature very different types of structures, mainly due to the construction of stone temples in Mesoamerica in contrast to the use of earth in Amazonia, LiDAR technology has substantially improved our spatial understanding of archaeological sites in forested landscapes by enabling the visualization of ancient large-scale earthworks (18, 19) beneath the forest canopy. Since deforestation in Amazonia has removed about 17% of the natural vegetation cover to date (20), LiDAR has the potential to reveal many more discoveries in the remaining 83% of the basin that is opaque to other remote sensing approaches.

Here, we report a large number of previously undocumented pre-Columbian earthworks with geometrically patterned enclosures in an Amazon-wide LiDAR dataset covering 0.08% of the basin (21). We combine these newly discovered sites with a comprehensive dataset of existing archaeological sites (ring ditches, geoglyphs, ponds, and wells) to model areas likely to harbor yet undetected earthworks hidden beneath remote forest landscapes. Based on our predictive model, we estimate the number of undocumented earthworks and identify domesticated tree species associated with earthwork presence.

Scanning 5,315 km² of LiDAR data originally obtained for estimating aboveground biomass throughout the Amazonian forest (22) revealed 24 unreported earthworks in southern, southwestern, central, and northern (the Guiana Shield) Amazonia (Fig. 1[A]) (21). We detected a fortified village in southern Amazonia (Fig. 1[B]), defensive and ceremonial sites in the southwestern (Fig. 1[C-F]), crowned mountains and megalithic structures in the Guiana Shield (Fig. 1[G-I]), and riverine sites on floodplains in central Amazonia (Fig. 1[J-K]).

In southern Amazonia, we found an ancient plaza town located in the Upper Xingu Basin (Fig. 1[B]). This region is known to have supported dense populations in the past, distributed in plaza villages interconnected by road networks, and surrounded by domesticated landscapes with a diverse array of terrestrial and aquatic resources (10, 23). It is also clear that the earthworks in this region extend beyond the sampled area of the 200 m-wide LiDAR transect, restraining their full identification. The layout of these earthworks is similar to that of other fortified villages documented in this region, supporting the idea that these structures were built before European contact (10, 15, 24).

In southwestern Amazonia, we found a combination of rectangular and circular features, known as “geoglyphs”, without detectable interconnecting roads occurring on flat terrain close to water bodies (Fig. 1[C-F]). Documented defensive and ceremonial earthworks in this region were built around two millennia ago and are dispersed across the well-drained plateaus of the tributaries of the Purus and Madeira rivers (25).

In the Guiana Shield, we detected a combination of rectangular and circular features on plateaus near water bodies (Fig. 1[G-I]). The region holds different types and usages of earthworks: permanent settlements within crowned mountains in French Guiana (26), and ceremonial sites

featuring megalithic structures arranged in circular clusters found along the coast of Amapá, Brazil (27).

In the floodplains of central Amazonia, a hotspot of pre-Columbian riverine settlements (3, 23, 28), we identified two other earthworks (Fig. 1[J–K]). We considered these sites to be anthropogenic because of their straight edges, although the geometry of these sites is distinct from that of the earthworks found in upland forests. Constant sedimentary deposition over the centuries, through periodic floods, may have buried smaller features, preserving only the observed structures, which elsewhere have been associated with pre-Columbian fisheries management (29).

By extrapolating the density of earthworks observed in our LiDAR data (0.0062 earthworks / km²) to the extent of Amazonia (6.7 million km²), we calculated that over 41,000 earthworks may occur throughout the forest. However, given that our LiDAR data covered only 0.08% of the total area of Amazonia and earth-building societies were not evenly distributed across the basin (15, 30), more rigorous methods were needed to estimate how many other previously undocumented pre-Columbian earthworks might occur and where. To answer these questions, we used newly developed statistical techniques and an Inhomogeneous Poisson Process (IPP) model (31), with an intensity function using intensity covariates and thinned by observability covariates (32). Recently, the use of other machine learning techniques such as Random Forests have become popular for Species Distribution Models (SDMs). There is still some uncertainty about this use (33) and their adaptation to IPPs is still not available but it might be a welcomed addition to the toolkit of SDM analysis.

This statistical analysis was based on the records of 937 known earthworks complemented by our discoveries (24 earthworks) with three bioclimatic, three edaphic, and three topographic variables as intensity covariates. Over 40 variables were considered in the model (table S1), and the selected ones (9 variables) cover gradients of temperature, precipitation, soil structure and fertility, topography, water-table depth, and distance to water bodies (21). Observability covariates were used to describe the dataset sample preference by indicating the most favorable location for sample acquisition (32). The effect of sample selection bias was individually weighted for each sample (21).

Our model predicts the number of yet undiscovered pre-Columbian structures as 10,272 – 23,648, with 95% probability, giving an average of 16,187 new sites (Fig. 2[B]). These estimates suggest that the earthworks already documented in the Amazon to date account for a mere 4 – 9% of the total, and that 91–96% of Amazonian earthworks remain undiscovered.

5 This predictive model indicated that earthworks are likely concentrated in southwestern Amazonia (Fig. 2[A]) and corroborated previous studies that found this region to be a hotspot of earth-building societies (13, 15, 34). In addition, nearly all the highest probability cells ($\geq 25\%$ predicted probability) occur in a 94,713-km² rectangle that overlays a significant portion of the Brazilian state of Acre. Indeed, southwestern Amazonia contains the earliest plant cultivation and domestication (9, 35), the oldest anthropogenic soils (35), low-density urbanism (19), and
10 now a much higher density of earthworks. The underlying spatial data distribution may offer valuable information about pre-Columbian practices before European contact (36).

Our analysis also suggests that pre-Columbian societies engaged in earthwork construction in all other regions, covering a broader area than previously thought. However, earthworks are
15 heterogeneously distributed across Amazonian regions. Almost 80% of the basin has a 0 to 1% of predicted probability of earthwork presence for 1-km² cells. These low-probability areas are mostly located in northwestern, northern and central Amazonia, while higher-probability areas ($\geq 25\%$ of predicted probability that cover 1.41% of the basin) are located in southwestern Amazonia. Earth-building societies were very common in some parts of the basin, but they may
20 not have occupied all of Amazonia (6, 15, 30, 37). Other types of domesticated landscapes, such as Amazonian Dark Earths, are widespread (see maps of 37–39) in regions (e.g., central Amazonia) where the earthworks analyzed in our study (ring ditches, geoglyphs, ponds and wells) are not commonly found. Given the diversity of pre-Columbian societies and their land-use practices over 12,000 years of ancient Amazonian history, forests were likely modified at
25 varying intensities by different Indigenous populations through time (7, 38).

Forests modified by earth-building societies are more likely to occur in locations with high temperature and low precipitation during the wettest and driest quarters (Fig. 2[C–D]). Areas with high soil contents of clay and silt, and high cation concentrations, also show high probabilities of earthwork presence. In addition, earthworks tend to be located on plateaus with
30 deep water tables, yet close to water bodies. This combination of environmental conditions

probably facilitated the construction of earthworks by offering periods with less precipitation and higher temperature, and soils with a better texture for earthmoving. In addition, the presence of a drier season facilitates burning, which could help remove the vegetation for building earth structures (12), while higher soil cation concentrations could attract settlements for the development of diversified food production systems with plants managed and domesticated to different degrees (15, 30).

As expected, observability covariates indicate that previously reported earthworks are mostly found near roads, which facilitate field research (Fig. 2[C]). Tree cover, however, has no effect on the current distribution of earthworks. Thus, new earthworks can still be found even in deforested areas. The use of conventional very-high resolution remote sensing data, guided by the probability surfaces produced here in Fig. 2[A], is likely to reveal more previously undetected earthworks in both closed-canopy and deforested areas of Amazonia. In addition, the rise of machine learning techniques applied to archaeological site detection may lead to a rapid discovery of new sites across deforested areas (40, 41).

In forested areas, LiDAR surveys guided by our discoveries (e.g., a full coverage of the Fig. 1[B] site) and the probability surfaces in Fig. 2[A] are promising tools for discovering new sites. However, very high probability areas ($\geq 50\%$ of predicted probability) cover 32,120 km², for which a complete LiDAR survey would require six times more data than has been collected to date in the Amazon. Thus, other approaches, such as mapping the distribution and abundance of domesticated species associated with earthwork presence, may help locate new sites within Amazonian forest (42, 43).

We analyzed the relationship between the response (occurrence/abundance) of 79 domesticated tree species identified across 1,676 forest plots (6) and the predicted probability of earthwork presence using generalized linear models to test whether forests with higher probability of earthwork presence have a higher frequency and abundance of domesticated species (21). The occurrence and/or abundance of 35 domesticated species increased with the predicted probability of earthwork presence, while those of 18 species decreased. In total, the occurrence and/or abundance of 53 of the 79 domesticated species showed significant association with the predictive model of earthwork distribution (Fig. 3).

The species that most significantly increased their response with the probability of earthwork occurrence are *Bertholletia excelsa* ($p < 0.001$, $\beta = 1.13$), *Hevea brasiliensis* ($p < 0.001$, $\beta = 0.65$), and *Brosimum alicastrum* ($p < 0.001$, $\beta = 1.36$), based on occurrence data, and *Astrocaryum murumuru* ($p < 0.001$, $\beta = 0.71$), *Attalea phalerata* ($p < 0.001$, $\beta = 1.42$), and *Theobroma cacao* ($p < 0.001$, $\beta = 1.43$) based on abundance data (fig. S2). The species that most significantly decreased their responses are *Erismia japura* ($p < 0.001$, $\beta = -1.94$) based on occurrence data, and *E. japura* ($p < 0.001$, $\beta = -1.7$) and *Oenocarpus bataua* ($p < 0.001$, $\beta = -0.27$) based on abundance data (fig. S2). Although these highlighted species have multiple uses (44), they have been mainly used for their edible fruits and nuts in Amazonia, with the exception of *H. brasiliensis* which has been used intensively for latex production (Data S1). Species that are more frequent and abundant in forests with higher probability of earthwork occurrence were probably favored by a combination of interacting past Indigenous management practices and ecological processes (6). These results confirm previously archaeobotanical and ethnobotanical data that have already shown that some species (e.g., *Bertholletia excelsa*, *Astrocaryum* spp., and *Attalea* spp.) are more abundant on and near archaeological sites across Amazonia (8, 14, 36). Species that are less frequent and abundant in areas with higher probability of the earthwork occurrence likely prefer habitats where earthworks are usually not found, such as sandy soils with lower fertility (7), or were disfavored due to past practices that might had detrimental effects on some species (45).

The massive extent of archaeological sites and widespread human-modified forests across Amazonia is critically important for establishing a new understanding of interactions between human societies, Amazonian forests and the Earth's climate (37). Ecologically, considering the widespread extent of locations modified by pre-Columbian management and cultivation practices, Amazonia can be viewed as an ancient social-ecological system, with long-term responses to climate change (46), more similar to old secondary forests than pristine climax ecosystems (10).

The discovery of earthworks hidden beneath dense forest canopies also indicates that, given sufficient time after local areas became depopulated, forests were able to regenerate to a degree that we are still unknown about the structural differences between a pristine and domesticated forest. The forest reclaimed the land, but this is not the case for the Indigenous societies that

managed these forests and waterbodies and created these large structures. These archeological legacies can play a role in present-day debates around Indigenous territorial rights. They serve as tangible proof of an ancestor's occupation, way of life, and their relationship established within the forest. Today, Indigenous societies require land rights where originally were inhabited by their ancestors, along with the protection of their territories, languages, cultures, heritages, and others. In addition to protecting the natives that remain, the institution of Indigenous lands also collaborates through forest preservation in times of debates on climate change and the search for solutions that minimize impacts on the climate and carbon neutrality.

These human-modified landscapes harbor an impressive archaeological heritage. Of the 24 earthworks newly reported in our study, 50% are located in areas with some degree of legal protection. When all 937 known earthworks are considered, however, only 9% are located inside Indigenous lands and protected areas. To date, most pre-Columbian earthworks have been discovered after deforestation. The highest density of known earthworks in Amazonia is, therefore, outside protected areas and mostly located in the region with the highest historical and current rates of deforestation, called the “Arc of Deforestation”. Protected areas and Indigenous territories can act as barriers against illegal activities that promote the degradation and destruction of Amazonia’s natural and cultural heritage, but their implementation and expansion depend on strong government policies and law enforcement (47, 48).

Ironically, modern-day deforestation is removing the very evidence of pre-Columbian land-use strategies that were able to transform the landscape without causing large-scale deforestation (13). Today, Amazonia is experiencing expansion of agriculture and cattle ranching (49, 50), especially where earthworks are concentrated in the southern and southwestern regions, risking destroying earthworks and fracturing and hampering the identification of pre-Columbian occupation sites which provide direct evidence of ancient Indigenous territories. Our data on earthwork probability, suitable environmental conditions, and associated domesticated species should narrow the search for Indigenous heritage sites, enhanced by optical and LiDAR sensing to identify, monitor and help conserve archeological features. Amazonian forests clearly merit protection not only for their ecological and environmental values, but also for their high archaeological, social and biocultural values, which can teach modern society on how to sustainably manage its natural resources.

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10 commented on various versions of the manuscript.

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15 **Data and materials availability:** Data from publicly available sources are cited in the supplementary materials. Other data and computer codes used in the analysis are publicly available at Zenodo repository (51).

Supplementary Materials

Author Affiliations

20 Materials and Methods

figs. S1 to S19

tables S1 to S5

References (52–80)

25 **Other Supplementary Materials for this manuscript include the following:**

Data S1 and S2 as separate Excel file

Fig. 1

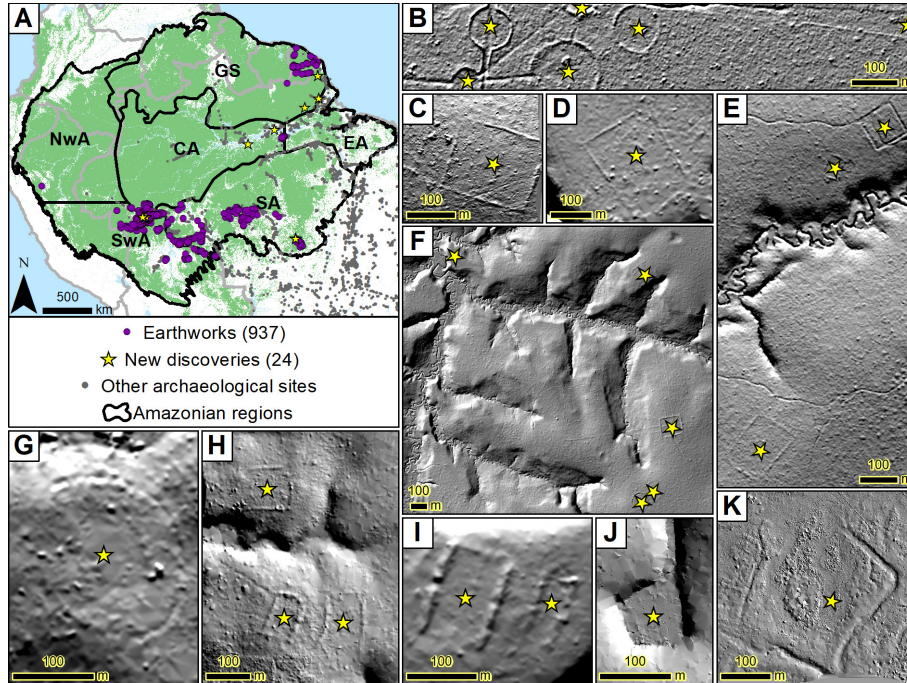


Fig. 1. Geographical distribution of known and newly discovered pre-Columbian geometrical earthworks in Amazonia. (A) Map of previously reported and newly discovered earthworks reported in this study across six Amazonian regions: Central Amazonia (CA); Eastern Amazonia (EA); Guiana Shield (GS); Northwestern Amazonia (NwA); Southern Amazonia (SA); and Southwestern Amazonia (SwA). (B) Newly discovered earthworks in SA. (C–F) Newly discovered earthworks in SwA. (G–I) Newly discovered earthworks in GS. (J–K) Newly discovered earthworks in CA.

Fig. 2

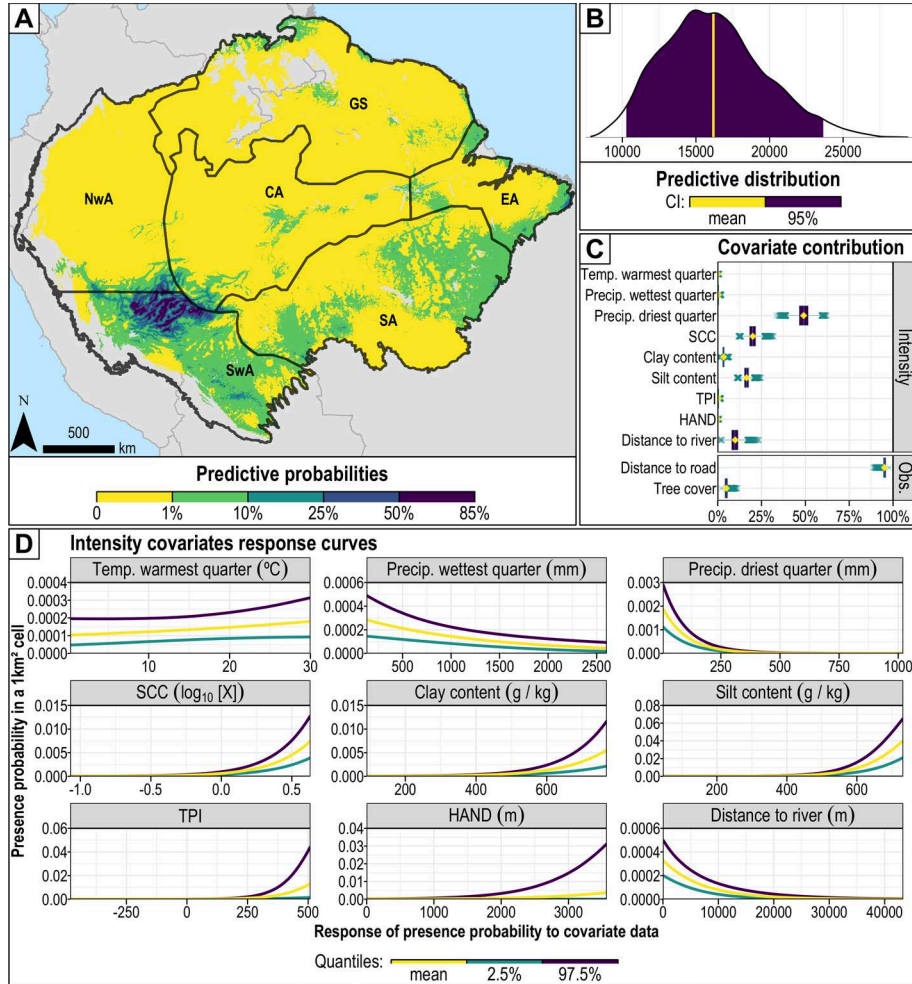


Fig. 2. Probability model of pre-Columbian earthworks across Amazonia. (A) Predicted probability of earthwork presence for 1-km² cells across six Amazonian regions using an Inhomogeneous Poisson Process predictive model: Central Amazonia (CA); Eastern Amazonia (EA); Guiana Shield (GS); Northwestern Amazonia (NwA); Southern Amazonia (SA); and Southwestern Amazonia (SwA). Areas not modeled (NA) are greyed out. (B) Predictive probability function for the number of as yet undetected earthworks; the dark area under the curve represents the credibility interval (CI) of the probabilities associated with each number. (C) Boxplot of the estimated relative contribution of each covariate; the yellow diamond indicates the mean value. (D) Individual predicted probability of earthwork presence against intensity covariates. SCC, TPI, and HAND are abbreviations for Soil Cation Concentration, Terrain Position Index, and Height Above the Nearest Drainage, respectively. For projected areas across each Amazonian region on different probability thresholds see table S2, and for the IPP model on continuous values see fig. S1.

Fig. 3

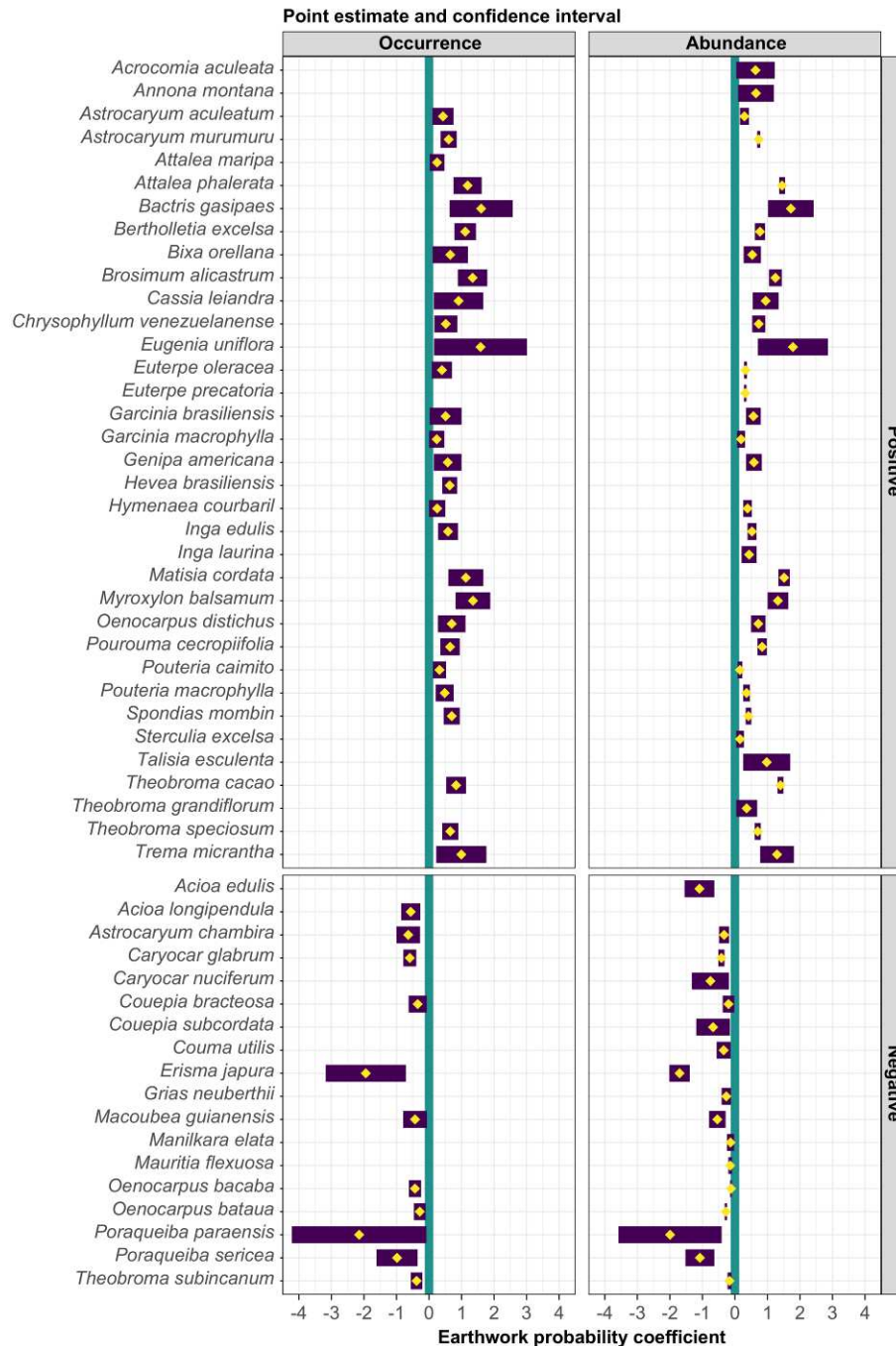


Fig. 3. Significant relationships between the occurrence and abundance of domesticated tree species and the modeled distribution of earthworks in Amazonia. Point estimates and confidence intervals of species significantly associated with predicted probability of earthwork presence, with an overall significance level of 5%. Positive species are more likely to occur and be abundant where predicted probability of earthwork presence is high, while negative species are less likely to occur and be abundant there.

Supplementary Materials for

Over 10,000 Pre-Columbian earthworks are still hidden throughout Amazonia

Vinicius Peripato^{1*†}, Carolina Levis^{2‡}, Guido A. Moreira³, Dani Gamerman⁴, Hans ter Steege⁵, Nigel C.A. Pitman⁶, Jonas G. de Souza⁷, José Iriarte⁸, Mark Robinson⁸, André Braga Junqueira⁹, Thiago B. Trindade¹⁰, Fernando O. de Almeida¹¹, Claide de Paula Moraes¹², Umberto Lombardo¹³, Eduardo K. Tamanaha¹⁴, Shira Y. Maezumi¹⁵, Jean P. H. B. Ometto¹, José R.G. Braga¹, Wesley A. Campanharo¹, Henrique L. G. Cassol¹, Philippe R. Leal¹, Mauro L. R. de Assis¹, Adriana M. da Silva¹⁶, Oliver L. Phillips¹⁷, Flávia R.C. Costa¹⁸, Bernardo Monteiro Flores², Bruce Hoffman¹⁹, Terry W. Henkel²⁰, Maria Natalia Umaña²¹, William E. Magnusson¹⁸, Elvis H. Valderrama Sandoval^{22,23}, Jos Barlow²⁴, William Milliken²⁵, Maria Aparecida Lopes²⁶, Marcelo Fragomeni Simon²⁷, Tinde R. van Andel^{5,28}, Susan G.W. Laurance²⁹, William F. Laurance²⁹, Armando Torres-Lezama³⁰, Rafael L. Assis³¹, Jean-François Molino³², Mickaël Mestre³³, Michelle Hamblin³⁴, Luiz de Souza Coelho³⁵, Diogenes de Andrade Lima Filho³⁵, Florian Wittmann^{36,37}, Rafael P. Salomão^{38,39}, Iêda Leão Amaral³⁵, Juan Ernesto Guevara^{40,41}, Francisca Dionízia de Almeida Matos³⁵, Carolina V. Castilho⁴², Marcelo de Jesus Veiga Carim⁴³, Dairon Cárdenas López^{44#}, Daniel Sabatier³², Mariana Victória Ireme³⁵, Maria Pires Martins³⁵, José Renan da Silva Guimarães⁴⁵, Olaf S. Bánki⁵, Maria Teresa Fernandez Piedade³⁷, José Ferreira Ramos³⁵, Bruno Garcia Luize⁴⁶, Evelyn Márcia Moraes de Leão Novo¹, Percy Núñez Vargas⁴⁷, Thiago Sanna Freire Silva⁴⁸, Eduardo Martins Venticinque⁴⁹, Angelo Gilberto Manzatto⁵⁰, Neidiane Farias Costa Reis⁵¹, John Terborgh^{52,29}, Katia Regina Casula⁵¹, Layon O. Demarchi³⁷, Euridice N. Honorio Coronado^{53,54}, Abel Monteagudo Mendoza^{47,55}, Juan Carlos Montero^{56,35}, Jochen Schöngart³⁷, Ted R. Feldpausch^{57,17}, Adriano Costa Quaresma^{36,37}, Gerardo A. Aymard C.⁵⁸, Chris Baraloto⁵⁹, Nicolás Castaño Arboleda⁴⁴, Julien Engel^{32,59}, Pascal Petronelli⁶⁰, Charles Eugene Zartman³⁵, Timothy J. Killeen⁶¹, Beatriz S. Marimon⁶², Ben Hur Marimon-Junior⁶², Juliana Schietti³⁵, Thaiane R. Sousa⁶³, Rodolfo Vasquez⁵⁵, Lorena M. Rincón³⁵, Erika Berenguer^{64,24}, Joice Ferreira⁶⁵, Bonifacio Mostacedo⁶⁶, Dário Dantas do Amaral³⁹, Hernán Castellanos⁶⁷, Marcelo Brilhante de Medeiros²⁷, Ana Andrade⁶⁸, José Luís Camargo⁶⁸, Emanuelle de Sousa Farias^{69,70}, José Leonardo Lima Magalhães^{71,65}, Henrique Eduardo Mendonça Nascimento³⁵, Helder Lima de Queiroz⁷², Roel Brienien¹⁷, Juan David Cardenas Revilla³⁵, Pablo R. Stevenson⁷³, Alejandro Araujo-Murakami⁷⁴, Bruno Barçante Ladvoat Cintra⁷⁵, Yuri Oliveira Feitosa⁷⁶, Flávia Rodrigues Barbosa⁷⁷, Rainiellen de Sá Carpanedo⁷⁷, Joost F. Duivenvoorden⁷⁸, Janáina Costa Noronha⁷⁷, Domingos de Jesus Rodrigues⁷⁷, Hugo F. Mogollón⁷⁹, Leandro Valle Ferreira³⁹, John Ethan Householder³⁶, José Rafael Lozada⁸⁰, James A. Comiskey^{81,82}, Freddie C. Draper⁸³, José Julio de Toledo⁸⁴, Gabriel Damasco⁸⁵, Nállarett Dávila^{46##}, Roosevelt García-Villacorta^{86,87}, Aline Lopes⁸⁸, Fernando Cornejo Valverde⁸⁹, Alfonso Alonso⁸², Francisco Dallmeier⁸², Vitor H.F. Gomes^{90,91}, Eliana M.

Jimenez⁹², David Neill⁹³, Maria Cristina Peñuela Mora⁹⁴, Daniel P. P. de Aguiar^{95,96}, Luzmila Arroyo⁷⁴, Fernanda Antunes Carvalho^{18,97}, Fernanda Coelho de Souza^{18,17}, Kenneth J. Feeley^{98,99}, Rogério Gribel³⁵, Marcelo Petratti Pansonato^{35,100}, Marcos Ríos Paredes¹⁰¹, Izaías Brasil da Silva¹⁰², Maria Julia Ferreira¹⁰³, Paul V.A. Fine¹⁰⁴, Émile Fonty^{105,32}, Marcelino Carneiro Guedes¹⁰⁶, Juan Carlos Licono⁵⁶, Toby Pennington^{57,107}, Carlos A. Peres¹⁰⁸, Boris Eduardo Villa Zegarra¹⁰⁹, Germaine Alexander Parada⁷⁴, Guido¹¹⁰, Vincent Antoine Vos¹¹⁰, Carlos Cerón¹¹¹, Paul Maas⁵, Marcos Silveira¹¹², Juliana Stropp¹¹³, Raquel Thomas¹¹⁴, Tim R. Baker¹⁷, Doug Daly¹¹⁵, Isau Huamantupa-Chuquimaco¹¹⁶, Ima Célia Guimarães Vieira³⁹, Bianca Weiss Albuquerque³⁷, Alfredo Fuentes^{117,118}, Bente Klitgaard¹¹⁹, José Luis Marcelo Pena¹²⁰, Miles R. Silman¹²¹, J. Sebastián Tello¹¹⁸, Corine Vriesendorp⁶, Jerome Chave¹²², Anthony Di Fiore^{123,124}, Renato Richard Hilário⁸⁴, Juan Fernando Phillips¹²⁵, Gonzalo Rivas-Torres^{124,126}, Patricio von Hildebrand¹²⁷, Luciana de Oliveira Pereira⁵⁷, Edelcilio Marques Barbosa³⁵, Luiz Carlos de Matos Bonates³⁵, Hilda Paulette Dávila Doza¹⁰¹, Ricardo Zárate Gómez¹²⁸, George Pepe Gallardo Gonzales¹⁰¹, Therany Gonzales¹²⁹, Yadvinder Malhi¹³⁰, Ires Paula de Andrade Miranda³⁵, Linder Felipe Mozombite Pinto¹⁰¹, Adriana Prieto¹³¹, Agustín Rudas¹³¹, Ademir R. Ruschel⁶⁵, Natalino Silva¹³², César I.A. Vela¹³³, Egleé L. Zent¹³⁴, Stanford Zent¹³⁴, Angela Cano^{73,135}, Yrma Andreina Carrero Márquez¹³⁶, Diego F. Correa^{73,137}, Janaina Barbosa Pedrosa Costa¹⁰⁶, David Galbraith¹⁷, Milena Holmgren¹³⁸, Michelle Kalamandeen¹³⁹, Guilherme Lobo³⁷, Marcelo Trindade Nascimento¹⁴⁰, Alexandre A. Oliveira¹⁰⁰, Hirma Ramirez-Angulo³⁰, Maira Rocha³⁷, Veridiana Vizoni Scudeller¹⁴¹, Rodrigo Sierra¹⁴², Milton Tirado¹⁴², Geertje van der Heijden¹⁴³, Emilio Vilanova Torre^{30,144}, Manuel Augusto Ahuite Reategui¹⁴⁵, Cláudia Baider^{146,100}, Henrik Balslev¹⁴⁷, Sasha Cárdenas⁷³, Luisa Fernanda Casas⁷³, William Farfan-Rios^{47,118,148}, Cid Ferreira³⁵, Reynaldo Linares-Palomino⁸², Casimiro Mendoza^{149,150}, Italo Mesones¹⁰⁴, Ligia Estela Urrego Giraldo¹⁵¹, Daniel Villarreal^{74,152}, Roderick Zagt¹⁵³, Miguel N. Alexiades¹⁵⁴, Edmar Almeida de Oliveira⁶², Karina Garcia-Cabrera¹²¹, Lionel Hernandez⁶⁷, Walter Palacios Cuenca¹⁵⁵, Susamar Pansini⁵¹, Daniela Pauletto¹⁵⁶, Freddy Ramirez Arevalo²³, Adeilza Felipe Sampaio⁵¹, Luis Valenzuela Gamarra⁵⁵, Luiz E. O. C. Aragão^{1,57*}

*Corresponding authors. Email: vinicius.peripato@gmail.com; luiz.aragao@inpe.br

†These authors contributed equally to this work;

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Data S1 and S2 as separate Excel file

Author Affiliations

¹Remote Sensing Division, National Institute for Space Research (INPE), Av. dos Astronautas, 1758, Jardim da Granja, São José dos Campos, SP, 12227-010, Brazil.

²Postgraduate Program in Ecology, Federal University of Santa Catarina, R. Eng. Agrônômico Andrei Cristian Ferreira., Trindade, Florianópolis, SC, 88040-900, Brazil.

³Centre of Molecular and Environmental Biology, Universidade do Minho, Braga, Portugal.

⁴Departamento de Métodos Estatísticos, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil.

⁵Naturalis Biodiversity Center, PO Box 9517, Leiden, 2300 RA, The Netherlands.

⁶Science and Education, The Field Museum, 1400 S. Lake Shore Drive, Chicago, IL, 60605-2496, USA.

⁷Department of Humanities, Universitat Pompeu Fabra, Barcelona, Spain.

⁸Department of Archaeology, College of Humanities, University of Exeter, Exeter, UK.

⁹Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain.

¹⁰Instituto do Patrimônio Histórico e Artístico Nacional, Centro Nacional de Arqueologia, Brasília, DF, Brazil.

¹¹Departamento de Arqueologia, Universidade Federal de Sergipe, Laranjeiras, SE, Brazil.

¹²Universidade Federal do Oeste do Pará, Santarém, PA, Brazil.

¹³Geographisches Institut, University of Bern, Bern, Switzerland.

¹⁴Instituto de Desenvolvimento Sustentável Mamirauá, Tefé, AM, Brazil.

¹⁵Department of Archaeology, Max Planck Institute of Geoanthropology, Jena, Germany.

¹⁶Postgraduate Program in Geography, Institute of Geography, Federal University of Uberlândia (UFU), Av. João Naves de Ávila, 2121, Santa Mônica, Uberlândia, MG, 38.408-100, Brazil.

¹⁷School of Geography, University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK.

¹⁸Coordenação de Pesquisas em Ecologia, Instituto Nacional de Pesquisas da Amazônia - INPA, Av. André Araújo, 2936, Petrópolis, Manaus, AM, 69067-375, Brazil.

¹⁹Amazon Conservation Team, 4211 North Fairfax Drive, Arlington, VA, 22203, USA.

²⁰Department of Biological Sciences, Humboldt State University, 1 Harpst Street, Arcata, CA, 95521, USA.

²¹Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI, 48109, USA.

²²Department of Biology, University of Missouri, St. Louis, MO, 63121, USA.

²³Facultad de Biología, Universidad Nacional de la Amazonia Peruana, Pevs 5ta cdra, Iquitos, Loreto, Peru.

²⁴Lancaster Environment Centre, Lancaster University, Lancaster, Lancashire, LA1 4YQ, UK.

²⁵Department for Ecosystem Stewardship, Royal Botanic Gardens, Kew, Richmond, Surrey, TW9 3AE, UK.

²⁶Instituto de Ciências Biológicas, Universidade Federal do Pará, Av. Augusto Corrêa 01, Belém, PA, 66075-110, Brazil.

²⁷Embrapa Recursos Genéticos e Biotecnologia, Parque Estação Biológica, Prédio da Botânica e Ecologia, Brasília, DF, 70770-917, Brazil.

²⁸Biosystematics group, Wageningen University, Droevendaalsesteeg 1, Wageningen, 6708 PB, The Netherlands.

²⁹Centre for Tropical Environmental and Sustainability Science and College of Science and Engineering, James Cook University, Cairns, Queensland, 4870, Australia.

³⁰Instituto de Investigaciones para el Desarrollo Forestal (INDEFOR), Universidad de los Andes, Conjunto Forestal, 5101, Mérida, Mérida, Venezuela.

³¹Natural History Museum, University of Oslo, Postboks 1172, Oslo, 318, Norway.

³²AMAP, IRD, Cirad, CNRS, INRAE, Université de Montpellier, Montpellier, F-34398, France.

³³Institut National de Recherches Archéologiques Préventives, Bègles, France.

³⁴Direction des Affaires Culturelles - Guyane, Cayenne, French Guiana.

³⁵Coordenação de Biodiversidade, Instituto Nacional de Pesquisas da Amazônia - INPA, Av. André Araújo, 2936, Petrópolis, Manaus, AM, 69067-375, Brazil.

³⁶Wetland Department, Institute of Geography and Geoecology, Karlsruhe Institute of Technology - KIT, Josefstr.1, Rastatt, D-76437, Germany.

³⁷Ecology, Monitoring and Sustainable Use of Wetlands (MAUA), Instituto Nacional de Pesquisas da Amazônia - INPA, Av. André Araújo, 2936, Petrópolis, Manaus, AM, 69067-375, Brazil.

³⁸Programa Professor Visitante Nacional Sênior na Amazônia - CAPES, Universidade Federal Rural da Amazônia, Av. Perimetral, s/n, Belém, PA, Brazil.

³⁹Coordenação de Botânica, Museu Paraense Emílio Goeldi, Av. Magalhães Barata 376, C.P. 399, Belém, PA, 66040-170, Brazil.

⁴⁰Grupo de Investigación en Biodiversidad, Medio Ambiente y Salud-BIOMAS, Universidad de las Américas, Campus Queri, Quito, Ecuador.

⁴¹Keller Science Action Center, The Field Museum, 1400 S. Lake Shore Drive, Chicago, IL, 60605-2496, USA.

⁴²Centro de Pesquisa Agroflorestal de Roraima, Embrapa Roraima, BR 174, km 8, Distrito Industrial, Boa Vista, RR, 69301-970, Brazil.

⁴³Departamento de Botânica, Instituto de Pesquisas Científicas e Tecnológicas do Amapá - IEPA, Rodovia JK, Km 10, Campus do IEPA da Fazendinha, Macapá, AP, 68901-025, Brazil.

⁴⁴Herbario Amazónico Colombiano, Instituto SINCHI, Calle 20 No 5-44, Bogotá, DC, Colombia.

⁴⁵Amcel Amapá Florestal e Celulose S.A, Rua Claudio Lucio - S/N, Novo Horizonte, Santana, AP, 68927-003, Brazil.

⁴⁶Departamento de Biologia Vegetal, Instituto de Biologia, Universidade Estadual de Campinas UNICAMP, CP 6109, Campinas, SP, 13083-970, Brazil.

⁴⁷Herbario Vargas, Universidad Nacional de San Antonio Abad del Cusco, Avenida de la Cultura, Nro 733, Cusco, Cuzco, Peru.

⁴⁸Biological and Environmental Sciences, University of Stirling, Stirling, FK9 4LA, UK.

⁴⁹Centro de Biociências, Departamento de Ecologia, Universidade Federal do Rio Grande do Norte, Av. Senador Salgado Filho, 3000, Natal, RN, 59072-970, Brazil.

⁵⁰Departamento de Biologia, Universidade Federal de Rondônia, Rodovia BR 364 s/n Km 9,5 - Sentido Acre, Unir, Porto Velho, RO, 76.824-027, Brazil.

⁵¹Programa de Pós- Graduação em Biodiversidade e Biotecnologia PPG- Bionorte, Universidade Federal de Rondônia, Campus Porto Velho Km 9,5 bairro Rural, Porto Velho, RO, 76.824-027, Brazil.

⁵²Department of Biology and Florida Museum of Natural History, University of Florida, Gainesville, FL, 32611, USA.

⁵³Instituto de Investigaciones de la Amazonía Peruana (IIAP), Av. A. Quiñones km 2,5, Iquitos, Loreto, 784, Peru.

⁵⁴School of Geography and Sustainable Development, University of St Andrews, Irvine Building, St Andrews, KY16 9AL, UK.

⁵⁵Jardín Botánico de Missouri, Oxapampa, Pasco, Peru.

⁵⁶Instituto Boliviano de Investigación Forestal, Av. 6 de agosto #28, Km. 14, Doble vía La Guardia, Casilla 6204, Santa Cruz, Santa Cruz, Bolivia.

⁵⁷Geography, College of Life and Environmental Sciences, University of Exeter, Rennes Drive, Exeter, EX4 4RJ, UK.

⁵⁸Programa de Ciencias del Agro y el Mar, Herbario Universitario (PORT), UNELLEZ-Guanare, Guanare, Portuguesa, 3350, Venezuela.

⁵⁹International Center for Tropical Botany (ICTB) Department of Biological Sciences, Florida International University, 11200 SW 8th Street, OE 243, Miami, FL, 33199, USA.

⁶⁰Cirad UMR Ecofog, AgrosParisTech, CNRS, INRAE, Univ Guyane, Campus agronomique, Kourou Cedex, 97379, France.

⁶¹Agteca-Amazonica, Santa Cruz, Bolivia.

⁶²Programa de Pós-Graduação em Ecologia e Conservação, Universidade do Estado de Mato Grosso, Nova Xavantina, MT, Brazil.

⁶³Programa de Pós-Graduação em Ecologia, Instituto Nacional de Pesquisas da Amazônia - INPA, Av. André Araújo, 2936, Petrópolis, Manaus, AM, 69067-375, Brazil.

⁶⁴Environmental Change Institute, University of Oxford, Oxford, Oxfordshire, OX1 3QY, UK.

⁶⁵Empresa Brasileira de Pesquisa Agropecuária, Embrapa Amazônia Oriental, Trav. Dr. Enéas Pinheiro s/nº, Belém, PA, 66095-903, Brazil.

⁶⁶Facultad de Ciencias Agrícolas, Universidad Autónoma Gabriel René Moreno, Santa Cruz, Santa Cruz, Bolivia.

⁶⁷Centro de Investigaciones Ecológicas de Guayana, Universidad Nacional Experimental de Guayana, Calle Chile, urbaniz Chilemex, Puerto Ordaz, Bolívar, Venezuela.

⁶⁸Projeto Dinâmica Biológica de Fragmentos Florestais, Instituto Nacional de Pesquisas da Amazônia - INPA, Av. André Araújo, 2936, Petrópolis, Manaus, AM, 69067-375, Brazil.

⁶⁹Laboratório de Ecologia de Doenças Transmissíveis da Amazônia (EDTA), Instituto Leônidas e Maria Deane, Fiocruz, Rua Terezina, 476, Adrianópolis, Manaus, AM, 69060-001, Brazil.

⁷⁰Programa de Pós-graduação em Biodiversidade e Saúde, Instituto Oswaldo Cruz - IOC/FIOCRUZ, Pav. Arthur Neiva Térreo, Av. Brasil, 4365, Manguinhos, Rio de Janeiro, RJ, 21040-360, Brazil.

⁷¹Programa de Pós-Graduação em Ecologia, Universidade Federal do Pará, Av. Augusto Corrêa 01, Belém, PA, 66075-110, Brazil.

⁷²Diretoria Técnico-Científica, Instituto de Desenvolvimento Sustentável Mamirauá, Estrada do Bexiga, 2584, Tefé, AM, 69470-000, Brazil.

⁷³Laboratorio de Ecología de Bosques Tropicales y Primatología, Universidad de los Andes, Carrera 1 # 18a- 10, Bogotá, DC, 111711, Colombia.

⁷⁴Museo de Historia Natural Noel Kempff Mercado, Universidad Autónoma Gabriel Rene Moreno, Avenida Irala 565 Casilla Post al 2489, Santa Cruz, Santa Cruz, Bolivia.

⁷⁵Instituto de Biociências - Dept. Botanica, Universidade de Sao Paulo - USP, Rua do Matão 277, Cidade Universitária, São Paulo, SP, 05508-090, Brazil.

⁷⁶Programa de Pós-Graduação em Biologia (Botânica), Instituto Nacional de Pesquisas da Amazônia - INPA, Av. André Araújo, 2936, Petrópolis, Manaus, AM, 69067-375, Brazil.

⁷⁷ICNHS, Federal University of Mato Grosso, Av. Alexandre Ferronato 1200, Setor Industrial, Sinop, MT, 78.557-267, Brazil.

⁷⁸Institute of Biodiversity and Ecosystem Dynamics, University of Amsterdam, Sciencepark 904, Amsterdam, 1098 XH, The Netherlands.

⁷⁹Endangered Species Coalition, 8530 Geren Rd., Silver Spring, MD, 20901, USA.

⁸⁰Facultad de Ciencias Forestales y Ambientales, Instituto de Investigaciones para el Desarrollo Forestal, Universidad de los Andes, Via Chorros de Milla, 5101, Mérida, Mérida, Venezuela.

⁸¹Inventory and Monitoring Program, National Park Service, 120 Chatham Lane, Fredericksburg, VA, 22405, USA.

⁸²Center for Conservation and Sustainability, Smithsonian Conservation Biology Institute, 1100 Jefferson Dr. SW, Suite 3123, Washington, DC, 20560-0705, USA.

⁸³Department of Geography and Planning, University of Liverpool, Liverpool, L69 3BX, UK.

⁸⁴Universidade Federal do Amapá, Ciências Ambientais, Rod. Juscelino Kubitschek km2, Macapá, AP, 68902-280, Brazil.

⁸⁵Gothenburg Global Biodiversity Centre, University of Gothenburg, Carl Skottbergs gata 22b, Gothenburg, 413 19, Sweden.

⁸⁶Programa Restauración de Ecosistemas (PRE), Centro de Innovación Científica Amazónica (CINCIA), Jr. Cajamarca Cdra. 1 s/n, Tambopata, Madre de Dios, Peru.

⁸⁷Peruvian Center for Biodiversity and Conservation (PCBC), Iquitos, Loreto, Peru.

⁸⁸Department of Ecology, Institute of Biological Sciences, University of Brasilia, Brasilia, DF, 70904-970, Brazil.

⁸⁹Andes to Amazon Biodiversity Program, Madre de Dios, Madre de Dios, Peru.

⁹⁰Escola de Negócios Tecnologia e Inovação, Centro Universitário do Pará, Belém, PA, Brazil.

⁹¹Environmental Science Program, Geosciences Department, Universidade Federal do Pará, Rua Augusto Corrêa 01, Belém, PA, 66075-110, Brazil.

⁹²Grupo de Ecología y Conservación de Fauna y Flora Silvestre, Instituto Amazónico de Investigaciones Imani, Universidad Nacional de Colombia sede Amazonia, Leticia, Amazonas, Colombia.

⁹³Universidad Estatal Amazónica, Puyo, Pastaza, Ecuador.

⁹⁴Universidad Regional Amazónica IKIAM, Km 7 via Muyuna, Tena, Napo, Ecuador.

⁹⁵Procuradoria-Geral de Justiça, Ministério Público do Estado do Amazonas, Av. Coronel Teixeira, 7995, Manaus, AM, 69037-473, Brazil.

⁹⁶Coordenação de Dinâmica Ambiental, Instituto Nacional de Pesquisas da Amazônia - INPA, Av. André Araújo, 2936, Petrópolis, Manaus, AM, 69067-375, Brazil.

⁹⁷Universidade Federal de Minas Gerais, Instituto de Ciências Biológicas, Departamento de Genética, Ecologia e Evolução, Av. Antônio Carlos, 6627 Pampulha, Belo Horizonte, MG, 31270-901, Brazil.

⁹⁸Department of Biology, University of Miami, Coral Gables, FL, 33146, USA.

⁹⁹Fairchild Tropical Botanic Garden, Coral Gables, FL, 33156, USA.

¹⁰⁰Instituto de Biociências - Dept. Ecologia, Universidade de São Paulo - USP, Rua do Matão, Trav. 14, no. 321, Cidade Universitária, São Paulo, SP, 05508-090, Brazil.

¹⁰¹Servicios de Biodiversidad EIRL, Jr. Independencia 405, Iquitos, Loreto, 784, Peru.

¹⁰²Postgraduate program in Biodiversity and Biotechnology Bionorte, Federal University of Acre, Rodovia 364, km 4.5, Distrito industrial, Rio Branco, AC, 69900-000, Brazil.

¹⁰³Postgraduate program in Ethnobiology and Nature Conservation, Federal Rural University of Pernambuco (UFRPE), Rua Dom Manuel de Medeiros, s/n, Dois Irmãos, Pernambuco, PB, 52171-900, Brazil.

¹⁰⁴Department of Integrative Biology, University of California, Berkeley, CA, 94720-3140, USA.

¹⁰⁵Direction régionale de la Guyane, Office national des forêts, Cayenne, F-97300, French Guiana.

¹⁰⁶Empresa Brasileira de Pesquisa Agropecuária, Embrapa Amapá, Rod. Juscelino Kubitschek km 5, Macapá, AP, 68903-419, Brazil.

¹⁰⁷Tropical Diversity Section, Royal Botanic Garden Edinburgh, 20a Inverleith Row, Edinburgh, Scotland, EH3 5LR, UK.

¹⁰⁸School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK.

¹⁰⁹Dirección de Evaluación Forestal y de Fauna Silvestre, Av. Javier Praod Oeste 693, Magdalena del Mar, Peru.

¹¹⁰Instituto de Investigaciones Forestales de la Amazonía, Universidad Autónoma del Beni José Ballivián, Campus Universitario Final, Av. Ejercito, Riberalta, Beni, Bolivia.

¹¹¹Escuela de Biología Herbario Alfredo Paredes, Universidad Central, Ap. Postal 17.01.2177, Quito, Pichincha, Ecuador.

¹¹²Centro de Ciências Biológicas e da Natureza, Universidade Federal do Acre, Rodovia BR 364, Km 4, s/n, Distrito Industrial, Rio Branco, AC, 69915-559, Brazil.

¹¹³Museo Nacional de Ciencias Naturales (MNCN-CSIC), C. de José Gutiérrez Abascal 2, Madrid, 28006, Spain.

¹¹⁴Iwokrama International Centre for Rain Forest Conservation and Development, Georgetown, Guyana.

¹¹⁵New York Botanical Garden, 2900 Southern Blvd, Bronx, New York, NY, 10458-5126, USA.

¹¹⁶Herbario HAG, Universidad Nacional Amazónica de Madre de Dios (UNAMAD), Av. Jorge Chávez 1160, Puerto Maldonado, Madre de Dios, Peru.

¹¹⁷Herbario Nacional de Bolivia, Universitario UMSA, Casilla 10077 Correo Central, La Paz, La Paz, Bolivia.

¹¹⁸Center for Conservation and Sustainable Development, Missouri Botanical Garden, P.O. Box 299, St. Louis, MO, 63166-0299, USA.

¹¹⁹Department for Accelerated Taxonomy, Royal Botanic Gardens, Kew, Richmond, Surrey, TW9 3AE, UK.

¹²⁰Universidad Nacional de Jaén, Carretera Jaén San Ignacio Km 23, Jaén, Cajamarca, 6801, Peru.

¹²¹Biology Department and Center for Energy, Environment and Sustainability, Wake Forest University, 1834 Wake Forest Rd, Winston Salem, NC, 27106, USA.

¹²²Laboratoire Evolution et Diversité Biologique, CNRS and Université Paul Sabatier, UMR 5174 EDB, Toulouse, 31000, France.

¹²³Department of Anthropology, University of Texas at Austin, SAC 5.150, 2201 Speedway Stop C3200, Austin, TX, 78712, USA.

¹²⁴Estación de Biodiversidad Tiputini, Colegio de Ciencias Biológicas y Ambientales, Universidad San Francisco de Quito-USFQ, Quito, Pichincha, Ecuador.

¹²⁵Fundación Puerto Rastrojo, Cra 10 No. 24-76 Oficina 1201, Bogotá, DC, Colombia.

¹²⁶Department of Wildlife Ecology and Conservation, University of Florida, 110 Newins-Ziegler Hall, Gainesville, FL, 32611, USA.

¹²⁷Fundación Estación de Biología, Cra 10 No. 24-76 Oficina 1201, Bogotá, DC, Colombia.

¹²⁸PROTERRA, Instituto de Investigaciones de la Amazonía Peruana (IIAP), Av. A. Quiñones km 2,5, Iquitos, Loreto, 784, Peru.

¹²⁹ACEER Foundation, Jirón Cusco N° 370, Puerto Maldonado, Madre de Dios, Peru.

¹³⁰Environmental Change Institute, Oxford University Centre for the Environment, Dyson Perrins Building, South Parks Road, Oxford, England, OX1 3QY, UK.

¹³¹Instituto de Ciencias Naturales, Universidad Nacional de Colombia, Apartado 7945, Bogotá, DC, Colombia.

¹³²Instituto de Ciência Agrárias, Universidade Federal Rural da Amazônia, Av. Presidente Tancredo Neves 2501, Belém, PA, 66.077-830, Brazil.

¹³³Escuela Profesional de Ingeniería Forestal, Universidad Nacional de San Antonio Abad del Cusco, Jirón San Martín 451, Puerto Maldonado, Madre de Dios, Peru.

¹³⁴Laboratory of Human Ecology, Instituto Venezolano de Investigaciones Científicas - IVIC, Ado 20632, Caracas, DC, 1020A, Venezuela.

¹³⁵Cambridge University Botanic Garden, Cambridge University, 1 Brookside., Cambridge, CB2 1JE, UK.

¹³⁶Programa de Maestria de Manejo de Bosques, Universidad de los Andes, Via Chorro de Milla, 5101, Mérida, Mérida, Venezuela.

¹³⁷Centre for Biodiversity and Conservation Science CBCS, The University of Queensland, Brisbane, QLD, 4072, Australia.

¹³⁸Resource Ecology Group, Wageningen University & Research, Droevendaalsesteeg 3a, Lumen, building number 100, Wageningen, Gelderland, 6708 PB, The Netherlands.

¹³⁹School of Earth, Environment and Society, McMaster University, 1280 Main Street West, Hamilton, Ontario, L8S 4K1, Canada.

¹⁴⁰Laboratório de Ciências Ambientais, Universidade Estadual do Norte Fluminense, Av. Alberto Lamego 2000, Campos dos Goytacazes, RJ, 28013-620, Brazil.

¹⁴¹Departamento de Biologia, Universidade Federal do Amazonas - UFAM Instituto de Ciências Biológicas ICB1, Av General Rodrigo Octavio 6200, Manaus, AM, 69080-900, Brazil.

¹⁴²GeoIS, El Día 369 y El Telégrafo, 3° Piso, Quito, Pichincha, Ecuador.

¹⁴³Faculty of Social Sciences, University of Nottingham, University Park, Nottingham, NG7 2RD, UK.

¹⁴⁴Wildlife Conservation Society (WCS), 2300 Southern Boulevard, Bronx, New York, NY, 10460, USA.

¹⁴⁵Medio Ambiente, PLUSPRETOL, Iquitos, Loreto, Peru.

¹⁴⁶The Mauritius Herbarium, Agricultural Services, Ministry of Agro-Industry and Food Security, Reduit, 80835, Mauritius.

¹⁴⁷Department of Biology, Aarhus University, Building 1540, Aarhus C, Aarhus, 8000, Denmark.

¹⁴⁸Living Earth Collaborative, Washington University in Saint Louis, St. Louis, MO, 63130, USA.

¹⁴⁹Escuela de Ciencias Forestales (ESFOR), Universidad Mayor de San Simon (UMSS), Sacta, Cochabamba, Bolivia.

¹⁵⁰FOMABO, Manejo Forestal en las Tierras Tropicales de Bolivia, Sacta, Cochabamba, Bolivia.

¹⁵¹Departamento de Ciencias Forestales, Universidad Nacional de Colombia, Calle 64 x Cra 65, Medellín, Antioquia, 1027, Colombia.

¹⁵²Fundación Amigos de la Naturaleza (FAN), Km. 7 1/2 Doble Vía La Guardia, Santa Cruz, Bolivia.

¹⁵³Tropenbos International, Horaplantsoen 12, Ede, 6717 LT, The Netherlands.

¹⁵⁴School of Anthropology and Conservation, University of Kent, Marlowe Building, Canterbury, Kent, CT2 7NR, UK.

¹⁵⁵Herbario Nacional del Ecuador, Universidad Técnica del Norte, Quito, Pichincha, Ecuador.

¹⁵⁶Instituto de Biodiversidade e Florestas, Universidade Federal do Oeste do Pará, Rua Vera Paz, Campus Tapajós, Santarém, PA, 68015-110, Brazil.

Materials and Methods

Types of pre-Columbian structures that are referred to as “earthworks” in our study

Pre-Columbian earthworks covered in this research include geometrically patterned enclosures, which have been variously referred to in the literature as: earth structures delimited by trenches (52); geometrically patterned ditched enclosures (53, 54); earthworks (54–56); ringed ditches (55, 57); ditches and sculpted plazas (10, 11, 23, 24, 58, 59); geoglyphs (25, 30, 60); and wells (5). These different types of pre-Columbian anthropogenic structures are all referred to as “earthworks” in this study.

Light Detection and Ranging (LiDAR) data

In order to identify pre-Columbian earthworks beneath the forest canopy, we used three datasets provided by: (1) the Sustainable Landscapes Brazil project, a technical and financial cooperation agreement between the United States Forest Service (USFS) and the Brazilian Agricultural Research Corporation (EMBRAPA); (2) the Environmental Monitoring via Satellite in the Amazon Biome (MSA) project, funded by the Amazon Fund with resources from Brazil’s National Development Bank (BNDES) and overseen by the Center for Science of the Terrestrial System (CCST); and (3) the TRopical Ecosystems and Environmental Sciences (TREES) laboratory research group, located at Brazil’s National Institute for Space Research (INPE). The datasets consist of airborne LiDAR obtained along transects across Amazonian forests from 2008 to 2017, see table S3 for airborne LiDAR equipment, parameters and spatial resolution (point density). The full dataset covers 5,315 km², which accounts for 0.08 % of the Amazon forest and represents the largest LiDAR dataset available for Amazonia. All LiDAR data sources are listed in tables S3, and S4, and their spatial distribution is shown in fig. S3[A–C].

The methodology used in these projects differed, which required different parameter settings for LiDAR data processing. We processed the data using the following steps in LAStools software version 1.8.0 (61): (1) division of LiDAR files (.laz) into tiles to enable multithread processing in the next steps with the lastile tool; (2) noise filtering with the lasnoise tool, using default parameters; (3) first ground classification of the point cloud to acquire sparse control points with the lasground tool; (4) aggregation of points close to the control points (from 1st classification) with the lasheight tool; (5) dilution of the point cloud to flag points with lower elevation with the lasthin tool performed three times sequentially; (6) second ground classification, observing only flagged points from the previous step, with the lasground tool; and (7) interpolation of the ground points (from 2nd classification) of the Digital Terrain Model (DTM) into a regular grid with the blast2dem tool to create a Digital Elevation Model (DEM) which allowed us to generate products of altimetry, slope, hillshade, and canopy height model, with 0.5 m spatial resolution (see table S5 for parameters).

Detecting earth-builders’ architecture (earthworks)

The first author (VP) searched for earthworks by visual inspection using hillshade data created from the DEM combined, when necessary, with ESRI high spatial resolution imagery. The geolocation was excluded to prevent any bias associated with the viewer's knowledge about the distribution of well-known earthworks, such as the ones that occur on the southern rim of Amazonia. Viewer mental and visual fatigue were minimized by setting a maximum of 50 images to analyze per day. The viewer was trained to search for geometric shapes not congruent with the landscape. Archaeological experts confirmed approximately half of the features flagged by the viewer as evidence of historical human occupation.

Using LiDAR inspected data we identified 24 new earthworks and nine other earthworks that were already cataloged in archaeological databases. Therefore, within the 5,631 km² of LiDAR data, we obtained an estimate of 0.0062 earthworks/km². These 33 records were seen on 12 of the 861 LiDAR flight lines. All the identified earthworks hillshade data, elevation, slope, tree cover, location, and a brief description is shown in figs. S4 to fig. S13.

Modeling earthwork distribution

We performed a statistical analysis based on novel statistical techniques and on an Inhomogeneous Poisson Process (IPP) model (31), using an intensity function based on intensity covariates and thinned by observability covariates (32) to map the potential extent of pre-Columbian earth-building societies across Amazonia. Statistical novelties in our approach include a fully model-based framework for all model components and a data augmentation technique to handle the analytical intractability of the likelihood function of IPPs. Combined with a Bayesian paradigm, these features allow us to analyze the data without model approximations. Quadratic and interaction effects were not included, leaving only linear terms. The IPP model fit was performed using the 'fit_bayesPO' function of the 'bayesPO' library in R version 4.0.2 (62, 63).

Presence data of earthworks were compiled using our newly-discovered sites (24 sites) together with sites obtained from four datasets provided by: (1) Amazonian Archaeological Sites Network (AmazonArch); (2) Brazilian National System of Archaeological Sites (CNSA); (3) Pre-Columbian Amazon Scale Transformations (PAST) project; and (4) France's National Institute for Preventive Archaeological Research (INRAP). The compilation was carried out by merging data from different datasets within a 500-m radius. This compilation resulted in 937 presence data records. All earthworks data sources are listed in table S4, and their spatial distribution is shown in fig. S3[D–H].

The spatial distribution of earthwork occurrences across the Amazon suffers from a large sampling bias (fig. S14). The current distribution of earthwork sites is skewed towards regions with a higher degree of accessibility and less forest cover (fig. S15). Sampling of all archaeological sites in the Amazon (not only earthworks) follows a similar pattern: a greater number of records in areas with greater accessibility and more intensive research histories. With this biased data collection, the effects of sampling bias in species distribution models (SDMs) applied to archaeological elements throughout the Amazon are always present. However, presence-only data is the only information available. It has become more abundant over the years and, therefore, is a valuable source of information if handled properly (32).

In order to reduce the effects of sampling bias in presence-only datasets, a methodology developed by Moreira & Gamerman (2022) that aims to include components that describe sampling preference was used to develop an appropriate Inhomogeneous Poisson Process (IPP) model (31). Inhomogeneous Poisson processes (IPP) are statistical models for the probabilistic description of occurrences over a region of interest when the intensity of occurrences varies (continuously) over that region. It is also possible to accommodate the effect of explanatory variables on their specification. In addition to these strengths, the IPP approach has an advantage regarding interpretability. Each variable's individual contribution to earthwork presence and observability can be quantified by its respective effect parameter. Thus, the inclusion of observability components, such as the distance from roads and tree cover, as an indication of more favorable locations for the acquisition of samples in the Inhomogeneous Poisson Process

(IPP) model weighted the individual sampling bias of each sample (64–66) and provided better and more satisfactory results in the predictive model.

For observability covariates, the distance to roads was calculated using data from OpenStreetMap (67) data (<https://planet.osm.org>) and tree-cover was based on global forest change 2000-2018 (68), version 1.6 data (<https://glad.earthengine.app/view/global-forest-change>). For intensity covariates (environmental layers), we selected over 19 bioclimatic variables from WordClim (69), 12 edaphic variables from SoilGrids (70) and Zuquim et al. (2019) data (71), and 9 topographic variables derived from the elevation data from HydroSHEDS (72) data (<https://www.hydrosheds.org>), global surface water from JRC (73) data (<https://global-surface-water.appspot.com>), and water-table depth from AMBDATA (74) data (<http://www.dpi.inpe.br/Ambdata/hand.php>). All environmental layers used are listed in table S1.

Topographic aspect, roughness, slope, Topographic Position Index (TPI), and Terrain Ruggedness Index (TRI) were derived from elevation data using the ‘terrain’ function of the ‘raster’ library in R version 4.0.2 (63). Distance data (distance to nearest river and road) to earthworks location were calculated using the ‘gridDistance’ function of the ‘raster’ library in R version 4.0.2 (63). Water accessibility was estimated from elevation, surface water, and slope data using the ArcGIS Spatial Analyst tool (75).

We excluded areas higher than 500 m elevation, because they have bioclimatic and topographic characteristics different enough from Amazonian lowlands that they could skew our model predictions. All data (observability and intensity) were resampled, when necessary, to match the spatial resolution of 30 arc seconds (~ 1 km) and cropped to the extent of the six geological and geographical regions of the Amazon basin (NwA, northwestern Amazonia; SwA, southwestern Amazonia; SA, southern Amazonia; CA, central Amazonia; GS, Guiana Shield; and EA, eastern Amazonia).

None of the intensity covariates included pre-Columbian human occupation density, dating period, or cultural stratification. Those data could be used to refine the analysis of the distribution and occupation of land builders. However, they were not available at a fine enough scale (1 km²) to be included in our modeling analysis.

We selected the most informative variables that were not highly correlated with each other (see figs. S16, S17, and S18). Variables retained for the final model were: (1) mean temperature of warmest quarter (Bio 10); (2) precipitation of wettest quarter (Bio 16); (3) precipitation of driest quarter (Bio 17); (4) soil cation concentration; (5) clay content; (6) silt content; (7) Topographic Position Index (TPI); (8) Height Above the Nearest Drainage (HAND); and (9) Distance to nearest river.

We ran a similar distribution model using another presence-only model (MaxEnt) using a sampling probability surface – which regulates the weight of the pseudo-random background data of the model (76–80), created by a Gaussian kernel density map of the presence data – to predict and compare the distribution of earthworks using a pseudo-absence model (fig. S19). We opted for the Inhomogeneous Poisson Process (IPP) model based on the results that are obtained based on probabilistic reasoning, and are provided with their associated measure of uncertainty.

Because the archaeological databases used in this study (AmazonArch, CNSA, INRAP&DAC, and PAST) is constantly being updated, we expect that the incorporation of new data – relevant to describe the distribution of Amazonian earth-building societies – may refine the predicted number of earthworks. Future studies can be done to refine and validate our reproducible and available prediction model (51). Furthermore, the model can also be restricted to specific types of archaeological structures or Amazonian regions.

Indicators of pre-Columbian domestication and settlements

Data from 1,676 forest inventories provided by the Amazon Tree Diversity Network (ATDN) were used to analyze the: (1) occurrence (presence/absence) of domesticated tree species, and (2) abundance (total number of individuals of the same species). We considered “domesticated species” to be 79 arboreal species strongly associated with indigenous management and cultivation practices and with archaeological sites across Amazonia, following Levis et al. (2017). We used a generalized linear model to analyze the relationship between the occurrence and abundance of domesticated species and their individual responses and the probability of earthwork occurrence obtained from the Inhomogeneous Poisson Process (IPP) model on a log-transformed (base 10) scale. We used binomial and Poisson distributions for the occurrence and abundance data respectively. The forest inventory size was used to specify the component fitting. An overall significance level of 0.05 was used as a threshold to identify domesticated species that significantly increased or decreased with the IPP model. The significance level for each species was adjusted based on the desired overall significance (5%) and the total number of species (79). This analysis was conducted using the ‘glm’ function of the ‘stats’ library in R version 4.0.2 (63). ATDN data sources are listed in table S4, and their spatial distribution is shown in fig. S3[I].

fig. S1

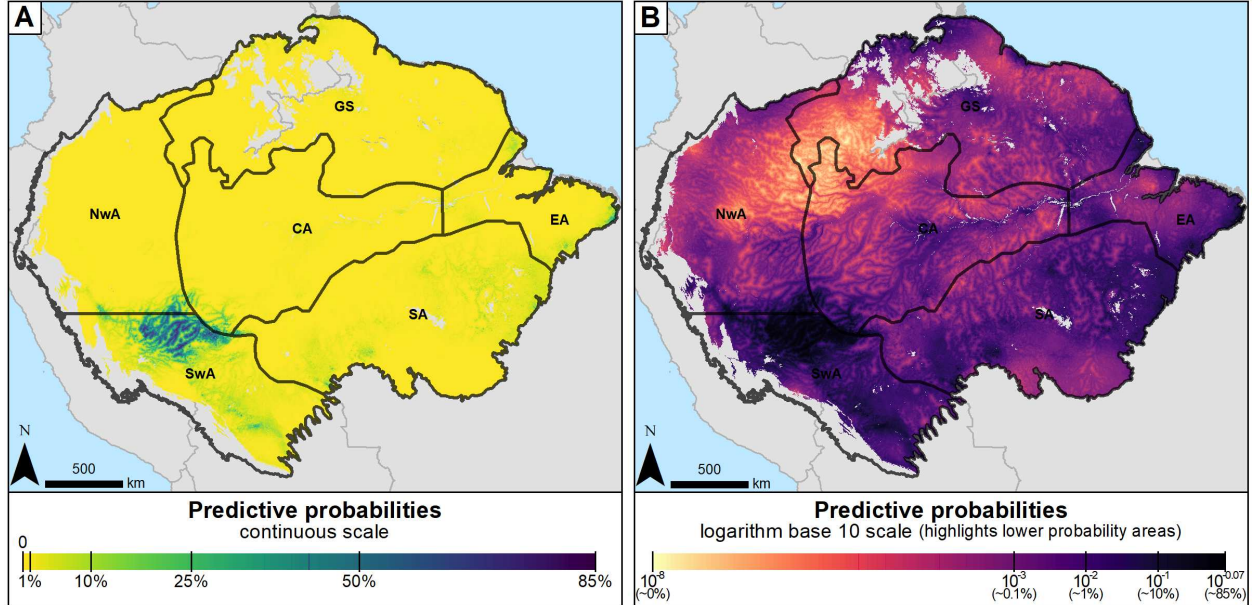


fig. S1. Predicted probability of earthwork presence across Amazonia. (A) Predicted probability of earthwork presence for 1 km² pixels using an Inhomogeneous Poisson Process predictive model (IPP model) on a continuous scale. (B) Predicted probability of earthwork presence for 1 km² pixels using IPP model on a log-transformed scale (log₁₀) highlighting the lower probability variation (< 1%) throughout Amazonia. Six Amazonian regions are labeled: Central Amazonia (CA); Eastern Amazonia (EA); Guiana Shield (GS); Northwestern Amazonia (NWA); Southern Amazonia (SA); and Southwestern Amazonia (SwA). Areas not modeled (NA) are greyed out.

fig. S2

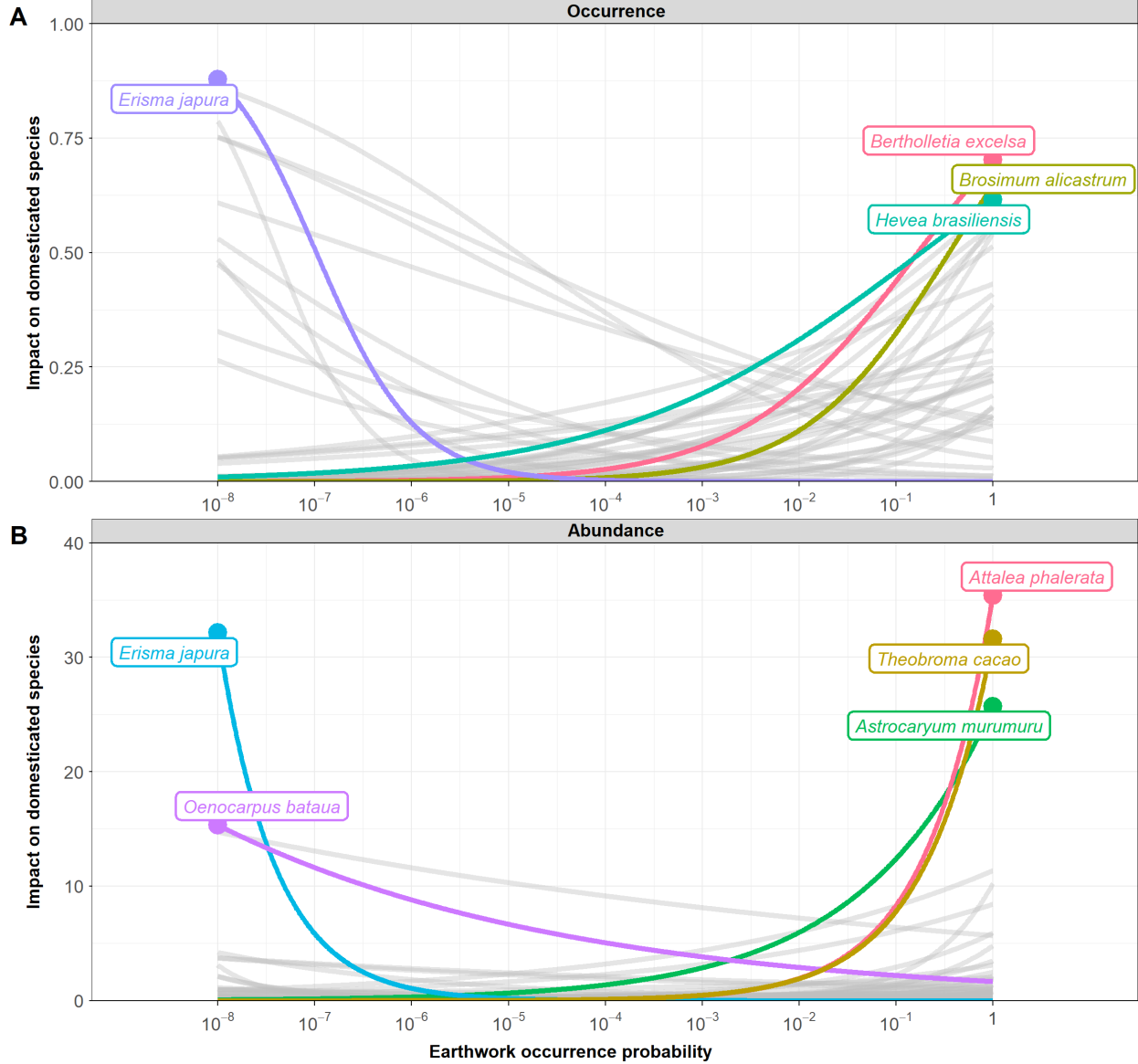


fig. S2. Impact of earthwork occurrence probability on significant domesticated tree species across Amazonia. (A) Relationship between occurrence (presence/absence) data and the predicted probability of earthwork presence. (B) Relationship between abundance data and the predicted probability of earthwork presence. Highlighted species are the 10% most significantly (positive or negative) associated with probability of earthwork presence. Other significant species are greyed-out and without names.

fig. S3

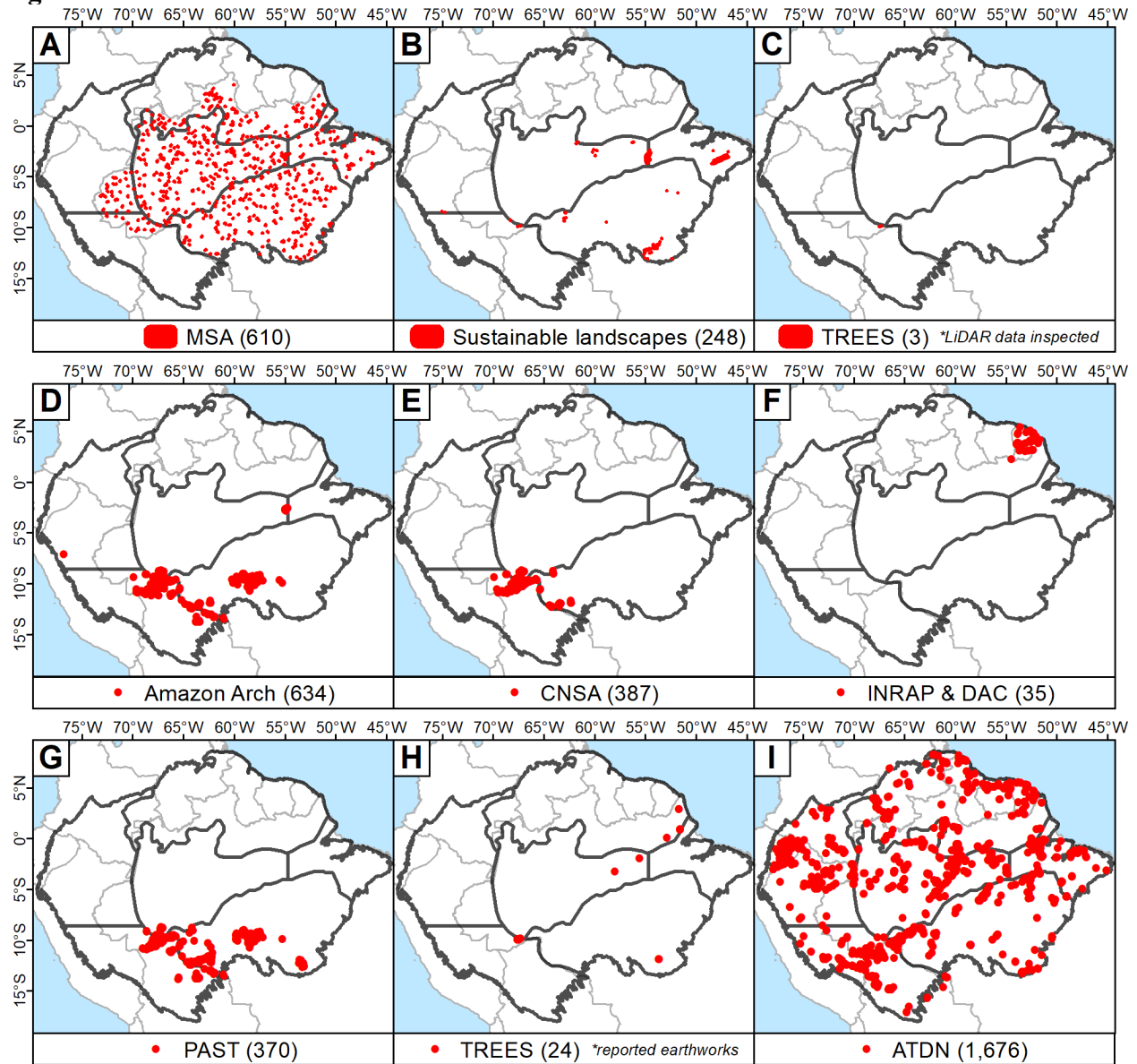


fig. S3. Spatial distribution of the data used within this study. (A–C) Distribution of processed and inspected LiDAR data in the three datasets compiled for this study. (D–H) Distribution of pre-Columbian earthworks in the five datasets compiled for this study. (I) Distribution of Amazon Tree Diversity Network plot sites.

fig. S4

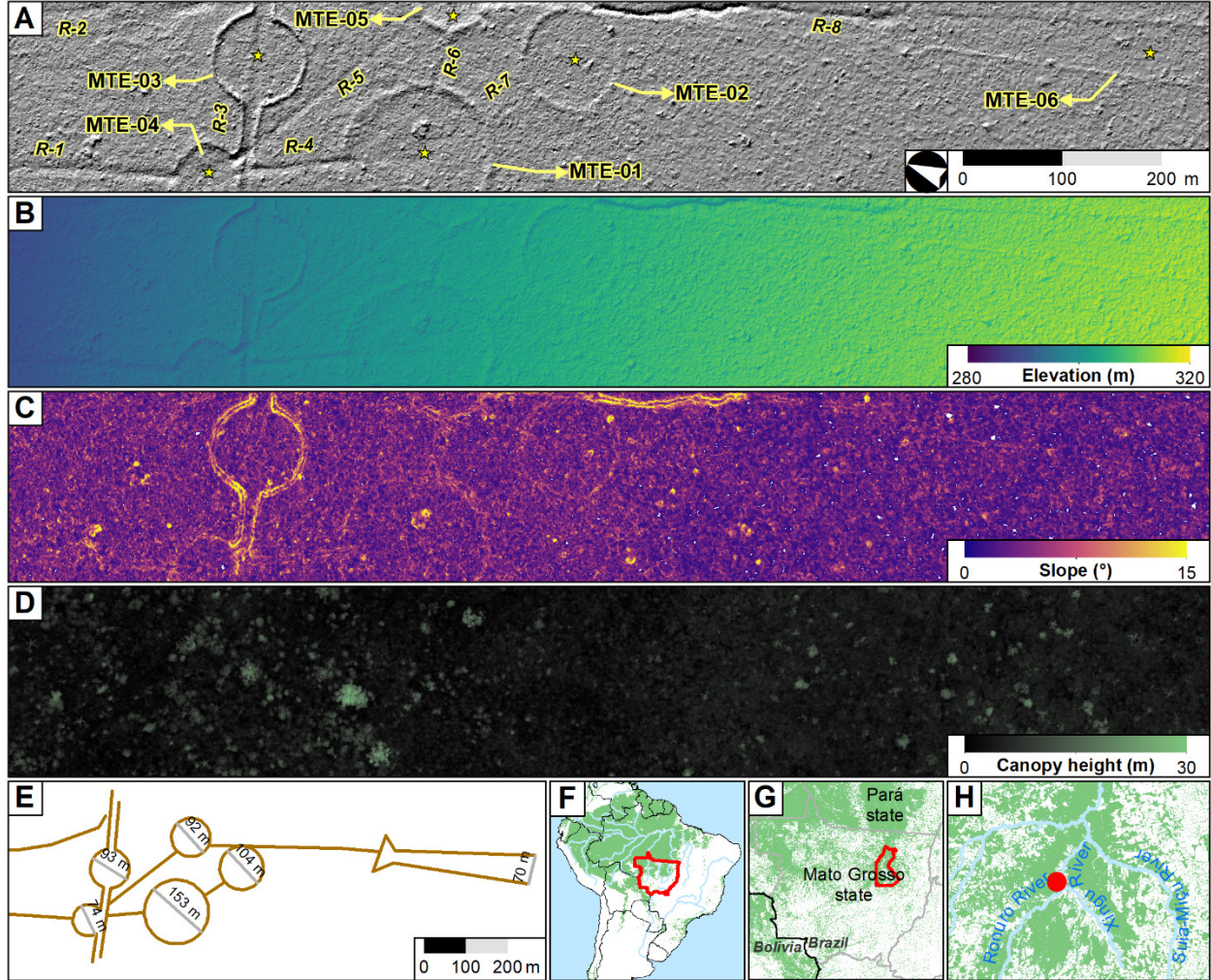


fig. S4. New earthworks discovered using LiDAR in Southern Amazonia (SA). (A) Shaded relief, showing detected earthworks and roads. The digital removal of the forest canopy revealed 5 circular plazas (measuring 70 to 150 m in diameter) and 1 rectangular feature (measuring 1,650 m²) connected by roads. Two of these minor roads (R-1 and R-2) connect to a 200 m long linear path leading to the Imaçu River. (B) Elevation in meters. (C) Slope in degrees. The Digital Terrain Model (DTM) indicated that all earthworks were located on flat portions of the landscape. (D) Canopy Height Model (CHM), in meters. Near these circular plazas, the Canopy-Height Model (CHM) derived from the LiDAR data revealed an emergent canopy with 35 m tall trees, and palms reaching ~20 m. (E) Schematic design of the detected earthworks. It is also clear that the earthworks in this region extend beyond the sampled area of the 200 m wide LiDAR transect, restraining their full identification. (F) Location of Brazil's Mato Grosso state. (G) Location of the Upper Xingu indigenous resource management area. (H) Location of the earthworks sites.

fig. S5

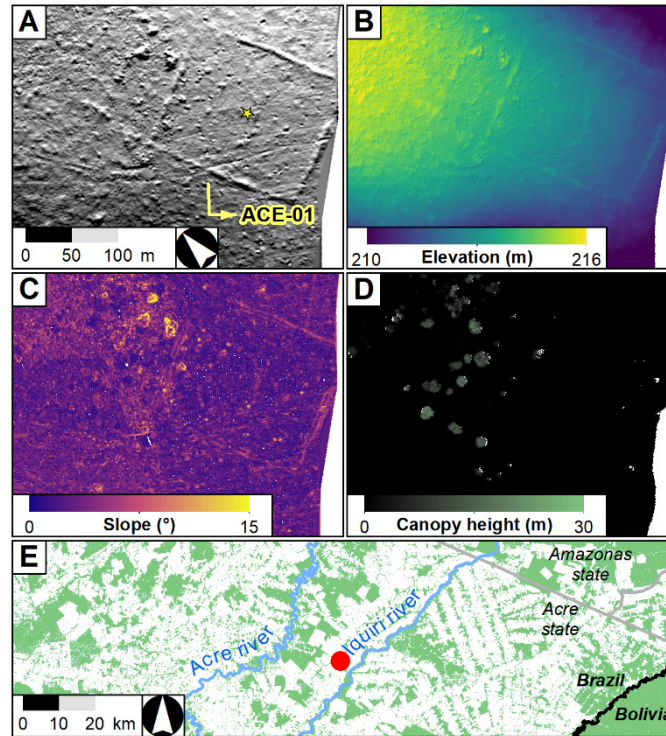


fig. S5. New earthworks discovered using LiDAR in Senador Guimard, in Acre State, Brazil. (A) Shaded relief, showing detected earthwork. (B) Elevation in meters. (C) Slope in degrees. (D) Canopy Height Model (CHM), in meters. (E) Location of the earthwork site. The ACE-01 site is located in a pasture.

fig. S6

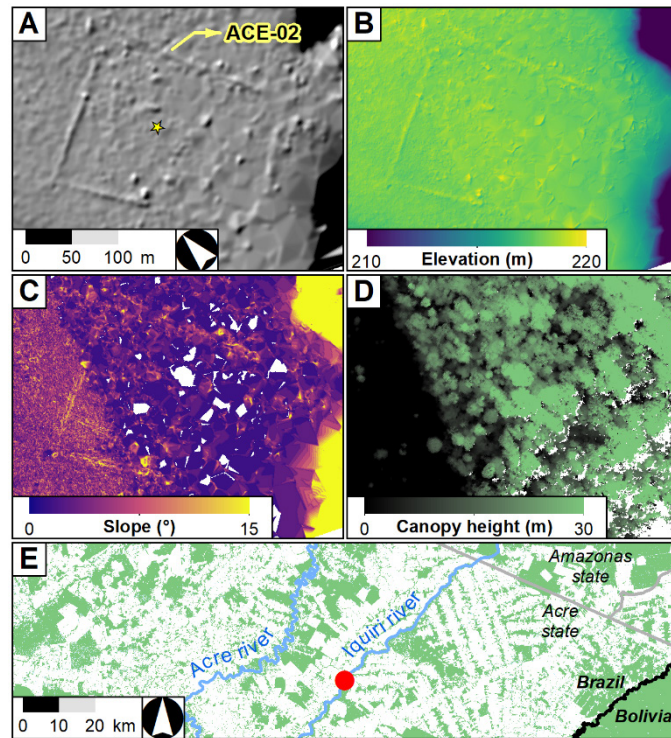


fig. S6. New earthworks discovered using LiDAR in Senador Guimard, in Acre State, Brazil. (A) Shaded relief, showing detected earthwork. (B) Elevation in meters. (C) Slope in degrees. (D) Canopy Height Model (CHM) in meters. (E) Location of the earthwork site. The ACE-02 site is located in a forest edge area, with disturbed vegetation covering a portion of the site.

fig. S7

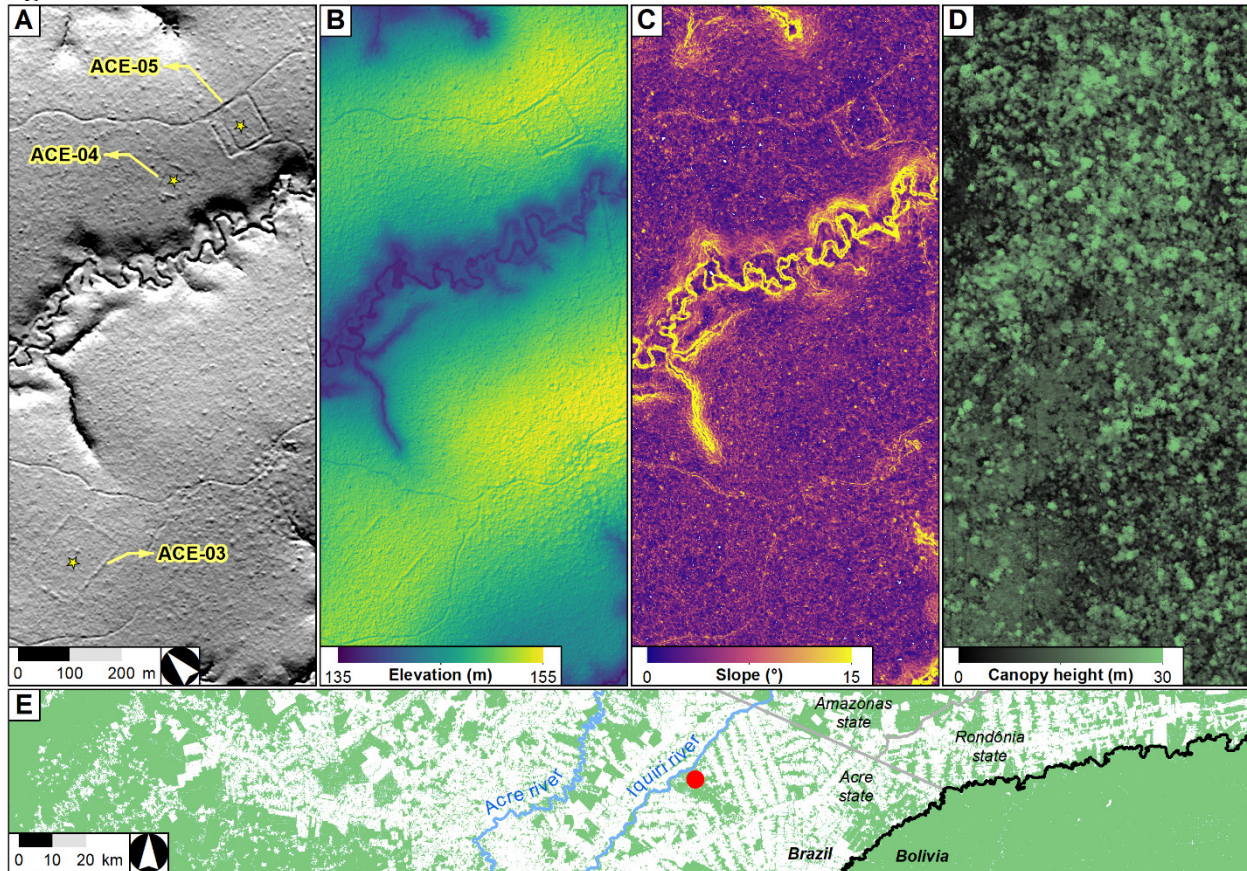


fig. S7. New earthworks discovered using LiDAR in Senador Guimard, in Acre State, Brazil. (A) Shaded relief, showing detected earthworks. The sites are located beneath the forest canopy, next to a perennial tributary of the Iquiri River. (B) Elevation in meters. (C) Slope in degrees. (D) Canopy Height Model (CHM) in meters. The LiDAR data indicated that the landscape around these sites has trees with canopy heights reaching ~22 m. (E) Location of the earthworks sites.

fig. S8

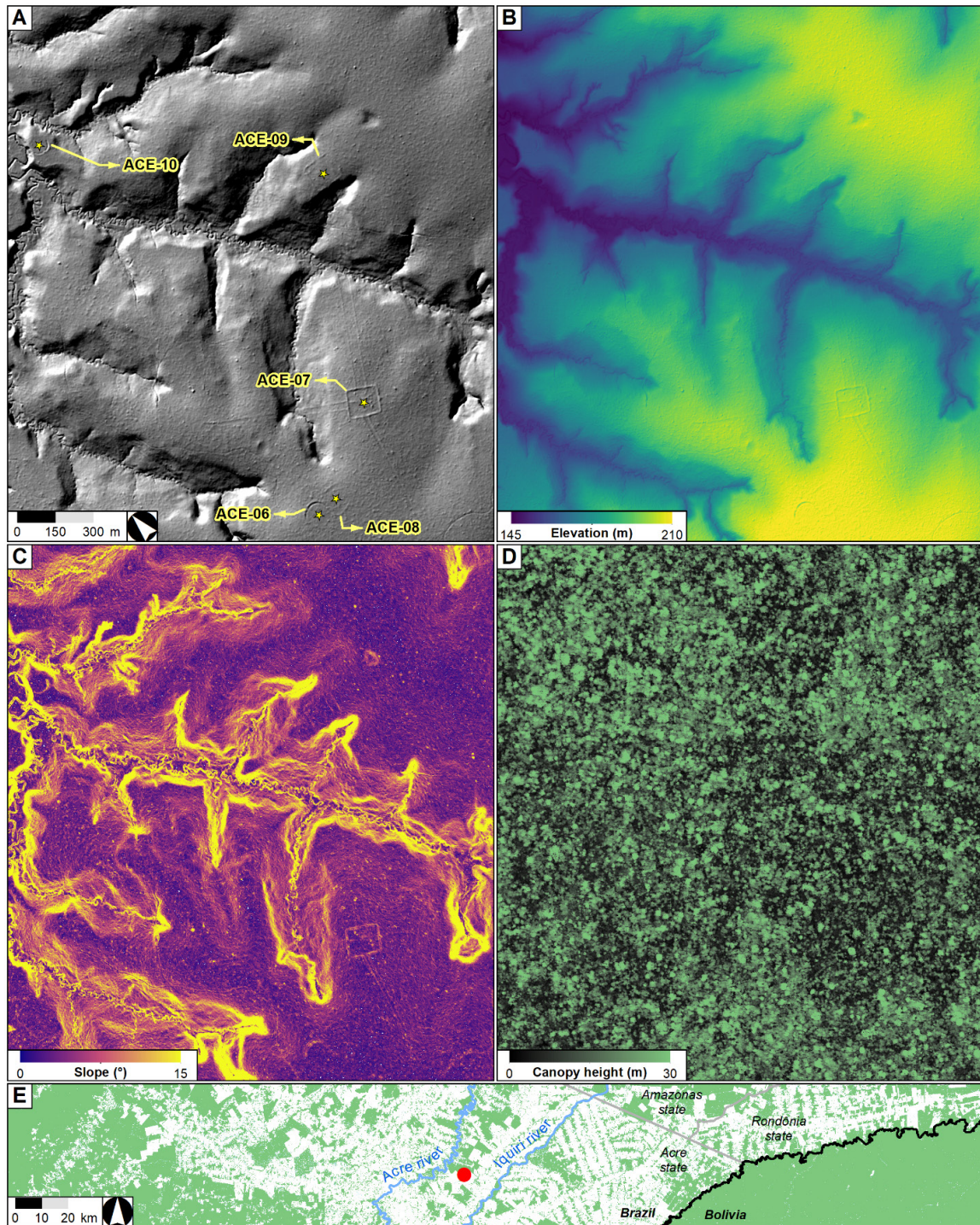


fig. S8. New earthworks discovered using LiDAR in Rio Branco, in Acre State, Brazil. (A) Shaded relief, showing detected earthworks. ACE-07 site has prominent road features delimited by embankments, and ACE-06 and ACE-10 have a semi-circular pattern. **(B)** Elevation in meters. **(C)** Slope in degrees. **(D)** Canopy Height Model (CHM) in meters. The LiDAR data indicated that the landscape around these sites has trees with canopy heights reaching ~22 m. **(E)** Location of the earthworks sites.

fig. S9

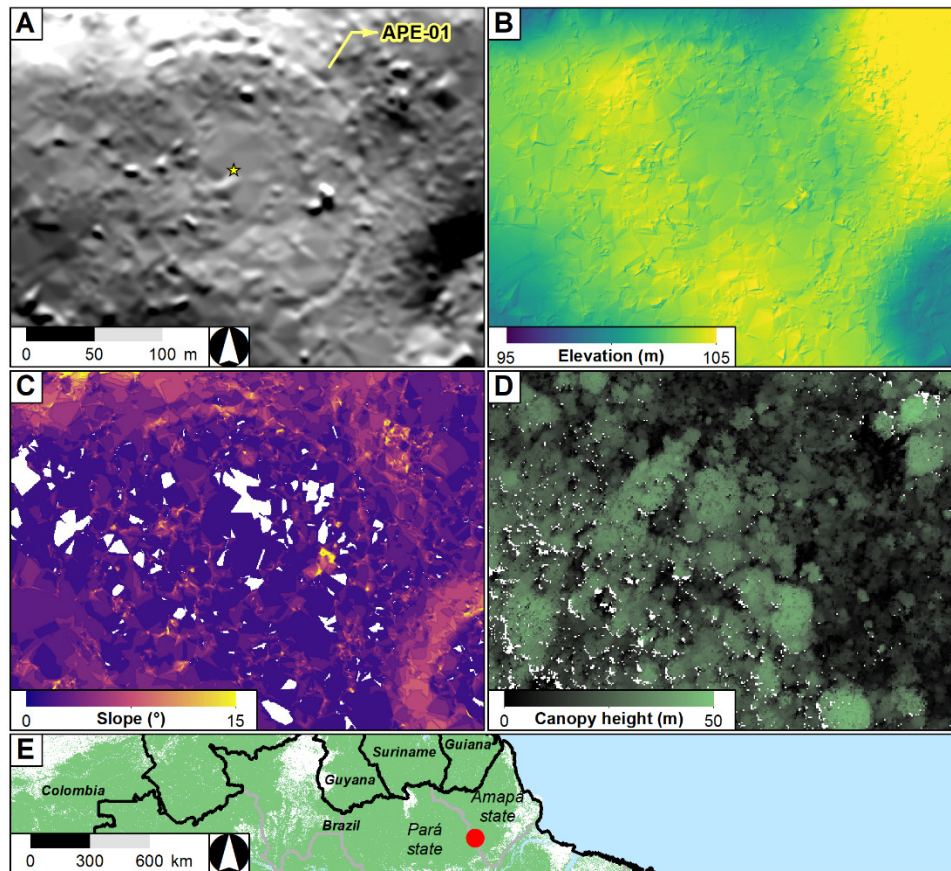


fig. S9. New earthworks discovered using LiDAR in Laranjal do Jari, in Amapá State, Brazil. (A) Shaded relief, showing detected earthwork. The APE-01 site is composed of a rectangular feature surrounded by a circular trench. (B) Elevation in meters. (C) Slope in degrees. (D) Canopy Height Model (CHM) in meters. The site is covered by a forest with emergent trees with heights up to 45 m and palms reaching ~20 m. (E) Location of the earthwork site., the site's location on a plateau top, combined with the distinct geometric pattern, suggests that it was once a crowned mountain used as permanent settlement (26).

fig. S10

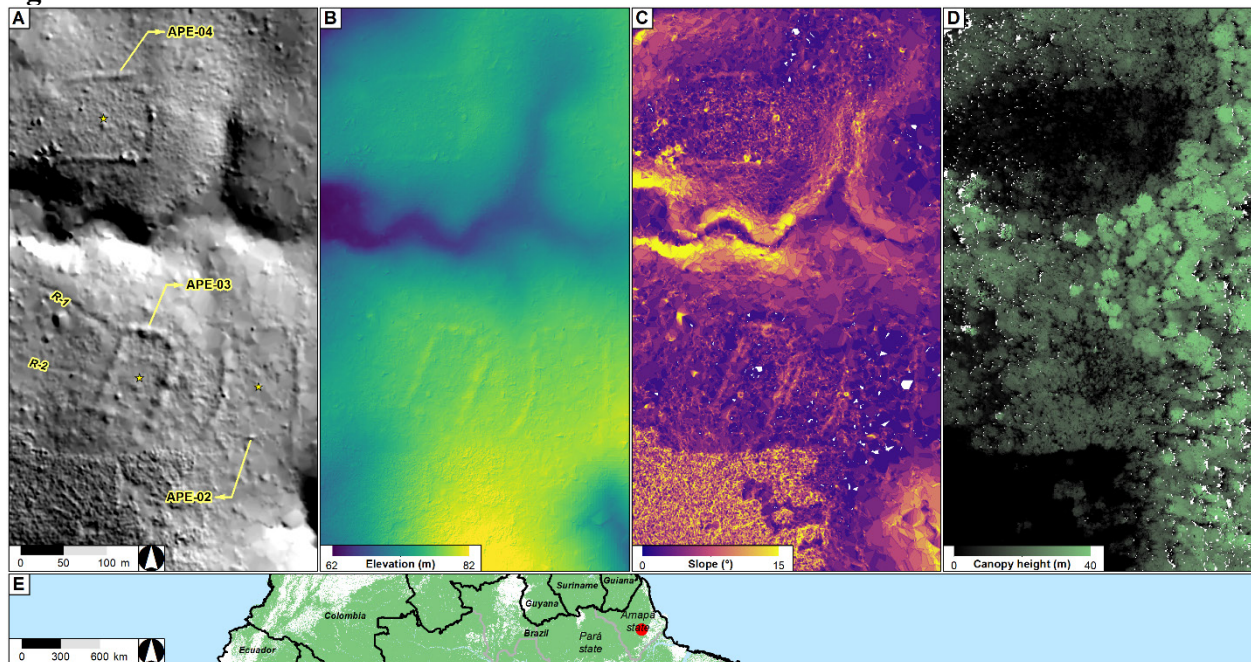


fig. S10. New earthworks discovered using LiDAR in Ferreira Gomes, in Amapá State, Brazil. (A) Shaded relief, showing detected earthworks and roads. (B) Elevation in meters. (C) Slope in degrees. (D) Canopy Height Model (CHM) in meters. The sites are surrounded by tall forests (45 m) and are structurally comparable to each other. (E) Location of the earthworks sites. Their proximity to Solstice Archaeological Park (200 km), a location where several pre-Columbian ceremonial sites were found (popularly known as Amazonian Stonehenge), suggests that these features may be formed by megalithic structures (27).

Fig. S11

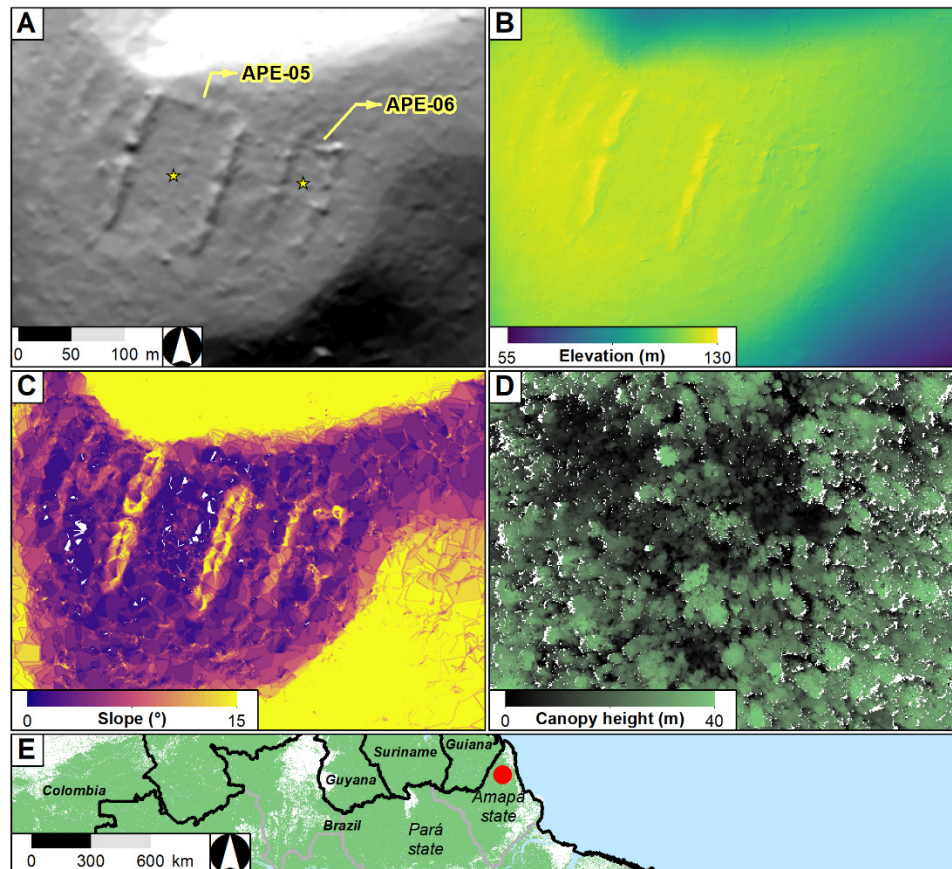


fig. S11. New earthworks discovered using LiDAR in Oiapoque, in Amapá State, Brazil. (A) Shaded relief, showing detected earthworks. (B) Elevation in meters. (C) Slope in degrees. (D) Canopy Height Model (CHM) in meters. (E) Location of the earthworks sites. The sites are covered by tall forests (45 m) and are structurally comparable to each other. Their proximity to Solstice Archaeological Park (80 km), a location where several pre-Columbian ceremonial sites were found (popularly known as Amazonian Stonehenge), suggests that these features may be formed by megalithic structures (27).

fig. S12

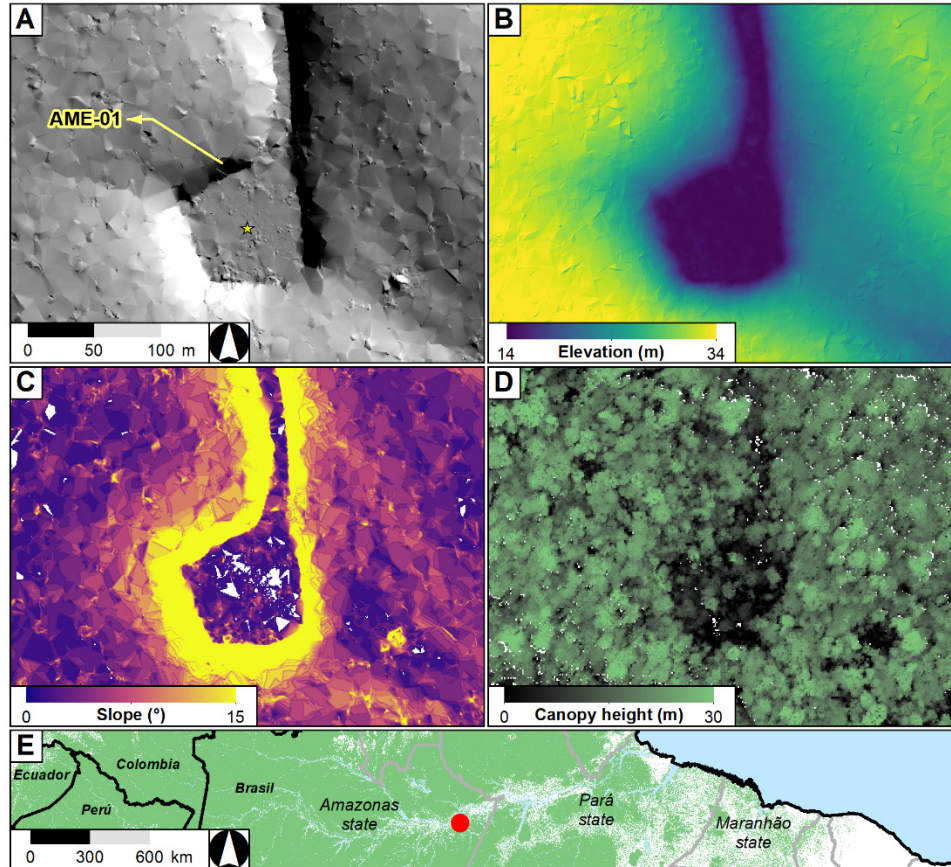


fig. S12. New earthworks discovered using LiDAR in Boa Vista do Ramos, in Amazonas State, Brazil. (A) Shaded relief, showing detected earthwork. The geometric-like feature from AME-01 site measures $\sim 100 \times 100$ m carved 5 m into the ground maintaining a continuous plain terrain of the flooded area. **(B)** Elevation in meters. **(C)** Slope in degrees. **(D)** Canopy Height Model (CHM) in meters. **(E)** Location of the earthwork site.

fig. S13

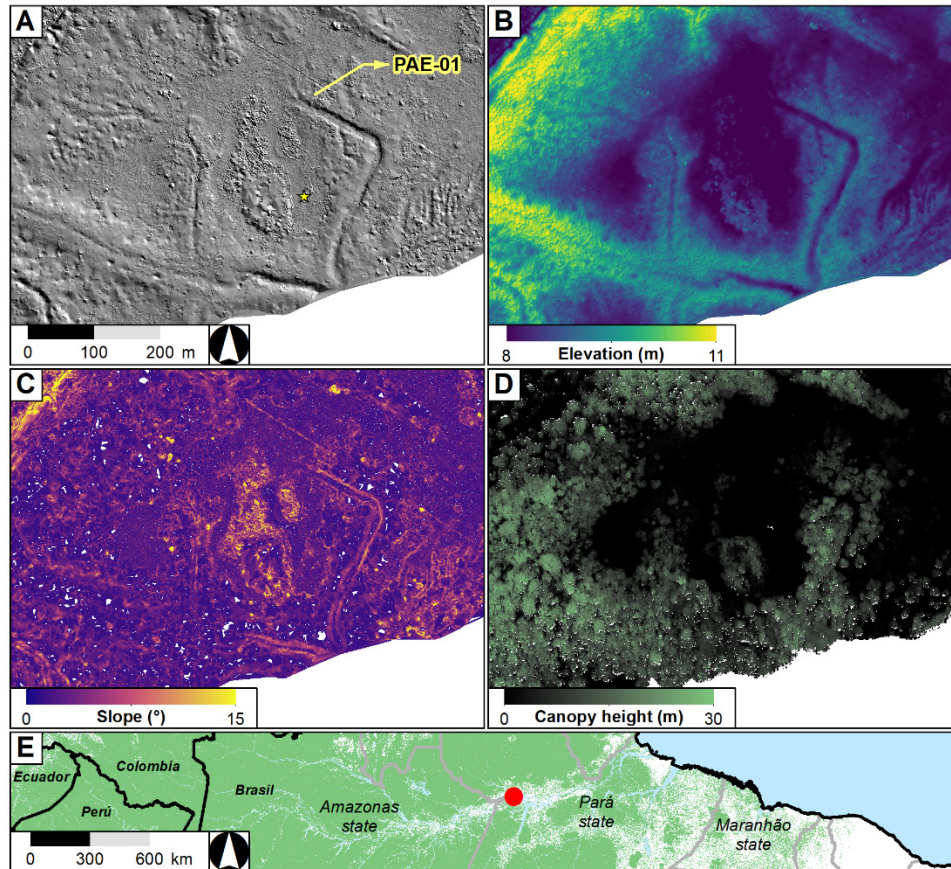


fig. S13. New earthworks discovered using LiDAR in Óbidos, in Pará State, Brazil. (A) Shaded relief, showing detected earthwork. It features a linear ditch (~ 0.6 m deep) with one or more 90° angle turns. (B) Elevation in meters. (C) Slope in degrees. (D) Canopy Height Model (CHM) in meters. (E) Location of the earthwork site. The PAE-01 site is located next to the Amazon River.

fig. S14

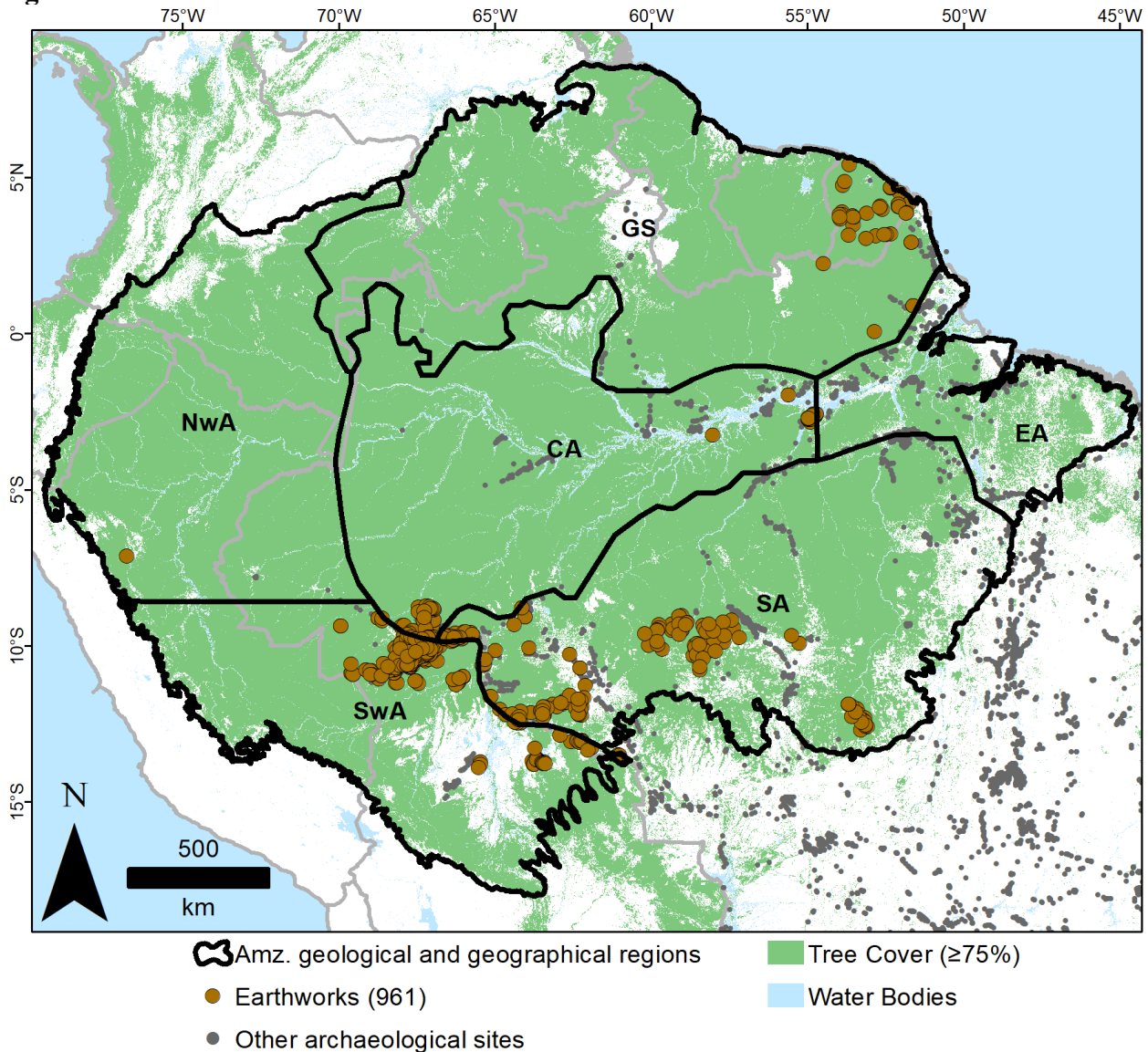


fig. S14. Spatial distribution of known earthworks across Amazonia. Map of previously reported and new earthworks discovered in this study across six Amazonian regions: Central Amazonia (CA); Eastern Amazonia (EA); Guiana Shield (GS); Northwestern Amazonia (NWA); Southern Amazonia (SA); and Southwestern Amazonia (SwA). Note the higher concentration of occurrences in the southern regions of the basin.

fig. S15

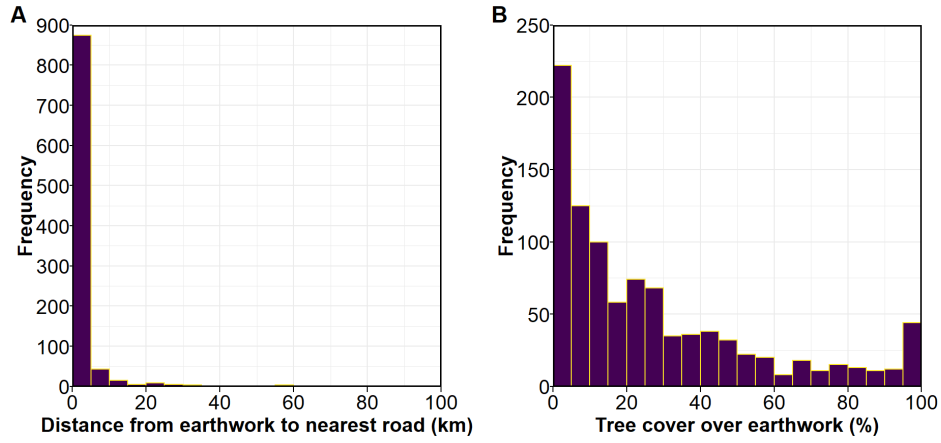


fig. S15. Histograms of observability covariates. (A) Distance from earthworks to nearest road. (B) Tree cover over earthwork. A-B bin width is equal to 5 units.

fig. S16

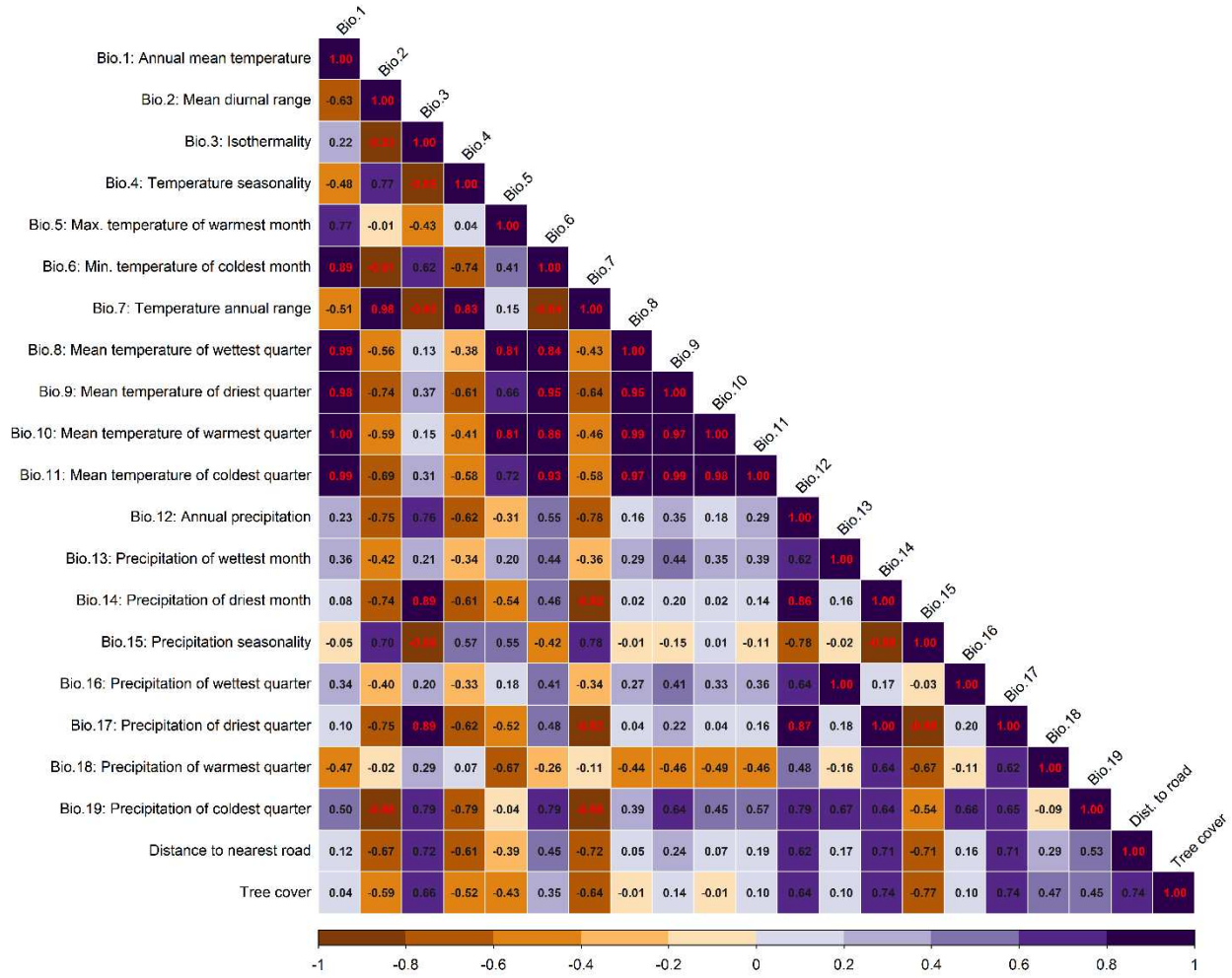


fig. S16. Pearson correlation matrix for bioclimatic variables. Values in red indicate strong correlation ($> |0.8|$).

fig. S17

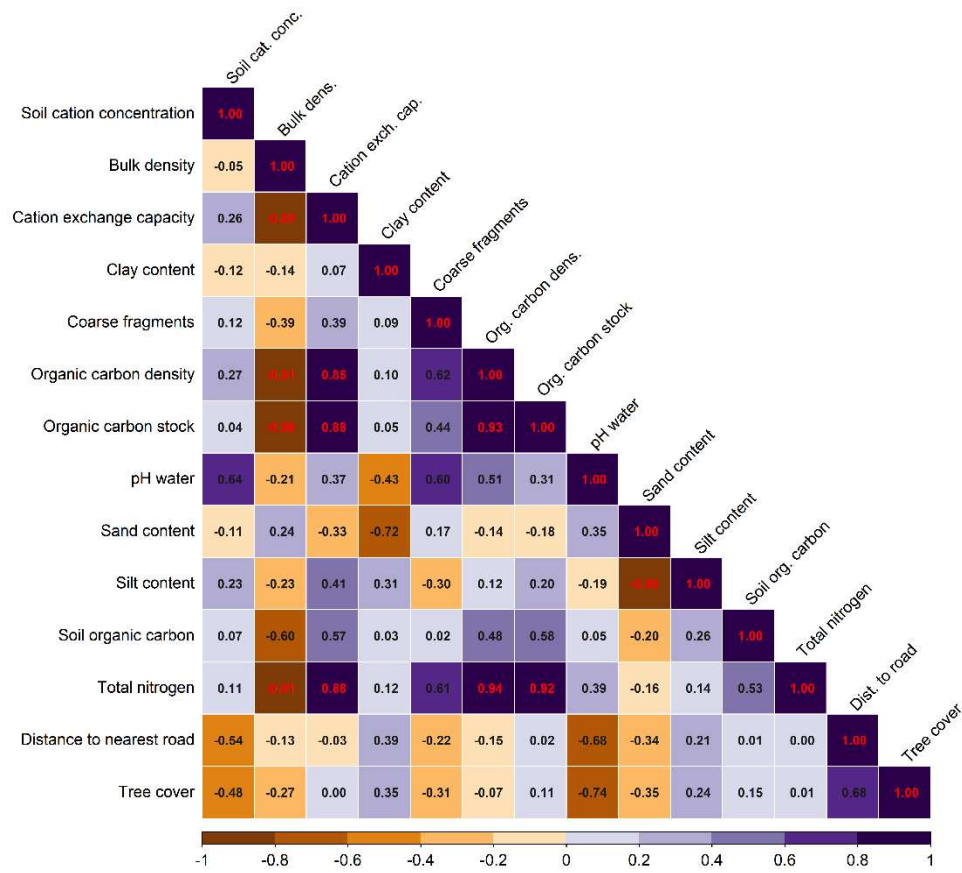


fig. S17. Pearson correlation matrix for edaphic variables. Values in red indicate strong correlation ($> |0.8|$).

fig. S18

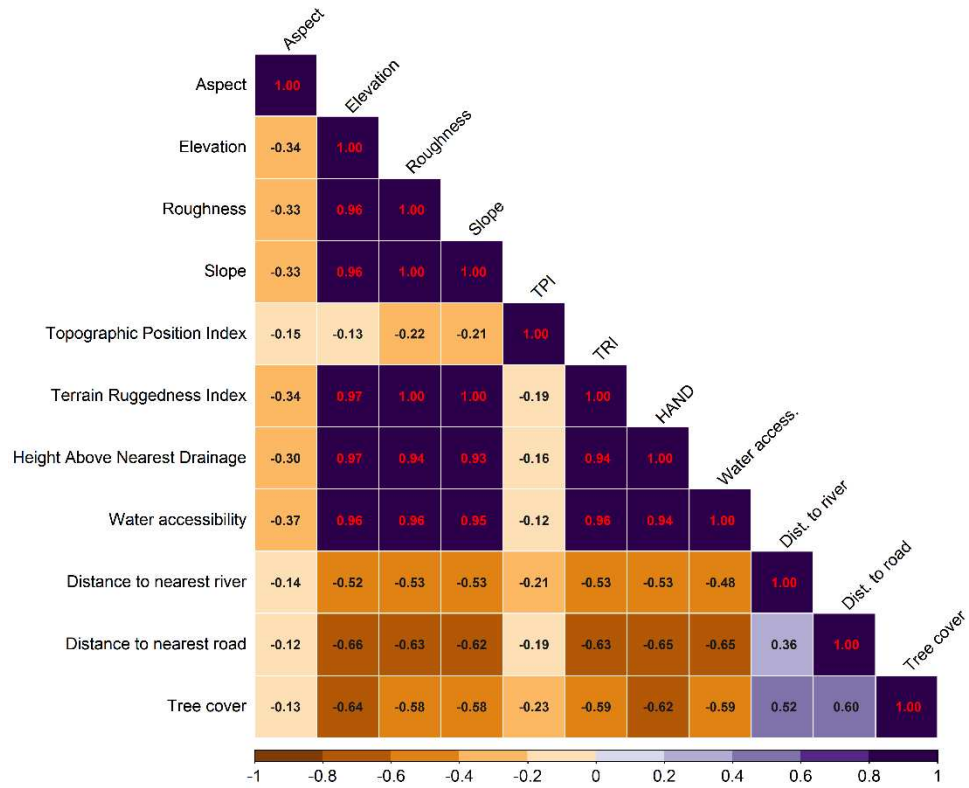


fig. S18. Pearson correlation matrix for topographic variables. Values in red indicate strong correlation ($> |0.8|$).

fig. S19

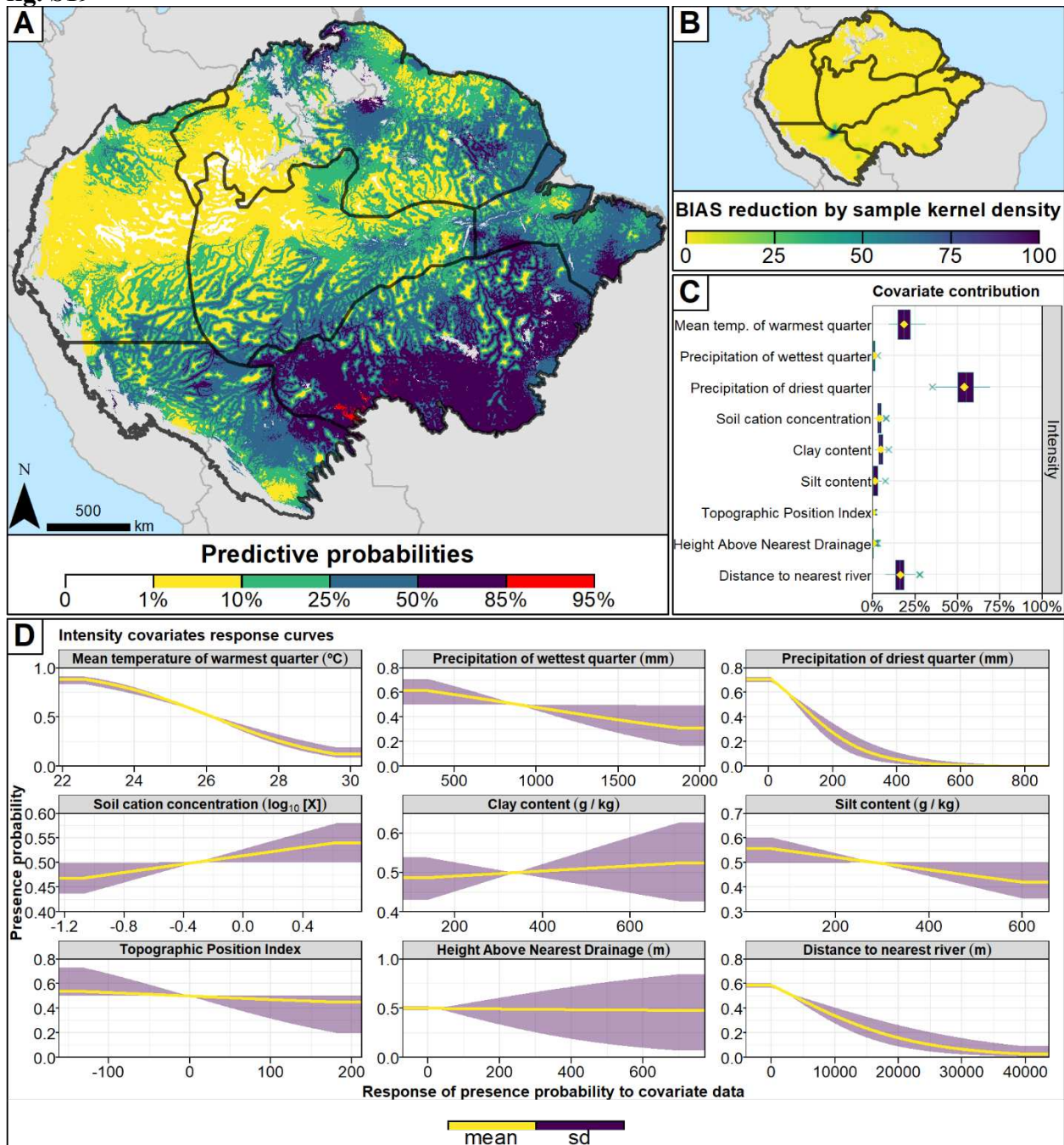


fig. S19. Maximum entropy model of pre-Columbian earthworks across Amazonia. (A) Predicted probability of earthwork presence for 1-km² pixels across six Amazonian regions. Central Amazonia (CA); Eastern Amazonia (EA); Guiana Shield (GS); Northwestern Amazonia (NwA); Southern Amazonia (SA); and Southwestern Amazonia (SwA). **(B)** Gaussian kernel density map of the presence data that regulates the contribution of MaxEnt random pseudo-absence (background) data. **(C)** Boxplot of the individual estimates of covariates' relative contributions, with the yellow diamond indicating mean value. **(D)** Individual predicted probabilities of earthwork presence plotted against intensity covariates.

table S1

Type	Variable
Bioclimatic	Bio.1: Annual mean temperature (°C)
	Bio.2: Mean diurnal range (mean of monthly (max. temp – min. temp))
	Bio.3: Isothermality ((Bio2/Bio7)*100)
	Bio.4: Temperature seasonality (Std.Dev. * 100)
	Bio.5: Max. temperature of warmest month (°C)
	Bio.6: Min. temperature of coldest month (°C)
	Bio.7: Temperature annual range (Bio.5 – Bio,6)
	Bio.8: Mean temperature of wettest quarter (°C)
	Bio.9: Mean temperature of driest quarter (°C)
	Bio.10: Mean temperature of warmest quarter (°C)
	Bio.11: Mean temperature of coldest quarter (°C)
	Bio.12: Annual precipitation (mm)
	Bio.13: Precipitation of wettest month (mm)
	Bio.14: Precipitation of driest month (mm)
	Bio.15: Precipitation seasonality (coefficient of variation)
	Bio.16: Precipitation of wettest quarter (mm)
	Bio.17: Precipitation of driest quarter (mm)
	Bio.18: Precipitation of warmest quarter (mm)
	Bio.19: Precipitation of coldest quarter (mm)
Edaphic	Soil cation concentration (log10)
	Bulk density (cg/cm ³)
	Cation exchange capacity (mmol(c)/kg)
	Clay content (g/kg)
	Coarse fragments (cm ³ /dm ³)
	Organic carbon density (dg/dm ³)
	Organic carbon stock (t/ha)
	pH water (ph*10)
	Sand content (g/kg)
	Silt content (g/kg)
	Soil organic carbon (dg/kg)
	Total nitrogen (cg/kg)
	Topographic
Elevation (m)	
Roughness (m)	
Slope (degrees)	
Topographic Position Index (TPI)	
Terrain Ruggedness Index (TRI)	
Height Above the Nearest Drainage (HAND) (m)	
Water accessibility	
Distance to nearest river (m)	
Obs. Comp	Distance to nearest road (m)
	Tree cover (%)

table S1. Environmental parameters considered as predictors for modeling.

table S2

Probability threshold	Projected area (km ²)	Distribution across six Amazonian regions					
		CA	EA	GS	NwA	SA	SwA
≥ 1%	1,412,738	8%	9%	6%	5%	34%	37%
≥ 10%	207,915	7%	3%	1%	9%	5%	74%
≥ 25%	94,713	4%	1%	0%	7%	1%	86%
≥ 50%	32,120	1%	0%	0%	4%	0%	96%
≥ 75%	581	0%	0%	0%	0%	0%	100%

table S2. IPP Model projected area across six Amazonian regions on different probability thresholds.

table S3

Dataset	Scanner specification	Scanner frequency	GNSS Specification	GNSS Frequency	IMU Specification	IMU Frequency	Flight altitude	Flight line overlap	FOV	Average point density (last only)	
Sustainable Landscapes	2008	LEICA, ALS-50 PHASE II, SN 52	58 - 90 Hz	NOVATEL, OEMV4	2 Hz	IMAR, LN200	200 kHz	805 m	27%	10 - 24°	15 points.m ²
	2011	OPTECH INC., ALTM 3100	59.8 Kz	APPLANIX, 09SEN243	5 Hz	LITTON, 413996	100 kHz	850 m	65%	11°	15 points.m ²
	2012	OPTECH INC., ALTM 3100	59.8 Kz	APPLANIX, 09SEN243	5 Hz	LITTON, 413996	100 kHz	850 m	65%	11°	16 points.m ²
	2013	OPTECH INC., ORION M300	61.4 - 67.5 Hz	APPLANIX, 09SEN243	5 Hz	LITTON, 413996	100 kHz	860 m	65%	10 - 11 °	13 points.m ²
	2014	OPTECH INC., ORION M300 * TRIMBLE, HARRIER 681 **	83 Hz * 400 kHz **	APPLANIX, 09SEN243 * APPLANIX, AV510 **	5 Hz * 1 Hz **	LITTON, 413996 * APPLANIX, AV510 **	100 kHz * 200 Hz **	850 m * 500 m **	65%	10 - 12° * 15° **	20 points.m ²
	2015	OPTECH INC., ALTM 3100	40 - 55 Hz	OMNISTAR, PGPS16	1 Hz	APPLANIX, AV510	200 kHz	700 m	70%	15°	37 points.m ²
	2016	OPTECH INC., ALTM 3100	40 Hz	OMNISTAR, PGPS16	1 Hz	APPLANIX, AV510	200 kHz	750 m	70%	15°	23 points.m ²
	2017	OPTECH INC., ALTM 3100	40 Hz	OMNISTAR, PGPS16	1 Hz	APPLANIX, AV510	200 kHz	850 m	70%	15°	15 points.m ²
MSA	TRIMBLE, RIEGL Q680I	5 - 200 Hz	APPLANIX, AV510	1 Hz	APPLANIX, AV510	200 Hz	600 m	0%	22.5°	7 points.m ²	
TREES	RIEGL, VUX-1UAV	50 - 550 kHz	APPLANIX, APX15	1 Hz	APPLANIX, APX15	200 Hz	300 m	0%	35°	8 points.m ²	

table S3. Equipment and parameters in the data collection of each LiDAR database.

table S4

Group	Name	Source data	Website
AmazonArch	Amazonian Archaeological Sites Network	Earthwork	https://sites.google.com/view/amazonarch
PAST	Pre-Columbian Amazon Scale Transformations	Earthwork	http://amazoniapast.exeter.ac.uk/
CNSA/IPHAN	Brazilian National System of Archaeological Sites	Earthwork	http://portal.iphan.gov.br/pagina/detalhes/1701
INRAP	National Institute for Preventive Archaeological Research	Earthwork	https://www.inrap.fr/
EMBRAPA	Sustainable Landscapes Brazil	LiDAR	http://www.paisagenslidar.cnptia.embrapa.br/webgis/
CCST	Center of Science of the Terrestrial System	LiDAR	http://www.ccst.inpe.br/projetos/eba-estimativa-de-biomassa-na-amazonia/
TREES	Tropical Ecosystems and Environmental Sciences laboratory	LiDAR	https://www.treeslab.org/
ATDN	Amazon Tree Diversity Network	Domesticated Species	https://sites.google.com/naturalis.nl/amazon-tree-diversity-network/homepage

table S4. LiDAR, Earthwork and Domesticated Species data sources.

table S5

<i>Description</i>	<i>Tool</i>	<i>switches</i>	<i>Values by dataset</i>		
			<i>Sustainable landscapes</i>	MSA	TREES
Tiles point cloud into a specific size	<i>lastile</i>	-tile_size	400	400	200
		-buffer	50	50	50
Flags or removes noisy points	<i>lasnoise</i>		Default settings		
Classifies LiDAR points into ground points	<i>lasground</i>	-step	8	10	8
		-stddev	0.5	0.5	0.5
		-spike	0.5	1	0.5
		-offset	0.1	0.1	0.1
Computes height of each point above the ground	<i>lasheight</i>	- classify_between	-5 / 1	-10 / 1	-5 / 1
		- classify_above	1	1	1
Flags only points with the lowest elevation inside a uniform grid	<i>lasthin</i>	-step	0.25	0.25	0.25
		-percentile	50 / 1	50 / 1	50 / 1
	<i>lasthin</i>	-step	0.5	0.5	0.5
		-percentile	50 / 1	50 / 1	50 / 1
	<i>lasthin</i>	-step	1	1	1
		-percentile	50 / 1	50 / 1	50 / 1
Classifies LiDAR points into ground points	<i>lasground</i>	-step	0.85	0.85	0.85
		-stddev	0.5	0.5	0.5
		-spike	0.2	0.2	0.2
		-offset	0.1	0.1	0.1
Triangulates the point cloud over a continuous Triangular Irregular Network (TIN)	<i>blast2dem</i>	-step	0.5	0.5	0.5
		-hillshade	-	-	-
		-elevation	-	-	-

table S5. Filtering parameters in LiDAR data processing.

Data S1 (separate file).

List of 79 tree species with populations domesticated to different degrees by pre-Columbian peoples in Amazonia according to Levis et al. (2017). The dataset includes the main use of each species, the degree of domestication, origin, local names (in Brazilian Portuguese), and the individual relative significance based on occurrence (presence/absence) and abundance data. Overall significance level of 5% ($p < 0.05$) with adjusted significance level ($p < 0.00065$) is also provided. Values highlighted in blue, red, and grey indicate positive, negative, and null significance respectively.

Data S2 (separate file): Forest plot metadata

ATDNNR: Number in ATDN database

Country: country in which plot is located.

Subdivision: Mostly state/province.

Site: site name.

PlotCode: Unique ATDN plot code.

Altitude, Latitude, Longitude.

PlotSize: plot size in ha.

PlotType: single: 1 single contiguous area; combi; few plots very close added.
together; pcq: plots built from point center quarter data.

DBHmin: min dbh cut off.

Owner/contact: Owner of plot data.

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