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

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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 km^2 (*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 km^2 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 / km^2) to the extent of Amazonia (6.7 million km^2), 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.

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 (≥ 25% predicted probability) occur in a 94,713-km^2 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 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 heterogeneously distributed across Amazonian regions. Almost 80% of the basin has a 0 to 1% of predicted probability of earthwork presence for 1-km^2 cells. These low-probability areas are mostly located in northwestern, northern and central Amazonia, while higher-probability areas (≥ 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 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 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 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 (≥ 50% of predicted probability) cover 32,120 km^2, 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 *Erisma 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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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

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Materials and Methods

figs. S1 to S19

tables S1 to S5

References (*52–80*)

Other Supplementary Materials for this manuscript include the following:

Data S1 and S2 as separate Excel file

Fig. 1

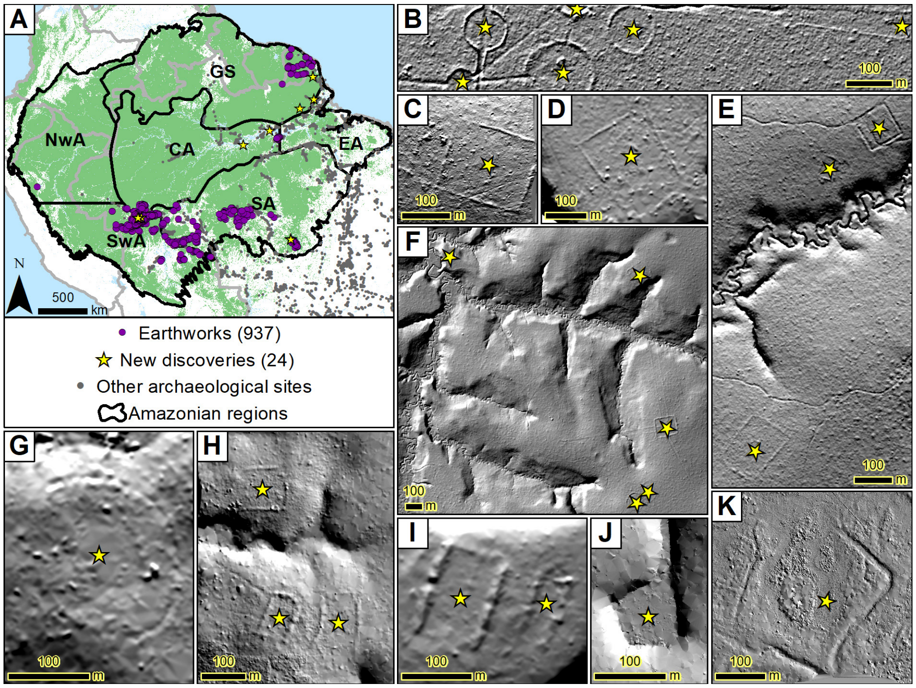

Fig. 1. Geographical distribution of known and newly discovered pre-Columbian geometrical earthworks in Amazonia. (**A**) Map of previously reported and newly discovered earthworks reported in this study across six Amazonian regions: Central Amazonia (CA); Eastern Amazonia (EA); Guiana Shield (GS); Northwestern 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

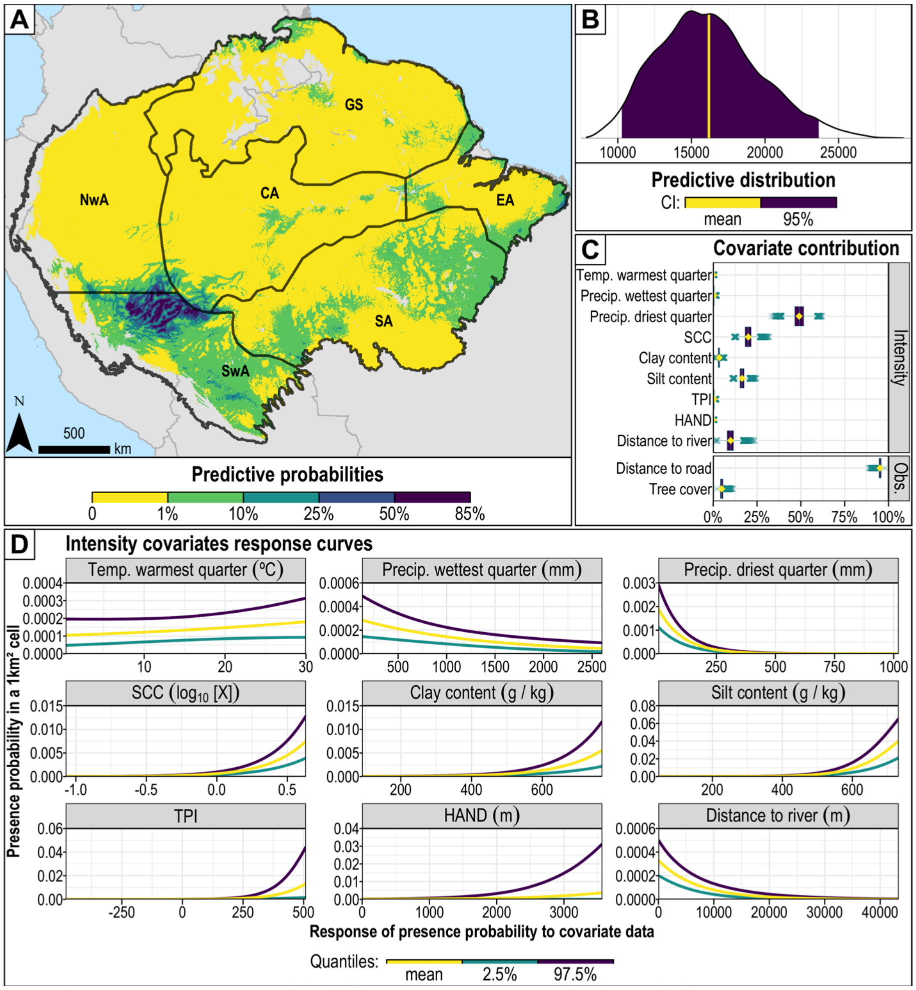

Fig. 2. Probability model of pre-Columbian earthworks across Amazonia. (**A**) Predicted probability of earthwork presence for 1-km^2 cells across six Amazonian regions using an Inhomogeneous Poisson Process predictive model: Central Amazonia (CA); Eastern Amazonia (EA); Guiana Shield (GS); Northwestern 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.

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Supplementary Materials for

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

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This PDF file includes:

Author Affiliations
Materials and Methods
figs. S1 to S19
tables S1 to S5
References

Other Supplementary Materials for this manuscript include the following:

Data S1 and S2 as separate Excel file

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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 km^2, 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 180.605 (*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 1^{st} 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 2^{nd} 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 km^2 of LiDAR data, we obtained an estimate of 0.0062 earthworks/km^2. 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 km^2) 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

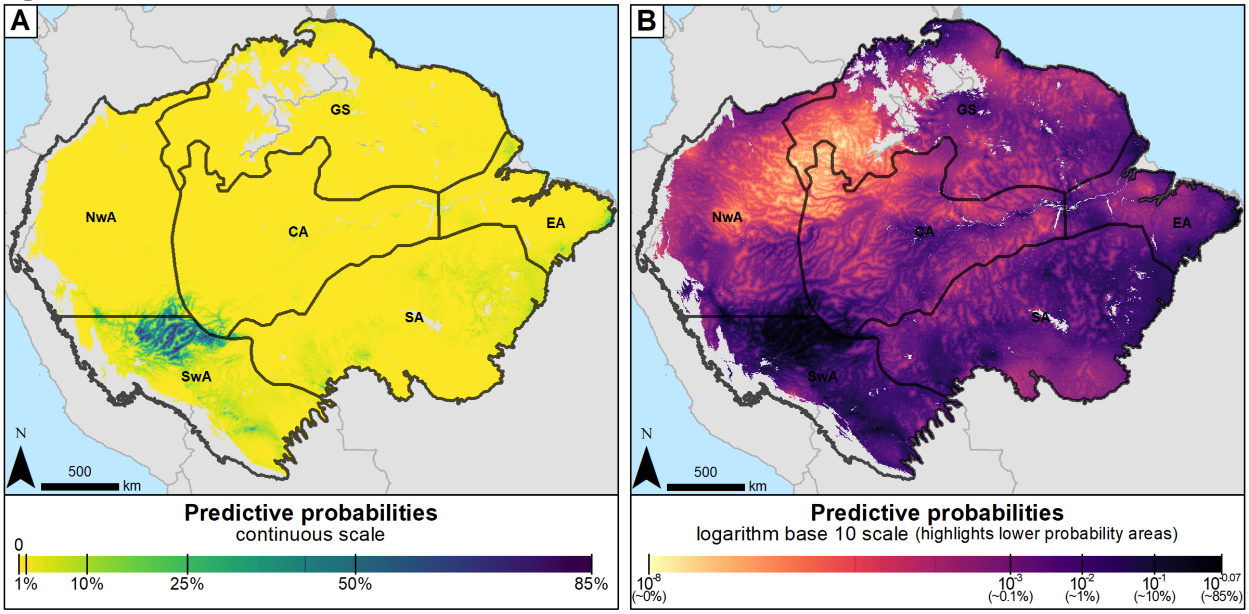

fig. S1. Predicted probability of earthwork presence across Amazonia. (**A**) Predicted probability of earthwork presence for 1 km2 pixels using an Inhomogeneous Poisson Process predictive model (IPP model) on a continuous scale. (**B**) Predicted probability of earthwork presence for 1 km2 pixels using 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

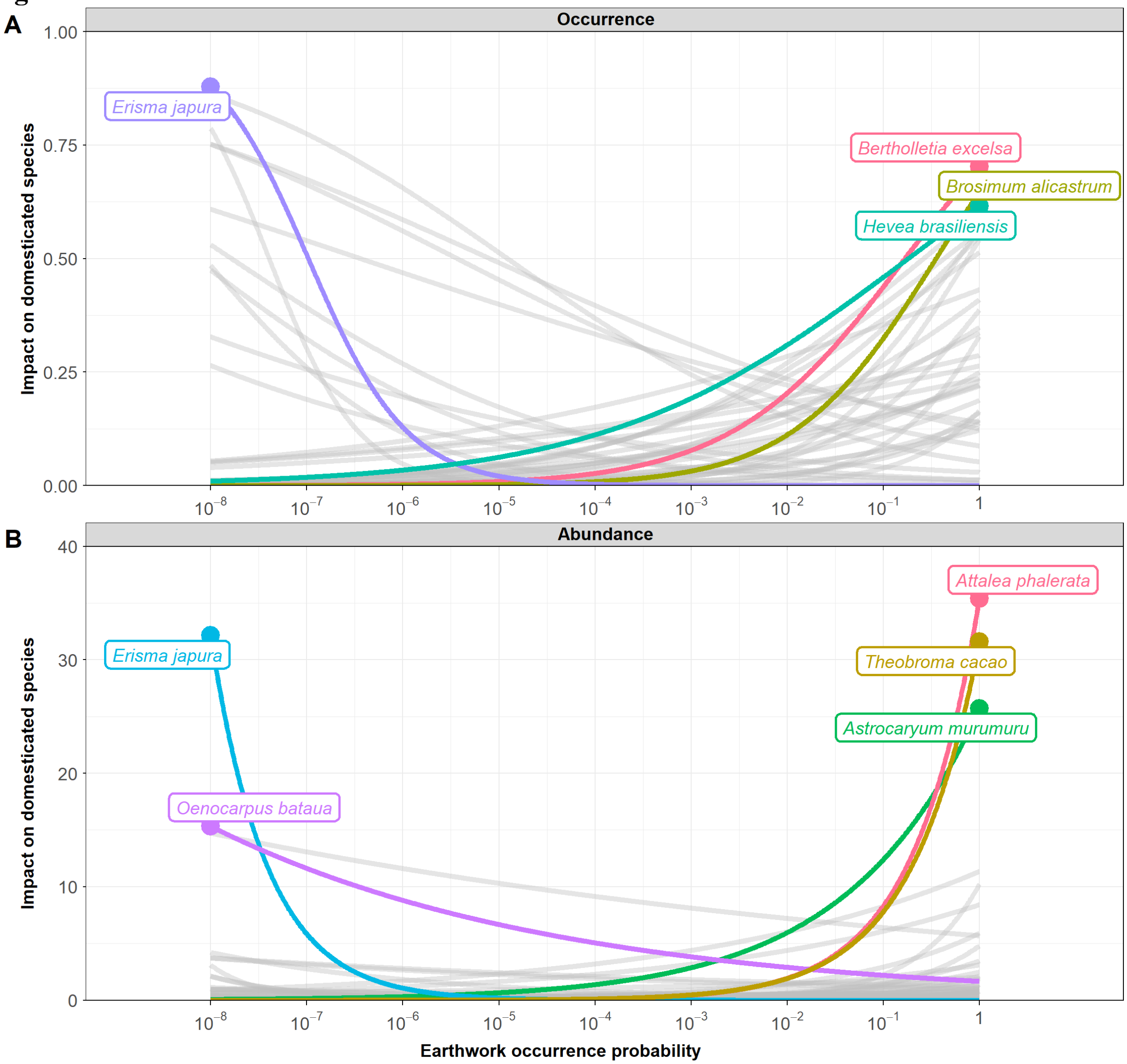

fig. S2. Impact of earthwork occurrence probability on significant domesticated tree species across Amazonia. (**A**) Relationship between occurrence (presence/absence) data and the predicted probability of earthwork presence. (**B**) Relationship between abundance data and the predicted probability 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

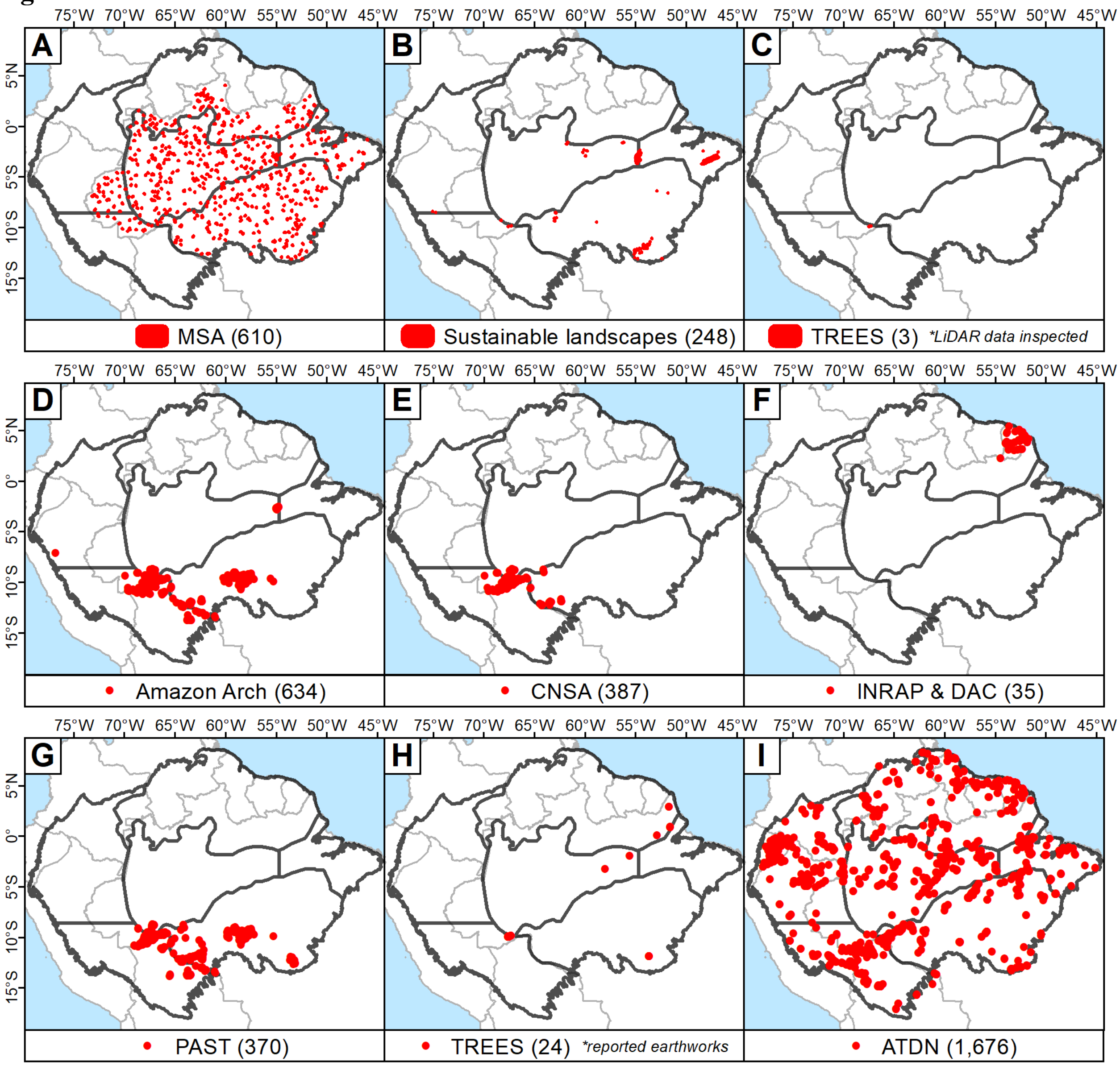

fig. S3. Spatial distribution of the data used within this study. (**A–C**) Distribution of processed and inspected LiDAR data in the three datasets compiled for this study. (**D–H**) Distribution of pre-Columbian earthworks in the five datasets compiled for this study. (**I**) Distribution of Amazon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

fig. S4

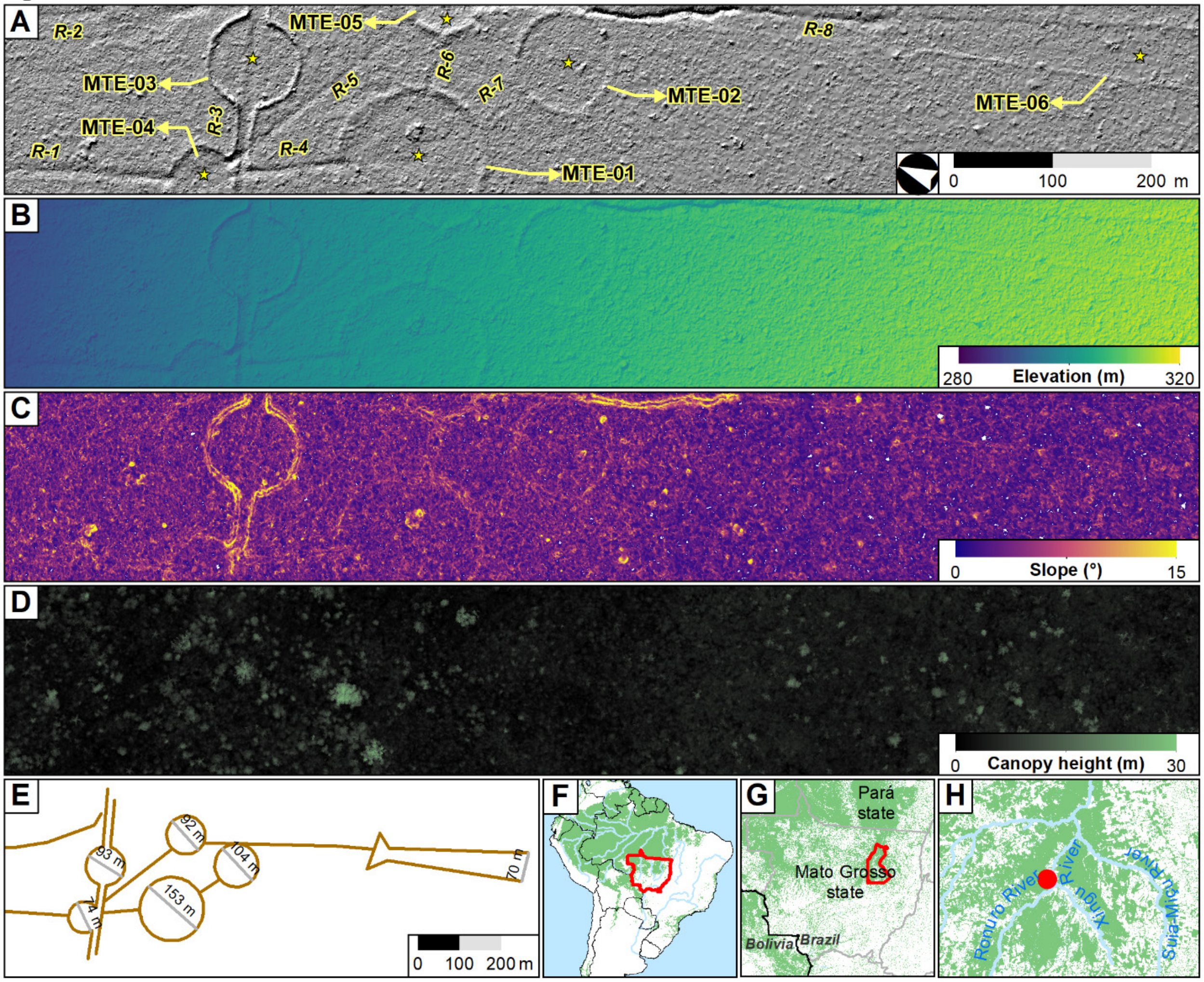

fig. S4. New earthworks discovered using LiDAR in Southern Amazonia (SA). (**A**) Shaded relief, showing detected earthworks and roads. The digital removal of the forest canopy revealed 5 circular plazas (measuring 70 to 150 m in diameter) and 1 rectangular feature (measuring 1,650 m²) connected by roads. Two of these minor roads (R-1 and R-2) connect to a 200 m long linear path leading to the Iamaçu 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

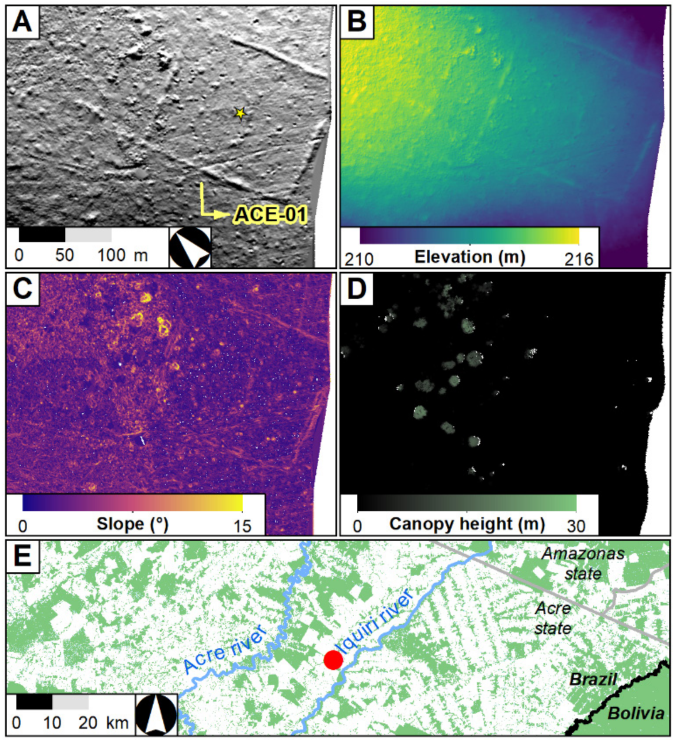

fig. S5. New earthworks discovered using LiDAR in Senador Guiomard, in Acre State, Brazil. (**A**) Shaded relief, showing detected earthwork. (**B**) Elevation in meters. (**C**) Slope in degrees. (**D**) Canopy Height Model (CHM), in meters. (**E**) Location of the earthwork site. The ACE-01 site is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

fig. S6

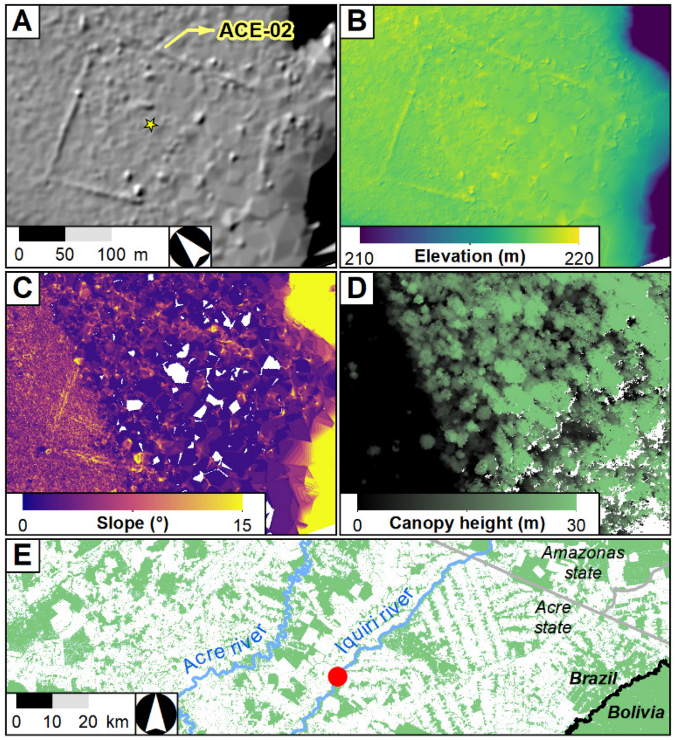

fig. S6. New earthworks discovered using LiDAR in Senador Guiomard, in Acre State, Brazil. (**A**) Shaded relief, showing detected earthwork. (**B**) Elevation in meters. (**C**) Slope in degrees. (**D**) Canopy Height Model (CHM) in meters. (**E**) Location of the earthwork site. The ACE-02 site is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

fig. S7

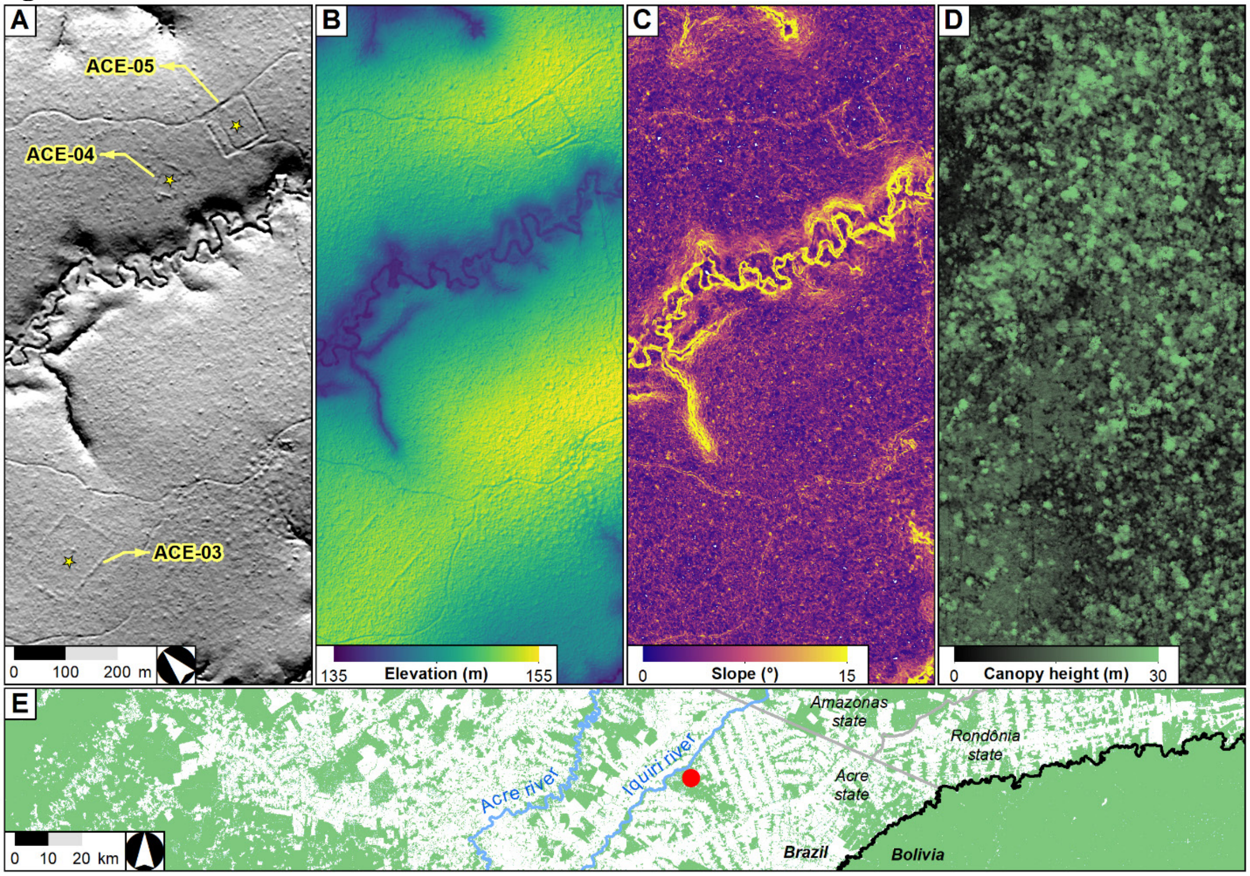

fig. S7. New earthworks discovered using LiDAR in Senador Guiomard, in Acre State, Brazil. (A) Shaded relief, showing detected earthworks. The sites are located beneath the forest canopy, next to a perennial tributary of the Iquiri River. (**B**) Elevation in meters. (**C**) Slope in degrees. (**D**) 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

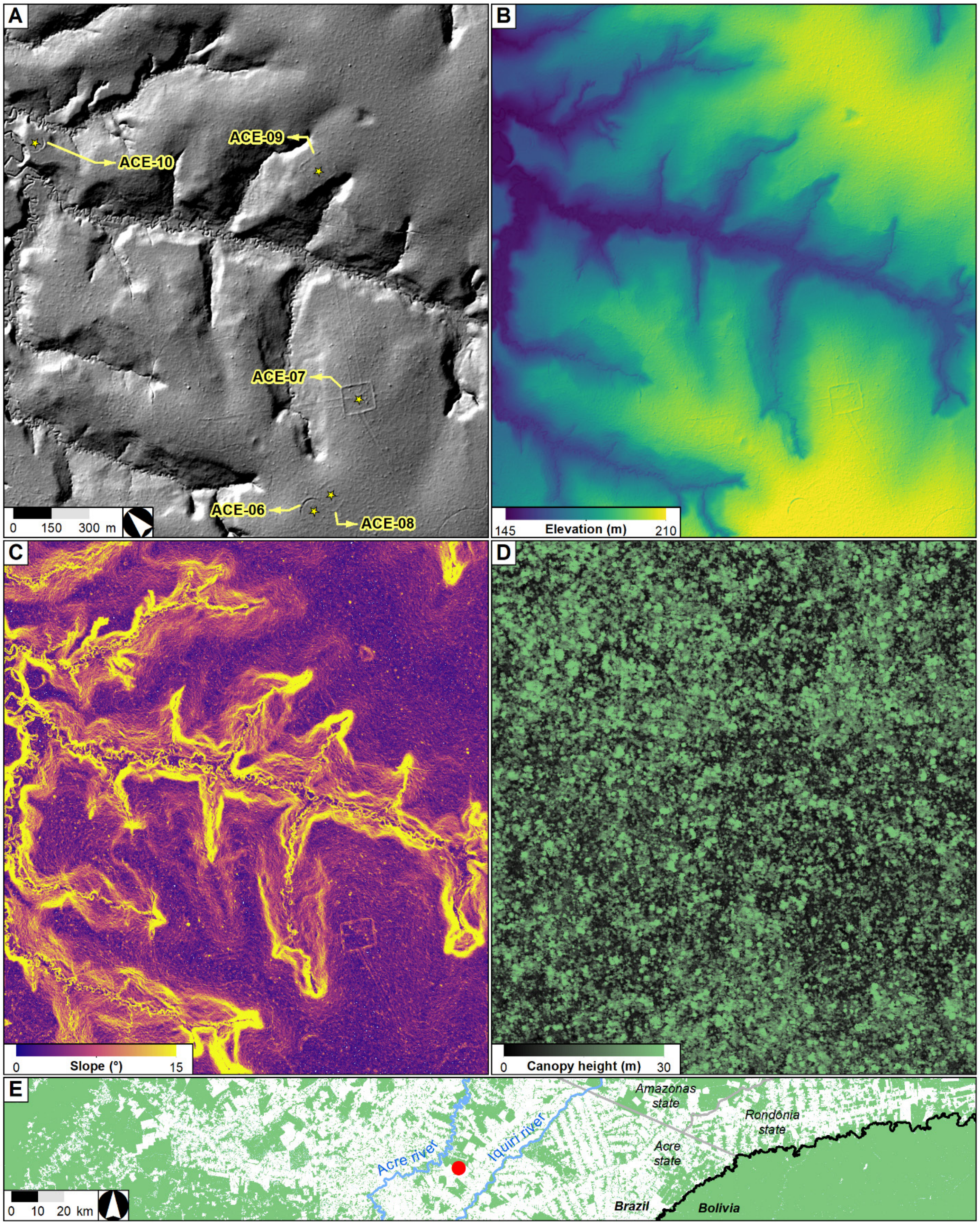

fig. S8. New earthworks discovered using LiDAR in Rio Branco, in Acre State, Brazil. (**A**) Shaded relief, showing detected earthworks. ACE-07 site has prominent road features delimited by embankments, and ACE-06 and ACE-10 have a semi-circular pattern. (**B**) Elevation in meters. (**C**) Slope in 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

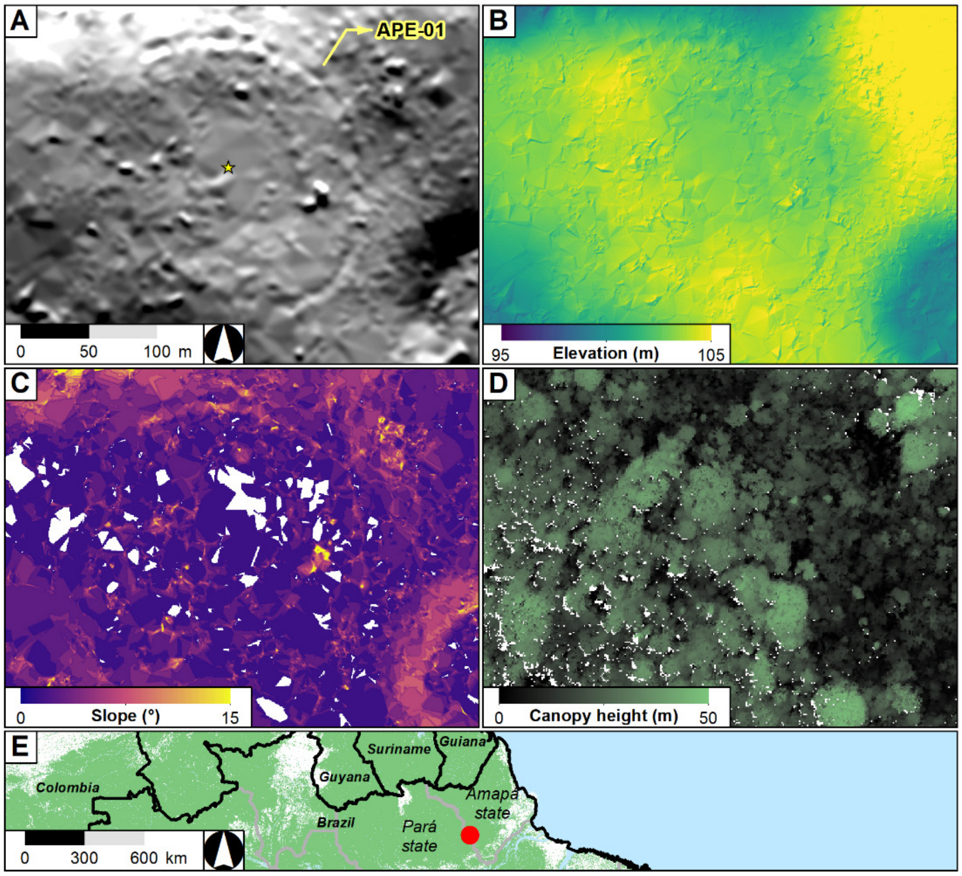

fig. S9. New earthworks discovered using LiDAR in Laranjal do Jari, in Amapá State, Brazil. (**A**) Shaded relief, showing detected earthwork. The APE-01 site is composed of a rectangular feature surrounded by a circular trench. (**B**) Elevation in meters. (**C**) Slope in degrees. (**D**) Canopy Height 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

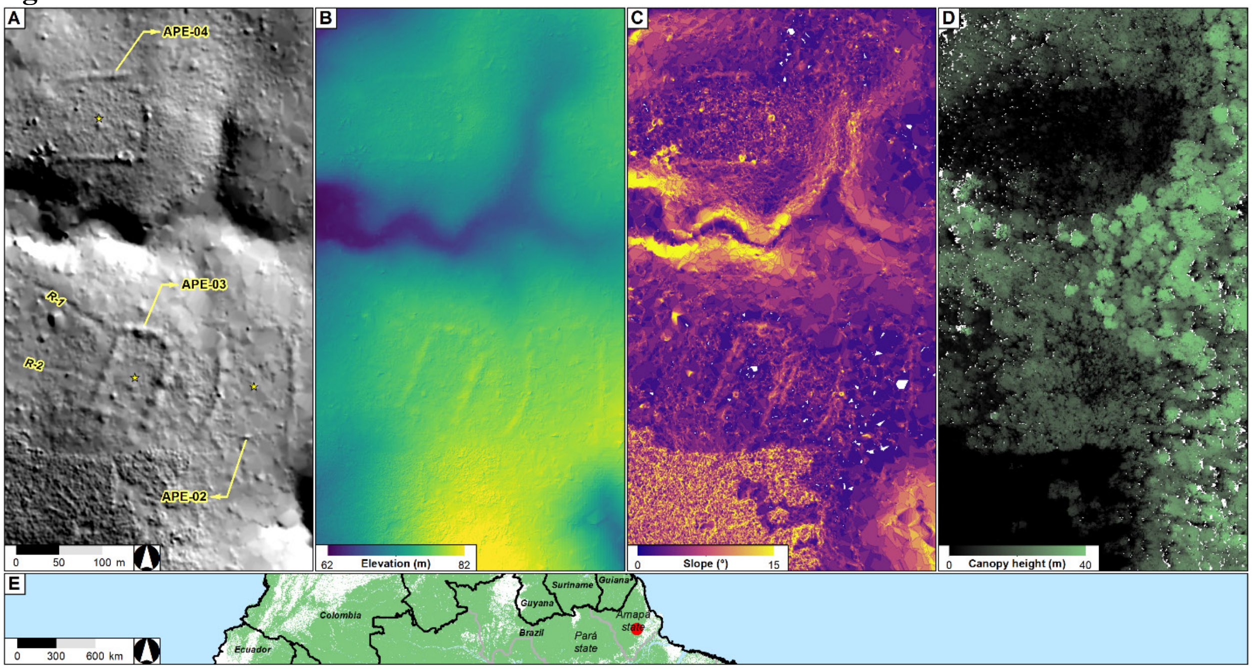

fig. S10. New earthworks discovered using LiDAR in Ferreira Gomes, in Amapá State, Brazil. (**A**) Shaded relief, showing detected earthworks and roads. (**B**) Elevation in meters. (**C**) Slope in degrees. (**D**) Canopy Height Model (CHM) in meters. The sites are surrounded by tall forests (45 m) 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

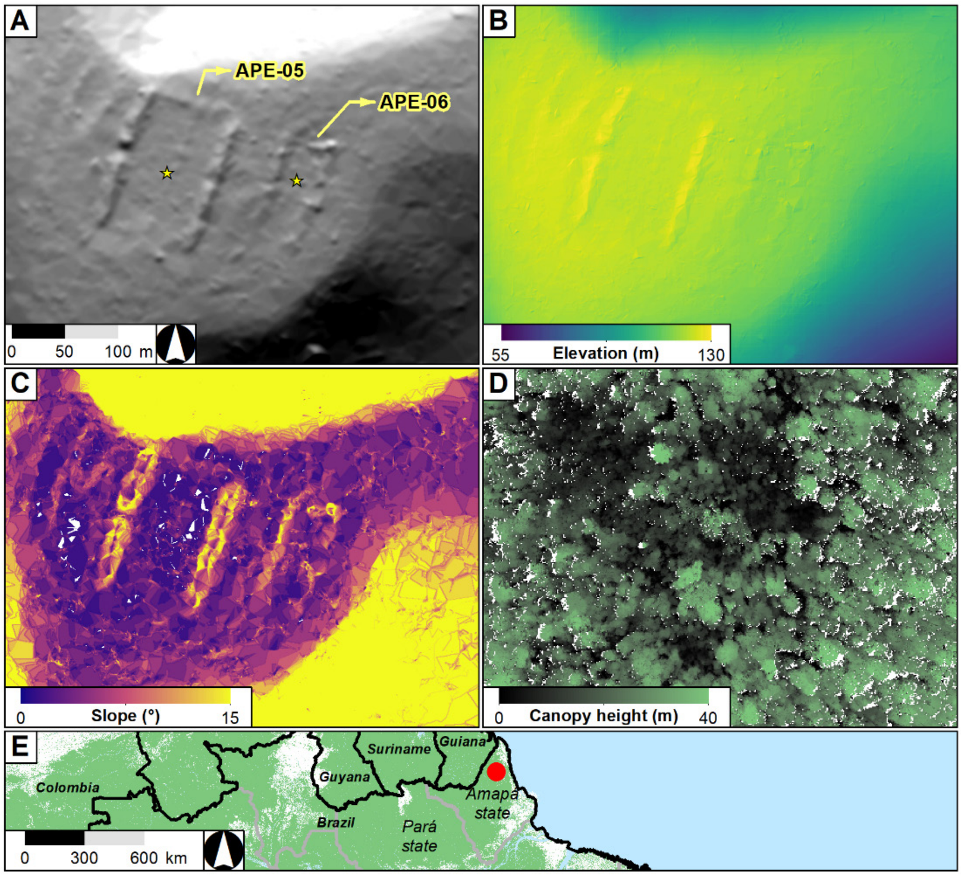

fig. S11. New earthworks discovered using LiDAR in Oiapoque, in Amapá State, Brazil. (**A**) Shaded relief, showing detected earthworks. (**B**) Elevation in meters. (**C**) Slope in degrees. (**D**) Canopy Height Model (CHM) in meters. (**E**) Location of the earthworks sites. The sites are covered 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

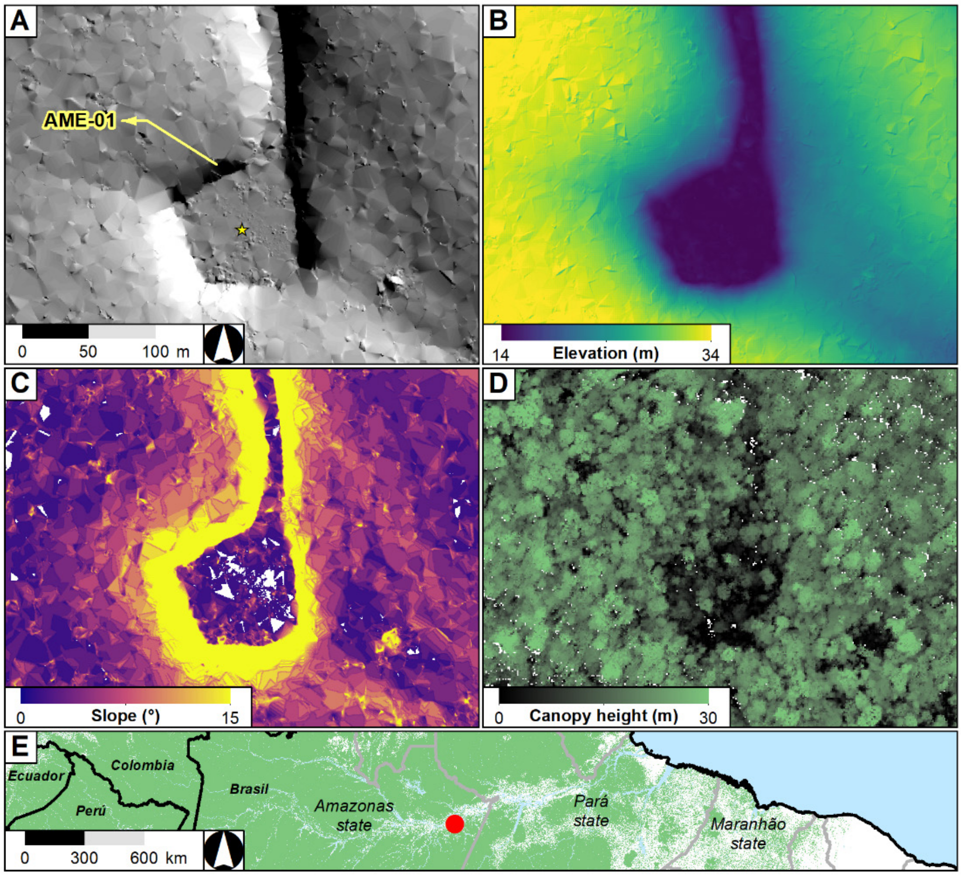

fig. S12. New earthworks discovered using LiDAR in Boa Vista do Ramos, in Amazonas State, Brazil. (**A**) Shaded relief, showing detected earthwork. The geometric-like feature from AME-01 site measures ~100 x 100 m carved 5 m into the ground maintaining a continuous plain terrain of the flooded area.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

fig. S13

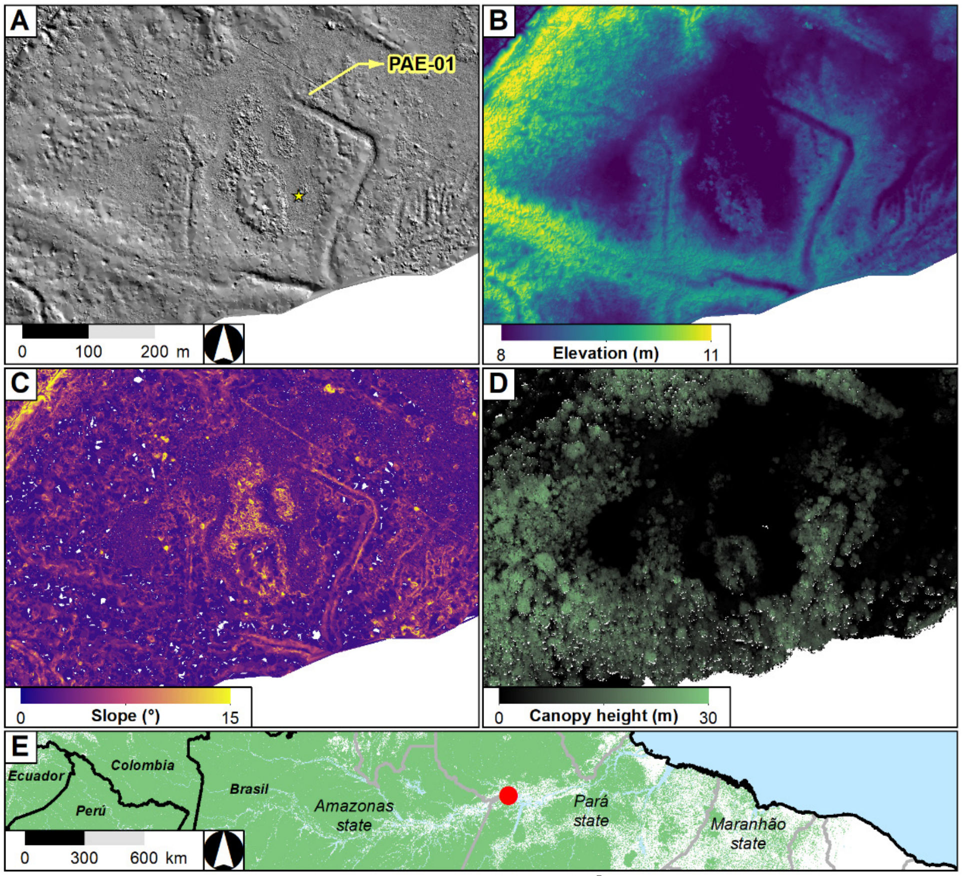

fig. S13. New earthworks discovered using LiDAR in Óbidos, in Pará State, Brazil. (**A**) Shaded relief, showing detected earthwork. It features a linear ditch (~ 0.6 m deep) with one or more 90° angle turns. (**B**) Elevation in meters. (**C**) Slope in degrees. (**D**) Canopy Height Model (CHM) in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

fig. S14

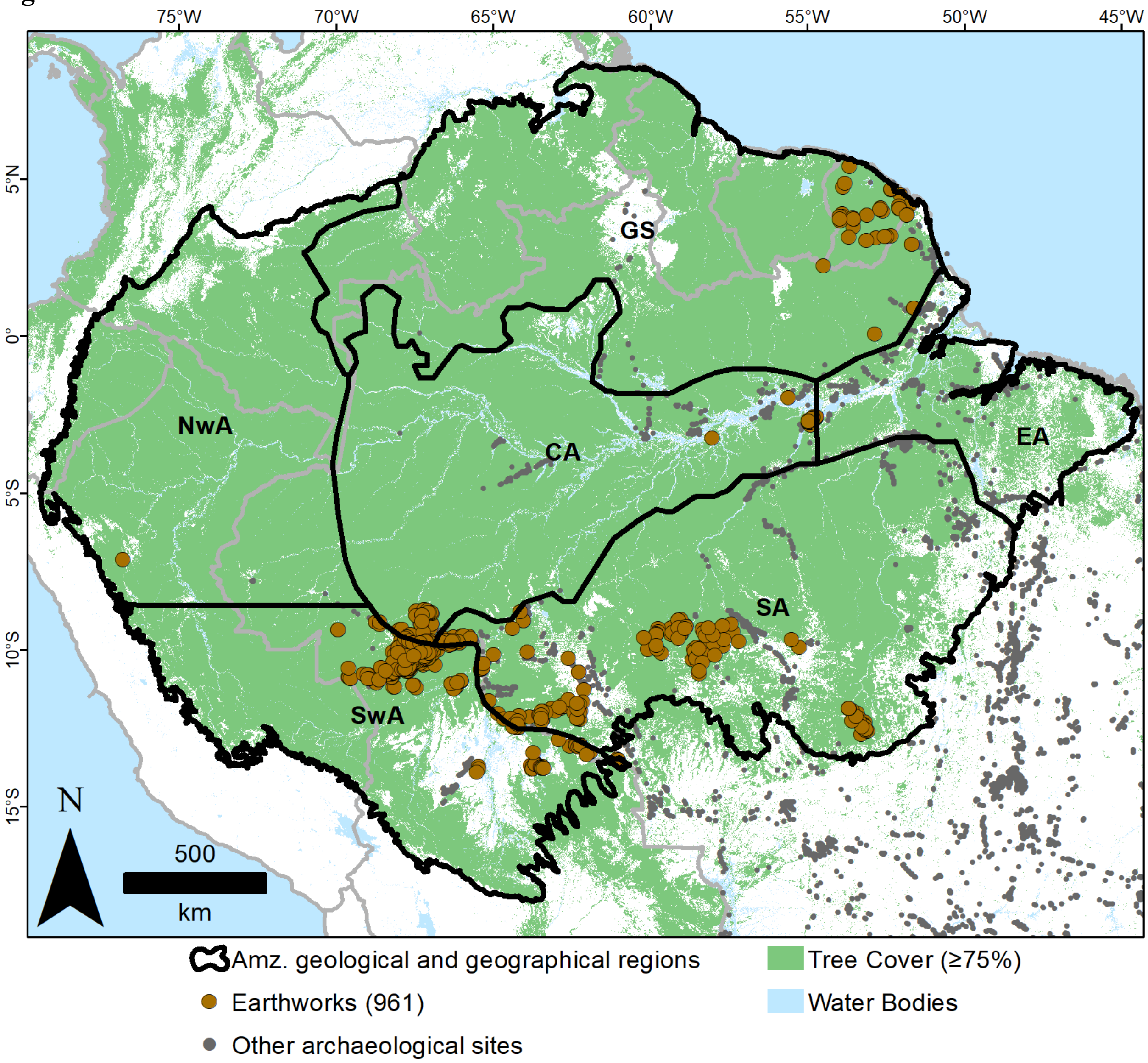

fig. S14. Spatial distribution of known earthworks across Amazonia. Map of previously reported and new earthworks discovered in this study across six Amazonian regions: Central Amazonia (CA); Eastern Amazonia (EA); Guiana Shield (GS); Northwestern Amazonia (NwA); Southern Amazonia (SA); and Southwestern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

fig. S15

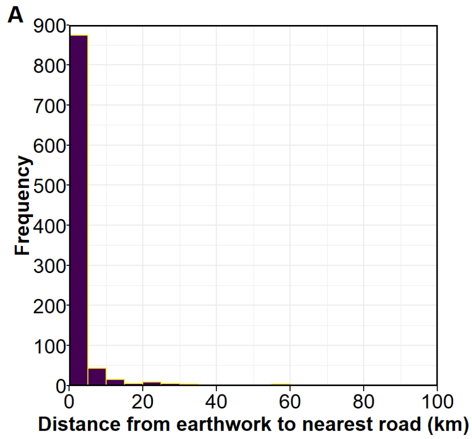

fig. S15. Histograms of observability covariates. (**A**) Distance from earthworks to nearest road. (**B**) Tree cover over earthwork. **A-B** bin width is equal to 5 units.

fig. S16

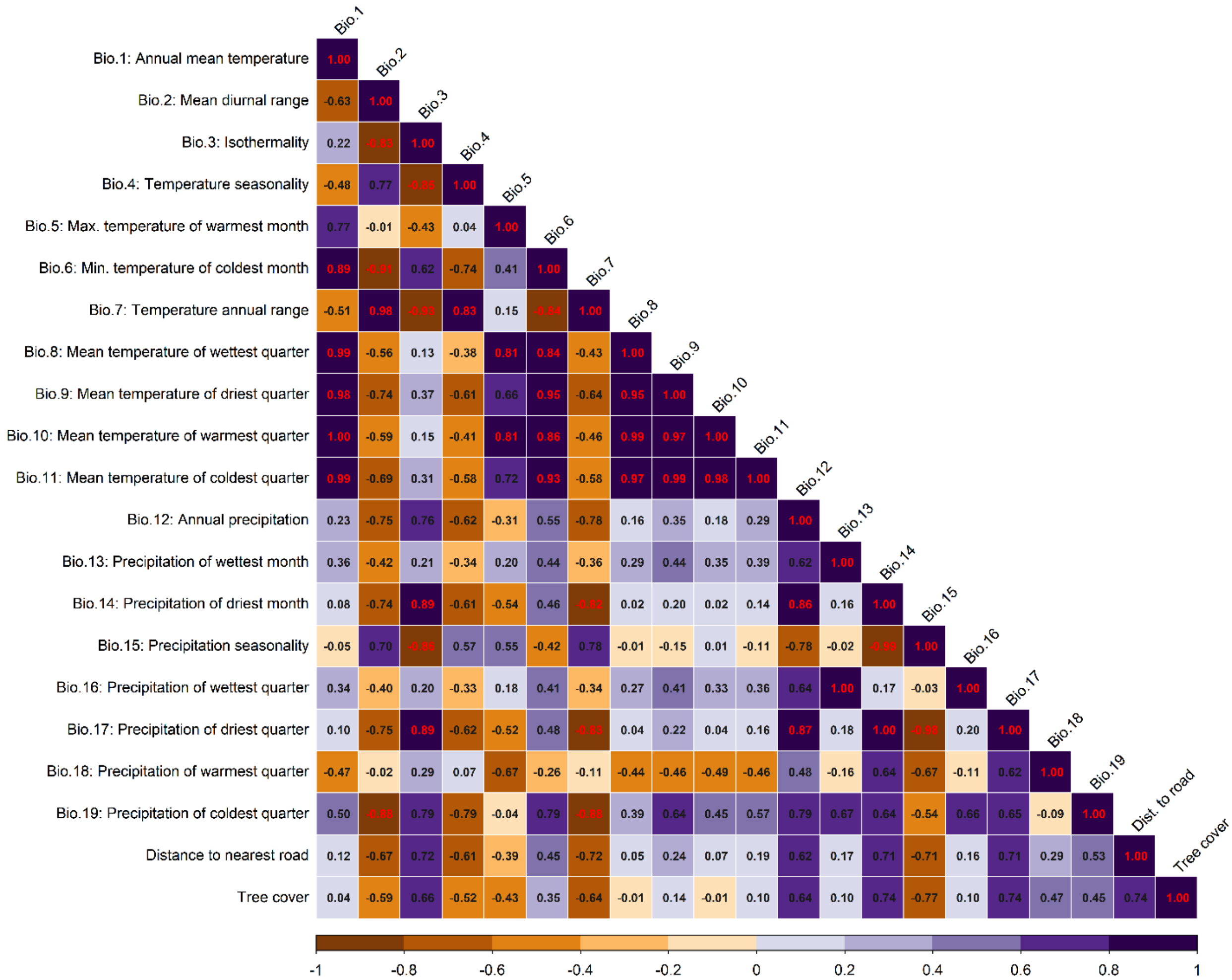

fig. S16. Pearson correlation matrix for bioclimatic variables. Values in red indicate strong correlation (> |0.8|).

fig. S17

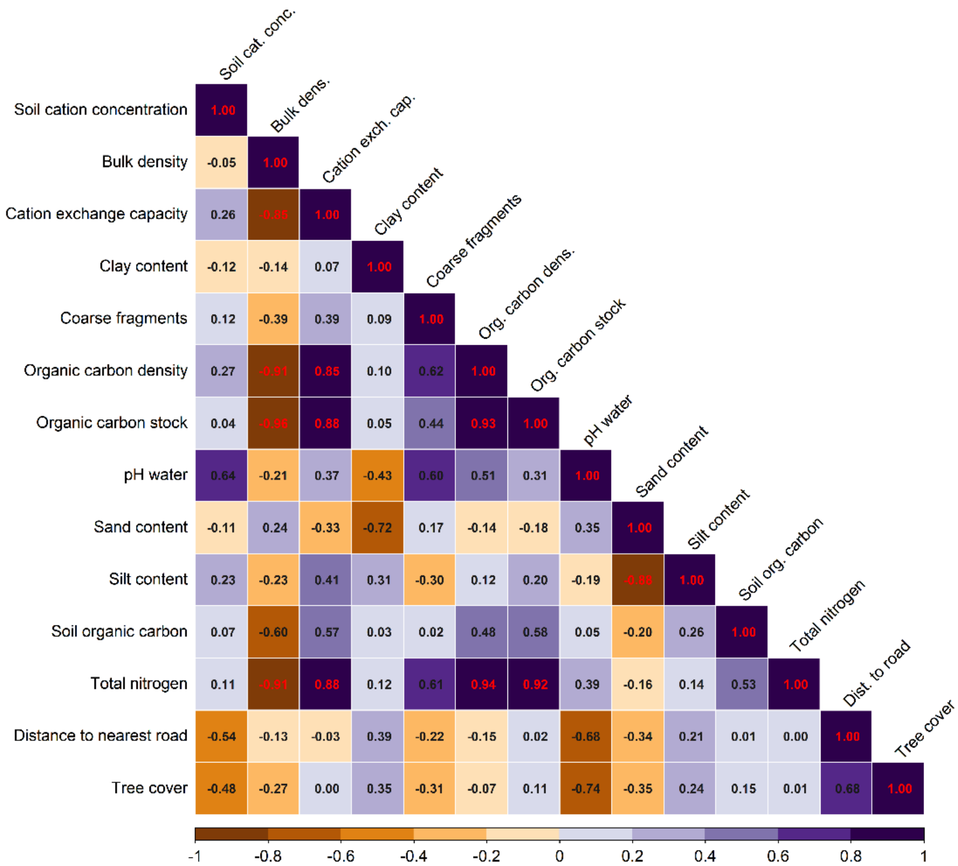

fig. S17. Pearson correlation matrix for edaphic variables. Values in red indicate strong correlation (> |0.8|).

fig. S18

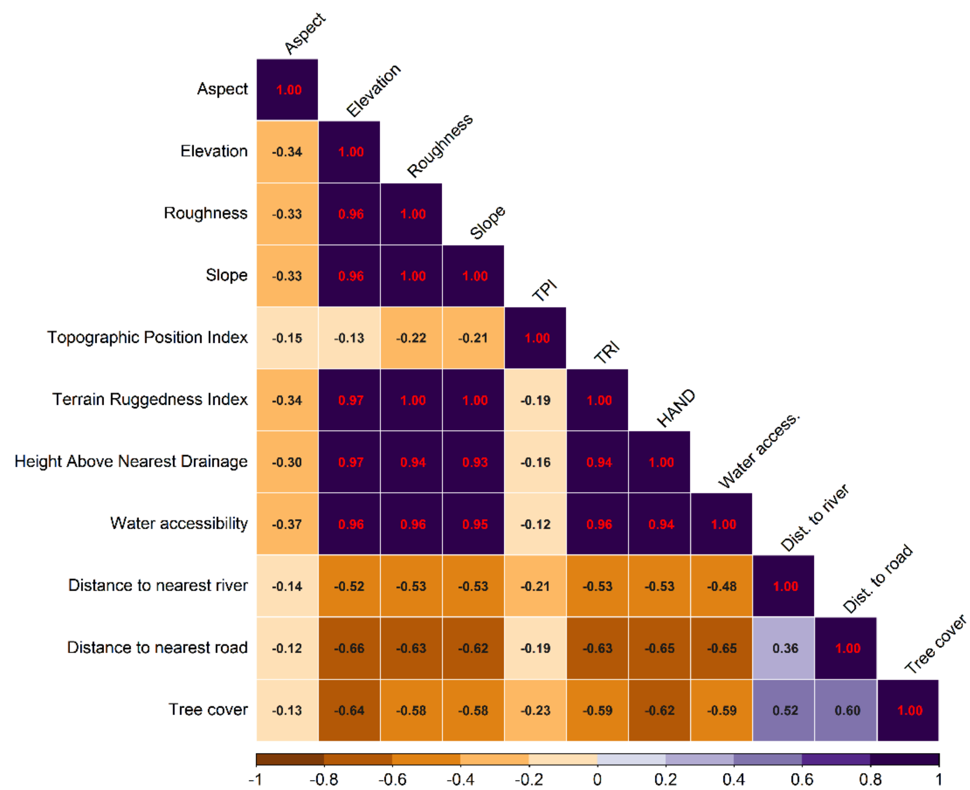

fig. S18. Pearson correlation matrix for topographic variables. Values in red indicate strong correlation (> |0.8|).

fig. S19

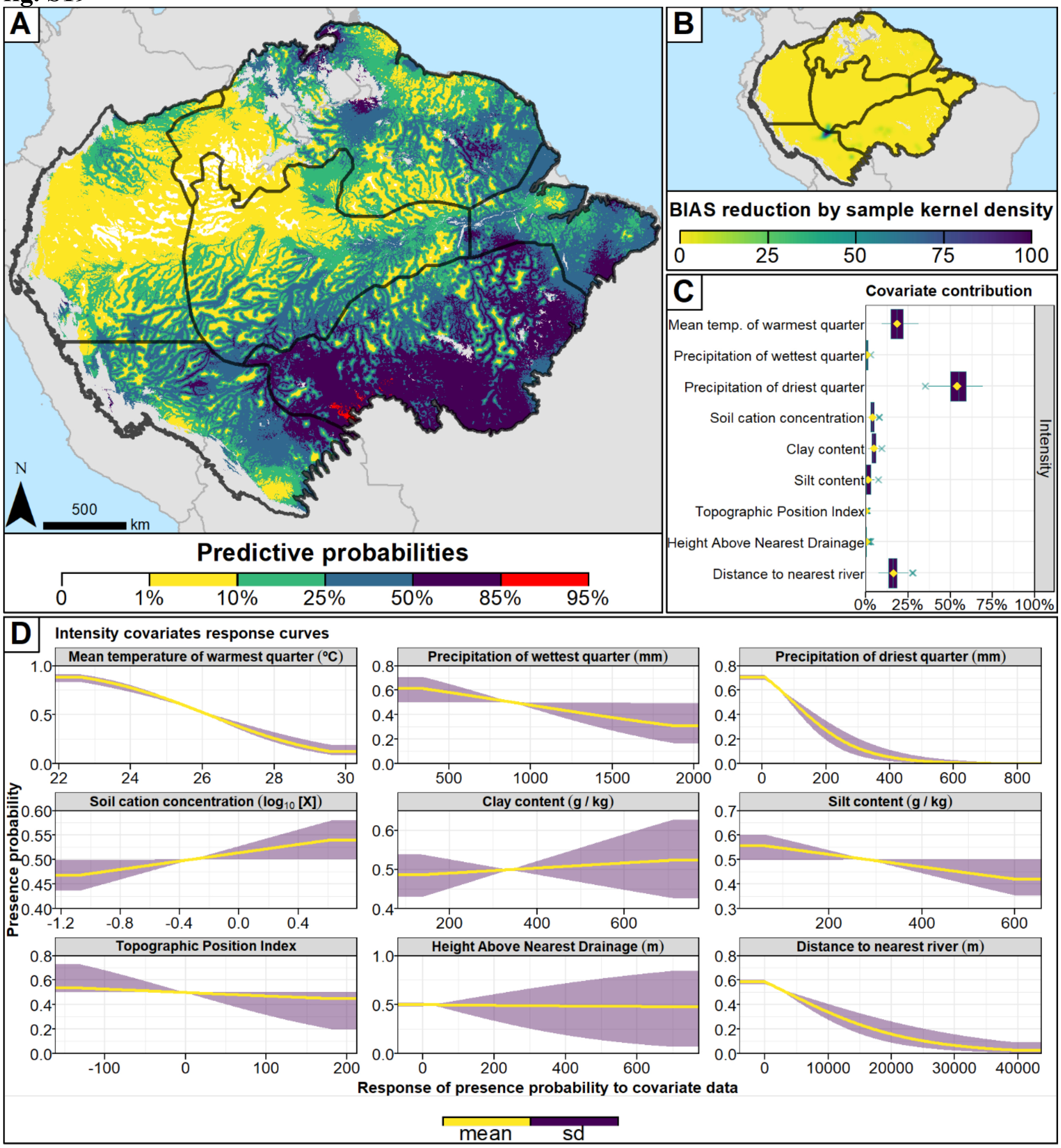

fig. S19. Maximum entropy model of pre-Columbian earthworks across Amazonia. (**A**) Predicted probability of earthwork presence for 1-km^2 pixels across six Amazonian regions. Central Amazonia (CA); Eastern Amazonia (EA); Guiana Shield (GS); Northwestern Amazonia (NwA); Southern Amazonia (SA); and Southwestern 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	Aspect (degrees)
	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 68I **	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

Description	*Tool*	*switches*	*Values by dataset* Sustainable landscapes	MSA	TREES
Tiles point cloud into a specific size	*lastile*	-tile_size	400	400	200
		-buffer	50	50	50
Flags or removes noisy points	*lasnoise*	Default settings			
Classifies LiDAR points into ground points	*lasground*	-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	*lasheight*	-classify_between	-5 / 1	-10 / 1	-5 / 1
		-classify_above	1	1	1
Flags only points with the lowest elevation inside a uniform grid	*lasthin*	-step	0.25	0.25	0.25
		-percentile	50 / 1	50 / 1	50 / 1
	lasthin	-step	0.5	0.5	0.5
		-percentile	50 / 1	50 / 1	50 / 1
	lasthin	-step	1	1	1
		-percentile	50 / 1	50 / 1	50 / 1
Classifies LiDAR points into ground points	*lasground*	-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)	*blast2dem*	-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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