

Title: Impact of pre-Columbian ‘geoglyph’ builders on Amazonian forests

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Classification: SOCIAL SCIENCES, Environmental Sciences

Keywords: Amazonian archaeology, Amazon rainforest, paleoecology, pre-Columbian land-use

Abstract:

Over 450 pre-Columbian (pre-AD1492) geometric ditched enclosures ('geoglyphs') occupy ~13,000 km² of Acre state, Brazil, representing a key discovery of Amazonian archaeology. These huge earthworks were concealed for centuries under *terra firme* (upland interfluvial) rainforest, directly challenging the 'pristine' status of this ecosystem and its perceived vulnerability to human impacts. We reconstruct the environmental context of geoglyph construction and the nature, extent and legacy of associated human impacts. We show that bamboo forest dominated the region for ≥ 6000 y and that only small, temporary clearings were made to build the geoglyphs; however, construction occurred within anthropogenic forest that had been actively managed for millennia. In the absence of widespread deforestation, exploitation of forest products shaped a largely forested landscape that survived intact until the late 20th century.

Significance statement:

Amazonian rainforests once thought to be pristine wildernesses are increasingly known to have been inhabited by large populations before European Contact. How and to what extent these societies impacted their landscape through deforestation and forest management is still controversial, particularly in the vast interfluvial uplands which have been little studied. In Brazil, the ground-breaking discovery of hundreds of geometric earthworks by modern deforestation would seem to imply that this region was also deforested to a large extent in the past, challenging the apparent vulnerability of Amazonian forests to human land-use. We reconstructed environmental evidence from the geoglyph region and found that earthworks were built within man-made forests that had been previously managed for millennia. In contrast, long-term, regional-scale deforestation is strictly a modern phenomenon.

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Main text:

The notion of Amazonia as a pristine wilderness has now been overturned by increasing evidence for large, diverse and socially complex pre-Columbian societies in many regions of the basin. The discovery of numerous, vast *terra preta* (Anthropogenic Dark Earth) sites bordering the floodplains of major rivers, and extensive earthwork complexes in the seasonally-flooded savannas of the Llanos de Mojos (NE Bolivia), Marajó Island (NE Brazil) and coastal French Guiana, are seen to represent examples of major human impacts carried out in these environments (1–10).

However, major disagreement still resides in whether interfluvial forests, which represent over 90% of Amazonian ecosystems, were settings of limited, temporary human impacts (11–13), or were instead extensively transformed by humans over the course of millennia (14–16). A paucity of paleoecological studies conducted in interfluvial areas has been responsible for the polarisation of this debate, which encompasses different hypothetical estimates of pre-Contact population size and carrying capacity in the interfluves (17), and the relative importance of different land-use strategies in the past. The extent of ancient forest burning is particularly contested, since some have proposed that pre-Columbian deforestation was on a large enough scale to have influenced the carbon cycle and global climate (18, 19), while others argue that large-scale slash-and-burn agriculture is a largely post-Contact phenomenon (20). Modern indigenous groups often subject slash-and-burn plots for crop cultivation to long fallow periods, during which useful plants, including many tree species, continue to be encouraged and managed in different stages of succession within a mosaic-type landscape (21, 22). Also known as ‘agroforestry’, this type of land-use is thought to have been common in pre-Columbian times, but its detection in the paleoecological record is often problematic (15) and

studies based on modern distributions of useful species lack demonstrable time-depth of forest modifications (23). Terrestrial paleoecology programmes are essential for a better understanding of these issues, which have strong implications for the resilience of Amazonian forests to human impact and, subsequently, their future conservation (24–26).

With ditches up to 11 m wide, 4 m deep and 100–300 m in diameter, and with some sites having up to six enclosures, the geoglyphs of western Amazonia rival the most impressive examples of pre-Columbian monumental architecture anywhere in the Americas (27). Excavations of the geoglyphs have shown that they were built and used sporadically as ceremonial and public gathering sites between 2000 and 650 calibrated years before present (BP), but that some may have been constructed as early as 3500–3000 BP (28–30). Evidence for their ceremonial function is based on an almost complete absence of cultural material found within the enclosed areas, which suggests they were kept ritually ‘clean’, alongside their highly formalized architectural forms (mainly circles and squares) – features that distinguish the geoglyphs from similar ditched enclosures in northeast Bolivia (5, 31). Surprisingly, little is known about who the geoglyph builders were and how and where they lived, as contemporary settlement sites have not yet been found in the region. It is thought that the geoglyph builders were a complex network of local, relatively autonomous groups connected by a shared and highly developed ideological system (32). Although some have proposed a connection between the geoglyphs and Arawak-speaking societies (33), the ceramics uncovered from these sites defy a close connection with Saladoid-Barrancoid styles normally associated with this language family, and instead present a complex mixture of distinct local traditions (34). Furthermore, it is likely that the geoglyphs were used and reused by different culture groups throughout their life spans (29).

As archaeological evidence points to interfluvial populations in Acre on such an impressive scale, understanding the nature and extent of the landscape transformations that they carried out is vital to how we perceive Amazonian forests in the present and conserve them in the future. Crucially, if the region's forests were intensively cleared for geoglyph construction and use, this might imply that *terra firme* forests are more resilient to human impacts than previously thought.

Paleolimnology is unsuited to tackle these questions. Most geoglyphs are situated away from lakes, which generally occupy abandoned river channels too young to capture the full temporal span of pre-Columbian occupation. Instead, we applied phytolith, charcoal and stable carbon-isotope analyses to radiocarbon-dated soil profiles at two excavated and dated geoglyph sites: Jaco Sá (JS) (9°57'38.96"S, 67°29'51.39"W) and Fazenda Colorada (FC) (9°52'35.53"S, 67°32'4.59"W) (Fig. 1; *SI Text, Site descriptions*) to reconstruct vegetation and land use before, during and after geoglyph construction (*SI Text, Terrestrial paleoecology methods*).

We aimed to answer the following questions: (i) What was the regional vegetation when the geoglyphs were constructed? Today, the region is dominated by bamboo (*Guadua* sp.) forests (Fig. 1B), which cover roughly 161,500 km² of southwest Amazonia (35). Was bamboo forest also dominant before the geoglyphs, as some have suggested (36–38)? Or did people exploit and maintain a more open landscape afforded by dryer climatic conditions of the mid-Holocene (8000–4000 BP) (39), as recently found to be the case for pre-Columbian earthworks < 1000 y old in the forest-savanna ecotone of northeast Bolivia (26, 40)?; (ii) What was the extent of environmental impact associated with geoglyph construction? If the study area was forested, was clearance effected on a local (i.e. site-level) or regional (i.e. > several km) scale, and how long were openings maintained?; (iii) How was the landscape transformed for subsistence

purposes (e.g. through burning or agroforestry)? (iv) What happened to the vegetation once the geoglyphs were abandoned? Did previously cleared areas undergo forest regeneration?

Study area:

The study area is characterized by seasonal precipitation (average, 1,944 mm/y), the majority of which falls between October and April (41). The eastern part of the state where the geoglyphs are located can experience severe drought during its 4- 5-mo dry season and has been subject to several recent wildfires, partly exacerbated by the loss of roughly 50% of the region's forest to cattle ranching since the 1970s (42). The local vegetation is dominated by bamboo forest with patches of palm forest, grading into dense humid evergreen forest closer to the southern border with Bolivia (43) (Fig. 1A). Soils of the region are sandy clay Acrisols; a relatively fertile type of Ultisol that still has low agricultural potential (44). More fertile alluvial soils are found only along the region's three major rivers – the Purus, Juruá and Acre.

Typical of most geoglyphs, JS and FC are situated on topographical highpoints (191 and 196 m above sea level.), within a landscape of gently rolling hills belonging to the Solimões geological Formation. We excavated five soil profiles (JS1–JS5) along a linear transect starting at the centre of the JS geoglyph (JS1) and at distances of 0.5, 1.5, 3.5 and 7.5 km (JS5) away from the site (Fig. 1C). This sample design allowed quantification of the spatial scale of environmental impact associated with geoglyph construction and use, ranging from highly localized (< 0.5-km radius) to regional (> 7.5-km radius). An additional soil profile was placed inside the FC geoglyph, situated 10 km away from JS, to compare the context of earthwork construction at that site. All of the soil profiles were located within pasture dominated by non-native grasses and palm trees (mostly *Attalea* sp., *Mauritia flexuosa* and *Euterpe precatoria*), except for JS4, which lay within bamboo forest.

Results and discussion:

Exploiting bamboo forest

Basal dates from the soil profiles range from 6500 BP (JS5) to 4500 BP (JS3) (*SI Table 1*). Phytolith assemblages dominated by bamboo bulliform phytoliths in the sand fraction (*SI Methods*) and >15% bamboo short cells in the silt fraction (Fig. 2; *SI Methods, Phytolith analysis*), demonstrate that the bamboo forest ecosystem that exists in the region today was present throughout the past ~6,000 y. These data compelling empirical evidence that the dominance of bamboo in this region is not a legacy of pre-Columbian human impact but is instead a natural phenomenon reflecting the distinctive climate and topography of the region. They also demonstrate the resilience of this forest ecosystem to the drier-than-present climatic conditions of the mid-Holocene (~6000 BP), a period exemplified by a major lowstand of Lake Titicaca (45) and a shift from forest to savanna in northeast Bolivia and neighbouring Rondônia state, Brazil (46–48) (Fig. 1A: a, b, c).

The phytolith assemblages continue to record bamboo forest in the late Holocene (after ~4000 BP), during which increases in smaller (125–250 μm) charcoal particles demonstrate intensification of forest clearance and/or management by humans. Wetter-than-previous climatic conditions characterized the late Holocene (39), which would have made the vegetation less naturally-flammable, while archaeological dates attest to people in the landscape from at least 4400 BP (28); thus we can be confident that fire activity in these levels was human – rather than naturally – driven. It is likely that these cultures took advantage of the bamboo life-cycle to facilitate deforestation (36), as *Guadua* bamboo undergoes periodic mass die-offs every 27–28 y across areas averaging 330 km² (35). The resulting dead vegetation is

flammable in the dry season, which favours clearance using fire, rather than laborious tree felling with stone axes. The recovery of maize (*Zea mays*) and squash (*Cucurbita* sp.) phytoliths at the Tequinho and JK geoglyph sites (49) (*SI Text, JK phytoliths*) suggests that clearance was related to agricultural practices, as well as the creation of dwelling spaces.

Geoglyph construction

Surprisingly, despite the relative ease with which bamboo forest could be cleared, we found no evidence that sizeable clearings were created for any significant length of time (i.e. over multidecadal to centennial timescales) for geoglyph construction and use. Charcoal peaks at FC1 (45-50 cm) and JS1 (30-35 cm), with 2σ date ranges (respectively, 1385-1530 BP from charcoal and 2158-2333 BP from associated soil humin) that agree with archaeological dates for site construction, represent initial earthwork building at both locations; however, true grass (nonbamboo) phytoliths remain below 10%, as opposed to ~40–60%, which would be expected if open, herbaceous vegetation was subsequently maintained (50). Furthermore, $\delta^{13}\text{C}$ values of soil organic matter (SOM) at JS1 (30–25 cm) remain between -23‰ and -24‰, attesting to the persistence of predominantly C3 (closed-canopy) vegetation during this time. Given that peak values of 20% for grass phytoliths and -19.7‰ for $\delta^{13}\text{C}$ in surface samples (0–5 cm) represent 40-y post-deforestation, we deduce that the vegetation was never kept completely open for this length of time in the pre-Columbian era. This finding is consistent with archaeological evidence that the geoglyphs were used on a sporadic basis rather than continually inhabited (28, 29). Furthermore, the absence of a charcoal peak or abrupt vegetation change 500 m away (JS2) implies that forest clearance for geoglyph construction was highly localized. This suggests that the geoglyphs were not designed for inter-visibility, but were instead hidden from view: an unexpected conclusion.

Rather than being built within largely ‘untouched’ bamboo forest, our phytolith data suggest that the geoglyphs were constructed within anthropogenic forests that had already been fundamentally altered by human activities over thousands of years. At FC1 and JS1, pregeoglyph forest clearance events dated to ~3600 and ~4000 BP, respectively, were followed by remarkably consistent increases in palm taxa (+28% at FC1, +30% at JS1) that continued for ~3000 y, throughout the period of construction and use of the geoglyph sites. The same trend is observed at JS2 (+25%) after a small charcoal peak contemporary to that at JS1 (~4000 BP), whereas a rise in palm abundance (+8%) at JS4 also follows increased fire activity (~2600 BP), although the pattern is less pronounced than in the other three profiles.

No natural explanation exists for this increase in palms, because a wetter late Holocene climate (45) would have discouraged their colonisation as the canopy became denser. Instead, palm increase correlates with an overall increase in human land use, documented by the charcoal data. Preliminary data gathered in 2011 from a soil profile within the JK geoglyph (*SI Text, JK; phytoliths*; Fig. S1) further documented up to 90% palm phytoliths at 30-cm depth, suggesting that many of Acre’s geoglyphs were constructed within similar palm-rich forests. Because >450 geoglyph sites have been discovered in eastern Acre, this implies anthropogenic forest transformation over a large area of the interfluvial uplands.

The long-term concentration of palm species in the past was likely both intentional and unintentional, given their high economic importance for food and construction material (51, 52) and the very long timescales over which they appear to have proliferated. We suggest a positive feedback mechanism for this trend, whereby pre-Columbian groups initially cleared and occupied these locations and manipulated forest composition (marked by the first charcoal

peaks), and the subsequent concentration of useful species later attracted other groups to the same locations, who in turn encouraged them further.

Legacies of anthropogenic forests

What happened once the geoglyphs were abandoned ~650 BP? Towards the top of the profiles, a sudden decrease in palm taxa [between -15% (JS4) and -25% (JS1)] occurs at all four locations where they have proliferated. Dated charcoal from these levels gave erroneous dates at FC1 and JS1 (*SI Text, Age Inversions*); however, concordant dates from JS2 and JS4 (~600–670 BP) associate the beginning of the palm decline with the period of geoglyph abandonment, suggesting a link between these two phenomena.

Such a scenario finds support in studies of forest succession. In the Amazonian *terra firme*, palms are often the first trees to colonize forest clearings after herbs and lianas (53), but are eventually out-competed by slower-growing trees (54). If humans stopped maintaining this artificial succession stage, palm communities would eventually be replaced by other species. The sudden resurgence of palms observed in the 0–5 cm horizons is explicable by the same mechanism, as modern deforestation has favoured their colonisation by creating completely open landscapes.

Instead of reverting back to a more ‘natural’ state, however, other evidence suggests that the species that out-competed palms after geoglyph abandonment were already managed alongside them. A botanical inventory of a residual forest patch adjacent to the JS2 profile found that 9 out of 10 of its most abundant species are of current socio-economic importance (*SI Methods, JS2 forest patch methods*; Table S2). However, several of these species do not produce diagnostic phytoliths [e.g. *Bertholettia excelsa* (Brazil nut)], or produce them rarely (e.g.

Tetragastris altissima). Furthermore, in a principal-components analysis, average surface-soil phytolith assemblages from this forest patch plotted close to phytolith sample 20–25 cm in the JS2 profile (Fig. S2), immediately below the peak in palm phytoliths, implying that legacies of pre-Columbian agroforestry still exist today within Acre’s remaining forests.

Implications:

In contrast to studies that argue for either minimal (11, 12) or widespread (15, 16) pre-Columbian impact on the Amazonian interfluves, we suggest that in Acre, geoglyph construction was not associated with deforestation over large spatial and temporal scales but instead with a long tradition of agroforestry and resource management which altered the composition of native bamboo forest over millennia.

Our findings challenge the hypothesis that reforestation after the Columbian Encounter led to a sequestration of CO₂ that triggered the Little Ice Age global cooling event (18, 19). This hypothesis was formerly criticized in light of findings that many earthworks in northeast Bolivia were constructed in non-forested landscapes (26), but our data indicate that even in an archaeologically rich area that remained forested during the mid- to late-Holocene, pre-Columbian deforestation was on a more localized scale than previously thought. Despite the number and density of geoglyphs, we did not find any pre-Columbian parallel for the length and extent of modern-day forest clearance in Acre.

Our data also raise a methodological concern crucial to the interpretation of terrestrial paleoecological data—namely, that low soil charcoal frequencies do not necessarily correlate with sparse pre-Columbian populations in Amazonia (11). There is little question that the geoglyphs are a product of sizeable, socially-complex societies that once inhabited the region (27, 32), so the absence of evidence of large-scale deforestation in our soil profiles casts doubt

over whether quantification of forest burning should play such a central role in delimiting areas of high vs. low populations, and minimal vs. widespread environmental impacts associated with them.

In contrast, our study has provided empirical, paleoecological evidence for the importance of forest management practices in the pre-Columbian interfluves. The proliferation of palms and other useful species over apparently millennial timescales suggests a long history of forest manipulation before the JS and FC geoglyphs were even constructed, consistent with some arguments that long-term accumulations of small-scale disturbances can fundamentally alter species composition (15, 16).

We did not detect anthropogenic forest in all profile locations, but recognize that formations not rich in palms are currently very difficult to detect in the phytolith record. This point is made clear by the species and phytolith data from the JS2 forest plot, which hint at the other species which were favoured by pre-Columbian populations (e.g. Brazil nut) that do not produce diagnostic phytoliths.

We have shown that at least some of Acre's surviving forest owes its composition to sustainable pre-Columbian forest management practices that, combined with short-term, localized deforestation, maintained a largely forested landscape until the mid-20th century. The lack of a pre-Columbian analog for extensive modern deforestation means that we should not assume forest resilience to this type of land use, nor its recovery in the future.

Methods:

Soil profiles were dug to 1.5-m depth and sampled in 5-cm increments for paleoecological analyses. Chronologies were based upon four accelerator mass spectrometry (AMS) dates per soil profile, the majority being determined on bulk macroscopic ($>125\ \mu\text{m}$) charcoal (19 samples), and the remainder on soil humin (6 samples) (Table S1). Due to the occurrence of age inversions, the integrity of the proxy data were assessed based on inter-profile replicability of observed patterns (e.g. increases in palm phytoliths) and obtained dates consistent with geoglyph chronologies (*SI Text, Age Inversions*). Phytoliths were extracted every 5 cm in levels pertaining to geoglyph use and every 10 cm thereafter, following the wet oxidation method (55). Two hundred morphotypes were identified per soil sample, and taxa were identified using published atlases and the University of Exeter phytolith reference collection. Paleoecological phytolith assemblages were compared with assemblages from surface soils of modern forests in the region (56). Charcoal was extracted using a macroscopic sieving method (57) and divided into size classes to distinguish local ($> 250\ \mu\text{m}$) from extra-local (125–250 μm) burning signals. Stable carbon isotope analysis of SOM was conducted at JS1 (every 10 cm) and JS3 (every 10 cm, then every 20 cm below 0.4 m below surface) using standard procedures (58). Detailed information for the methodologies used in this study is provided in SI Methods.

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Acknowledgements:

Funding for this research was granted by the UK Arts and Humanities Research Council (AH/J500173/1) (J.W), NERC (NE/B501504) (NJL), NERC/OxCal Radiocarbon Fund (2013/2/8) (J.W/J.I) and National Geographic Society and Exploration Europe (GEFNE14-11) (F.M/J.I). We thank B. Whitney, M. Arroyo-Kalin, Y. Maezumi, M. Power, J. Carson and T.

Hermenegildo for their insights during the course of the project, J. Gregorio de Souza for creating Fig.1, and F. Braga for fieldwork support.

FIGURES

Fig. 1: Location maps. (A) Location of eastern Acre (inset) and palaeoecological studies which document a savanna-rainforest transition in the mid-Holocene: (a) Soil profiles between Porto Velho and Humaitá (stable carbon isotopes), (b) Lagunas Orícore and Granja (pollen), (c) Lagunas Bella Vista and Chaplin (pollen). (B) Geoglyph distributions in relation to modern vegetation and location of FC and JS sites (inset). (C) Locations of soil profiles in this study. From the JS geoglyph (0 km), profile distances along the transect are: JS2 = 0.5 km, JS3 = 1.5 km, JS4 = 3.5 km, JS5 = 7.5 km). (D) and (E) Aerial photos of the FC (D) and JS (E) geoglyphs. Black arrows show the locations of profiles FC1 and JS1.

Fig. 2: Percentage phytolith frequencies, charcoal concentrations, $\delta^{13}\text{C}$ values (expressed in ‰) and mid-range ^{14}C dates (cal yr. BP, 2σ accuracy) by depth for the six soil profiles. Shaded yellow bars delimit levels pertaining to geoglyph use. Geoglyph construction is represented at FC1 (45–50 cm) and JS1 (30–35 cm) by dates that are in rough agreement with archaeological dates for these events (FC: 1925–1608 BP, JS: 1220–985 or 1405–1300 BP). The abandonment of the geoglyph landscape (dated archaeologically to ~706–572 BP) is represented by ^{14}C dates for palm phytolith decline at JS2 and JS4 (10–15 cm), which can be extrapolated to FC1 and JS1 where this phenomenon also occurred, but where the intrusion of older charcoal hindered direct dating of these events (see *SI Text* and *SI Methods* for more information).

Figure 1

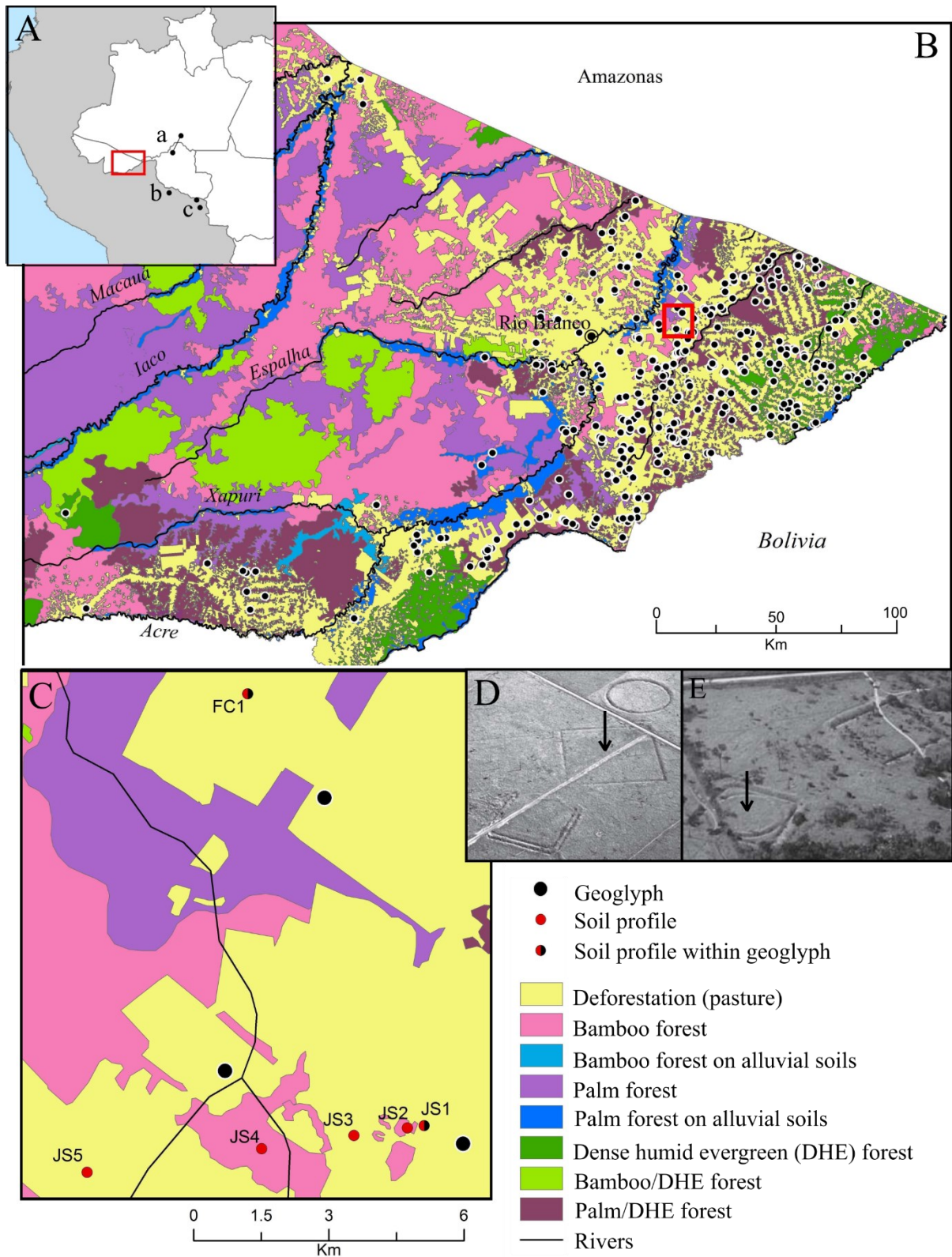
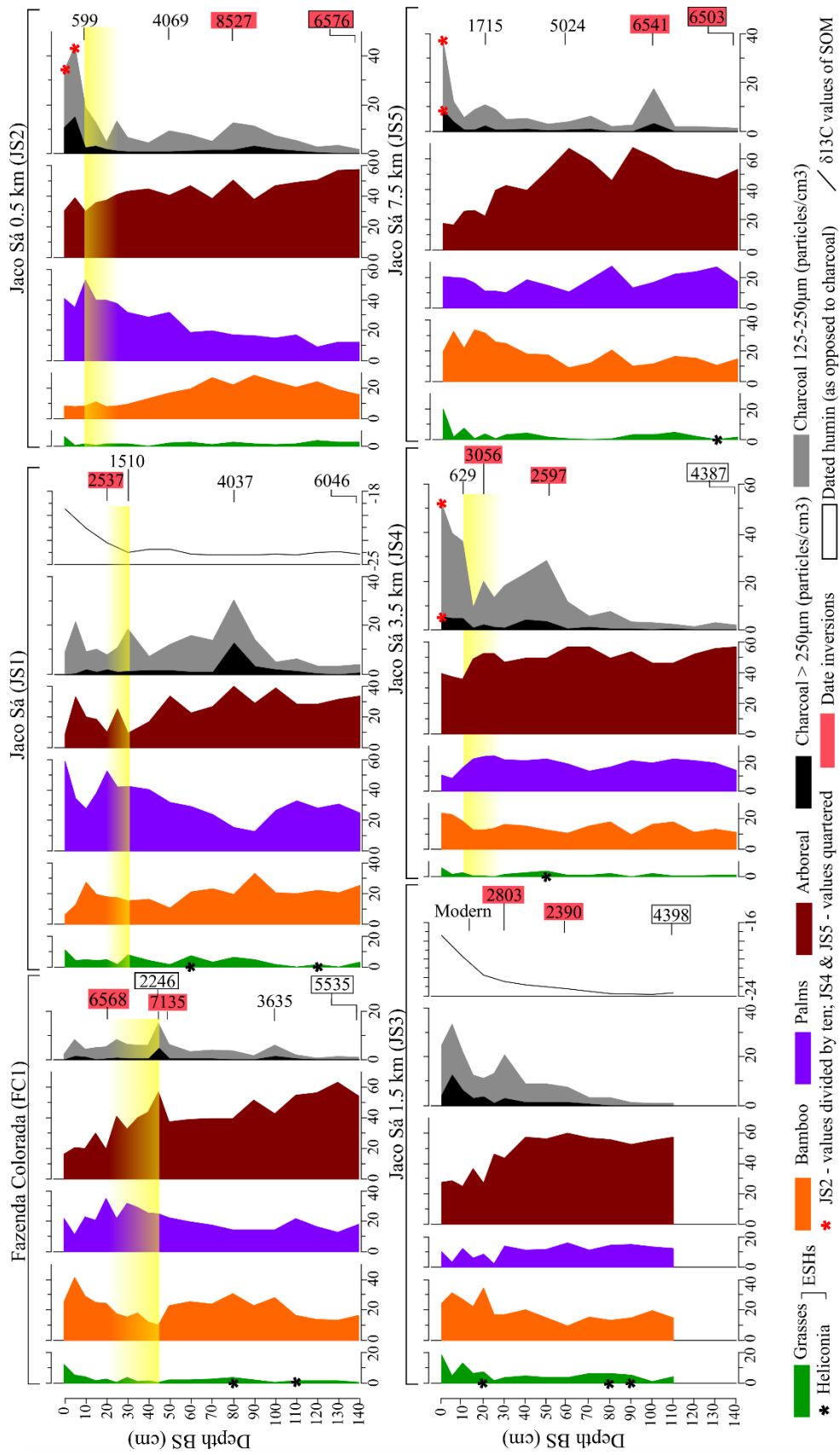


Figure 2



SUPPLEMENTARY INFORMATION TEXT

Site descriptions:

Fazenda Colorada consists of three earthworks: a circle, a square and a double U-shape. The U-shape encloses several small mounds and a trapezoidal enclosure, from which a road emanates and disappears into the terrain after 600 m. Radiocarbon dates from the site place its construction and use between 1925–1608 BP and 1275–1081 BP. Dating of one of the mounds inside the U-shape revealed that that this structure belongs to a later occupation, dated to 706–572 BP. This date represents the most recent cultural activity so far associated with the geoglyph culture (29).

Jaco Sá consists of a square earthwork, a circle within a square and a rectangular embankment between the two. Artefact recovery during excavation was minimal and restricted to the ditch structures. Dates from the external embankment of the square/circle and the single square place their construction as contemporary (1174–985 and 1220–988 BP, respectively). A slightly earlier date of 1405–1300 BP from ceramic residue is interpreted as a pre-earthwork occupation episode (29).

JK phytoliths:

In 2010, a pilot phytolith study was carried out at the JK geoglyph (9°43'57.3" S, 67°03'41.7" W), which consists of a square, double-ditched earthwork with slightly rounded corners and a causeway-like feature emanating from its northern side. Two units were excavated: one in the centre of the geoglyph (U1), which yielded almost no archaeological material, and one at the bottom of the southern inner ditch (U2), which contained higher quantities of ceramics and charcoal until ~200 cm below surface (BS). Dates obtained from this inner ditch place geoglyph construction between ca. 1866–1417 cal. BP (28). At U1, soil samples were analysed from the

surface (0–2 cm and 2–5 cm) and then every 5 cm until 30 cm BS. At U2, samples were analysed from the surface (0–5 cm), and then roughly every 30–40 cm of the profile until 180 cm BS.

Fig. S1 (A) shows how palms (Arecaceae) completely dominate phytolith assemblages from U1, with samples containing between 70–90% globular echinates and 5–20% hat-shaped bodies (see *SI Methods, Phytolith methods*). Phytoliths from domesticated squash (*Cucurbita* sp.) were identified in the 2–5 cm and 15–20 cm samples. The rest of the phytolith assemblages consisted of arboreal types and trace amounts (< 2%) of Panicoideae grasses, bamboo, and other herbs (e.g. *Cyperus* sp., *Heliconia* sp., Asteraceae, Marantaceae).

Phytoliths from U2, the ditch unit, were also dominated by palms and other arboreal types (Fig. S1 (B)). A change in forest composition around 100 cm BS is implied by the disappearance of hat-shaped palm phytoliths (produced by *Bactris* and *Astrocaryum* genera (59)) and an increase in arboreal globular granulate phytoliths. The timing of this transition occurred at some point during the use of the geoglyph, since the original ditch base was reached at ca. 200 cm BS. Squash phytoliths were not recovered, and the herbaceous component was very similar to U1. These results, while preliminary in nature, are sufficient to imply the presence of pre-Columbian palm-dominated forest at the JK geoglyph. As phytolith sampling was not extended below 30 cm at U1, we cannot estimate its antiquity. Its presence is also attested to in the U1 surface samples, perhaps hinting that this vegetation persisted until deforestation of the site in 2005.

Terrestrial palaeoecology methods:

Phytoliths

Phytoliths are opal silica bodies produced in the leaves, stems, inflorescences and roots of plants, and their three-dimensional morphologies are specific to the plant taxa that produce them (55). Studies comparing phytolith assemblages produced by modern forest analogues in

southwest Amazonia (50, 56) have demonstrated their effectiveness in distinguishing different vegetation types, while their high taxonomic resolution within early successional herbs (ESHs) (11) such as grasses and *Heliconia*, permit the identification of past forest disturbance events within the paleoecological record (11, 55).

Phytoliths were advantageous to this study for two reasons. Unlike pollen, they survive well in terrestrial soils – including the weathered, acidic Ultisols of eastern Acre – and the majority of geoglyph sites are situated in the interfluvial uplands away from lakes and rivers. Secondly, phytoliths are released into the soil where the host plant dies. Controlling for topography (i.e. not sampling on slopes or depressions where phytoliths may have arrived by colluvial transport), phytoliths from a soil profile provide a highly local representation of vegetation history at that location (55). This allows the identification of vegetation heterogeneity across horizontal space, important in identifying spatial scales of past landscape transformations.

Charcoal

Quantification of soil charcoal is a common means of detecting past fire occurrence. Since fire was a widely-used management tool in pre-Columbian Amazonia (20), it was deemed an essential proxy in our study.

Studies into charcoal deposition show that particle larger than 100–125 μm (macroscopic charcoal) are more likely to have arrived from local to extra-local fire events rather than having been transported over long distances (57, 60). Furthermore, particles measuring $>250 \mu\text{m}$ are considered as representative of *in situ* burning (61). We chose to quantify charcoal from two size classes (125–250 and $>250 \mu\text{m}$) to distinguish extra-local vs. more local burning and thus aid interpretation. Although charcoal recovery was low throughout the profiles, the presence of charcoal “peaks”, particularly in the larger fraction, was interpreted as evidence of singular burning episodes, and were targeted for AMS dating.

Stable carbon isotopes

In soil profiles, analysis of $\delta^{13}\text{C}$ values of carbon preserved within soil organic matter (SOM) may be used to indicate the ratio of C3: C4 plants that persisted in an environment and contributed to pedogenesis during the past (62). Soils from tropical savannas, which contain many grasses that use a C4 photosynthetic pathway, typically have $\delta^{13}\text{C}$ values (relative to Vienna PDB) between -19.5‰ and -16‰, while in forested sites, where the vegetation is typically C3, values range between -30‰ and -22.5‰ (63).

Stable carbon isotope analysis was conducted on soils from JS1 (sampled every 10 cm) and JS3 (sampled every 10 cm, then every 20 cm below 0.4 m below surface), to provide an indicator of the dominant vegetation types present prior to, during and following construction of the geoglyphs to provide information pertaining to the vegetation in the vicinity of the Jaco Sá geoglyph and its changes over time.

Charcoal and soil humin dates

Charcoal for dating was extracted in bulk from the soil samples to provide an average soil horizon age and minimize problems with dating singular fragments that may have been translocated in the profile. Dating efforts focussed on specific events recorded in the phytolith and charcoal records, in particular charcoal peaks that represented anthropogenic burning activity and the beginning of the decline in palm taxa (FC1, JS2, JS2 and JS4).

Basal dates for the profiles (all but JS1) were retrieved by ^{14}C dating of soil humin [benzene/liquid scintillation counting at Centro de Energia Nuclear na Agricultura (CENA) laboratories (64)] due to the lack of charcoal in these lower strata. Soil humin is considered the most stable component of SOM and provides more reliable dates for organic matter formation than bulk dates. A study comparing ^{14}C ages of humin, bulk SOM and charcoal in soil profiles from central Brazil found that humin and charcoal ages were in good agreement up to 1.0–1.5 m BS, while bulk SOM dates were significantly younger in the same horizons (65).

In the FC1 profile, an initial charcoal date from the 50–55 cm horizon (the beginning of a charcoal peak expected to relate to geoglyph construction) demonstrated an older source for charcoal than expected for its vertical depth (see below). An additional soil humin sample was subsequently obtained from the 45–50 cm horizon (the charcoal peak maxima), which yielded a date much more in accordance with the archaeological date for geoglyph construction.

Age inversions:

Charcoal age inversions (where younger charcoal appeared below older charcoal) occurred in four of the profiles (all but JS2 and JS5). This was not surprising, given other studies which report the same phenomenon in Amazonian soils (66, 67); but it did call into question the extent to which our proxy data could be trusted to represent a chronological series of events.

The integrity of each soil profile stratigraphy was judged qualitatively based on the available proxy data. Specifically, it was hypothesized that the profile data were broadly representative if:

1) Patterns observed in one profile were repeated in other profiles at similar depths.

Profiles with the strongest shared patterns are FC1 and JS1, which record initial peaks in charcoal, followed by a gradual, uninterrupted increase in palm taxa. In both profiles, palms continue to increase through a second charcoal peak and then suddenly decline further up in the sequence. The pattern of gradual palm increase and sudden decline is also repeated at JS2 at similar depths, while at JS4, a related pattern can be observed after 60–65 cm where a swell in palm abundance accompanies a general increase in burning activity at the locale.

JS3 is relatively poorly dated but shares some patterns with other profiles. Like at FC1 and JS5, there is a relative increase in bamboo and grasses at the expense of arboreal taxa in the top half of the profile, while $\delta^{13}\text{C}$ values of SOM reflect those from JS1, remaining fairly stable until

the top 10–20 cm, when the signal is enriched due to the influence of modern C4 grass cover. JS3 was deemed to be most disturbed of all the soil profiles.

2) The proxy data were in accordance with one another.

Throughout the profiles, the phytolith and charcoal data correspond well with one another, i.e. peaks in local (>250 μm) charcoal are accompanied by peaks in ESHs and/or a dip in bamboo phytoliths in the same horizons. Such sharp, temporary fluctuations in the proxy data would not be expected if the stratigraphies had undergone significant mixing, since bioturbation has the effect of homogenising soil horizons. A recent study of phytoliths from *surales* (earthworm mounds) in the Colombian llanos found stratigraphic and horizontal diversity in phytolith assemblages to be extremely low due to the soil-mixing activities carried out by these ecosystem engineers (68). In our study, fluctuations in local charcoal, grass and bamboo frequencies mirror one another at JS1, JS4 and JS5, which in turn correspond well with $\delta^{13}\text{C}$ values from JS1 and JS3.

3) Events dated in the soil profiles were consistent with archaeological dates

Dates for the first charcoal peaks at FC1 and JS1, after which extra-local (<125 μm) charcoal becomes overall more abundant, correspond well with archaeological data that demonstrate an increase in regional population around 4000 BP (28). The second charcoal peak at FC1 was dated by associated soil humin to 2158–2333 BP, only some 200 years before archaeological dates for geoglyph construction and use. While dated charcoal from the horizon below (50–55 cm) shows the inclusion of older charcoal in this portion of the profile, the pattern of a sharp dip in bamboo and a peak in larger charcoal at 45–50 cm is most parsimoniously related to geoglyph construction. At JS1, a direct date of the second charcoal peak (1385–1530 BP) is in agreement with archaeological dates of 1300–1405 BP for a (supposedly preearthwork) cultural level at the site, and roughly 100 years earlier than the archaeological dates for earthwork construction (between 985–1220 BP).

Dates from levels which contain peak palm phytolith percentages at FC1 and JS1 (20–25 cm) again demonstrated an older source for the associated charcoal than would be expected at these depths (6485–6651 and 2357–2698 BP respectively). However, charcoal associated with the same event at JS2 and JS4 (10–15 cm) yielded agreeing dates of 546–652 and 659–688 BP, which coincide with archaeological dates for geoglyph abandonment. It was therefore much more likely that the palm decline observed in FC1 and JS1 were part of the same phenomenon.

Causes of age inversions:

From the strength of shared patterns in the FC1 and JS1 profiles, the presence of charcoal over 6000 yr old at 50 cm BS at FC1 cannot be explained by significant bioturbation within the soil in the profile. One possibility is that older charcoal was deposited on the ground surface during earthwork construction; however, one might also expect this to show in the phytolith record—instead, the pattern of increasing palms is maintained, mirroring the situation at JS1 and JS2. The same is true of the charcoal date at 20–25 cm at JS1, although here the re-deposited charcoal was not so ancient (2357–2698 BP). At JS2 (80–85 cm) and JS5 (100–105 cm), charcoal dates were older than the basal soil humin dates. Since soil humin dates represent the minimum age of SOM (65), these disparities may have been caused by the downward movement of organic matter from the surface. At JS4, the charcoal date of 2955–3157 BP at 10–15 cm could be an effect of bioturbation, since a similar date was retrieved for charcoal at 50–55 cm. Alternatively, burning of older vegetation may have contributed older charcoal to the profile. Inverted but roughly contemporaneous dates from JS3 (30–35 and 60–65 cm) could also be the result of bioturbation.

SUPPLEMENTARY INFORMATION METHODS

Field and lab sampling:

Profiles were excavated to a depth of 1.5 m and soil sampled every 5 cm for phytoliths, charcoal and stable carbon isotopes. At JS3, profile excavation had to be halted at 1.2 m due to the presence of large, dense laterite concretions, making this profile shorter than the other five.

Samples were initially analyzed for phytoliths and charcoal every 10 cm before sending charcoal for AMS dating. Once the horizons relating to geoglyph construction were ascertained (above 50-55 cm for FC1 and 30-35 cm for JS1), resolution was increased to every 5 cm from these horizons to the surface.

Phytolith methods:

Phytoliths were extracted from soils following standard protocols (55). Each soil sample was wet-sieved into a silt (< 53 μm) and a sand (53–250 μm) fraction to better aid interpretations of palaeovegetation (50, 56), producing two data sets per soil horizon. Given the dominance of bamboo bulliform phytoliths recovered in the sand fractions (up to 90%), relative frequencies of silt fraction phytoliths (Fig. 1 of the ms) were deemed to provide a more sensitive reflection of palaeovegetation.

To aid data interpretation, morphotypes were grouped into four categories – ESH phytoliths (grasses (Poaceae) and *Heliconia*)(^{sensu} (11)), bamboo (Bambusoideae), palms (Arecaceae) and arboreal – once phytolith counts were completed (200 per slide). The grass category is represented by bilobate and saddle short cells belonging to the Panicoideae (C4) and Chloridoideae (C3 and C4) grasses (69, 70), respectively. Bamboo phytoliths consisted mainly of tall/collapsed and “blocky” saddle types, spiked rondels and chusquoid bodies (70), all of which are produced by *Guadua* (C3), the mono-dominant bamboo in southwest Amazonian bamboo forests. Rondel phytoliths were excluded from categorisation, as they are produced

both by true grasses and bamboos. Palms produce either hat-shaped or globular echinate phytoliths and are prolific phytolith producers, although identifications to genus level are not yet possible (55). Arboreal taxa were represented largely by globular phytoliths possessing granulate or smooth surface decoration which are produced in the wood and bark of many tropical tree families (71, 72) and are excellent indicators of past forest cover (73). Other arboreal forms identified included tracheary elements (tracheids and sclereids), faceted phytoliths and vesicular infillings (74, 75).

Bamboo forest and vegetation analogues:

To assign phytolith assemblages from the soil profiles to vegetation types, surface soil phytoliths were analysed from five different modern forest formations in Acre (bamboo, palm, fluvial, dense humid evergreen and dense humid evergreen with abundant palm) (56). All forest formations were able to be statistically separated by phytolith relative frequencies after applying Principal Components Analysis (PCA), apart from the dense humid evergreen types which clustered together.

Bamboo forest was able to be distinguished from other formations on account of bamboo short cell phytoliths (>10%) in the silt fraction and the dominance of bamboo bulliform phytoliths in the sand fraction (56). As both these conditions were met in the soil profile phytolith assemblages, we could be confident that this forest formation was present at all soil profile locations since the beginning of the records.

Charcoal methods:

Charcoal was extracted from 3 cm³ of soil using a modified macroscopic sieving method (57) and each fraction counted for charcoal in a gridded petri dish with a binocular loop microscope. Many of the samples contained black mineral particles that looked similar to charcoal, so pressure was applied with a glass rod to see if they fragmented when identification was

uncertain. Absolute charcoal abundances were transferred into charcoal volume (particles/cm³) upon analysis.

Stable carbon isotope methods:

As a comparative exercise, four surface soil samples ($n=3$) from three of the modern vegetation analogues sampled for phytoliths (bamboo, palm and dense humid evergreen forest) were also analysed, which yielded averaged $\delta^{13}\text{C}$ values of -28.4‰, -28.5‰ and -26.3‰, respectively ($n=3$).

It was noted that the $\delta^{13}\text{C}$ values from the profiles where bamboo forest vegetation was recorded were isotopically enriched relative to those from the modern bamboo forest surface soils. At JS1, values ranged between -23.9‰ and -24.3‰ where phytoliths recorded non-disturbed bamboo forest (100–140 cm), and between -23.2‰ and -23.8‰ at JS3 (90–110 cm). Such disparity may be explained by $\delta^{13}\text{C}$ enrichment from modern vegetation or the high rates of organic matter decompositions in the profile soils, which can lead to $\delta^{13}\text{C}$ enrichment of up to 4‰ (76).

$\delta^{13}\text{C}$ and total organic carbon (TOC) values for the soils were obtained using standard procedures (58). Special care was taken to avoid the inclusion of rootlets and similar non-representative materials in each sample. Analytic precision was typically 0.1‰ (σ_{n-1} , $n=10$).

Charcoal and soil humin dating:

AMS dating was performed on 19 charcoal samples (Beta and OxA laboratories) from the soil profiles and calibrated to 2σ accuracy using IntCal13 calibration curve (77) (Table S1). Northern hemisphere calibration was used because the study area falls within the seasonal migration of the Intertropical Convergence Zone which introduces northern hemispheric ^{14}C signals to these lower latitudes (78).

JS2 forest patch methods:

An opportunistic botanical inventory of the forest patch adjacent to the JS2 profile recorded all species > 10 cm diameter at breast height along a 50 m transect. A total of 61 species ($n=220$) were noted and the ten most abundant are presented in SI Table 2. Three surface soil samples, representing the top 2–3 cm of topsoil once leaf litter was removed, were collected at random points within the inventoried area and analysed for phytoliths. The phytolith assemblages were then averaged and fed into a PCA alongside averaged phytolith assemblages from the modern vegetation analogues and the JS2 soil profile samples. Resulting factor scores were plotted graphically, and revealed a similarity in phytolith assemblages from the modern day forest patch and the 20–25 cm horizon at JS2 (Fig. S2).

SI FIGURES

Fig. S1: Relative frequency diagram of phytoliths from the JK geoglyph site. (A) Excavation unit U1 located in the centre of the geoglyph. (B) Excavation unit U2 located at the bottom of one of the inner ditches. + = quantities < 2%

Fig. S2: Plotted factor scores from a PCA of averaged phytolith frequencies from the JS2 forest patch, modern vegetation analogues and paleoecological samples from the JS2 profile. The phytolith assemblage from sample 10 (20–25 cm) plots closely with that of the JS2 forest patch.

Figure S1

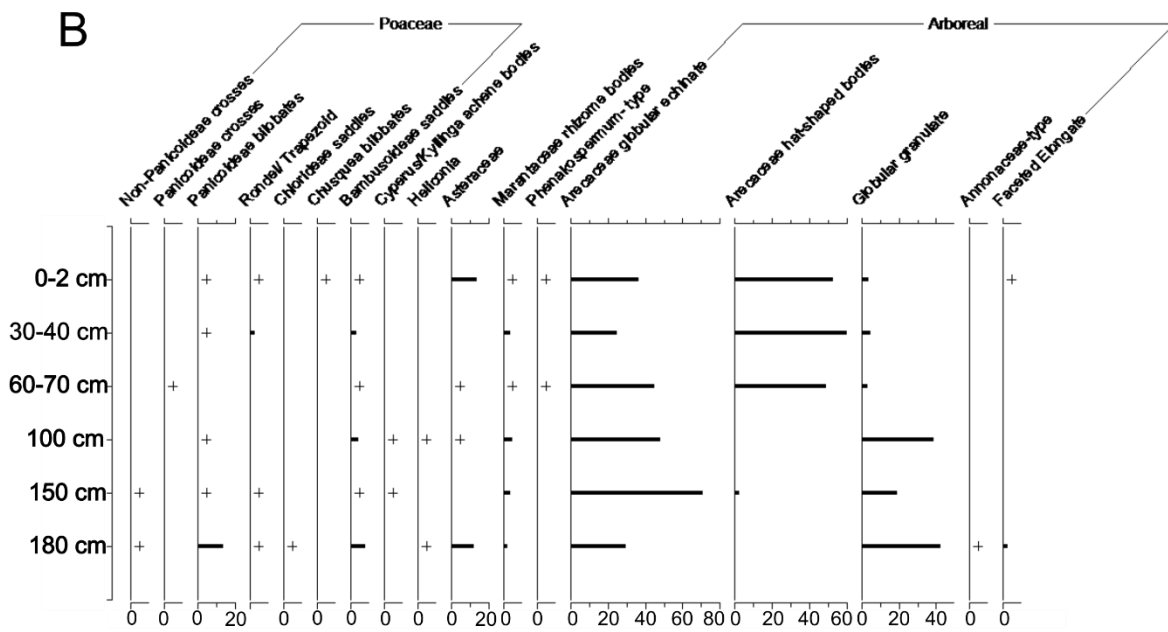
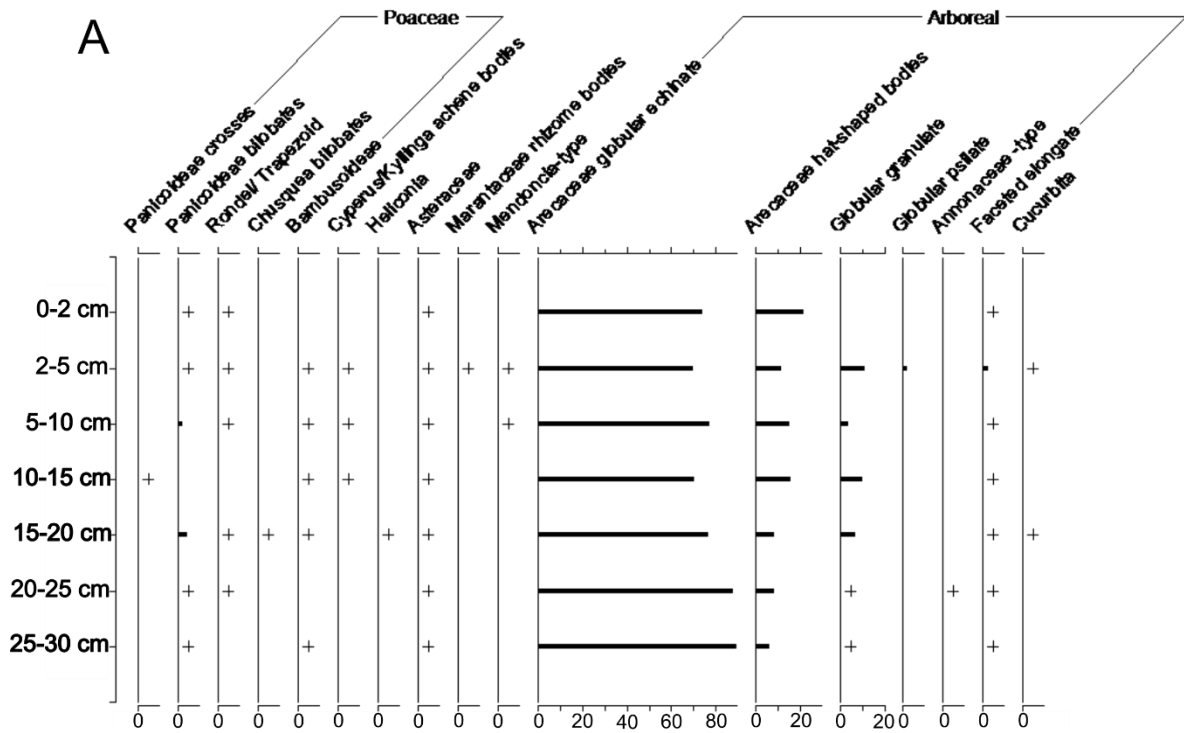


Figure S2

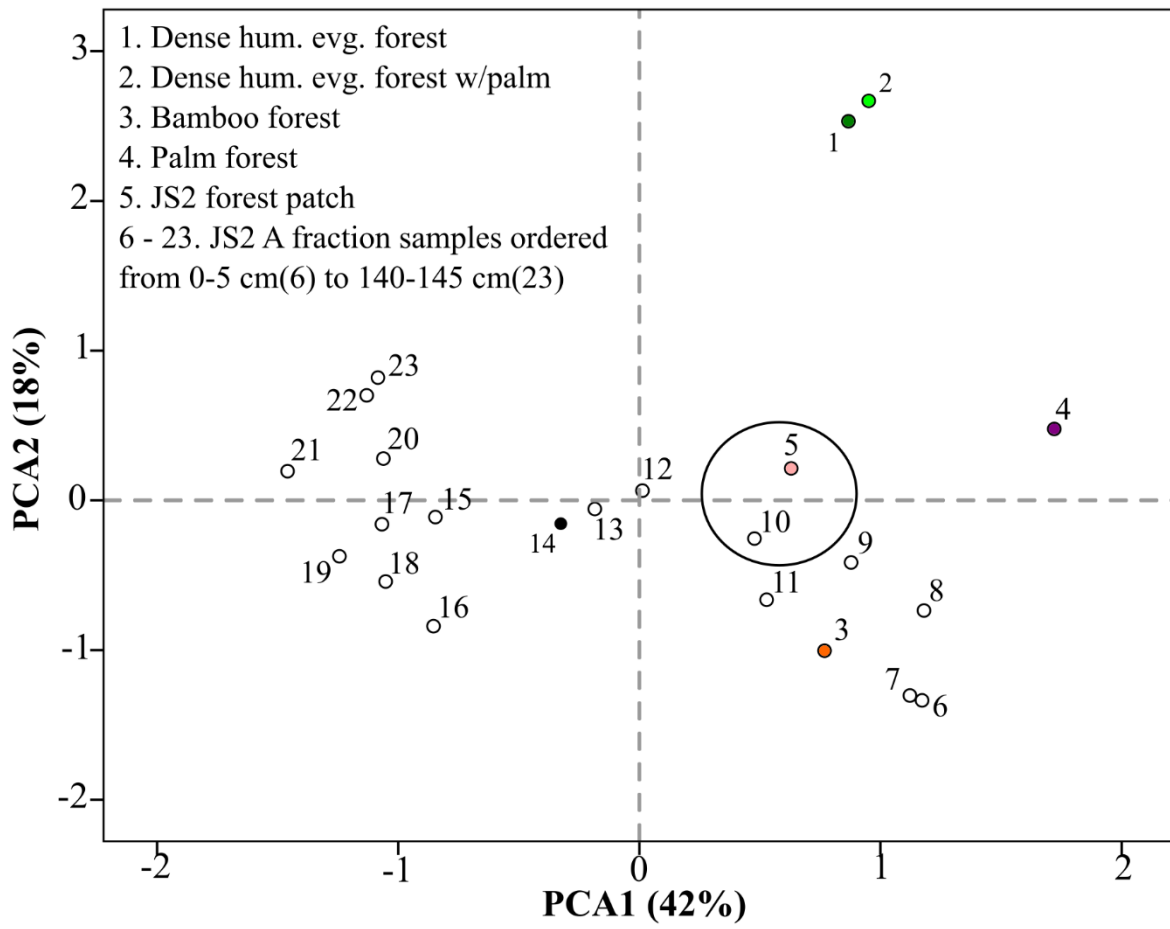


Table S1: List of radiocarbon dates obtained in the study

| Profile | Depth (cm) | Lab no. | Material | C14 age years BP (+/- 2σ error) | Cal. age BP |
|---------|------------|-------------|----------|---------------------------------|-------------|
| FC1 | 20-25 | Beta-377101 | Charcoal | 5760 +/- 30 | 6485-6651 |
| FC1 | 45-50 | CENA-959 | Humin | 2240+/-20 | 2158-2333 |
| FC1 | 50-55 | Beta-377102 | Charcoal | 5300 +/- 30 | 6186-8084 |
| FC1 | 100-105 | Beta-377103 | Charcoal | 3390 +/- 30 | 3569-3701 |
| FC1 | 140-145 | CENA-960 | Humin | 4800+/-20 | 5476-5594 |
| JS1 | 20-25 | OxA-29507 | Charcoal | 2432 +/- 25 | 2375-2698 |
| JS1 | 30-35 | Beta-355557 | Charcoal | 1560 +/- 30 | 1385-1530 |
| JS1 | 80-85 | Beta-355558 | Charcoal | 3690 +/- 30 | 3927-4146 |
| JS1 | 140-145 | OxA-29506 | Charcoal | 5230 +/- 29 | 5918-6174 |
| JS2 | 10-15 | OxA-29510 | Charcoal | 605 +/- 23 | 546-652 |
| JS2 | 50-55 | OxA-29509 | Charcoal | 3728 +/- 27 | 3986-4152 |
| JS2 | 80-85 | OxA-29508 | Charcoal | 6984 +/- 33 | 7720-9334 |
| JS2 | 140-145 | CENA-961 | Humin | 5780 +/-20 | 6501-6650 |
| JS3 | 10-15 | OxA-29512 | Charcoal | AD 1958 | Modern |
| JS3 | 30-35 | OxA-29511 | Charcoal | 2694 +/- 26 | 2756-2850 |
| JS3 | 60-65 | OxA-29694 | Charcoal | 2344 +/- 30 | 2319-2460 |
| JS3 | 115-120 | CENA-962 | Humin | 3940+/-20 | 4295-4500 |
| JS4 | 10-15 | OxA-29466 | Charcoal | 708 +/- 25 | 569-688 |
| JS4 | 20-25 | OxA-296465 | Charcoal | 2901 +/- 28 | 2955-3157 |
| JS4 | 50-55 | OxA-29513 | Charcoal | 2487 +/- 25 | 2471-2722 |
| JS4 | 140-145 | CENA-963 | Humin | 4090+/-20 | 4455-4800 |
| JS5 | 20-25 | OxA-29469 | Charcoal | 1783 +/- 25 | 1618-1812 |
| JS5 | 60-65 | OxA-29468 | Charcoal | 4350 +/- 50 | 4836-5212 |
| JS5 | 100-105 | OxA-29467 | Charcoal | 5731 +/- 32 | 6446-6635 |
| JS5 | 140-145 | CENA-964 | Humin | 5700+/-30 | 6406-6599 |

Table S2: Percentages of ten most abundant species and families recorded in JS2 forest patch. * = useful species

| Most common tree species % | | Most common tree families % | |
|--|------|-----------------------------|------|
| <i>Tetragastris altissima</i> (Burseraceae)* | COMM | Burseraceae | COMM |
| <i>Bertholettia excelsa</i> (Lecythidaceae)* | 15.2 | Arecaceae | 28.6 |
| <i>Euterpe precatorea</i> (Arecaceae)* | 11.2 | Fabaceae | 12.7 |
| <i>Jacaranda copaia</i> (Bignoniaceae)* | 7.9 | Lecythidaceae | 10.0 |
| <i>Astrocaryum murumuru</i> (Arecaceae)* | 5.6 | Bignoniaceae | 9.1 |
| <i>Astrocaryum tucuma</i> (Arecaceae)* | 5.6 | Moraceae | 7.7 |
| <i>Bellucia sp.</i> (Melastomataceae) | 3.9 | Melastomataceae | 4.1 |
| <i>Maclura tinctora</i> (Moraceae)* | 3.9 | Euphorbiaceae | 3.2 |
| <i>Cedrela odorata</i> (Meliaceae)* | 3.9 | Meliaceae | 3.2 |
| <i>Bactris coccinea</i> (Areaceae)* | 3.2 | Urticaceae | 3.2 |
| Total: | 57.3 | Total: | 78.6 |