Paper:

Watling, J., Iriarte, J., Mayle, F., Schaan, D., Pessenda, L., Loader, N., Street-Perrott, F., Dickau, R., Damasceno, A. & Ranzi, A. (2017). Impact of pre-Columbian "geoglyph" builders on Amazonian forests. *Proceedings of the National Academy of Sciences*, 201614359

http://dx.doi.org/10.1073/pnas.1614359114

Impact of pre-Columbian "geoglyph" builders on Amazonian forests

Jennifer Watling[a,b,1], José Iriarte[b], Francis E. Mayle[c], Denise Schaan[d], Luiz C. R. Pessenda[e], Neil J. Loader[f], F. Alayne Street-Perrott[f], Ruth E. Dickau[g], Antonia Damasceno[d], and Alceu Ranzi[h]

[a]Museum of Archaeology and Ethnography, University of São Paulo, São Paulo 05508-070, Brazil; [b]Department of Archaeology, College of Humanities, University of Exeter, Exeter EX4 4QE, United Kingdom; [c]Department of Geography and Environmental Science, School of Archaeology, Geography and Environmental Science, University of Reading, Reading RG6 6AB, United Kingdom; [d]Department of Anthropology, Federal University of Pará, Belém 66075-110, Brazil; [e]Centre of Nuclear Energy in Agriculture, University of São Paulo, Piracicaba 13416-000, Brazil; [f]Department of Geography, College of Science, Swansea University, Swansea SA2 8PP, United Kingdom; [g]HD Analytical Solutions, Inc., London, ON M5H 1V3, Canada; and [h]Laboratory of Paleontology, Federal University of Acre, Rio Branco 69916-900, Brazil

Edited by James O'Connell, University of Utah, Salt Lake City, UT, and approved December 28, 2016 (received for review August 27, 2016)

Over 450 pre-Columbian (pre-AD 1492) geometric ditched enclosures ("geoglyphs") occupy ~13,000 km^2 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 ≥6,000 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.

Amazonian archaeology | Amazonian rainforest | paleoecology | pre-Columbian land use

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 (northeast Bolivia), Marajó Island (northeast 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 polarization of this debate, which encompasses different hypothetical estimates of precontact 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, because some have proposed that pre-Columbian deforestation was on a large enough scale to have influenced the carbon cycle and global climate (18, 19), whereas others argue that large-scale slash-and-burn agriculture is a largely postcontact 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 programs 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

Significance

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 that have been little studied. In Brazil, the groundbreaking 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.

Author contributions: J.W., J.I., F.E.M., D.S., and A.R. designed research; J.W., L.C.R.P., N.J.L., F.A.S.-P., and R.E.D. performed research; J.W., J.I., F.E.M., L.C.R.P., N.J.L., F.A.S.-P., R.E.D., and A.D. analyzed data; and J.W., J.I., F.E.M., D.S., L.C.R.P., N.J.L., and F.A.S.-P. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed. Email: jenny.g.watling@gmail.com.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1614359114/-/DCSupplemental.

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. 1*B*), which cover roughly 161,500 km^2 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 <1,000 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., more than several kilometers) 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- to 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. 1*A*). 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 high points (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 center 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. 1*C*). 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 nonnative 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) (Table S1). 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 Methods*), demonstrate that the bamboo forest ecosystem that exists in the region today was present throughout the past ∼6,000 y. These data provide 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 neighboring Rondônia state, Brazil (46–48) (Fig. 1*A*, *a*, *b*, and *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, whereas 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 km^2 (35). The resulting dead vegetation is flammable in the dry season, which favors 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, $\delta^{13}C$ 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 $\delta^{13}C$ 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

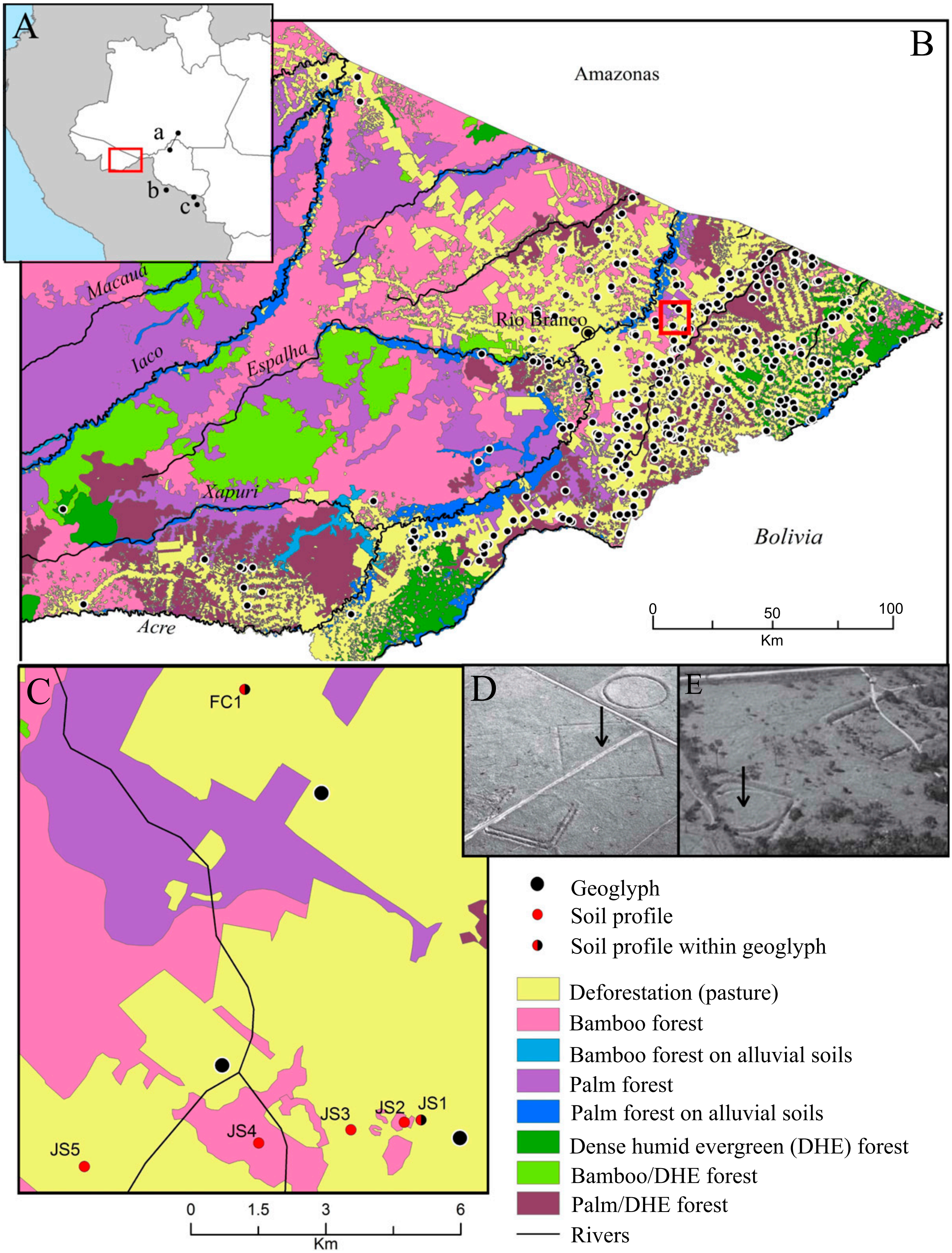

Fig. 1. Location maps. (*A*) Location of eastern Acre (*Inset*) and paleoecological studies that document a savanna–rainforest transition in the mid-Holocene: (*a*) soil profiles between Porto Velho and Humaitá (stable carbon isotopes), (*b*) Lagunas Orícore and Granja (pollen), and (*c*) Lagunas Bella 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 as follows: JS2 = 0.5 km, JS3 = 1.5 km, JS4 = 3.5 km, and 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.

localized. This suggests that the geoglyphs were not designed for intervisibility, 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

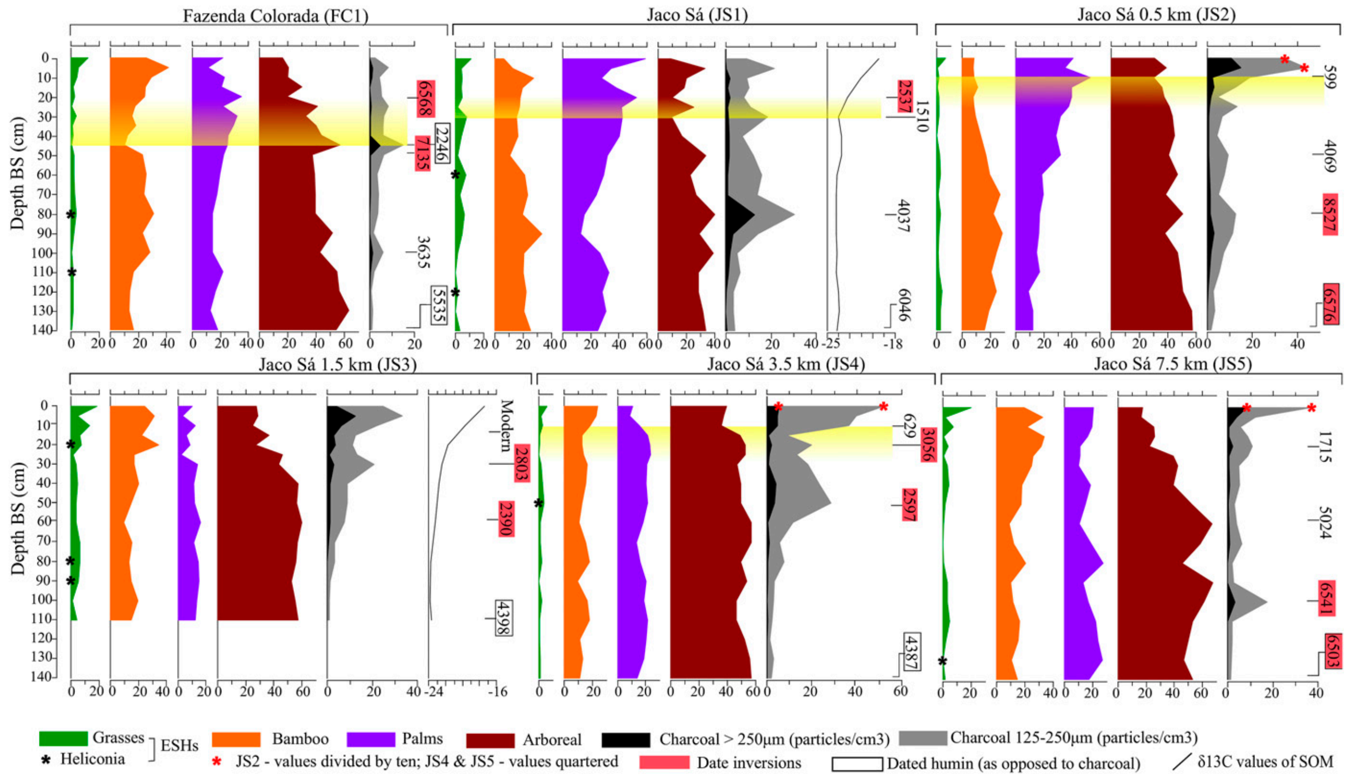

Fig. 2. Percentage phytolith frequencies, charcoal concentrations, $\delta^{13}C$ values (expressed in per mille) and midrange ^{14}C dates (in calibrated years before present, 2σ accuracy) by depth for the six soil profiles. Shaded yellow bars delimit levels pertaining to geoglyph use. Geoglyph construction 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).

by human activities over thousands of years. At FC1 and JS1, pre-geoglyph 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 ∼3,000 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 colonization 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? Toward 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 outcompeted 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- to 5-cm horizons is explicable by the same mechanism, as modern deforestation has favored their colonization by creating completely open landscapes.

Instead of reverting back to a more "natural" state, however, other evidence suggests that the species that outcompeted 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 socioeconomic 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 that 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 CO_2 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 nonforested 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 that were favored 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 μm) 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 was assessed based on interprofile 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 μm) from extralocal (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*.

ACKNOWLEDGMENTS. 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. Funding for this research was granted by the United Kingdom Arts and Humanities Research Council (AH/J500173/1) (to J.W.), Natural Environment Research Council (NERC) (NE/B501504) (to N.J.L.), NERC/OxCal Radiocarbon Fund (2013/2/8) (to J.W and J.I.), and National Geographic Society and Exploration Europe (GEFNE14-11) (to F.E.M. and J.I.).

1. Denevan WM (1992) The pristine myth: The landscape of the Americas in 1492. *Ann Assoc Am Geogr* 82(3):369–385.
2. Neves EG, Petersen JB (2006) Political economy and pre-Columbian landscape transformations in Central Amazonia. *Time and Complexity in Historical Ecology* (Columbia Univ Press, New York), pp 279–309.
3. Heckenberger M, Neves EG (2009) Amazonian archaeology. *Annu Rev Anthropol* 38(1):251–266.
4. McMichael CH, et al. (2014) Predicting pre-Columbian anthropogenic soils in Amazonia. *Proc Biol Sci* 281(1777):20132475.
5. Denevan WM (1966) *The Aboriginal Cultural Geography of the Llanos de Mojos of Bolivia*. Ibero-Americana 48 (University of California Press, Berkeley, CA).
6. Erickson CL (2006) The domesticated landscapes of the Bolivian Amazon. *Time and Complexity in Historical Ecology*, eds Erickson CL, Balée W (Columbia Univ Press, New York), pp 235–278.
7. Erickson CL (2000) The Lake Titicaca basin: A pre-Columbian built landscape. *Imperfect Balance: Landscape Transformations in the Pre-Columbian Americas*, ed Lentz D (Columbia Univ Press, New York), pp 311–356.
8. Schaan D (2008) The non-agricultural chiefdoms of Marajó Island. *Handbook of South American Archaeology*, eds Silverman H, Isbell WH (Springer, New York), pp 339–357.
9. Rostain S (2010) Pre-Columbian earthworks in coastal Amazonia. *Diversity (Basel)* 2(3): 331–352.
10. Iriarte J, et al. (2010) Late Holocene neotropical agricultural landscapes: Phytolith and stable carbon isotope analysis of raised fields from French Guianan coastal savannahs. *J Archaeol Sci* 37(12):2984–2994.
11. McMichael CH, et al. (2012) Sparse pre-Columbian human habitation in western Amazonia. *Science* 336(6087):1429–1431.
12. Piperno DR, McMichael C, Bush MB (2015) Amazonia and the Anthropocene: What was the spatial extent and intensity of human landscape modification in the Amazon Basin at the end of prehistory? *Holocene* 25(10):1588–1597.
13. Bush MB, et al. (2015) Anthropogenic influence on Amazonian forests in pre-history: An ecological perspective. *J Biogeogr* 42(12):2277–2288.
14. Roosevelt AC (2014) The Amazon and the Anthropocene: 13,000 years of human influence in a tropical rainforest. *Anthropocene* 4:69–87.
15. Clement CR, et al. (2015) The domestication of Amazonia before European conquest. *Proc Biol Sci* 282(1812):20150813.
16. Stahl PW (2015) Interpreting interfluvial landscape transformations in the pre-Columbian Amazon. *Holocene* 25(10):1598–1603.
17. Denevan WM (2014) Estimating Amazonian Indian numbers in 1492. *J Lat Am Geogr* 13(2):207–221.
18. Nevle RJ, Bird DK (2008) Effects of syn-pandemic fire reduction and reforestation in the tropical Americas on atmospheric CO_2 during European conquest. *Palaeogeogr Palaeoclimatol Palaeoecol* 264(1-2):25–38.
19. Dull RA, et al. (2010) The Columbian Encounter and the Little Ice Age: Abrupt land use change, fire, and greenhouse forcing. *Ann Assoc Am Geogr* 100(4):37–41.
20. Arroyo-Kalin M (2012) Slash-burn-and-churn: Landscape history and crop cultivation in pre-Columbian Amazonia. *Quat Int* 249:4–18.
21. Posey A, Balée W (1989) *Resource Management in Amazonia: Indigenous Folk Strategies* (New York Botanical Garden, New York).
22. Clement CR (2006) Demand for classes of traditional agroecological knowledge in modern Amazonia. *Human Impacts on Amazonia: The Role of Traditional Ecological Knowledge in Conservation and Development*, eds Posey DA, Balick MJ (Columbia Univ Press, New York), pp 33–50.
23. Clement CR, et al. (2015) Response to comment by McMichael, Piperno and Bush. *Proc Biol Sci* 282(1821):20152459.

24. Heckenberger MJ, Russell JC, Toney JR, Schmidt MJ (2007) The legacy of cultural landscapes in the Brazilian Amazon: Implications for biodiversity. *Philos Trans R Soc Lond B Biol Sci* 362(1478):197–208.
25. Bush MB, Silman MR (2007) Amazonian exploitation revisited: Ecological asymmetry and the policy pendulum. *Front Ecol Environ* 5(9):457–465.
26. Carson JF, et al. (2014) Environmental impact of geometric earthwork construction in pre-Columbian Amazonia. *Proc Natl Acad Sci USA* 111(29):10497–10502.
27. Schaan D (2012) *Sacred Geographies of Ancient Amazonia: Historical Ecology of Social Complexity* (Left Coast Press, San Francisco).
28. Saunaluoma S, Schaan D (2012) Monumentality in western Amazonian formative societies: Geometric ditched enclosures in the Brazilian state of Acre. *Antiqua* 2:e1.
29. Schaan D, et al. (2012) New radiometric dates for precolumbian (2000–700 B.P.) earthworks in western Amazonia, Brazil. *J Field Archaeol* 37(2):132–142.
30. Pärssinen M, Schaan D, Ranzi A (2009) Pre-Columbian geometric earthworks in the upper Purus: A complex society in western Amazonia. *Antiquity* 83(322):1084–1095.
31. Prümers H (2014) Sitios prehispánicos com zanjas en Bella Vista, Provincia Iténez, Bolivia. *Antes de Orellana. Actas Del 3er Encuentro Internacional de Arqueología Amazônica*, ed Rostain S (IFEA; FLASCO; MCCTH; SENESCYT, Quito, Ecuador), pp 73–91.
32. Saunaluoma S, Virtanen PK (2015) Variable models for organization of earthworking communities in Upper Purus, southwestern Amazonia: Archaeological and ethnographic perspectives. *Tipití J Soc Anthropol Lowl South Am* 13(1):23–43.
33. Eriksen L (2011) Nature and culture in prehistoric Amazonia. PhD dissertation (Lund University, Lund, Sweden).
34. Saunaluoma S (2016) Cerâmicas do Acre. *Cerâmicas Arqueológicas Da Amazônia: Rumo a Uma Nova Síntese*, eds Barreto C, Lima HP, Betancourt CJ (IPHAN: Ministério de Cultura, Belém, PA, Brazil), pp 414–419.
35. de Carvalho AL, et al. (2013) Bamboo-dominated forests of the southwest Amazon: Detection, spatial extent, life cycle length and flowering waves. *PLoS One* 8(1): e54852.
36. McMichael CH, Palace MW, Golightly M (2014) Bamboo-dominated forests and pre-Columbian earthwork formations in south-western Amazonia. *J Biogeogr* 41(9): 1733–1745.
37. McMichael CH, et al. (2013) Historical fire and bamboo dynamics in western Amazonia. *J Biogeogr* 40(3):299–309.
38. Olivier J, et al. (2009) First macrofossil evidence of a pre-Holocene thorny bamboo cf. Guadua (Poaceae: Bambusoideae: Bambuseae: Guaduinae) in south-western Amazonia (Madre de Dios–Peru). *Rev Palaeobot Palynol* 153:1–7.
39. Mayle FE, Power MJ (2008) Impact of a drier Early-Mid-Holocene climate upon Amazonian forests. *Philos Trans R Soc Lond B Biol Sci* 363(1498):1829–1838.
40. Carson JF, et al. (2015) Pre-Columbian land use in the ring-ditch region of the Bolivian Amazon. *Holocene* 25(8):1285–1300.
41. Duarte AF (2005) Variabilidade e tendência das chuvas em Rio Branco, Acre, Brasil. *Rev Bras Meteorol* 20:37–42.
42. Aragão LEOC, et al. (2008) Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. *Philos Trans R Soc Lond B Biol Sci* 363(1498):1779–1785.
43. Daly DC, Silveira M (2008) *First Catalogue of the Flora of Acre* (Universidade Federal do Acre, Rio Branco, Brazil).
44. Quesada CA, et al. (2011) Soils of Amazonia with particular reference to the RAINFOR sites. *Biogeosciences* 8(6):1415–1440.
45. Baker PA, et al. (2001) The history of South American tropical precipitation for the past 25,000 years. *Science* 291(5504):640–3.
46. Mayle FE, Burbridge R, Killeen TJ (2000) Millennial-scale dynamics of southern Amazonian rain forests. *Science* 290(5500):2291–2294.
47. Pessenda LCR, et al. (2001) Origin and dynamics of soil organic matter and vegetation changes during the Holocene in a forest-savanna transition zone, Brazilian Amazon region. *Holocene* 11(2):250–254.
48. de Freitas HA, et al. (2001) Late Quaternary vegetation dynamics in the southern Amazon basin inferred from carbon isotopes in soil organic matter. *Quat Res* 55(1): 39–46.
49. Watling J, Saunaluoma S, Pärssinen M, Schaan D (2015) Subsistence practices among earthwork builders: Phytolith evidence from archaeological sites in the southwest Amazonian interfluves. *J Archaeol Sci Reports* 4:541–551.
50. Dickau R, et al. (2013) Differentiation of neotropical ecosystems by modern soil phytolith assemblages and its implications for palaeoenvironmental and archaeological reconstructions. *Rev Palaeobot Palynol* 193:15–37.
51. Clement CR (1999) 1492 and the loss of Amazonian crop genetic resources. I: The relation between domestication and human population decline. *Econ Bot* 53(2): 188–202.
52. Kahn F (1988) Ecology of economically important palms in Amazonia. *Adv Econ Bot* 6: 42–49.
53. Kahn F, Granville JJ (1992) Palms in forest ecosystems of Amazonia. *Ecological Studies* (Springer, Berlin), Vol 95, pp 41–89.
54. Salm R, Jalles-filho E, Schuck-paim C (2005) A model for the importance of large arborescent palms in the dynamics of seasonally-dry Amazonian forests. *Biota Neotropica* 5(1):1–6.
55. Piperno DR (2006) *Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists* (Altimira, Oxford, UK).
56. Watling J, et al. (2016) Differentiation of neotropical ecosystems by modern soil phytoliths assemblages and its implications for palaeoenvironmental and archaeological reconstructions. II: Southwestern Amazonian forests. *Rev Palaeobot Palynol* 226:30–43.
57. Whitlock C, Larsen C (2001) Charcoal as a fire proxy. *Tracking Environmental Change Using Lake Sediments, Volume 3: Terrestrial, Algal and Siliceous Indicators*, eds Smol JP, Birks HJB, Last WM (Kluwer Academic, Dordrecht, The Netherlands), pp 75–97.
58. Metcalfe SE, et al. (2014) Hydrology and climatology at Laguna La Gaiba, lowland Bolivia: Complex responses to climatic forcings over the last 25,000 years. *J Quat Sci* 29(3):289–300.
59. Morcote-Ríos G, Bernal R, Raz L (2016) Phytoliths as a tool for archaeobotanical, palaeobotanical and palaeoecological studies in Amazonian palms. *Bot J Linn Soc* 182(2):348–360.
60. Clark JS (1988) Particle motion and the theory of charcoal analysis: Source area, transport, deposition and sampling. *Quat Res* 30:67–80.
61. Gardner JJ, Whitlock C (2001) Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. *Holocene* 11(5):541–549.
62. Kelly E, et al. (1998) Stable isotope composition of soil organic matter and phytoliths as paleoenvironmental indicators. *Geoderma* 82(1-3):59–81.
63. Pessenda LCR, et al. (1998) The carbon isotope record in soils along a forest-cerrado ecosystem transect: Implications for vegetation changes in the Rondonia state, southwestern Brazilian Amazon region. *Holocene* 8(5):599–603.
64. Pessenda LCR, Camargo PB (1991) Datação radiocarbônica de amostras de interesse arqueológico e geológico por espectrometria de cintilação líquida de baixa radiação de fundo. *Quim Nova* 2:98–103.
65. Pessenda LCR, Gouveia SEM, Aravena R (2001) Radiocarbon dating of total soil organic matter and humin fraction and its comparison with ^{14}C ages of fossil charcoal. *Radiocarbon* 43(2B):595–601.
66. Soubiès F (1979) Existence d'une phase sèche en Amazonie Brésilienne datée par la présence de charbons dans les sols (6.000-8.000 ans B.P.). *Cah ORSTOM Ser Geol* 9(1): 133–146.
67. Piperno DR, Becker P (1996) Vegetational history of a site in the central Amazon basin derived from phytolith and charcoal records from natural soils. *Quat Res* 45(2): 202–209.
68. Zangerlé A, et al. (2016) The Surales, self-organized earth-mound landscapes made by earthworms in a seasonal tropical wetland. *PLoS One* 11(5):e0154269.
69. Twiss PC, Suess E, Smith RM (1969) Morphological classifications of grass phytoliths. *Soil Sci Soc Am J* 33(1):109–115.
70. Piperno DR, Pearsall DM (1998) The silica bodies of tropical American grasses: Morphology, taxonomy, and implications for grass systematics and fossil phytolith identification. *Smithson Contrib Bot* 85:1–40.
71. Geis JW (1973) Biogenic silica in selected species of deciduous angiosperms. *Soil Sci* 116:113–130.
72. Wilding LP, Drees LR (1974) Contributions of forest opal and associated crystalline phases to fine silt and clay fractions of soils. *Clays Clay Miner* 22:295–306.
73. Bremond L, Alexandre A, Hely C, Guiot J (2005) A phytolith index as a proxy of tree cover density in tropical areas: Calibration with leaf area index along a forest-savanna transect in southeastern Cameroon. *Global Planet Change* 45(4):277–293.
74. Runge F (1999) The opal phytolith inventory of soils in central Africa—quantities, shapes, classification, and spectra. *Rev Palaeobot Palynol* 107(1-2):23–53.
75. Strömberg CE (2004) Using phytolith assemblages to reconstruct the origin and spread of grass-dominated habitats in the great plains of North America during the late Eocene to early Miocene. *Palaeogeogr Palaeoclimatol Palaeoecol* 207(3-4):239–275.
76. Sanaiotti ATM, et al. (2002) Past vegetation changes in Amazon savannas determined using carbon isotopes of soil organic matter. *Biotropica* 34(1):2–16.
77. Reimer PJ, et al. (2013) IntCal13 and Marine13 radiocarbon age calibration curves, 0–50,000 years cal BP. *Radiocarbon* 55(4):1869–1887.
78. McCormac FG, et al. (2004) SHCal04 Southern hemisphere calibration, 0–11.0 cal kyr BP. *Radiocarbon* 46(3):1087–1092.