Pre-Columbian fire management and control of climate-driven floodwaters over 3,500 years in southwestern Amazonia

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In landscapes that support economic and cultural activities, human communities actively manage environments and environmental change at a variety of spatial scales that complicate the effects of continental-scale climate. Here, we demonstrate how hydrological conditions were modified by humans against the backdrop of Holocene climate change in southwestern Amazonia. Paleoecological investigations (phytoliths, charcoal, pollen, diatoms) of two sediment cores extracted from within the same permanent wetland, ∼22 km apart, show a 1,500-y difference in when the intensification of land use and management occurred, including raised field agriculture, fire regime, and agroforestry. Although rising precipitation is well known during the mid to late Holocene, human actions manipulated climate-driven hydrological changes on the landscape, revealing differing histories of human landscape domestication. Environmental factors are unable to account for local differences without the mediation of human communities that transformed the region to its current savanna/forest/wetland mosaic beginning at least 3,500 y ago. Regional environmental variables did not drive the choices made by farmers and fishers, who shaped these local contexts to better manage resource extraction. The savannas we observe today were created in the post-European period, where their fire regime and structural diversity were shaped by cattle ranching.

pre-Colombian Amazon | paleoenvironment | hydrological change | agriculture | landscape domestication

The archaeological record has often been interpreted in relationship to the environment, with links drawn to hydrological or climate change in the Maya region (1), Mesopotamia (2), and the Amazon (3), among other cases. These narratives risk ignoring the active role of communities in the context of changing environments and the spatial variability of local conditions, both of which complicate the effects of continental-scale climate forcings. Despite the large synthetic studies that show temporal correlation of sociopolitical reorganization and climate change (4), there is limited empirical evidence of the agency of past societies, or how they changed land management strategies in response to climate change, especially at finer resolution examples that belie the mega-narratives of causal climate/society relationships (5). Research has converged on this topic from a variety of perspectives (6–10), but few studies have explored both spatial and temporal dimensions of local-scale environmental management that are necessary to contextualize societal response to regional climate change.

Southwestern Amazonian landscapes present an ideal opportunity to study climate–society interactions at these finer scales, which were created over millennia during pre-Columbian times alongside the development of crops, such as sweet potato and manioc. The domesticated Amazonian landscape is epitomized by the Llanos de Mojos, a 135,000-km^2 subbasin of the Madeira and the Amazon rivers, characterized by its flat topography and pronounced annual flood regime, that is covered in an abundance of pre-Columbian earthworks that were created for habitation (11–17), crop production (18), and water control (19). Mojos is a mosaic landscape, consisting of seasonally flooded open savannas and wetlands, interspersed with rivers, streams, and patches of forest. Forests inhabit areas of higher relief, and thus better drainage, such as among “islands” located throughout the savannas and along the levees of the Rio Mamore and its branches, a major tributary of the Amazon. These multiple landscape components not only differ in the economic activities they support (fish weirs, savanna game, fruits, wood products, palms, and many others), but these ecosystems also would show variable responses to precipitation change depending on their level of flood tolerance, and thus regional climate change would create fine-scale effects on this mosaic.

The Llanos de Mojos is part of the Guaporé-Mamoré linguistic area, one of the two areas with the highest linguistic diversity in the world (20, 21). Linguistic evidence suggests that the languages of the Guaporé-Mamoré area have been in contact over hundreds and perhaps thousands of years. Alongside this deep linguistic antiquity, previous archaeological and paleoenvironmental investigations have described past human–environmental interactions, such as crop production, forest management, and fire regimes altered through landscape domestication, but also with the catastrophic disruption associated with disease, technologies, and conflict, brought by the European encounter (22). This long history of socio-environmental interactions occurred against a backdrop of the strengthening of the South American summer monsoon, beginning ca. 6,000 y ago (4000 BCE) until present (23). The strong foundation of archaeological and paleoenvironmental information in the Llanos de Mojos, therefore, represents an excellent opportunity

Significance

The Chavín, Moche, Tiwanaku, and Inka are well-known pre-Columbian cultures, but during the same time, in the southwestern Amazon, people were transforming a 100,000-km^2 landscape over thousands of years. The extent of earthworks in the Llanos de Mojos has become clear since the 1960s, but dating these features has been difficult. We show that pre-Columbian people used hydrological engineering and fire to maximize aquatic and terrestrial resources beginning at least 3,500 years ago. In the 17th century CE, cattle and new technologies brought by Jesuit missions altered the form and function of these landscapes. The scale and antiquity of these Amazonian earthworks demand comparison with domesticated landscapes and civilizations from around the world.

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to investigate how past societies changed land management strategies as climate changed. Here, we apply paleoenvironmental approaches to reconstruct land, plant, fire, and water management in an area of pre-Columbian habitation as precipitation increased in the Holocene.

Study Context

This study focuses on the Quinato wetland in the Llanos de Mojos (Fig. 1), a permanent wetland that seasonally varies in area up to about 200 km^2. Its irregular shape is the result of its creation through past avulsions of the river that in the late Pleistocene would move to the west to become the Beni River. Channel activity is proposed to have been inactive for the past ca. 12,000 y (24). The area is very flat today, with differences in elevation of about 4 m over about 40 km. The wetland is surrounded by at least three kinds of evidence of pre-Columbian landscape management: forest islands, raised fields, and fish weirs. Forest islands exhibit evidence of habitation at a rate of at least 75%, in the form of ceramics (on the surface and in test excavations), ring ditches and similar earthworks, and burned clay within dark soils (14, 15, 25). Large raised fields are one of seven distinctive patterns of earthworks in Mojos. More than 44,000 have been mapped, with a typical area of 0.3 ha, perhaps 15 m wide by 200 m long. Fish weirs, not unlike those documented in eastern Mojos (26, 27) have also been observed on the margins of the wetland using satellite imagery, and one has been verified on the ground. In short, the Quinato wetland and surrounding higher ground are an anthropogenic landscape, created by pre-Columbian communities.

The Quinato wetland lies between two other previous channels of the paleo-Beni River, which are now at least partly navigable rivers: the Omi River to the north, and the Yacuma River to the south. The hydrological regime is very complicated, with a connection to other wetlands upstream to the southwest, and downstream to the northeast, as well as at least two connections to the Omi River to the northwest, and at least two connections to the Yacuma River to the southeast, all depending on the magnitude of the annual floods, which varies both year to year, and between the rivers. The much larger and more dynamic Mamoré River lies downstream to the northeast. Because of the high clay content of the soils, river basins flood both because of seasonal monsoon rains, and also when rivers back up from downstream.

To gain an understanding of anthropogenic landscape domestication in the context of Holocene environmental change, two locations in the Quinato wetland, Quinato-Miraflores and Mercedes, chosen due to their relative proximity to known inhabited forest islands and adjacent raised fields, were cored in 2018 using a modified Livingston Corer (Fig. 1). The Quinato-Miraflores (QM) core was extracted from a location at 145.6 m above sea level (asl) in an area surrounded by several large forest islands, including Miraflores, Cobamos, and Quinato (Fig. 1), and for which there is abundant evidence of past inhabitation, including surface ceramics, ring ditches, and raised fields located 650 m to the southeast. The Mercedes (ME) core was extracted 22 km northeast of QM at 143.6 m asl in an area located near one large forest island that contains a ring ditch and abundant surface pottery. Raised fields are located 480 m to the south-southeast, and 880 m to the north-northwest.

Sediment cores were analyzed for pollen, phytoliths, diatoms, and macroscopic charcoal to infer changes to past vegetation communities, hydrology, and fire regimes (*Materials and Methods*). Phytolith and pollen analysis have been demonstrated to be highly complementary techniques because they reflect different spatial scales on the landscape; with phytoliths showing local vegetation changes while pollen contained an extralocal or regional component, depending on the size of the depositional environment. Given the low water flow through the paleochannel, the pollen signals in the wetland are interpreted to be extralocal. Additionally, the two proxies provide complementary taxonomic resolution. Phytoliths provide higher taxonomic resolution of grasses, key to the identification of many cereal crops, while pollen better differentiates arboreal and herb taxa. Changes in the hydrology of the wetland were inferred from diatom assemblages (28). Changes within all proxies were temporally constrained with accelerator mass spectrometry (AMS) ^{14}C dates on organic sediments, and age

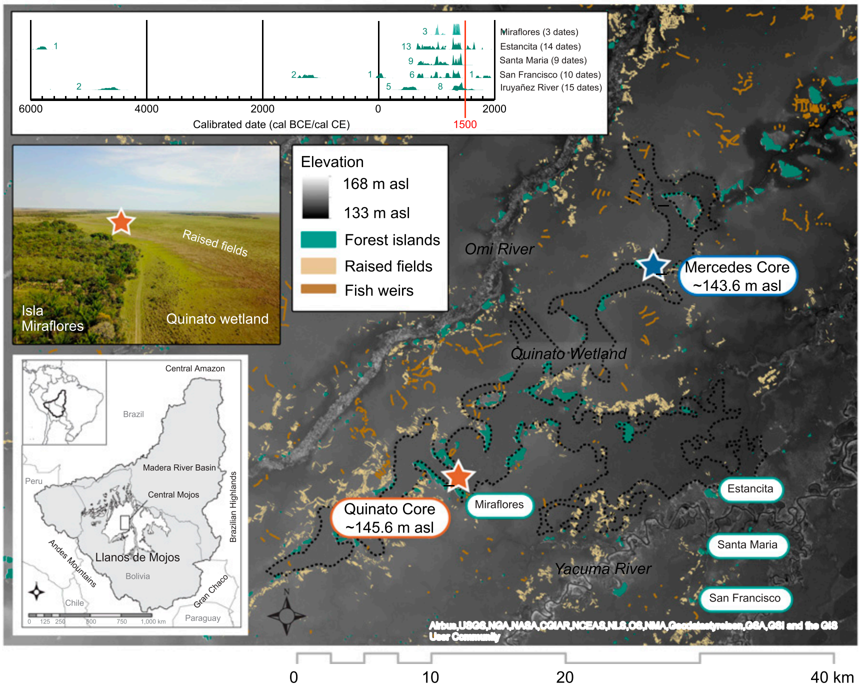

Fig. 1. Location map showing archaeological landscape, excavated forest islands, wetland outline, and core locations. Elevation is taken from SRTM data and represents the top of vegetation rather than the surface of the earth.

models were created using a mixed calibration curve (29, 30) and Bayesian modeling (31). Zoned pollen, phytolith, charcoal, and diatom data are presented in Fig. 2.

Results

ME and QM span 7,500 and 5,160 y, respectively, and phytolith analysis demonstrates that seasonally inundated savanna dominates the records (Fig. 2 and *SI Appendix*, Fig. S8). Both cores demonstrate similar patterns of change in the multiproxy records, where initial conditions are dry or seasonally dry and pollen is poorly preserved, followed by the establishment of a permanent wetland. The onset of intensive fire use, hydrological shifts, and evidence of crop production are broadly coincident in both records. They differ in that these similar sets of changes are separated by a minimum of 1,500 y (taking into account the uncertainties in dating and the resolution of analysis), despite being only 22 km distant, and 2 m different in elevation. Summary descriptions of results are presented below, and detailed figures are available in *SI Appendix*.

ME. The 95-cm core from ME spans the past 7,500 y (5550 BCE). Phytolith assemblages show that seasonally inundated savanna persisted through the record; however, initiation of fire use occurs as early as 4110 BCE (72 cm), inferred from macrocharcoal (12 fragments >250 μm and 241 fragments 125–250 μm per cm^3). Pollen is not well preserved in the lower half of the core, because, initially, conditions in the paleochannel are dry, but flood levels increase between 40 and 36 cm (1750 to 1450 BCE) as evidenced by the appearance of relatively high abundances of centric *Aulacoseira* diatom species, the preservation of pollen in the record, and a transition to more organic sediment between 43 and 36 cm. Crucially, this inferred shift in hydrology is associated with a sharp increase in charcoal concentrations, which began at 44 cm (2080 BCE). Charcoal concentrations peak between 36 cm (1450 BCE) and 28 cm (830 BCE) with extraordinarily high concentrations (>1,000 per cm^3) of large (>250 μm) charcoal fragments. Phytolith evidence of crop taxa, specifically *Cucurbita* and *Zea mays*, accompany this burning signal and were recovered at 1380–950 and 650–320 BCE, respectively. Wetter conditions continue during this period of high fire activity, as evidenced by the presence of *Aulacoseira ambigua* var. *robusta* at 34 cm, a heavily silicified diatom normally found in deep freshwater environments. This diatom species could also be an indicator of silica in-wash (erosion) into the wetlands from the adjoining landscape.

Fire activity lessens following 16 cm (80 BCE), concurrent with a change in relative pollen abundances at 17.5 cm (170 BCE), where arboreal taxa characteristic of forest islands increase. Strong peaks in benthic diatom abundances are commonly reported as being aligned to periods of land clearance for agriculture and erosion (e.g., ref. 32). The upper 7 cm of ME represents the period following 300 CE, possibly due to extremely low sedimentation rates or differential preservation of organic matter during this period. Therefore, detailed changes in landscape management cannot be inferred for this period from ME but are well resolved in the QM core (see below).

QM. This 97-cm core spans the past 5,160 y (3210 BCE) and provides better temporal resolution over the final ca. 1,500 y. As in ME, pollen preservation is poor in the lower half of the core (prior to ca. 500 CE), due to initially dry conditions. Phytolith assemblages show a clear signal of seasonally dry tropical forest occupying the old river channel prior to 1260 BCE (*SI Appendix*, Fig. S8), in line with previous evidence of tree cover under drier conditions in the early to mid-Holocene (33). The disappearance of these local trees is likely associated with rising water tables leading to permanent flooding as diatoms become well preserved in the record by ca. 68 cm (450 BCE). *Eunotia papilio* suggests the onset of wetland conditions, supported by the concomitant appearance of Cyperaceae in the phytolith record.

By ca. 300 CE, the established diatom communities reflect those of the ME core, showing more permanently wet conditions and indicative of in-wash from the surrounding floodplains. Similar to ME, the initiation of pollen preservation, the onset of wet conditions inferred from the diatoms, and the establishment of Cyperaceae co-occurs with a shift in lithology (at 55 cm) from clay to organic sediment. Above 40 cm (from ca. 1150 CE), more deeply flooded conditions and floodwater in-wash into the swamp are indicated by the decline in Cyperaceae phytoliths and corresponding appearance of the aerophilous diatom taxon *Eunotia bilunaris*. As in the ME core, the inferred shift in hydrology co-occurs with the initiation of high charcoal concentrations; the burning signal becomes established at ca. 68 cm (450 BCE) and rises sharply to 56 cm (690 CE), peaking at 44 cm (1050 CE) with >1,000 fragments >250 μm. Although evidence of crops is inconclusive in the phytolith data, *Ipomoea batatas* type pollen (sweet potato) appears in QM at 1150–1420 CE, following the shift to wetter conditions in the swamp, with undifferentiated *Ipomoea* appearing alongside the increase in inferred burning (720 CE).

The temporal resolution of the QM record reveals changes in landscape management associated with the European encounter. Prior to 1450 CE (25.5 cm), the savanna tree *Curatella americana* (1–11%) is abundant relative to modern pollen signatures (34), suggesting that woody biomass was higher than modern in the wider savanna landscape. Following 1450 CE, an increase in arboreal pollen abundances reflects regrowth of forest on the islands due to less intensive land use in these ecosystems. This change, however, is accompanied by a clear decline in *Curatella* pollen (<4%), as land use intensifies in savannas with the introduction of cattle in the 17th century.

Discussion

Our results show a consistent fire signal first at ME, followed by QM 1,500 y later, and demonstrate that integrated landscape management began at least 3,500 y earlier than reported in previous paleoecological interpretations (18, 35–38) (Fig. 3). This evidence places the origins of land use intensification as early as 4100 BCE, which complements and expands upon recent research that shows habitation of forest islands as early as 8900 BCE (38). The significant change in the fire regime is unlikely to have been driven by climate because the South American summer monsoon began intensifying ca. 4000 BCE (39, 40) in western Amazonia, with evidence of precipitation-driven expansion of the southern margin of the rainforest occurring as late as 50 BCE (41); thus the opposite pattern would be expected (less burning) if precipitation forced changes in the fire regime. Charcoal concentrations are linked to quantity of burnable fuel, which is controlled by precipitation (42), but the savannas of the Llanos de Mojos are edaphically determined; thus precipitation and biomass are weakly linked, and increased rainfall would only serve to decrease forest habitat through flooding the flat and impermeable landscape. It is highly unlikely that regional-scale drivers were responsible for the alteration of the fire regime because of the spatiotemporal differences in the establishment of high levels of burning at these two sites. This evidence of burning, combined with the early crop signal from ME phytolith data, strongly point to anthropogenic fire use beginning no later than 1700 BCE, and as early as 4100 BCE.

The first recorded hydrological change at ME is broadly concurrent with the strengthening of the South American summer monsoon in the mid-Holocene. However, as with the fire signal, if regional climate change was the driving factor, hydrological change should have occurred coevally, at two sites located only 22 km apart in the same wetland. Instead, the rising water table occurs a minimum of 1,500 y earlier in ME, pointing again to human modification of the landscape, likely made possible by the greater availability of flood waters for fish and water

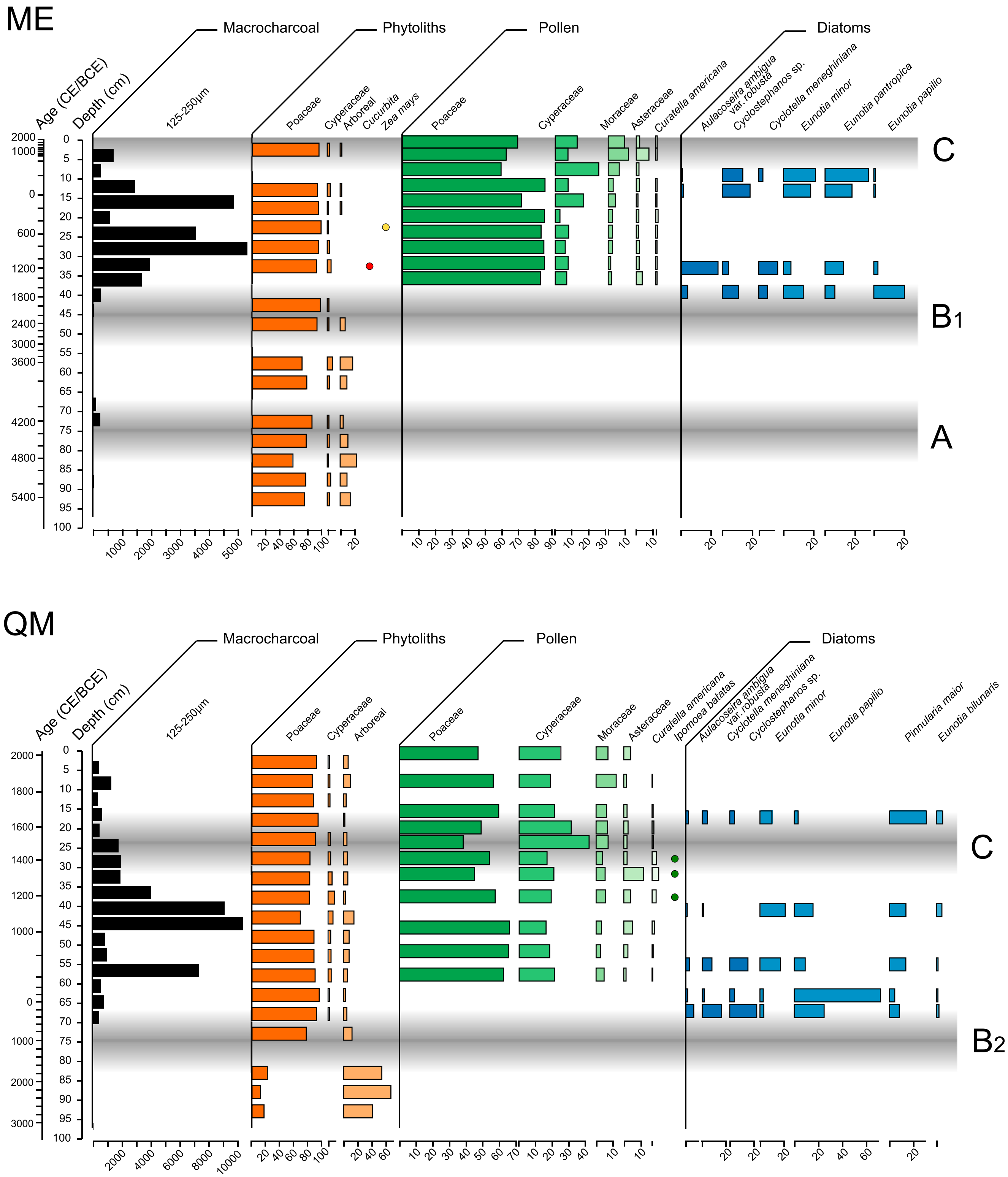

Fig. 2. Synthetic summary proxy diagrams for Mercedes (ME) and Quinato-Miraflores (QM) cores. The gray bars represent periods of broad environmental change across proxies; (*A*) early fire initiation at ME; (*B*$_1$) permanent wetland creation and consistent fire use at ME; (*B*$_2$) permanent wetland creation and consistent fire use at QM; (*C*) European encounter and resulting land use change. Due to low sedimentation rates, events at *C* are represented by few samples at the top of ME Full macrocharcoal (fragments per cubic centimeter), phytolith, pollen, and diatoms (percentage) diagrams are included in *SI Appendix*.

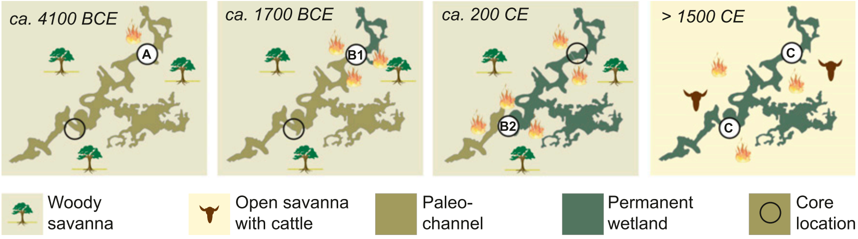

Fig. 3. History of spatiotemporal changes in hydrology, fire use, and vegetation in and around the Quinato wetland inferred from paleoenvironmental data. Letters correspond to transitions in Fig. 2.

management due to precipitation change. Pre-Columbian fish weirs have been widely mapped around the wetland (Fig. 1), which supports our interpretation that the hydrological change at both sites was the result of wetland engineering for aquatic resources (food or industrial). Landscapes of raised fields and fish weirs could have retained water longer into the dry season or drained water more effectively in the wet season. Furthermore, both sites record high levels of fire use around the time of the creation of the wetland conditions, indicating an intensification of land management in the area adjacent to the wetlands. Finally, large raised fields are widespread in the area and near both coring locations. Although the raised fields have not yet been dated as a group, they surround the wetland and present a third line of evidence for the domestication of the landscape by pre-Columbian communities. These combined signals of fire and wetland establishment are indicative of an integrated water- and land-management strategy for mixed economy in the diverse landscapes of the Llanos de Mojos. Evidence of crop production from the phytolith assemblages at ME dating from as early as 1380–950 BCE suggest that nearby raised fields might have been used over the course of three millennia (see also ref. 38).

The Quinato wetland is part of one of seven distinct landscapes in Mojos (16, 43). Evidence from across eastern Bolivia (13, 14, 44, 45) suggests that all of these landscapes were in use during the period from about 300 CE to 1500 CE. Wetlands are often thought of as wastelands or nonhuman spaces, but this was not the case in the Llanos de Mojos, where ethnohistoric evidence describes a wide range of lifeways, oriented around all aspects of the mosaic landscape, including wetlands, for hunting, fishing, and farming (12, 46, 47). Ceramics were well developed and required harvesting sponge for temper, exploiting clay deposits, and collecting firewood (45, 48, 49). Industrial use of plants including palm leaves, rushes, and cotton fiber are evidenced in basket-impressed ceramics, and Mojos groups were famed for their cotton weaving and featherwork. Fire was used for hunting, to flush game out of forest islands to waiting hunters. One group, the Cayuvava, used a distinctive open-ended basket for fishing in shallow water, a technique compatible with the evidence for fishing from Mojos (26, 27). The coordination of activities with the rise and fall of floodwaters, and specific growing seasons for plants and movement patterns for animals, required a granular knowledge of the landscape over the course of the year (14, 50). The diverse economies of the Llanos de Mojos, elucidated through these ethnohistorical and archaeological accounts, were enabled by the domestication of terrestrial and aquatic domains, as demonstrated by our paleoenvironmental reconstruction.

Indigenous depopulation of the Americas following European arrival (1492 CE) led to the reforestation of large parts of the Neotropics (22, 51) and changes in fire regime across ecosystems (52, 53). In the Llanos de Mojos, the arrival of Jesuits, and with them, the introduction of metal tools and cattle, brought fundamental changes to their economies and resource management and extraction, as well as significant impacts on the population and social organization due to disease. The largest change in the pollen assemblages in the QM record occurs ca. 1450 CE (1350–1575 CE), with rising abundance of forest taxa, comparable to the increase in riparian tree flora seen in the environmental reconstruction from the raised fields area of El Cerro between 1400 and 1500 CE (18). The pollen data indicate that increased pressures on savanna occurred alongside this regrowth of arboreal taxa on the forest islands. Changes in these two distinctive vegetation communities implies that the introduction of cattle in the mid-17th century CE, along with the spread of metal tools, led to fundamental shifts in agricultural and pastoral economies, and impacted both the savannas and the forests in the mosaic landscape of the Llanos de Mojos.

Our paleoenvironmental reconstruction demonstrates thousands of years of landscape domestication, particularly changes in the fire regime and hydrology. Precipitation change over the Holocene no doubt influenced these two processes, but did not determine social or economic organization. Instead, communities responded by manipulating and controlling water and fire resources. These landscape modifications were of a sufficient magnitude to obscure a signal of climate-driven change through the Quinato swamp. Broadscale correlations between regional climate change and cultural processes have been widely reported in paleo science, but people interact with environments at a local scale, and it is these detailed reconstructions that are needed to fully comprehend societal response to climate change. The Llanos de Mojos we observe today is not the product of only 300 or 500 y of forest clearance, cattle ranching, and soybean farming. Pre-Columbian peoples on the Quinato wetland used fire, water, and earth to domesticate the landscape over the last 3,500 and probably more than 6,000 y. When this heritage of construction, fishing, hunting, farming, and fire is better understood, modern stakeholders will be better equipped to make informed decisions about this Amazonian landscape.

Materials and Methods

QM and ME cores were extracted from the Quinato wetland using a modified Livingston corer and a floating platform in 2018. Cores were shipped in their polycarbonate tubes to University of Central Florida where they were extracted, described, subsampled, and stored at 0 °C. Bulk sediments were analyzed at Beta Analytic for AMS radiocarbon dating. Age–depth models were created in the R statistical computing environment (54) (R Core Team 2020) using the package Bacon and a mixed (50:50) IntCal20/SHCal20 atmospheric curve (29, 30). Phytoliths were isolated from sediments by microwave chemical digestion (nitric, hydrochloric, hydrogen peroxide) using an Anton Paar Multiwave GO followed by heavy liquid flotation using lithium metatungstate and mounted on slides using Canada balsam. Phytoliths were identified using a Zeiss Axio Imager.A1 microscope at 400× with a reference database (55) and comparative collection. Pollen, charcoal, and diatom samples, measuring 1 cm^3 each were shipped to Northumbria University for processing and analysis. Diatom samples were prepared by digesting organic matter using repeated 20% hydrogen peroxide treatments in a hot water bath. Residues were mounted in Naphrax and identified at 1,000× magnification using a Leica DM2000 microscope. Pollen preparation followed standard chemical digestion (10% sodium hydroxide, 40% hydrofluoric), acetolysis (9:1 acetic anhydride: concentrated sulfuric acid), and dehydration (isopropanol), and mounting in silicone oil. Pollen preparation included an additional sieving stage at 53 μm to concentrate large crop pollen. Pollen was identified using a Leica DM2000 microscope with reference manuals (56, 57) and a comparative collection. Charcoal samples were prepared by disaggregating sediments in 10% sodium hydroxide in a warm water bath, then passing through nested sieves of 250 and 125 μm. Charcoal fragments were identified and counted using a Leica M80 stereomicroscope. All stratigraphic diagrams were produced in R (4.0.2) and RStudio (1.3.1093) using the packages vegan (58) and rioja (59).

Data Availability. All study data are included in the article and/or supporting information.

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1. D. J. Kennett *et al*., Development and disintegration of Maya political systems in response to climate change. *Science* **338**, 788–791 (2012).
2. S. A. Carolin *et al*., Precise timing of abrupt increase in dust activity in the Middle East coincident with 4.2 ka social change. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 67–72 (2019).
3. L. C. R. Silva *et al*., A new hypothesis for the origin of Amazonian Dark Earths. *Nat. Commun.* **12**, 127 (2021).
4. J. G. de Souza *et al*., Pre-Columbian earth-builders settled along the entire southern rim of the Amazon. *Nat. Commun.* **9**, 1125 (2018).
5. K. W. Butzer, G. H. Endfield, Critical perspectives on historical collapse. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 3628–3631 (2012).
6. S. Murray, E. A. Jones, S. Madry, "Resilience of agrarian land use practices in Burgundy, France: Evolving approaches to historical ecology" in *Historical Ecologies, Heterarchies and Transtemporal Landscapes*, C. Ray, M. Fernández-Götz, Eds. (Routledge, 2019), pp. 101–117.
7. T. H. McGovern, G. Hambrecht, M. Hicks, "Historical Ecology and longitudinal research strategies around Lake Myvatn, Iceland" in *Historical Ecologies, Heterarchies and Transtemporal Landscapes*, C. Ray, M. Fernández-Götz, Eds. (Routledge, 2019), pp. 32–42.
8. E. Ostrom, *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge University Press, 1990).
9. J. M. Acheson, "The tragedy of the commons: A theoretical update" in *Global Perspectives on Long Term Community Resource Management*, L. R. Lozny, T. H. McGovern, Eds. (Studies in Human Ecology and Adaptation, Springer International Publishing, 2019), pp. 9–22.
10. G. M. Feinman, D. M. Carballo, "The scale, governance, and sustainability of central places in pre-Hispanic Mesoamerica" in *Global Perspectives on Long Term Community Resource Management*, L. R. Lozny, T. H. McGovern, Eds. (Studies in Human Ecology and Adaptation, Springer International Publishing, 2019), pp. 235–253.
11. E. Nordenskiöld, Urnengraber und mounds im Bolivianischen Flachlande. *Baessler Arch. Beitr. Volkerkd.* **3**, 205–255 (1913).
12. W. M. Denevan, *The Aboriginal Cultural Geography of the Llanos de Mojos of Bolivia* (University of California Press, 1966).
13. C. L. Erickson, "The domesticated landscapes of the Bolivian Amazon" in *Time and Complexity in Historical Ecology*, W. L. Balee, C. L. Erickson, Eds. (Columbia University Press, 2006), pp. 235–278.
14. J. H. Walker, *Island, River, and Field: Landscape Archaeology in the Llanos de Mojos* (University of New Mexico Press, 2018).
15. J. H. Walker, *Agricultural Change in the Bolivian Amazon: Cambio Agricola en la Amazonia Boliviana* (Department of Anthropology, University of Pittsburgh, Pittsburgh, 2004).
16. H. Prümers, C. Jaimes Betancourt, 100 años de investigación arqueológica en los Llanos de Mojos. *Arqueoantropológicas* **4**, 11–54 (2014).
17. U. Lombardo *et al*., Early and middle Holocene hunter-gatherer occupations in western Amazonia: The hidden shell middens. *PLoS One* **8**, e72746 (2013).
18. B. S. Whitney *et al*., Pre-Columbian raised-field agriculture and land use in the Bolivian Amazon. *Holocene* **24**, 231–241 (2014).
19. C. Erickson, J. Walker, "Precolumbian causeways and canals as landesque capital" in *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective*, J. Snead, C. Erickson, A. Darling, Eds. (University of Pennsylvania Press, 2009), pp. 232–252.
20. P. Epps, L. Michael, "The areal linguistics of Amazonia" in *The Cambridge Handbook of Areal Linguistics*, R. Hickey, Ed. (Cambridge University Press, Cambridge, 2017), pp. 934–963.
21. M. Crevels, H. van der Voort, "The Guaporé-Mamoré region as a linguistic area" in *From Linguistic Areas to Areal Linguistics*, P. Muysken, Ed. (Studies in Language Companion Series: 90, Benjamins, 2008), pp. 151–179.
22. A. Koch, C. Brierley, M. M. Maslin, S. L. Lewis, Earth system impacts of the European arrival and Great Dying in the Americas after 1492. *Quat. Sci. Rev.* **207**, 13–36 (2019).
23. B. S. Whitney *et al*., A 45kyr palaeoclimate record from the lowland interior of tropical South America. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **307**, 177–192 (2011).
24. U. Lombardo, Neotectonics, flooding patterns and landscape evolution in southern Amazonia. *Earth Surf. Dyn.* **2**, 493–511 (2014).
25. J. H. Walker, Amazonian dark earth and ring ditches in the central Llanos de Mojos, Bolivia. *Cult. Agric. Food Environ.* **33**, 2–14 (2011).
26. C. L. Erickson, An artificial landscape-scale fishery in the Bolivian Amazon. *Nature* **408**, 190–193 (2000).
27. D. B. McKey *et al*., Present-day African analogue of a pre-European Amazonian floodplain fishery shows convergence in cultural niche construction. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 14938–14943 (2016).
28. M. S. Nardelli, *Diatomaceas (Diatomeae): Descritores Paleoambientais em Lagoas do Pantanal Brasileiro* (State University of the West of Paraná, 2019).
29. P. J. Reimer *et al*., The IntCal20 northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* **62**, 725–757 (2020).
30. A. G. Hogg *et al*., SHCal20 Southern Hemisphere calibration, 0–55,000 years cal BP. *Radiocarbon* **62**, 759–778 (2020).
31. M. Blaauw, J. A. Christen, M. A. Aquino Lopez, rbacon: Age-depth modelling using Bayesian statistics (2020). https://cran.r-project.org/web/packages/rbacon/rbacon.pdf. Accessed 6 December 2020.
32. R. Dickau, J. Iriarte, T. Quine, D. Soto, F. Mayle, Reconstructing pre-Colombian agricultural Practices in the Bolivian savannah: Stratigraphic and phytolith evidence from raised fields at Campo España, western Llanos de Moxos. *Cad. LEPAARQ* **13**, 224–267 (2016).
33. R. Dickau *et al*., Differentiation of neotropical ecosystems by modern soil phytolith assemblages and its implications for palaeoenvironmental and archaeological reconstructions. *Rev. Palaeobot. Palynol.* **193**, 15–37 (2013).
34. L. F. Costa, C. E. Wetzel, H. Lange-Bertalot, L. Ector, D. C. Bicudo, *Taxonomy and Ecology of Eunotia Species (Bacillariophyta) in Southeastern Brazilian Reservoirs* (Bibliotheca Diatomologica, 2017).
35. M. B. Bush *et al*., A 6900-year history of landscape modification by humans in lowland Amazonia. *Quat. Sci. Rev.* **141**, 52–64 (2016).
36. U. Lombardo *et al*., Holocene land cover change in south-western Amazonia inferred from paleoflood archives. *Global Planet. Change* **174**, 105–114 (2019).
37. H. T. Jones, F. E. Mayle, R. T. Pennington, T. J. Killeen, Characterisation of Bolivian savanna ecosystems by their modern pollen rain and implications for fossil pollen records. *Rev. Palaeobot. Palynol.* **164**, 223–237 (2011).
38. U. Lombardo *et al*., Early Holocene crop cultivation and landscape modification in Amazonia. *Nature* **581**, 190–193 (2020).
39. H. Cheng *et al*., Climate change patterns in Amazonia and biodiversity. *Nat. Commun.* **4**, 1411 (2013).
40. J. P. Bernal *et al*., High-resolution Holocene South American monsoon history recorded by a speleothem from Botuverá Cave, Brazil. *Earth Planet. Sci. Lett.* **450**, 186–196 (2016).
41. J. F. Carson *et al*., Environmental impact of geometric earthwork construction in pre-Columbian Amazonia. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 10497–10502 (2014).
42. J. R. Marlon *et al*., Global biomass burning: A synthesis and review of Holocene paleofire records and their controls. *Quat. Sci. Rev.* **65**, 5–25 (2013).
43. J. H. Walker, "The Llanos de Mojos" in *The Handbook of South American Archaeology*, H. Silverman, W. H. Isbell, Eds. (Springer, 2008), pp. 927–939.
44. H. Prümers, "Sitios prehispánicos con zanjas en Bella Vista, Provincia Iténez, Bolivia" in *Amazonía: Memorias de Las Conferencias Magistrales Del 3er Encuentro Internacional de Arqueología Amazónica*, S. Rostain, Ed. (IFEA, FLACSO, 2014), pp. 73–89.
45. C. Jaimes Betancourt, *La Ceramica de la Loma Salvatierra* (DAI, 2012).
46. A. Metraux, *Native Tribes of Eastern Bolivia and Western Matto Grosso* (BAE, 1942).
47. F. J. Eder, *Breve Descripcion de las Reducciones de Mojos (ca. 1772)*, J. M. Barnadas, Ed. (Historia Boliviana, Cochabamba, Bolivia, 1985).
48. J. H. Walker, Regional associations and a ceramic assemblage from the fourteenth century Llanos de Mojos. *Andean Past* **10**, 241–261 (2012).
49. J. H. Walker, Ceramic assemblages and landscape in the mid-1st millenium Llanos de Mojos, Beni, Bolivia. *J. Field Archaeol.* **36**, 119–131 (2011).
50. J. H. Walker, Social implications from agricultural taskscapes in the southwestern Amazon. *Lat. Am. Antiq.* **22**, 275–295 (2011).
51. N. J. D. Loughlin, W. D. Gosling, P. Mothes, E. Montoya, Ecological consequences of post-Columbian indigenous depopulation in the Andean-Amazonian corridor. *Nat. Ecol. Evol.* **2**, 1233–1236 (2018).
52. C. I. Roos *et al*., Fire suppression impacts on fuels and fire intensity in the western U.S.: Insights from archaeological luminescence dating in northern New Mexico. *Fire (Basel)* **3**, 32 (2020).
53. S. Y. Maezumi, B. S. Whitney, F. E. Mayle, J. Gregorio de Souza, J. Iriarte, Reassessing climate and pre-Columbian drivers of paleofire activity in the Bolivian Amazon. *Quat. Int.* **488**, 81–94 (2018).
54. R Core Team, R: A Language and Environment for Statistical Computing (R Foundation for Statistical Computing, 2020).
55. D. M. Pearsall, *Phytoliths in the Flora of Ecuador* (The University of Missouri, 2000).
56. D. W. Roubik, J. Moreno, *Pollen and Spores of Barro Colorado Island [Panama]* (Missouri Botanical Garden, St. Louis, MO, 1991), 36, p. iv-270.
57. P. A. Colinvaux, P. E. de Oliveira, J. E. M. Patiño, *Amazon Pollen Manual and Atlas* (Harwood Academic, 1999).
58. J. Oksanen *et al*., vegan: Community Ecology Package (2020). https://cran.r-project.org/web/packages/vegan/vegan.pdf. Accessed 28 November 2020.
59. S. Juggins, rioja: Analysis of Quaternary Science Data (2020). https://cran.r-project.org/web/packages/rioja/rioja.pdf. Accessed 6 December 2020.