Climate change and culture in late pre-Columbian Amazonia

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Abstract

The long-term response of ancient societies to climate change has been a matter of global debate. Until recently, the lack of integrative studies using archaeological, palaeoecological and palaeoclimatological data prevented an evaluation of the relationship between climate change, distinct subsistence strategies and cultural transformations across the largest rainforest of the world, Amazonia. Here we review the most relevant cultural changes seen in the archaeological record of six different regions within Greater Amazonia during late pre-Columbian times. We compare the chronology of those cultural transitions with high-resolution regional palaeoclimate proxies, showing that, while some societies faced major reorganization during periods of climate change, others were unaffected and even flourished. We propose that societies with intensive, specialized land-use systems were vulnerable to transient climate change. In contrast, land-use systems that relied primarily on polyculture agroforestry, resulting in the formation of enriched forests and fertile Amazonian dark earth in the long term, were more resilient to climate change.

Introduction

The consequences of the European encounter on the indigenous populations of the Americas, following Columbus' landing in Hispaniola 1492 CE, cannot be overstated. Some estimates suggest as much as 90-95% population decline due to epidemics and genocide[1,2]. With a population of up to 10 million inhabitants[3,4] now postulated for Greater Amazonia in late pre-Columbian times, it is likely that the demographic losses following the European contact reshaped landscapes, subsistence practices, socio-political organisations and cultural geographies across the region. Prevailing popular opinion is that indigenous cultures in the Americas were experiencing a trajectory of growth and increasing complexity that was interrupted by the arrival of Europeans, but periods of oscillation with growth, demise and discontinuity are expected to have occurred. In the Amazon, this question remains unresolved. Elsewhere in the Americas, there is mounting evidence of dramatic population declines and climate-driven transformation and collapse of complex societies preceding the Columbian encounter – from the Pueblos of the US Southwest[5], through the Classic Maya in Mesoamerica[6,7], to the Tiwanaku state in the Andean highlands[8,9]. In other parts of the globe, the vulnerability or resilience of ancient societies to environmental degradation have been shown to be mediated by distinct economic practices[10]. Yet, comparatively little is known about pre-Columbian human responses to climate change in the tropical South American lowlands, and whether some land-use systems were more prone to collapse than others.

Here, we explore spatio-temporal patterns of climate and culture change in Amazonia to assess the role of distinct land-use systems in either vulnerability or resilience of past societies to climate change. We review the most significant transformations observed in the archaeological record across six regions where research has been more intensive, chronologies are robust (Supplementary Note 1, Supplementary Tables 1-6), and pre-Columbian land-use patterns are best understood (Figure 1, Table 1). We compare the archaeology of each region with relevant palaeoecology records. To investigate potential natural and anthropogenic drivers of palaeofire (past fire activity), existing charcoal records were compiled into composite regional charcoal curves (RCCs)[11,12] to reconstruct changes in regional scale biomass burning. As a result of the paucity of charcoal records across Amazonia, all charcoal records that occurred within the six study regions were included. Three of the areas had charcoal data available: the eastern Amazon, the southwestern Amazon, and the Llanos de Moxos. RCCs were created for each of these regions and compared with cultural and climate data. In the latter case, they could be used as further proxies for changes in human activity, cultural phases and subsistence strategies considering what is known about pre-Columbian land use in each region. It is expected that changes in fire activity that do not coincide with climate trends (increase or decrease in precipitation) are better explained as resulting from human activity. Given the heterogeneity of local climatic regimes, we consider each archaeological region separately and highlight the broader cultural and climatic patterns that emerged during the late Holocene in lowland South America.

We argue that the broad patterns of land-use change in late pre-Columbian Amazonia can be understood from the perspective of risk management strategies and adaptive cycles. Two principal land-use strategies have been identified among the late pre-Columbian Amazonian societies reviewed here; One involves maximisation and specialisation in "landesque capital" infrastructure, the other focuses on diversification through polyculture agroforestry and long-term anthropogenic soil formation. From the point of view of risk management, maximisation strategies lead to short-term benefits in unstable environments, but result in heavier losses during climatic oscillations, whereas the diversity of low intensity polyculture is more resilient to external stressors. The flexibility, or lack thereof, of these systems explains the decline of some Amazonian societies and not others according to their economic base[13]. We suggest that the societies that collapsed in the face of climate change were approaching the end of an adaptive cycle that progresses through phases of growth, accumulation, restructuring and renewal. These societies had accumulated rigidities, and were less likely to absorb unforeseen disturbances resulting in dramatic transformation[14-16].

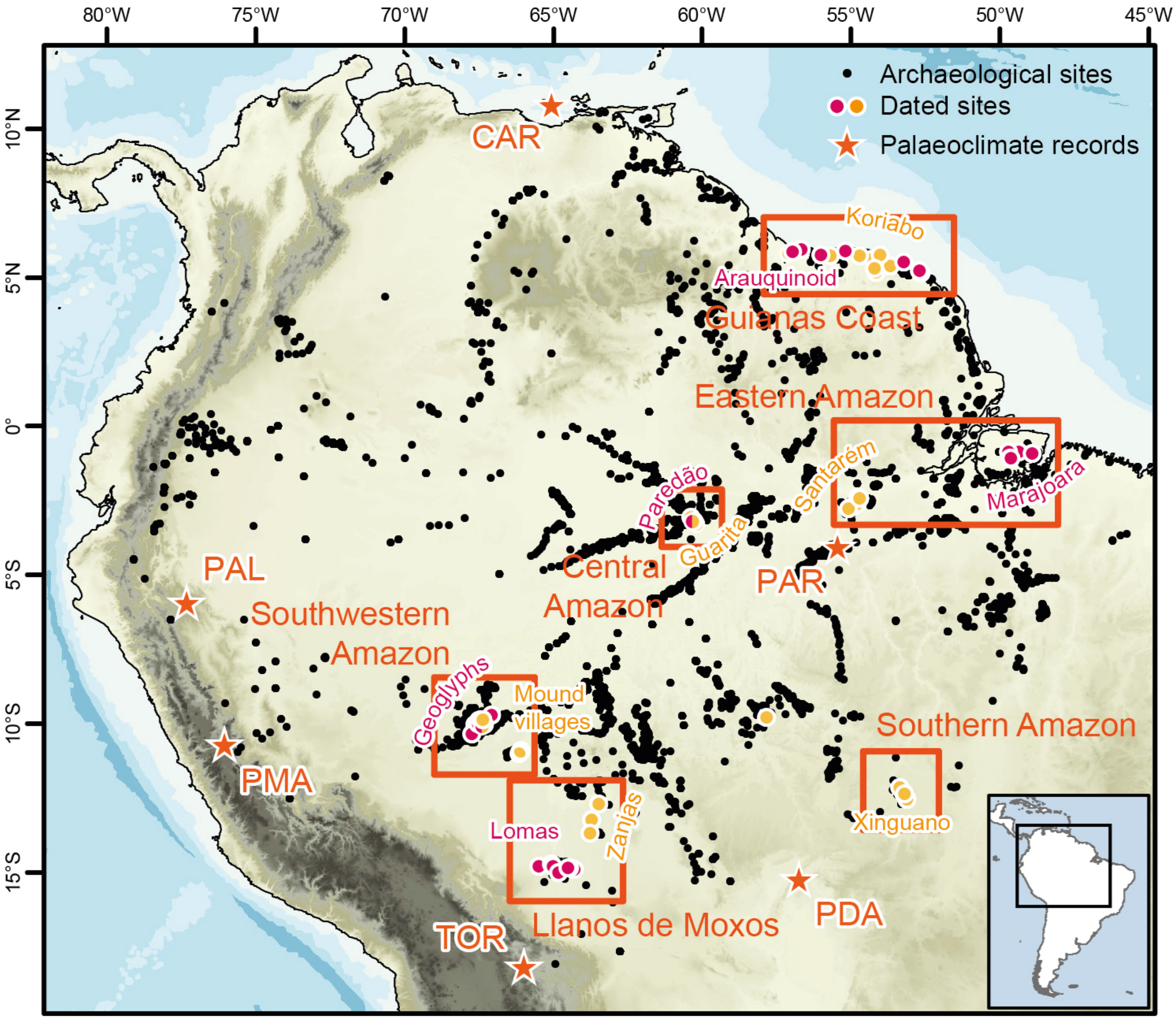

Figure 1. Regions, archaeological sites[17-19] and palaeoclimate records discussed in the text. CAR = Cariaco Basin[20], PAR = Paraíso Cave[21], PMA = Pumacocha Lake[22], TOR = Torotoro[23], PDA = Pau d'Alho Cave[24]. Only the dated sites for the respective regions and cultures are shown. Colours of dated sites corresponds to different regional archaeological cultures as they appear in Figure 3, and these are identified by labels using the same colour scheme. Dots with more than one colour represent multicomponent sites (occupied by more than one culture).

Region	Archaeological tradition	Time period	Socio-political organisation	Land use	References
Guianas Coast	Arauquinoid	650-1400 CE	Settlement hierarchy of residential and ceremonial mounds, well-defined chiefdom	Raised fields for cultivation of maize, *Cucurbita*, manioc.	[25-28]

			territories.		
	Koriabo	1000-1600 CE	Reoccupation of earlier sites	Possible ADE.	25,29
Eastern Amazon	Marajoara	500-1200 CE	Settlement hierarchy of residential mounds, elite burials and prestige ceramics.	Ponds for aquaculture, no evidence of maize.	30-32
	Santarém	1050-1650 CE	Settlement hierarchy is debated.	ADE polyculture, cultivation of maize, *Cucurbita*, manioc and sweet potato.	33-38
Central Amazon	Paredão	750-1250 CE	Permanent mound villages.	ADE polyculture, cultivation of maize, yam, *Cucurbita*.	39-42
	Guarita	1200-1600 CE	Smaller settlements, rapid pan-Amazonian expansion.	ADE.	43,44
Southwestern Amazon	Geoglyphs	400 BCE - 950 CE	Vacant ceremonial centres.	Small clearings in bamboo forest, cultivation of maize and squash.	32,45-48
	Mound villages	1000-1650 CE	N/A	N/A	49
Llanos de Moxos	Lomas	450-1400 CE	Settlement hierarchy of residential mounds, elite burials.	Drainage canals and reservoirs, savanna burning, cultivation of maize, manioc, yam, squash, peanuts, cotton.	50-56
	Zanjas	1200-1500 CE	Fortified sites.	Savanna burning, cultivation of maize.	54,57-60
Southern Amazon	Xinguano	1050-1650 CE	Fortified settlement network, political-ceremonial	ADE.	61-63

			hierarchy.		

Table 1. Time span and main characteristics of the archaeological cultures discussed in the text. For a complete list of the radiocarbon dates, see Supplementary Tables 1-6.

BOX 1: Synthesis and Integration of the Data

Palaeoprecipitation: Metal concentration and oxygen isotopes, which respond to rainfall intensity and strength of the South American Summer Monsoon (SASM) respectively, were used as proxies for past precipitation. We selected the records with the highest resolution that were most representative and closest to the archaeological sites of the six selected regions. **Palaeofire:** Where sufficient data were present, existing lake sediment charcoal records were compiled using standard methodologies (see Supplementary Methods), to create regional charcoal curves to assess changes in past biomass burning with relative changes in climate, cultural phases and land use strategies. **Cultural change:** Periods of cultural change have been identified based on discontinuities in material culture (ceramic typologies) and in the architecture, size and distribution of settlements. These are thought to reflect either the replacement of one population by another or deep transformations within the same society over time. Figure 3 compares the chronology of cultural changes with the palaeoprecipitation records of each region discussed in the text.

Climate dynamics in the Amazon

Annual and daily temperature variability is low across the Amazon basin. Mean annual temperatures vary between 18 and 23°C. Rainfall over the Amazon Basin is sourced from two convective systems: the Intertropical Convergence Zone (ITCZ) and the South American Summer Monsoon (SASM). The ITCZ is characterised by a tropical belt of deep convective clouds that provide a high amount of precipitation[65,66]. Seasonally, the ITCZ migrates towards the hemisphere that is warmest relative to the other. Over the Americas, the ITCZ migrates from approximately 9°N in the austral winter to approximately 2°S in the austral summer. However, a positioning of the ITCZ further south has been documented by palaeoclimate records[67]. The SASM is the main convective system over South America, and its intensity is closely related to the position of the ITCZ, with southward migrations of the ITCZ increasing the advective moisture carried by the SASM. During the austral summer, the South American continent experiences warmer conditions relative to the Atlantic Ocean, which favours the entry of moisture into the continent in association with the southward displacement of the ITCZ, ultimately resulting in a wet monsoonal season.

High convection over the SASM domain is also associated with the formation of the South Atlantic Convergence Zone (SACZ), which is an internal structure of the SASM characterised by a NW-SE band of convection that extends from the centre of convection to eastern Brazil. As the ITCZ, the SACZ migrates, though in a SW-NE axis due to the adjustment of atmospheric cells over the continent. The migration of the SACZ creates a rainfall dipole at the borders of the monsoon, resulting in a climatic antiphase between western and eastern Amazon Basin[68].

Palaeoclimate records

To characterise the palaeoclimatic conditions over the six regions that we review, we used the following palaeoclimatic archives: metal concentration (%Ti) from the sedimentary record from the Cariaco Basin[20] and oxygen isotope ($\delta^{18}O$) records from the Pumacocha Lake sediment core[22] and stalagmites collected at Paraíso[21], Pau d'Alho[24] and Torotoro[23] cave systems (Supplementary Methods).

All records document that climatic conditions were different over the Amazon during the periods known as the Medieval Climate Anomaly (MCA) ~900-1250 CE and the Little Ice Age (LIA) ~1450-1850 CE[70] (Figure 2). During the MCA period, the ITCZ was shifted to the north of its current range, resulting in wet conditions over the Cariaco Basin and Paraíso cave and dry conditions in most of the remaining sites[69] with the exception of Torotoro[23]. The LIA period, in contrast, was characterised by dry conditions east of the SACZ (Paraíso Cave) and wet conditions west of the SACZ (Pumacocha Lake), with regions in between (Pau d'Alho Cave) not showing significant anomalies[68].

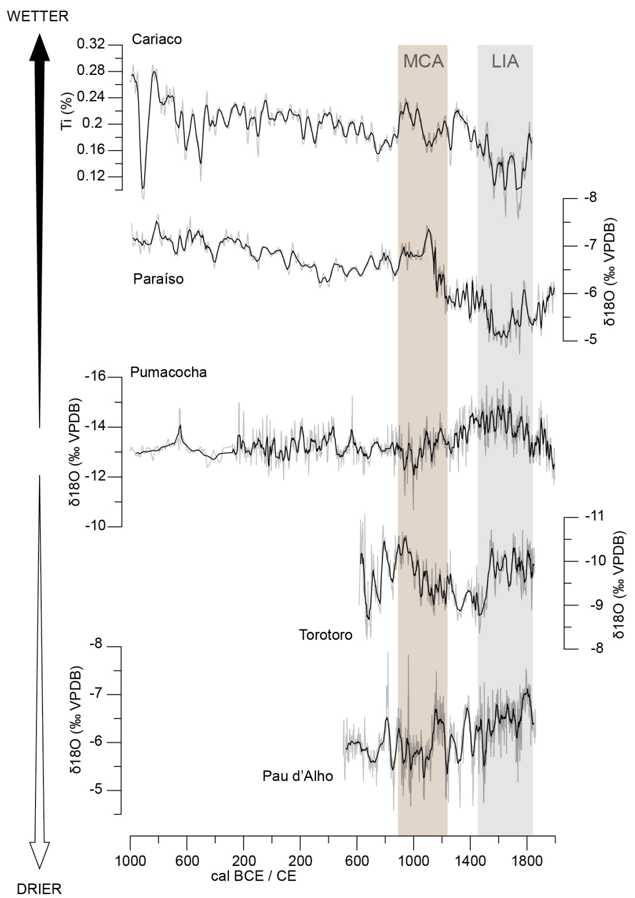

Figure 2. Palaeoclimate records discussed in the text (see location in Figure 1). MCA and LIA intervals are highlighted, demonstrating the antiphase between north and south of ITCZ and between western and eastern Amazon.

The rise and fall of late pre-Columbian Amazonian cultures

In what follows, we describe the most significant ruptures and transformations seen in the archaeological record of the six chosen regions. We focus on changes in settlement patterns and land use, when these are known, directing the reader to the Supplementary Discussion for a summary of the material culture (ceramic typologies) associated with each culture.

Guianas Coast. In this region, the most important transition in late pre-Columbian times is the breakdown in socio-political complexity of the coastal Arauquinoid societies, concomitant with the expansion of the unrelated inland Koriabo tradition, marking a significant cultural transformation in the Guianas coast, ca. 1300 CE (Figure 3a). From Suriname to French Guyana, the Arauquinoid terraformed entire landscapes in the coastal savannas starting ~700 CE[25,26]. Over 600 complexes of raised fields covering ~3000 ha exist in French Guyana[25]. Phytolith, starch grain and stable isotope evidence documents the cultivation of maize, squash and manioc in the raised fields[27,28]. A survey of charcoal records across the Guianas, however, did show an increase of fire activity ~1000-2000 BP, confirming that modern closed-canopy forests were subject to burning in the past[71]. Given the general trend of decline in the charcoal record across the Americas after the Columbian encounter[72], it is likely that fire was a widespread form of land management in the past, with some local and specific productive systems, such as the raised fields in the savannas, representing an exception.

At the peak of the Arauquinoid occupation, the coast was divided into territories of major sites and associated satellite settlements. In western French Guyana and Suriname, central places took the form of large platform mounds serving ceremonial and domestic functions[25,26]. Large residential mounds were surrounded by a network of roads and agricultural earthworks that extended for up to 5 km, with an estimated population of over 1000 inhabitants[25]. Archaeological research points to coastal Arauquinoid cultures as organised in well-defined chiefdom territories, some of which were economically specialised, such as in the production and circulation of greenstone figurines[73]. Status differences, however, are not evident in other cultural domains, such as funerary treatment[26].

The disruption of the Arauquinoid regional organisation took place after ~1300 CE. This was a period of major upheavals marked by the spread of the Koriabo tradition, bringing an abrupt discontinuity with the previous mound builders in terms of settlement patterns and material culture. The earliest Koriabo sites are inland, suggesting a progressive settlement expansion towards the coast. Pottery is remarkably homogeneous across the Koriabo territory and may have spread with a rapid demographic expansion or through adoption of the style as a trade ware[25,29]. Synchronicity between the Arauquinoid demise and the Koriabo expansion is clear across the Guianas Coast, especially along its western extent, where Arauquinoid earthwork density and complexity had been highest, whereas in the eastern sector there is Arauquinoid continuity, interaction and emergence of new hybrid traditions during the centuries before contact with Europeans. Koriabo ceramics are found in eastern Barbakoeba (Arauquinoid) sites and vice-versa, at the same time that the Thémire culture emerged from a local Arauquinoid background incorporating stylistic influences from the Aristé (polychrome) pottery, also in expansion[25].

Climate change, documented in the Cariaco Basin record, could have been the ultimate driver of the Arauquinoid decline (Figure 3a). The raised fields associated with the Arauquinoid culture provide better drainage and moisture retention, allowing increased agricultural production in a region subject to a long rainy season and severe dry season, as is the case of the Guianas coast[74]. If the agricultural system was designed for and reliant on predictable seasonal precipitation, it is likely that the subsistence base of the Arauquinoid societies was vulnerable to climate instability, and in particular, prolonged drought. The decline of the mound centres ~1300 CE could have been instigated by the prolonged droughts documented in the palaeoclimate records. Alternatively, pressure from the Koriabo expansion itself could have been responsible for conflicts leading to the Arauquinoid demise, or at least accelerating a process triggered by climate change. This is reinforced by the expansion, at the same time, of influences of the Polychrome tradition, the same cultural horizon of the Guarita in Central Amazon (see below), that deeply affected the Aristé culture of eastern Guiana[25].

Eastern Amazon. The eastern Amazon region experienced major transformations in late pre-Columbian times, highlighted by the histories of two prominent cultural areas: the decline of complex polities on Marajó Island, and the rise of Santarém culture in the lower Tapajós (Figure 3b).

One of the best documented archaeological cultures of the Amazon developed on Marajó Island after ~400 CE. Beyond the elaborate polychrome Marajoara pottery, numerous habitation mounds are found in the island's flooded savannas. Mounds reached ~3 ha in area and 7 m height and probably supported multiple perishable structures, with archaeological remains including prepared floors and domestic features. Population estimates are of up to 2000 for a mound group[30,31]. Unlike the Arauquinoid, there is no evidence that the subsistence of the Marajoara depended substantially on cultivated plants. Macro-botanical remains of maize are absent[30] and human bone isotopic values indicate a diet based on non-domesticated C_3 plants and aquatic resources[75]. Earthworks associated with residential mounds include ponds for management of aquatic fauna[31]. Evidence from settlement patterns, artefact assemblages and burial practices suggests that a stratified society was in place at the peak of the Marajoara phase ca. 700-1100 CE. The elite lived on the largest mounds, controlling access to prestige ceramics and water-management systems[30,32,76]. Cemeteries with polychrome funerary urns and feasting grounds are found exclusively on elite mounds, and include infant burials with exotic goods and other prestige artefacts[30,31]. Mound clusters across the island potentially represent several competing chiefdoms whose territories are also delimited by distinct regional ceramic styles[31].

The disintegration of the Marajoara chiefdoms ~1200 CE overlaps with the introduction of unrelated ceramics that mark abrupt changes in settlement patterns and material culture. Mound use declines, hierarchies between settlements disappear, elaborate urn burials are gradually abandoned, and the polychrome Marajoara style becomes intermixed with foreign traditions[31,77]. The historical Aruã people of Marajó, descendants of these latecomers, were described as nomadic foragers, mostly restricted to the island's coast[30]. Their arrival at the island during the disintegration of the chiefdoms has led to suggestions that the Aruã may have played a role in the Marajoara demise[31]. As in the Arauquinoid case, it is possible that, if the arrival of outsiders did not cause the fall of the Marajoara chiefdoms, it at least contributed to a process initiated by climate deterioration.

While the Marajoara culture was in decline, another was flourishing in the lower Tapajós River. The Santarém culture, archaeologically known for its elaborate effigy vessels, was established after ~1100 CE and had its epicentre at the modern city of Santarém. Comprising an area of ca. 23,000 km² with some of the highest population densities of the pre-Columbian Amazon, over a hundred Santarém sites have been recorded, extending for hundreds of miles along river bluffs and interior plateaus. Historical accounts describe the lower Tapajós polity as a centralised chiefdom with a "noble class"[33,34] but there is little archaeological evidence of social stratification[35-37]. Virtually all sites are composed of anthropogenically modified Amazonian Dark Earth (ADE), the largest of which were initially established in the floodplains, with smaller settlements later moving to the upland areas[36]. The ubiquity of ADEs is exemplified by the city of Santarém, estimated to contain 500 ha of these soils[33,34,37,78,79], although only 16 ha are occupied by the core of the pre-Columbian settlement[36]. Recent pollen and phytolith data suggest the cultivation of maize, sweet potato, squash and manioc combined with the enrichment of edible forest species[38]. These data suggest the Santarém subsistence economy relied on a diverse land-use strategy based on polyculture agroforestry[38].

The Paraíso cave speleothem record provides a high-resolution proxy for precipitation changes in eastern Amazon[21,80] (Figure 3b). A marked increase in $\delta^{18}O$ values following ~1100 CE shows that the dissolution of the Marajoara chiefdoms occurred during a time of decreased precipitation. The relationship between decreased river discharges linked with increased water salinity and the decline of the aquaculture-based Marajoara chiefdoms during this period has previously been suggested based on pollen data[81]. The close association between high-status mounds and reliance on water-management facilities has been interpreted in terms of monopolisation of resources and surplus production by the elite[31]. Therefore, the land-use strategies that sustained the Marajoara chiefdoms would have been sensitive to prolonged droughts. During the same period, however, archaeological data indicates that the Santarém culture flourished in spite of the drier conditions. The regional charcoal curve for eastern Amazon shows an increase in fire activity synchronous with the rise of the Santarém culture and the decline of Marajoara chiefdoms. Previous research suggests the changes in regional scale fire activity during the apex of the Santarem culture were attributed to human opposed to climate drivers[38] (Figure 3b). As will be discussed at the end of the paper, we suggest that the flourishing of Santarém in spite of climate change may be explained by greater resilience offered by an economy based on polyculture agroforestry[38].

Central Amazon. At the confluence of the Negro and Solimões rivers, crucial transformations in the millennium preceding the European contact saw the demise of mound villages and their replacement by smaller sites of the polychrome tradition, lacking earthen architecture (Figure 3c). The large villages of the Paredão phase, containing mound architecture, emerged after ~700 CE as a local development of the Incised-Modelled ceramic tradition[43]. Rings of house mounds at Paredão sites surround a central plaza, showing a well-planned village layout, sometimes with multiple mound circles[39-41]. Sites contain thick layers of ADE, eventually reworked for the construction of residential mounds[82]. The recovery of phytoliths of maize, yam, squash and *Bactris* palm, coupled with archaeobotanical evidence of managed forests in the sites' catchment suggest a subsistence strategy of polyculture agroforestry associated with the development of fertile ADE soils[42] similar to that employed in Santarém. Ultimately, Paredão sites were replaced by smaller, ephemeral and amorphous or linear settlements with polychrome Guarita ceramics[44]. This was a pan-Amazonian tradition that originated from the southwestern part of the basin ~750 CE and spread rapidly throughout the Amazon[83]. In central Amazon, the appearance of polychrome ceramics coincides with the beginning of the disintegration of the Paredão complex ~1000 CE. After ~1200 CE the Paredão mound villages are fully replaced by Guarita polychrome occupation[40]. The homogeneity in polychrome ceramics of western-central Amazon, in conjunction with their rapid spread, appear to point to demographic expansions[43]. Alternatively, it is possible that the style was diffused as a prestige technology among groups with access to floodplain resources as is the case with modern polychrome ceramics in the upper Amazon[84]. What is clear is that the process of transition from Paredão to Guarita polychrome does not appear to have been a peaceful one, as evidenced by defensive ditches and palisades built around Paredão sites which are later reoccupied by the Guarita tradition[43,44].

Comparing the cultural changes in central Amazon with climatic events is a challenge given the absence of local palaeoclimatic records and the fact that the region lies in the middle of an east-west precipitation dipole[80]. As in the case of the Marajoara, the decline of Paredão mound villages coincides with a drier period starting after ~1100 CE in the eastern Paraíso record[21] (Figure 3c). However, it is unclear whether a similar change to drier conditions would have manifested in the central Amazon. Palaeoclimate records including Pumacocha Lake[22] in the Andes and Palestina Cave[85] in western Amazonia, are recurrently antiphased with the eastern records. These proxies show a period of marked drought (increased $\delta^{18}O$) during the MCA period, followed by strengthening of the monsoon reflected in more negative $\delta^{18}O$ values during the period corresponding to the LIA[24,69,86]. Given the western origin of the polychrome expansion, the MCA drought could have been one of the drivers of the Guarita incursions towards eastern Amazon, ultimately leading to the demise of the Paredão villages.

Southwestern Amazon. Starting ~400 BCE, a large portion of the southwestern Amazon was transformed into a dense ceremonial landscape populated with large-scale geometric enclosures known as geoglyphs[45,47,48]. Over 500 geoglyphs have been recorded in a recently deforested area of ~20,000 km^2. They are characterised by large dimension, architectural complexity and geometric symmetry. Geoglyphs combine square and circular contiguous ditches surrounding areas of 1-3 ha with walled enclosures, avenues and other earthworks. The low ceramic density, presence of votive deposits inside the ditches, and lack of occupation debris associated with the enclosures suggests the geoglyphs were public spaces used for repeated gatherings and communal feasting, rather than permanent settlements[32,46,47]. Geoglyphs are often associated with bamboo forests and appear to have been constructed to take advantage of this easy-to-clear vegetation[87]. In spite of the grandeur of the earthworks, there is no evidence of large-scale clearance beyond their immediate vicinity[48]. Nothing is known about the domestic sites of the geoglyph builders, but the absence of size-hierarchies and relative spatial regularity of the geoglyphs suggests populations were likely dispersed[32,45,88]. These populations were also likely practising polyculture agroforestry, as phytolith evidence from the ceremonial centres points to the consumption of maize and squash combined with the management of palms[48]. The formative ceremonial network of the southwestern Amazon was dissolved after ~1000 CE and replaced by a new architectural tradition in the form of smaller mound villages, sometimes built on top of or adjacent to earlier geoglyphs (Figure 3d). This discontinuity is also visible in the ceramics recovered from mound villages, which differ markedly from those of the earlier earthworks[89]. Unlike the ceremonial geoglyphs, the later sites are settlements, incorporating living floors separated by construction episodes of mound expansion[49]. Numerous carbonised macro-botanical remains have been recovered from mound habitation strata, including Brazil nuts, palm seeds (*Attalea* and *Euterpe*) and maize kernels, suggesting the persistence of polycrop cultivation at the sites[49].

The termination of geoglyph construction and use coincides with an increase in $\delta^{18}O$ values observed during the MCA period at Pumacocha Lake and Palestina Cave, indicating a weakening of the monsoon and consequent decrease of precipitation over the Andes and western Amazon[22,85] (Figure 3d). Other palaeoclimate records from the Andean slopes/western Amazonia show a double peak in $\delta^{18}O$ values with precipitation minima at ~940 and 1025 CE[22,85,90]. Any causal relationship between drought during the MCA and the cessation of construction of new ceremonial enclosures must remain tentative, given that the settlement patterns of the geoglyph-builders are poorly understood, but the temporal coincidence between the two events is remarkable. Variability in the RCC from southwestern Amazon is synchronous with changes in precipitation showing the largest increase in regional burning associated with the driest period of the MCA (~900 to 1100 CE; Figure 3d), prior to the earliest dates for the mound villages. These data suggest that climate is the first order driver of regional scale fire activity in the southwest Amazon. However, anthropogenic ignitions may have contributed to regional burning during the transition from geoglyphs to mound villages during the MCA associated with increased land clearance for the construction of new sites. However, site construction and regional burning are inversely correlated as conditions get progressively wetter during the LIA, further supporting the interpretation that climate opposed to anthropogenic ignitions was the first order control for regional scale fire activity.

A strengthening of the monsoon is documented in the Pumacocha record over the following centuries[22,85], coinciding with the development of mound ring villages. Ceramics from the latter differ from the ceramics of the geoglyphs, although whether they represent intrusion from a foreign tradition rather than a local development is yet to be resolved. If the latter is the case, the situation of Southwestern Amazon could be similar to the Guianas, Central Amazon and Eastern Amazon in that waves of migrants may have been a factor contributing to the decline of local cultures, beyond climate change.

Llanos de Moxos. The flooded savanna-forest mosaics of the Llanos de Moxos extend over a vast area of 150,000 km^2 and are one of the most intensely modified landscapes in Amazonia[91]. Different regions of the Llanos de Mojos experienced major cultural transformations at the eve of the European contact, from the abandonment of large habitation mounds in the south to the emergence of fortified settlements in the northern part of the Moxos (Figure 3e).

Monumental Mound Region

The monumental mound region, located in the surroundings of the modern city of Trinidad, Bolivia, is characterised by habitation mounds or *lomas* up to 21 m high and 20 ha in fertile area that started to be built ~400 CE[50]. Such sites are part of a broader network of earthworks including surrounding walled enclosures and causeways connecting the settlements, as well as drainage and irrigation canals[50,53,54]. Agricultural raised fields, ubiquitous elsewhere in the Llanos de Moxos, are absent, which has attributed to the relatively good natural drainage in this region[51,52]. Cultivation of maize, manioc, yam, squash, peanuts and cotton has been evidenced by phytoliths, fossil pollen grains and macro-botanical remains[55,56]. Beyond the construction of canals, presumably for drainage of cultivated areas[51], pre-Columbian land use in the monumental mound region also involved more extensive burning of the savannas than was practised in historical times[55]. Funerary evidence points to a highly stratified society, with lavish burial goods reserved for few individuals[53,54]. A hierarchical organisation of sites has also been noticed, with the largest *lomas* placed on important nodes in the network of causeways[50]. The abandonment of this system ~1400 CE precedes contact with Europeans and is accompanied by changes in land use with the decline of savanna burning[55].

Ring Ditch Region

Around 1200 CE, when the large habitation mounds near the more southern city of Trinidad were in decline, settlements surrounded by ditches known as *zanjas* began to emerge in the northern portion of the Llanos de Moxos, near modern-day Iténez and Baures, Bolivia. Not to be confused with geoglyphs, *zanjas* exhibit irregular layouts and clear evidence of habitation, including house floors, domestic debris, and urn burials[54,57-59] most of which are absent from the geoglyphs. Ditches enclosing settlements are part of broader compounds of canals and other earthworks that connect different sites[54,59]. However, there is no evidence of a regional hierarchy of sites comparable to that of the *lomas*. Phytolith and pollen evidence show that maize was cultivated and heavy burning was practised in the surrounding area, maintaining an open savanna environment around the sites during a period of forest expansion[58]. *Zanjas* are likely the archaeological correlates of fortified settlements described in historical times, attributed by the early chroniclers to increased warfare provoked by incursions from the Guarayos, a Tupi-Guarani-speaking group[60].

Insights on past climate change in the Llanos de Moxos can be gained from the Umajalanta-Chiflonkhakha caves speleothem records in the Torotoro Park, tropical slopes of the Bolivian eastern Andes[23] (Figure 3e). Importantly, changes in precipitation documented in this region are antiphased with those observed further north[23]. Notably, the depleted $\delta^{18}O$ values observed during the MCA show an anomalous wet period when compared to other records influenced by the SASM[23]. Although this period of drought coincides with an increase in fire activity documented in the RCC (Figure 3b), the latter could also be explained by forest clearance practised by the inhabitants of the *zanjas*[58]. Previous studies have argued that pre-Columbian fire management in the *zanjas* was used to clear agricultural lands from encroaching forests in response to the orbitally driven southward migration of the rainforest ecotone[92].

The abandonment of the *lomas* took place in the centuries between the MCA and the LIA, during which time conditions of prolonged drought reached their peak ~1300-1500 CE. This is in agreement with a trend of increased aridity recorded in Lake Titicaca's water levels[93] and documented in the Quelccaya ice cap[94], possibly linked to the collapse of the Tiwanaku state in the Lake Titicaca basin[8,9,95]. We argue that the same effects were felt in the Llanos de Moxos lowlands. In the monumental mound region, earthworks such as canals were possibly more important in the mitigation of seasonal floods than water retention for irrigation[96], suggesting that those societies might have been more resilient to conditions of increased precipitation than to droughts. Unlike the previous case studies, the abandonment of the sites does not seem to be followed or caused by the arrival of foreign cultural traditions to the same locale, reinforcing the predominant role of climate change. However, concomitant with the demise of the *lomas*, and potentially related to their abandonment, settlements further north began to be enclosed by defensive ditches, signalling the onset of a state of endemic warfare that lasted until colonial times[97].

Southern Amazon. The transitional forests of the southern Amazonian periphery demonstrate important cultural developments preceding the European encounter. This region was densely settled with enclosed sites and other earthworks. The best studied example is the network of fortifications and roads in the upper Xingu (Xinguano Tradition).

After ~1100 CE, habitation sites in this region were remodelled with the addition of multiple ditches, walled plazas and causeways (Figure 3f). Large, architecturally complex settlements constitute the hubs of a network of roads extending for ~20,000 km^2 that connect them to regularly-spaced smaller villages, apparently reflecting independent regional polities[61-63]. The largest sites, over 20 ha, contain extensive ADE, occupation debris, house floors and middens, and are estimated to have had a population over 2500 inhabitants[63]. The Xinguano system was probably heterarchical, revolving around political-ceremonial centres rather than a chiefdom-like organisation. Ditched enclosures associated with ADE in the Tapajós headwaters further to the west demonstrate spatial continuity from the upper Xingu to the Bolivian *zanjas*[98]. Together, these data indicate that the development of fortified sites must be understood as a large-scale phenomenon characterising the southern Amazon.

The $\delta^{18}O$ record from the Pau d'Alho cave speleothem documents oscillations in the intensity of the SASM in western and central Brazil for the past 1500 years[24] (Figure 3f). Trends observed at Pau d'Alho are reflected elsewhere in central Brazil and appear to be related to shifts in the mean position of the South Atlantic Convergence Zone (SACZ)[68]. Regions under significant influence of the SACZ do not show the same departures from the mean state of the monsoon during the MCA and LIA as western Amazonia or eastern Brazil, but rather a strong multi-decadal to centennial-scale variability in the transition between those two periods, attributed to variations in solar irradiance[24,68,99]. It was during this period of increased climatic volatility that the fortification network of the upper Xingu was established. Fortifications emerged elsewhere under different conditions. In the Llanos de Moxos, *zanjas* appeared during an episode of drought and regional abandonment of the *lomas*, suggesting a decisive climatic driver that may not have existed in southern Amazonia. Overall, we argue that defensive structures must be understood in a broader context of increased warfare in Amazonia, whether or not related to climate change.

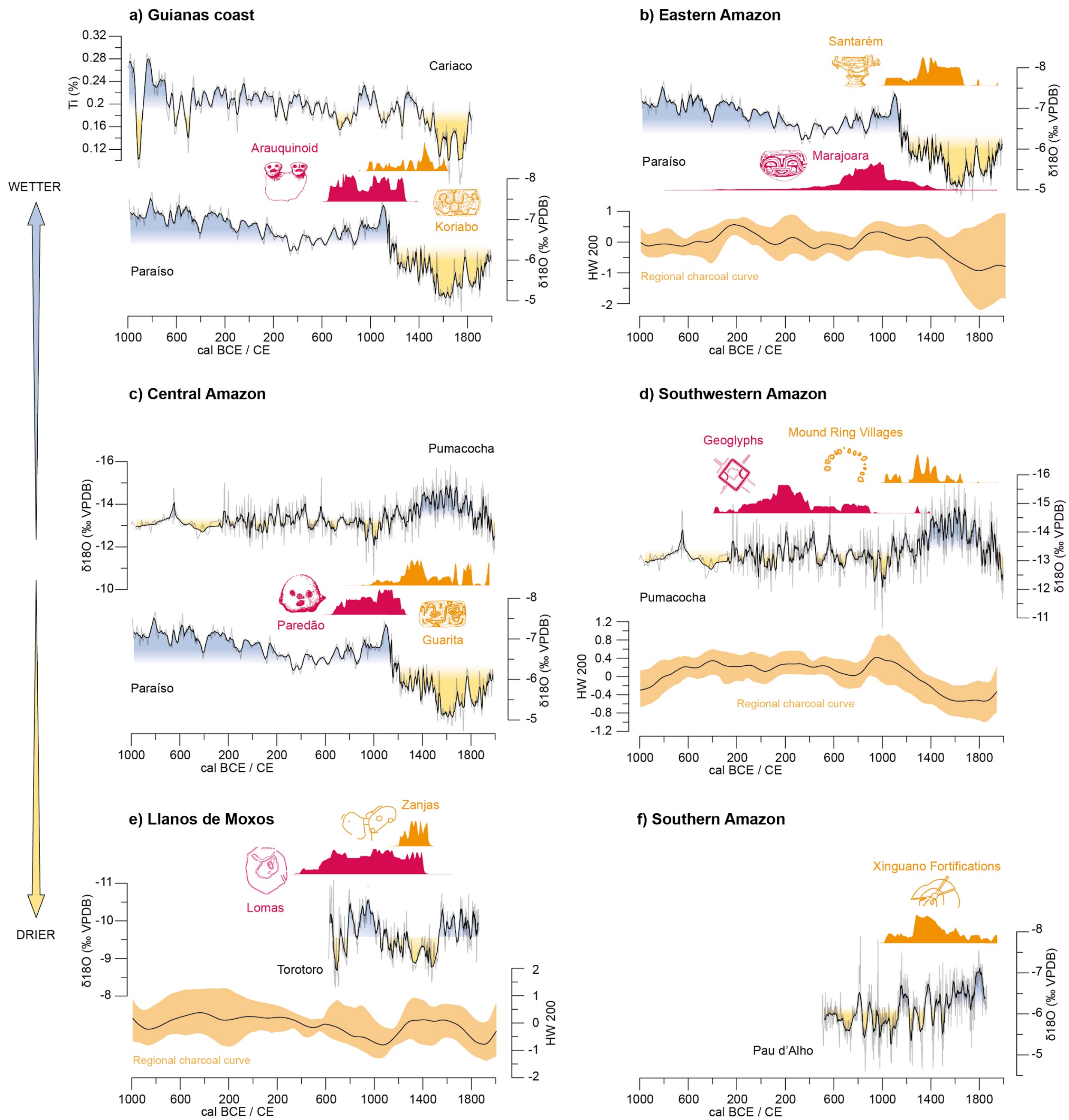

Figure 3. Periods of cultural change and palaeoclimate records for six regions of Greater Amazonia, and regional charcoal curves from the best sampled regions (Supplementary Methods). The duration of each archaeological culture is represented by summed calibrated probability distributions (SPDs) of the radiocarbon dates (magenta and orange lines) (Supplementary Tables 1-6, Supplementary Note, Supplementary Methods). The "wetter" and "drier" arrows refer to the interpretation of the palaeoprecipitation records. For location of each region and palaeoclimate record, see Figure 1. For location of charcoal records, see Supplementary Figure.

Discussion

Early attempts to relate climate and cultural change in Amazonia postulated a deterministic link between environment and human societies[100]. The view that the environment imposed limitations to cultural development in the tropics was increasingly refuted by archaeological evidence of dense populations and complex societies in Amazonia, starting in the 1960s[101] and continuing today[3,98]. Due to this paradigm shift, potential correlations between climate change and cultural transformations were not thoroughly explored, as the topic may be perceived to evoke outdated deterministic views. Here, we have shown that temporal synchronicities between climate and cultural change can be identified in the tropical South American lowlands. Elsewhere in the Americas, periods of abrupt change in the archaeological record have been shown to coincide with extreme climatic events[102,103]. In Amazonia, however, the causality of these cultural changes is more difficult to ascertain. While some cultures were flourishing at the eve of the European encounter, sustaining dense populations with large and numerous permanent settlements (e.g. lower Tapajós), other societies with intensive landscape management systems, elaborate material culture and marked status inequalities had long disappeared and been replaced by smaller, more mobile groups (e.g. Marajó island). There is growing evidence that the millennium preceding the European encounter was a period of major cultural transformations, marked by long-distance migrations, increased conflict, disintegration of complex societies and the emergence of new orders across lowland South America[32,44,104].

Two models of land use

When differences in social organisation and land-use practices are taken into account, an interesting pattern emerges (Figure 4). Most of the pre-Columbian societies who occupied the regions reviewed in this paper developed economic strategies that can be encompassed under the concept of 'landesque capital', which entails the investment in permanent modifications of the terrain in order to provide increased yields not only for the duration of one lifespan, but also for future generations[105]. The construction of raised fields[106], the formation of fertile ADEs[42], forest enrichment with species of economic importance[18,38,107] and the creation of artificial ponds for management of aquatic fauna[31], are all examples of significant investment in landscape management. Nevertheless, these are very distinct subsistence strategies, and it is unlikely that all of them would have been vulnerable to the same climatic fluctuations.

Here, we suggest that pre-Columbian societies with more intensive and specialised systems of land use, whether in the form of hydraulic or agricultural earthworks – the type of landscape modification to which the term landesque capital has been traditionally applied – were inherently more vulnerable to events of climate change during the late Holocene. These societies also tended to exhibit greater social stratification and regional settlement hierarchies, as is clear from the examples of Marajó Island and the monumental mound region, in conformity with the cross-cultural observation that intensification coevolves with complex political structures[108-110]. The presence of institutionalised status inequality and incipient centralised decision-making may be key for understanding why those communities disappeared during periods of climate change whereas other societies were seemingly unaffected or even expanded. Political complexity may lead to rapid growth in the short term but also to increased vulnerability in the long term due to high interdependency of the constituent parts of the social system, so that changes in any component are more likely to compromise the system as a whole and cause its general collapse[111-113]. Furthermore, complex societies tend to promote and depend on the production of constant yields and generation of surplus through intensification and specialisation in resource exploitation, ultimately losing their ability to absorb unforeseen disturbances[14,15,114-116]. For example, economies depending on earthworks that changed hydrology, as in the case of drainage-enhancing canals found in the Llanos de Moxos, may become unstable during periods of drought. Vulnerability is further influenced by the very environment in which the later (as well as the Marajoara chiefdoms) developed, since flooded ecosystems are prone to fire and erosion during periods of drought[117].

We argue that some archaeological cultures became increasingly vulnerable to external factors, such as the rise in climate variability, which seems to have caused overall cultural reorganisation in societies featuring high population densities, settlement hierarchy, ruling elites, and intensive land-use systems (e.g. the monumental mounds in the Llanos de Moxos, Marajoara in the eastern Amazon, and Arauquinoid in the Guianas coast). This is well illustrated by the decline of the monumental mound region during the dry period ~1300-1500 CE, at the peak of regional political complexity and settlement density. The same societies were seemingly unaffected by a more severe drought ~700 CE (Figure 3e) when they were at the initial phases of their adaptive cycle (see below).

Alternatively, other pre-Columbian societies were experiencing a momentum of growth at the eve of the European encounter, as exemplified in the lower Tapajós and southern Amazonia. These regions had high population densities and numerous large settlements spread over considerable areas. However, unlike the cases above, there is little evidence of hierarchy. The Xinguano system in southern Amazonia has been described as a ‘galactic’ system with multiple political-ritual centres in a decentralised regional organisation, similar to, but on a larger scale than that of historical groups in the same region[61-63].

The Santarém culture is a potentially ambiguous case. Historical accounts suggest a warlike, tribute-based chiefdom established in the lower Tapajós[33,34] whose capital could be the large settlement under the modern city of Santarém[33]. However, no archaeological evidence was found of differential access to prestige goods, high-status burials, or conflict[36]. Sites at the periphery of the Santarém sphere of influence apparently were unaffected, which sheds doubt on the territorial extent of the supposed polity[37,118]. Recent reviews of the archaeology of the lower Tapajós propose heterarchical models of political organization, either with a centralised organisation encompassing independent communities[37] or a non-centralised polity based on a collaborative network integrating the region[36,119]. As for the Guarita of Central Amazon, Koriabo of the Guianas coast or mound villages of southwestern Amazon, there is little to no evidence of regional site hierarchies or pronounced social stratification.

Beyond their decentralised political structures, the crucial unifying factor in these societies’ perseverance may have been their land-use systems. Although archaeobotanical data are still scarce for many of the case studies listed above, Amazonian cultures like Santarém, which thrived before the European arrival, are known to have practised economic strategies combining (i) the exploitation of fertile ADEs and (ii) the enrichment of forests with plants of economic importance[38]. ADEs, estimated to cover up to 3.2% of the Amazon basin, have received considerable attention due to their persistent fertility, attributed to higher amount of nutrients, pH values, charcoal content and organic matter than most natural soils of the region, constituting a crucial resource for sustainable agricultural practices in modern-day Amazonia[120-122]. The mechanism behind the formation of ADEs have been widely debated, with ethnographic analogues and experiments suggesting the resilient fertility results from the long-term repeated incorporation of waste material and charred biomass[123-125]. Forests with hyperdominant edible and useful species are significantly associated with ADE sites throughout Amazonia, which has long been interpreted as an imprint of pre-Columbian land use[18,126,127]. Confirmation is provided by fossil pollen evidence, showing that modern floristic composition in ADE sites indeed results from millennia of forest enrichment associated with prolonged human settlement, but in the absence of large-scale deforestation[38]. The creation of 'domesticated forests' through selection, transportation and encouragement of useful species, often associated with improved soils (ADEs), ensured permanently enriched environments and food security in the long-term[18,107].

The present-day prevalence of extensive clearance for slash-and-burn agriculture in Amazonia has been suggested to result from the availability of metal axes and chainsaws, with more intensive management of gardens and forests in different stages of succession being the pattern in pre-Columbian times[39]. Nevertheless, clearance and burning do seem to have played a role in the establishment of ADE sites, with later fire management suppressing larger wildfires[38]. Furthermore, it is possible that an infield-outfield system, similar to what was practised in Mesoamerica, combining carefully managed polyculture gardens with less labour-intensive swidden further away from the settlements, also existed in ancient Amazonia[128]. In line with previous arguments about the sustainability of polyculture agroforestry in the Neotropics[38], our review of the archaeological and palaeoclimate record suggests that these land-use systems provided pre-Columbian societies of lowland South America with greater resilience to climate variability when compared to more specialised production maximisation strategies.

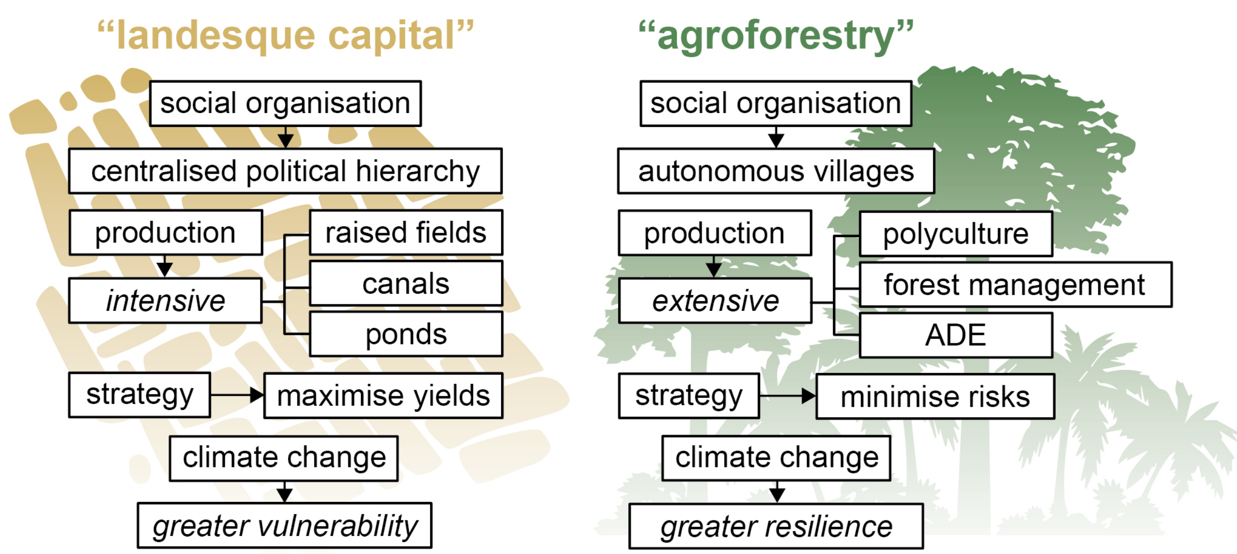

Figure 4. Two models of land use in late pre-Columbian Amazonia. Not all the characteristics listed in each figure are present simultaneously in one society, e.g. some may exhibit centralised political hierarchy but rely on polyculture agroforestry. Nevertheless, late pre-Columbian Amazonian cultures tend to resemble more closely one or another of these ideal types.

Risk management and adaptive cycles

The patterns summarised above are in agreement with the body of theory on risk management strategies and are comparable to other cases where different land use strategies have triggered opposing responses in the face of environmental change. Populations residing in stable environments have been suggested to benefit, at least in the short term, from productive maximisation strategies (specialisation, agricultural intensification, landesque capital), which provide high yields and surplus that can be diverted to the maintenance of political complexity, large populations and specialised economies. However, they were also found to suffer heavier losses in events of environmental perturbation. In contrast, populations practising risk minimisation strategies (population control, mobility, diversification) are considered to be more stable in unpredictable environments over the long term[13]. In that regard, the economic and social disparities between the various regions of Amazonia resemble the Polynesian cases of Mangaia and Tikopia[10]. Mangaia was covered by old growth forest depending on thin organic soils that were soon depleted by the slash-and-burn agriculture of the initial colonists. Soil depletion resulted in the eventual need to develop irrigation systems on valley bottoms, leading to strong leadership and competitive warfare. In contrast, Tikopia offered a more resilient environment, but the determining factor in its population success was the shift from slash-and-burn agriculture to a form of arboriculture that mimicked the diversity of the rainforest[10].

Beyond risk management, we propose that panarchy theory, through the concept of adaptive cycles, may be of value for understanding the patterns of growth and decline of late pre-Columbian Amazonian societies. Panarchy theory was devised to explain the dynamics of social-ecological systems, postulating the existence of interlinked adaptive cycles, observed at multiple independent spatial scales. The cycles involve stages of growth/exploitation (r), conservation/construction (k), release (Ω) and, ultimately, reorganisation (α)[14-16]. The first two phases comprise a long period during which resources are accumulated, whereas the later two phases develop over a short period of sudden release of energy. In human societies, reorganisation often involves rescaling of population towards smaller communities, only to begin a new growth cycle. Regionally-integrated, hierarchical societies, however, tend to resist such fluctuations and artificially prolong the growth and conservation stages. By attempting to maintain constant yields, e.g. through economic intensification and specialisation, as well political centralisation, these societies accumulate rigidities during their period of success. They may appear sustainable in the long term while, in fact, developing lower resilience and becoming more prone to crisis under the stress of external agents, such as climate hazards[16]. We argue that archaeological cultures including those of the monumental mound region in the Llanos de Moxos, Marajó island, and Guianas coast, with their high population densities, hierarchy of settlements, ruling elite, and intensive land use systems, were approaching the Ω phase and had become increasingly more vulnerable to climate change, causing their overall collapse and reorganisation.

Finally, we highlight that the different intentionality and social organisation behind the land-use systems, as discussed above, may have bearings on their resilience. The construction of raised fields, artificial ponds, canals and other earthworks are voluntary practices of terraforming with the immediate aim of intensifying production. In Amazonia as elsewhere, their construction both sustained and depended on complex political organisations[108]. Yet, productive earthworks were not reutilised after the European conquest. Despite improving agricultural potential in the short term, the raised fields of the Llanos de Moxos developed worse soil properties than the surrounding savannas in the long term due to increased leaching[51]. In addition, rehabilitation of raised field agriculture in the Llanos de Moxos has also failed due to social factors, reinforcing its purported dependence on a particular form of political organisation[129]. In contrast, anthropogenic forests and ADEs continue to be exploited by local

Amazonian communities, even though the actions that resulted in their formation, such as species selection and midden disposal, were integrated as part of broader economic strategies and not consciously intended for immediate advantage[107,130]. Crucially, anthropogenic forests with enriched flora and fertile soils were of benefit regardless of social organisation, one of the reasons behind their resilience.

Other drivers of change: migration and conflict

Obvious exceptions to the above are the cases of central and southwestern Amazon. In southwestern Amazon, little is known about the domestic sites of the geoglyph-builders, but they were most likely small-scale communities practising crop cultivation together with forest enrichment[48]. In this case, no evidence has been found of ADEs[121], which reinforces the observation that, elsewhere, anthropogenic soil formation was the key to provide a successful and resilient form of agricultural production in the Neotropics[38,121,131,132].

In central Amazon, climate change may be less relevant to explain the demise of the Paredão mound villages, which also practised polyculture agroforestry coupled with ADE formation, than the burst of conflict provoked by incursions of a foreign group represented by the Guarita polychrome ceramics[43,44]. The introduction of new traditions, assumed to reflect migrations, has also been invoked in the case of Marajó and the Guianas coast. Such displacements were a phenomenon documented throughout the lowlands during late pre-Columbian times[43]. Rather than suggesting climate change as the only cause for all cultural transformations across Amazonia reviewed in this paper, we recognise the turn of the second millennium CE as a period of widespread reorganisation and population movement, among which climate change may have played a role. A similar scenario is exemplified by the "crisis" of the Late Bronze Age (~1200-1150 BCE), when prolonged droughts set in motion migrations, warfare and internal upheavals throughout the Eastern Mediterranean, ultimately leading to the dissolution of once powerful polities[133-135]. One must consider the possibility that even societies otherwise unaffected by climate change could have thus faced challenges as part of a chain reaction set in motion by broader population relocations across South America – as has been previously suggested in the case of the 'ripple effects' of the Tiwanaku collapse[136].

Conclusion

Although there is general agreement that considerable population declines followed the European encounter (1492 CE) in the Americas, with some estimates reaching 95% loss, population dynamics preceding European contact remain underexplored. While major cultural demises in the US Southwest, Mesoamerica and the Andes are now agreed to have taken place in response to climate change in the centuries preceding the European arrival, similar changes in Amazonia remain poorly understood. By comparing synthesised archaeological data with palaeoclimate proxies and regional-scale patterns of burning, we show that some Amazonian cultures flourished during periods of climate change, whereas others collapsed. We argue that differences in land-use and socio-political organisation may be key to understanding vulnerability *versus* resilience to environmental stress.

Recent debates about the post-1492 CE population collapse in the Americas have focused on potential consequences for forest regrowth, decrease of atmospheric CO_2 and exacerbation of climate change and impacts on biodiversity that occurred during the Little Ice

Age[2,72,137,138]. As more archaeological, palaeoclimatological, and palaeoecological data become available, we foresee a refinement of our understanding about land-use, socio-political organisations, and population densities across the neotropics. As researchers continue to explore how different cultures responded to climate change, and document transformations before ad 1492, we expect major contributions will be made to understand the demographic and environmental consequences of the Columbian encounter.

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