Climate change and cultural resilience 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 between archaeological, palaeoecological, and palaeoclimatological data had 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 reorganisation during periods of climate change, others were unaffected and even flourished. We propose that societies with intensive, specialised 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 Earths in the long term, were more resilient to climate change.

Introduction

The consequences of the European encounter on the indigenous populations of the Americas cannot be overstated. Some estimate 90-95% population decline due to epidemics and violence[1,2]. With a population of up to 10 million inhabitants[3,4] now postulated for Amazonia in late pre-Columbian times, it is likely that the demographic losses following the European contact reshaped landscapes 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 are expected to have occurred. In Amazonia, this question remains unresolved. Elsewhere in the Americas, there is mounting evidence of population declines and climate-driven 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 climate change have been shown to be mediated by distinct economic practices[10]. Yet, little is known about pre-Columbian human responses to climate change in Amazonia.

Here, we explore spatio-temporal patterns of climate and culture change in Amazonia to assess the role of distinct land-use systems in vulnerability or resilience to climate change. We review 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 palaeoecological records (pollen, charcoal). Given the heterogeneity of local climatic regimes, we consider each region separately and highlight the broader cultural and climatic patterns that emerged during the late Holocene in Amazonia.

We argue that patterns of cultural change in pre-Columbian Amazonia can be understood from the perspective of risk management strategies and adaptive cycles. Two land-use strategies have been identified among late pre-Columbian Amazonian societies. One involves maximisation, specialisation in public infrastructure, and immediate impact. The other focuses on cumulative, long-term impact through diversification, polyculture agroforestry and 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 low intensity polyculture is more resilient to external stressors. The flexibility, or lack thereof, of these systems explains the decline of some societies and not others according to their economic base[11]. We suggest that the societies that collapsed under climate change were approaching the end of an adaptive cycle that progressed 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[12-14].

Figure 1. Regions, archaeological sites[15-17] and palaeoclimate records discussed in the text. CAR = Cariaco Basin[18], PAR = Paraíso Cave[19], PMA = Pumacocha Lake[20], TOR = Torotoro[21], PDA = Pau d'Alho Cave[22]. Only the dated sites for the respective regions and cultures are shown. Colours of dated sites correspond 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	**Archaeologica l tradition**	**Time period**	**Socio-political organisation**	**Land use**	**References**

Guianas Coast	Arauquinoid	AD 650-1400	Settlement hierarchy of residential and ceremonial mounds, well-defined chiefdom territories.	Raised fields for cultivation of maize, *Cucurbita*, manioc.	23-26
	Koriabo	AD 1000-1600	Reoccupation of earlier sites	Possible ADE.	23,27
Eastern Amazon	Marajoara	AD 500-1200	Settlement hierarchy of residential mounds, elite burials and prestige ceramics.	Ponds for aquaculture, no evidence of maize.	28-30
	Santarém	AD 1050-1650	Settlement hierarchy is debated.	ADE polyculture, cultivation of maize, *Cucurbita*, manioc and sweet potato.	31-36
Central Amazon	Paredão	AD 750-1250	Permanent mound villages.	ADE polyculture, cultivation of maize, yam, *Cucurbita*.	37-40
	Guarita	AD 1200-1600	Smaller settlements, rapid pan-Amazonian expansion.	ADE.	41,42
Southwestern Amazon	Geoglyphs	400 BC - AD 950	Vacant ceremonial centres.	Small clearings in bamboo forest, cultivation of maize and squash.	30,43-46

	Mound villages	AD 1000-1650	N/A	N/A	[47]
Llanos de Moxos	Lomas	AD 450-1400	Settlement hierarchy of residential mounds, elite burials.	Drainage canals and reservoirs, savanna burning, cultivation of maize, manioc, yam, squash, peanuts, cotton.	[48-54]
	Zanjas	AD 1200-1500	Fortified sites.	Savanna burning, cultivation of maize.	[52,55-58]
Southern Amazon	Xinguano	AD 1050-1650	Fortified settlement network, political-ceremonial hierarchy.	ADE.	[59-61]

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 Amazonia

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) (Supplementary Discussion 2). The climate systems impacting Amazonia create a precipitation dipole at the borders of the monsoon, resulting in a climatic antiphase between western and eastern Amazon Basin[62].

Palaeoclimate records

To characterise the palaeoclimatic conditions over the six regions, we used the following palaeoclimatic archives: metal concentration (%Ti) from the sedimentary record from the Cariaco Basin[18] and oxygen isotope ($\delta^{18}O$) records from the Pumacocha Lake sediment core[20] and stalagmites collected at Paraíso[19], Pau d'Alho[22] and Torotoro[21] cave systems (Supplementary Methods).

All records document different climatic conditions over Amazonia during the periods known as the Medieval Climate Anomaly (MCA) ~AD 900-1250 and the Little Ice Age (LIA) ~AD 1450-1850[63] (Figure 2). During the MCA, the ITCZ was shifted to the north of its current range, resulting in wet conditions over the Cariaco Basin and dry or neutral conditions in most of the sites under the influence of the SASM[62,64] with the exception of Paraíso Cave and Torotoro[21]. The LIA period, in contrast, was characterised by dry conditions in the east (Paraíso Cave) and wet conditions in the west (Pumacocha Lake), with regions in between (Pau d'Alho Cave) not showing significant anomalies[62].

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 1 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 inland Koriabo tradition ~AD 1300 (Figure 3a). From Suriname to French Guyana, the Arauquinoid terraformed entire landscapes in coastal savannas starting ~AD 700[23,24]. Raised fields cover ~3000 ha in French Guyana[23], with phytolith, starch grain and stable isotope evidence documenting the cultivation of maize, squash and manioc[25,26]. Charcoal records suggest that fire was used to a limited extent in land management[65].

At the peak of the Arauquinoid occupation, the coast was divided into territories centered around large platform mounds with ceremonial and domestic functions[23,24]. 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[23]. The disruption of the Arauquinoid regional organisation began ~AD 1300, a period of upheavals marked by the spread of the Koriabo tradition. The earliest Koriabo sites are inland, with a progressive expansion towards the coast. 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 continuity, interaction and emergence of hybrid traditions[23].

Climate change, documented in the Cariaco Basin record, could have been the ultimate driver of the Arauquinoid decline (Figure 3a). Raised fields provide better drainage and moisture retention, allowing increased agricultural production in a region subject to a long rainy season and severe dry season[66]. If the Arauquinoid agricultural system was reliant on predictable seasonal precipitation, it is likely that their subsistence base was vulnerable to climate instability. The decline of mound centres ~AD 1300 could have been instigated by 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.

Eastern Amazon. Major transformations in late pre-Columbian eastern Amazon are highlighted by 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 Amazonia developed on Marajó Island ~AD 400. Archaeological evidence suggests a stratified society at the peak of the Marajoara phase ~AD 700-1100. The elite lived on large mounds, controlling access to prestige ceramics and water-management systems[28,30,67]. Mounds in the flooded savannas reached ~3 ha in area and 7 m height. Population estimates are of up to 2000 for a mound group[28,29]. Unlike the Arauquinoid, there is no evidence that the subsistence of the Marajoara depended on cultivated plants. Macro-botanical remains of maize are absent[28] and human bone isotopic values indicate a diet based on non-domesticated C_3 plants and aquatic resources[68]. Marajoara earthworks include ponds for management of aquatic fauna[29].

The disintegration of Marajoara chiefdoms ~AD 1200 led to abrupt changes in settlement patterns and material culture. Mound use declines, hierarchies between settlements disappear, elaborate urn burials are abandoned, and the polychrome Marajoara style becomes intermixed with foreign traditions[29,69]. The arrival of the Aruã nomadic foragers during this period has led to suggestions that the Aruã may have played a role in the Marajoara demise[29]. As in the Arauquinoid case, it is possible that the arrival of outsiders contributed to a process initiated by climate change.

While the Marajoara culture was in decline, another was flourishing in the lower Tapajós River. The Santarém culture, known for its elaborate effigy vessels, was established ~AD 1100. Comprising an area of 23,000 km², over a hundred sites have been recorded, extending for hundreds of miles along river bluffs and interior plateaus. Historical accounts describe a chiefdom with a “noble class”[31,32], but there is little archaeological evidence of social stratification[33-35]. Virtually all sites are composed of anthropogenically modified Amazonian Dark Earth (ADE)[34]. Recent pollen and phytolith data suggest a diverse land-use strategy based on polyculture agroforestry, with the cultivation of maize, sweet potato, squash and manioc combined with the enrichment of forests with edible species[36].

The Paraíso cave speleothem record provides a high-resolution proxy for precipitation changes in eastern Amazon[19,70] (Figure 3b). An increase in $\delta^{18}O$ values following ~AD 1100 shows that the dissolution of the Marajoara chiefdoms coincided with decreased precipitation. A relationship between decreased river discharges, increased water salinity, and the decline of the aquaculture-based Marajoara chiefdoms during this period has previously been suggested based on pollen data[71]. High-status mounds are closely associated with water-management facilities, suggesting monopolisation of resources and surplus production by the elite[29]. Therefore, the land-use strategies that sustained the Marajoara chiefdoms would have been sensitive to prolonged droughts. During the same period, archaeological data indicate 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 Marajoara decline. Regional-scale fire activity during the apex of the Santarém culture has been attributed to human as opposed to climate drivers[36] (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[36].

Central Amazon. At the confluence of the Negro and Solimões rivers, the millennium preceding the European contact saw the demise of Paredão mound villages and their replacement by smaller sites of the polychrome tradition (Figure 3c). Emerging after ~AD 700, rings of house mounds at Paredão sites surround central plazas, showing well-planned village layouts[37-39]. Sites contain thick layers of ADE, and the recovery of phytoliths of maize, yam, squash and *Bactris* palm, coupled with archaeobotanical evidence of managed forests in the sites' catchment suggest polyculture agroforestry associated with the development of fertile soils[40] similar to that employed in Santarém. Ultimately, Paredão sites were replaced by smaller, ephemeral settlements with polychrome Guarita ceramics[42], a pan-Amazonian tradition that originated in the southwestern part of the basin ~AD 750[72].

In central Amazon, the appearance of polychrome ceramics coincides with the disintegration of the Paredão complex ~AD 1000[38]. The homogeneity and rapid spread of polychrome ceramics point to demographic expansions[41]. Alternatively, it is possible that the style was diffused as a prestige technology among groups with access to floodplain resources[73]. What is clear is that the process of transition from Paredão to Guarita polychrome was not a peaceful one, as evidenced by defensive ditches and palisades built around Paredão sites, which are later reoccupied by the Guarita tradition[41,42].

Comparing climate and cultural change in central Amazon 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[70]. As in the case of the Marajoara, the decline of Paredão mound villages coincides with a drier period starting ~AD 1100 in the Paraíso record[19] (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[20] in the Andes, are recurrently antiphased with the eastern records. These proxies show a period of drought during the MCA period, followed by strengthening of the monsoon during the LIA[22,64,74]. 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 Paredão collapse.

Southwestern Amazon. Starting ~400 BC, southwestern Amazon was transformed into a dense ceremonial landscape with geometric enclosures known as geoglyphs[43,45,46]. Over 500 geoglyphs have been recorded. They combine square and circular ditches surrounding areas of 1-3 ha with walled enclosures, avenues and other earthworks. The low ceramic density, presence of votive deposits, and lack of occupation debris suggests geoglyphs were public spaces used for repeated gatherings, rather than permanent settlements[30,44,45]. In spite of the grandeur of the earthworks, there is no evidence of large-scale clearance beyond their immediate vicinity[46]. 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 dispersed populations[30,43,75]. Phytolith evidence from the ceremonial centres points to the consumption of maize and squash combined with the management of palms[46]. The formative ceremonial network of the southwestern Amazon was dissolved ~AD 1000 and replaced by a new architectural tradition with smaller mound villages, sometimes built on top of or adjacent to earlier geoglyphs (Figure 3d). Discontinuity is also visible in the ceramics recovered from mound villages, which differ markedly from those of the earlier earthworks[76]. Carbonised macro-botanical remains from mound habitation strata include Brazil nuts, palm seeds (*Attalea* and *Euterpe*) and maize kernels, suggesting the persistence of polycrop cultivation[47].

The termination of geoglyph construction coincides with an increase in $\delta^{18}O$ values observed during the MCA period at Pumacocha Lake, indicating a weakening of the monsoon and decrease of precipitation over the Andes and western Amazon[20,77] (Figure 3d). Other palaeoclimate records from the Andean slopes/western Amazonia show precipitation minima at ~AD 940 and 1025[20,77,78]. Any causal relationship between drought and the cessation of construction of 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 not always synchronous with changes in precipitation, showing increase in regional burning after the driest period of the MCA (~AD 900 to 1100; Figure 3d), but coinciding with the earliest dates for the mound villages. Anthropogenic ignitions during the transition from geoglyphs to mound villages following the MCA may have been 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, suggesting that either climate was the first order control for regional fire activity or that burning for land clearance was only practised during the initial establishment of mound villages in the region - perhaps taking advantage of a sparsely inhabited landscape due to the decline of the geoglyph builders.

A strengthening of the monsoon is documented in the Pumacocha record over the following centuries[20,77], coinciding with the development of mound ring villages. Ceramics from the latter differ from the ceramics of the geoglyphs. The situation of Southwestern Amazon could be similar to that of the Guianas, Central Amazon and Eastern Amazon in that waves of migrants may have been a factor contributing to the decline of local cultures during events of climate change.

Llanos de Moxos. The flooded savanna-forest mosaics of the Llanos de Moxos extend over 150,000 km² and are one of the most intensely modified landscapes in Amazonia[79]. Different regions of the Llanos de Moxos experienced 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 surface[48]. Such sites started to be built ~AD 400 and are part of a network of enclosures, causeways that connect settlements and reservoirs, and drainage and irrigation canals[48,51,52]. Agricultural raised fields, ubiquitous elsewhere in the Llanos de Moxos, are absent, which has been attributed to the relatively good natural drainage in this region[49,50]. Mounds were built on a sedimentary lobe with higher elevation, better drainage and more fertile soils. The canals, some with several km extension, were built for multiple purposes. Some connect areas with differences in elevation, suggesting drainage as the main function, whereas others divert water from lakes to the surroundings of mounds, presumably for irrigation[80]. Cultivation of maize, manioc, yam, squash, peanuts and cotton has been evidenced by phytoliths, fossil pollen grains and macro-botanical remains[53,54]. Beyond the construction of canals for drainage of cultivated areas[49], pre-Columbian land use in the monumental mound region also involved more extensive burning of the savannas than was practised in historical times[53]. Funerary evidence points to a highly stratified society, with lavish burial goods reserved for few individuals[51,52]. A hierarchical organisation of sites has also been noticed[48]. Importantly, the extension of some canals suggest their role as public infrastructure built under supra-regional political organisation[80]. The abandonment of this system ~AD 1400 precedes contact with Europeans and is accompanied by changes in land use with the decline of savanna burning[53].

Ring Ditch Region

Around AD 1200, 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. The *zanjas* exhibit irregular layouts and clear evidence of habitation, including house floors, domestic debris, and urn burials[52,55-57]. Canals and other earthworks connect different enclosures[52,57]. 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 burning was practised to maintain an open savanna around the sites during a period of forest expansion[56]. *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[58].

Climate change in the Llanos de Moxos can be inferred from the Umajalanta-Chiflonkhakha speleothem records from Torotoro Park, tropical slopes of the eastern Andes[21] (Figure 3e). Changes in precipitation are antiphased with those observed further north[21]. The depleted $\delta^{18}O$ values during the MCA show an anomalous wet period when compared to other records influenced by the SASM[21]. The following period, marked by a shift to drier conditions, coincides with an increase in fire activity in the RCC (Figure 3e). However, the latter could also be explained by forest clearance[56]. 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[81]. Importantly, the RCCs for both southwestern Amazon and the Llanos de Moxos suggest human activity as the main driver of recent biomass burning, supporting the hypothesis that late Holocene fires in this region were anthropogenic[82].

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 ~AD 1300-1500. This is in agreement with a trend of increased aridity recorded in Lake Titicaca's water levels[83] and documented in the Quelccaya ice cap[84], possibly linked to the collapse of the Tiwanaku state[8,9,85]. We argue that the same effects were felt in the Llanos de Moxos. In the monumental mound region, earthworks such as canals were possibly more important in the mitigation of seasonal floods than for irrigation[80], 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 have been followed or caused by the arrival of foreigners, reinforcing the 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 intensification of warfare[86].

Southern Amazon. The transitional forests of southern Amazon were densely settled with enclosed sites and other earthworks, as exemplified by the network of fortifications and roads in the upper Xingu (Xinguano Tradition).

After ~AD 1100, settlements in this region were remodelled with the addition of ditches, walled plazas and causeways (Figure 3f). Large, complex settlements constitute the hubs of a network of roads extending for ~20,000 km^2 that connect them to smaller villages, reflecting independent regional polities[59-61]. 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[61]. The Xinguano system was probably heterarchical, revolving around political-ceremonial centres. Ditched enclosures associated with ADE in the Tapajós headwaters, further to the west, demonstrate spatial continuity from the upper Xingu to the Bolivian *zanjas*[87]. 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[22] (Figure 3f). Trends observed at Pau d'Alho are reflected elsewhere in central Brazil and are related to shifts in the mean position of the South Atlantic Convergence Zone (SACZ)[62]. 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[22,62,88]. It was during this period of increased climatic volatility that settlements in the upper Xingu were fortified. Enclosures emerged elsewhere under different conditions. In the Llanos de Moxos, *zanjas* appeared during an episode of drought, suggesting a climatic driver. Overall, defensive structures must be understood in a broader context of 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 Table 7 and Supplementary Figure 1.

Discussion

Previous attempts to relate climate and culture in Amazonia postulated a deterministic link between environment and society[89]. The view that the environment imposed limitations to development in the tropics has been refuted by archaeological evidence of dense populations and complex societies in Amazonia, starting in the 1960s[90] and continuing today[3,87]. Due to this paradigm shift, correlations between climate change and cultural transformations were not thoroughly explored, as the topic may be perceived to evoke outdated views. Here, we have identified temporal synchronicities between climate and cultural change in Amazonia. Elsewhere in the Americas, periods of abrupt change in the archaeological record have been shown to coincide with climatic events[91,92]. 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 and large settlements (e.g. lower Tapajós), other societies with intensive landscape management systems, elaborate material culture and status inequalities had long disappeared and been replaced by smaller, mobile groups (e.g. Marajó Island). There is growing evidence that the millennium preceding the European encounter was a period of transformations, with long-distance migrations, conflict, disintegration of complex societies and social reorganisation across lowland South America[30,42,93].

Two models of land use

When differences in social organisation and land-use are taken into account, a pattern emerges (Figure 4). Most of the pre-Columbian societies reviewed in this paper developed economic strategies that can be encompassed under the concept of 'landesque capital', which entails investment in infrastructure and landscape modifications that provide increased yields not only for the duration of one's lifespan, but also for future generations[94]. The construction of raised fields[95,96], the formation of ADEs[40], forest enrichment[16,36,97], and the creation of artificial ponds for management of aquatic resources[29], are all examples of landesque investment. Nevertheless, these are very distinct 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 land use systems were more vulnerable to transient (short-term but highly variable) events of climate change during the late Holocene. These societies also tended to exhibit greater social stratification and settlement hierarchies, as is clear from the examples of Marajó Island and the monumental mound region in the Llanos de Moxos, in conformity with the cross-cultural observation that intensification coevolves with complex political structures[98-100]. The presence of status inequality and centralised decision-making may be key for understanding why those communities disappeared during periods of climate change whereas other societies were unaffected. 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 likely to compromise the system as a whole and cause general collapse[101-103]. Furthermore, complex societies tend to promote and depend on the production of constant yields and surplus through intensification and specialisation in resource exploitation, losing their ability to absorb unforeseen disturbances[12,13,104-106]. 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 environment in which the later (as well as the Marajoara chiefdoms) developed, since flooded ecosystems are prone to fire and erosion during drought[107].

We argue that Amazonian 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) became vulnerable to external factors, such as climate change. This is well illustrated by the decline of the monumental mound region during the dry period ~AD 1300-1500, at the peak of regional political complexity and settlement density. The same societies were unaffected by a more severe drought ~AD 700 (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 large settlements spread over considerable areas. However, there is little evidence of political hierarchy. The Xinguano system in southern Amazonia has been described as a 'galactic' system with multiple political-ritual centres in a decentralised organisation[59-61].

The Santarém culture is an ambiguous case. Historical accounts describe a tribute-based chiefdom in the lower Tapajós[31,32] whose capital could be the large settlement under the modern city of Santarém[31]. However, no archaeological evidence was found of differential access to prestige goods, high-status burials, or conflict[34]. The cultural affiliation of sites at the periphery of the Santarém sphere of influence shed doubt on the territorial extent of the polity[35,108]. Recent reviews of the archaeology of the lower Tapajós propose heterarchical models of political organization, either with a centralised organisation encompassing independent communities[35] or a non-centralised polity based on a regional collaborative network[34,109]. 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 social stratification.

Beyond their decentralised political structures, the 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 are known to have combined (i) the exploitation of ADEs and (ii) the enrichment of forests with plants of economic importance[36]. ADEs, estimated to cover up to 3.2% of the Amazon Basin, have received considerable attention due to their persistent fertility, constituting a crucial resource for sustainable agricultural practices in modern-day Amazonia[110-112]. 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[113-115]. Forests with hyperdominant edible and useful species are significantly associated with ADE sites throughout Amazonia, which has been interpreted as an imprint of pre-Columbian land use[16,116,117]. Confirmation is provided by fossil pollen evidence, showing that modern floristic composition in ADE sites results from millennia of forest enrichment associated with prolonged human settlement, but in the absence of large-scale deforestation[36]. The creation of 'domesticated forests' through selection, transportation and encouragement of useful species, often associated with improved soils, ensured permanently enriched environments and food security in the long term[16,97].

The present-day prevalence of clearance for slash-and-burn agriculture in Amazonia has been suggested to result from the availability of metal tools, with more intensive management of gardens and forests in different stages of succession being the pattern in pre-Columbian times[37]. Nevertheless, clearance and burning do seem to have played a role in the establishment of ADEs, with later fire management suppressing larger wildfires[36]. Furthermore, it is possible that an infield-outfield system, similar to that of Mesoamerica, combining polyculture gardens with less labour-intensive swidden further from the settlements, also existed in Amazonia[118]. In line with previous arguments about the sustainability of polyculture agroforestry in the Neotropics[36], our review of the archaeological and palaeoclimate record suggests that these land-use systems provided pre-Columbian Amazonian societies with resilience to both transient and protracted (multi-year to multi-decade) climate variability when compared to specialised production maximisation strategies.

Figure 4. Two models of land use in late pre-Columbian Amazonia. Not all the characteristics listed in each panel are present simultaneously in one society, e.g. some may exhibit centralised political hierarchy but rely on polyculture agroforestry, while others may be decentralised but invest labour in raised fields and other earthworks. 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, in the short term, from maximisation strategies, which provide high yields and surplus that can be diverted to the maintenance of political complexity and large populations. 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[11]. 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 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, panarchy theory, through the concept of adaptive cycles, helps 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)[12-14]. The first two phases comprise a long period during which resources are accumulated, whereas the latter two phases develop over a short period of sudden energy release. In human societies, reorganisation often involves rescaling of population towards smaller communities, only to begin a new 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 through economic intensification, specialisation, and political centralisation, these societies accumulate rigidities. They may appear sustainable while, in fact, developing lower resilience and becoming prone to crisis under the stress of external agents, such as climate hazards[14]. 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 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[98]. 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 due to leaching[49]. Rehabilitation of raised field agriculture has also failed due to social factors, reinforcing its dependence on a particular form of political organisation[119]. 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 art of broader strategies and not consciously intended for immediate advantage[97,120]. 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 and forest enrichment[46]. No evidence has been found of ADEs[111], 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[36,111,121,122].

In central Amazon, climate change may be less relevant to explain the demise of the Paredão mound villages, which also practised polyculture agroforestry and ADE formation, than conflict provoked by incursions of the Guarita groups[41,42]. Migrations have also been invoked in the case of Marajó and the Guianas coast. Population displacements were a phenomenon documented throughout Amazonia during late pre-Columbian times[41]. Rather than suggesting climate change as the only cause for all transformations reviewed in this paper, we recognise the turn of the second millennium AD 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 BC), when prolonged droughts set in motion migrations, warfare and upheavals throughout the Eastern Mediterranean, leading to the dissolution of once powerful polities[123-125]. Societies otherwise unaffected by climate change could have faced challenges as part of a chain reaction set in motion by broader population relocations across South America – as in the case of the purported 'ripple effects' of the Tiwanaku collapse[126].

Conclusion

Considerable population declines followed the European encounter (AD 1492) in the Americas, but population dynamics preceding that date remain underexplored. While major cultural demises in the US Southwest, Mesoamerica and the Andes have taken place in response to climate change before the European arrival, similar changes in Amazonia remain poorly understood. By comparing archaeological data with palaeoclimate proxies and regional-scale 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-AD 1492 population collapse in the Americas have focused on consequences for forest regrowth, decrease of atmospheric CO_2 and exacerbation of climate change and impacts on biodiversity that occurred during the LIA[2,127-129]. As more archaeological, palaeoclimatological, and palaeoecological data become available and integrated, we foresee a refinement of our understanding about land-use and population densities across the neotropics. By continuing to explore how different cultures responded to climate change, and documenting transformations prior to AD 1492, we expect major contributions will be made to understand the demographic and environmental consequences of the Columbian encounter.

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Author contributions

J.I., J.G.S. and M.R. designed the research. J.G.S., M.R., J.C., J.A.H., U.L., D.T.A., S.R. and J.I. compiled and interpreted archaeological data. V.F.N., J.A. and F.W.C. compiled and interpreted palaeoclimatic data. S.Y.M. and M.J.P. compiled and interpreted palaeofire data.

B.W., D.U., F.E.M. and H.H. compiled and interpreted palaeoecological data. J.G.S. led the writing of the paper with inputs from all other authors.

Acknowledgements

This paper is the result of the 2016 international workshop “Land use and climate changes at the eve of conquest: an interdisciplinary approach”, part of the PAST project funded by the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No. ERC_Cog 616179). F.W.C. was supported by a São Paulo Research Foundation (FAPESP) grant: 2017/50085-3. V.F.N. was supported by a São Paulo Research Foundation (FAPESP) grant: 2016/15807-5. We thank the members of the PAGES sponsored Global Paleofire Working Group for their support for the global charcoal database.

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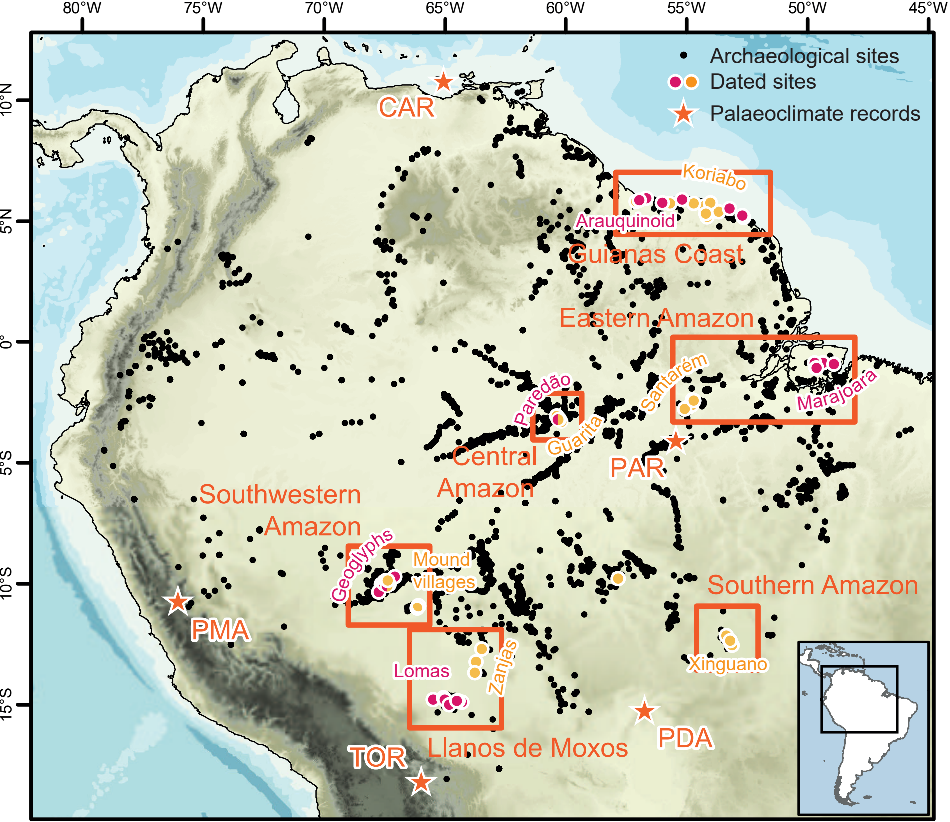
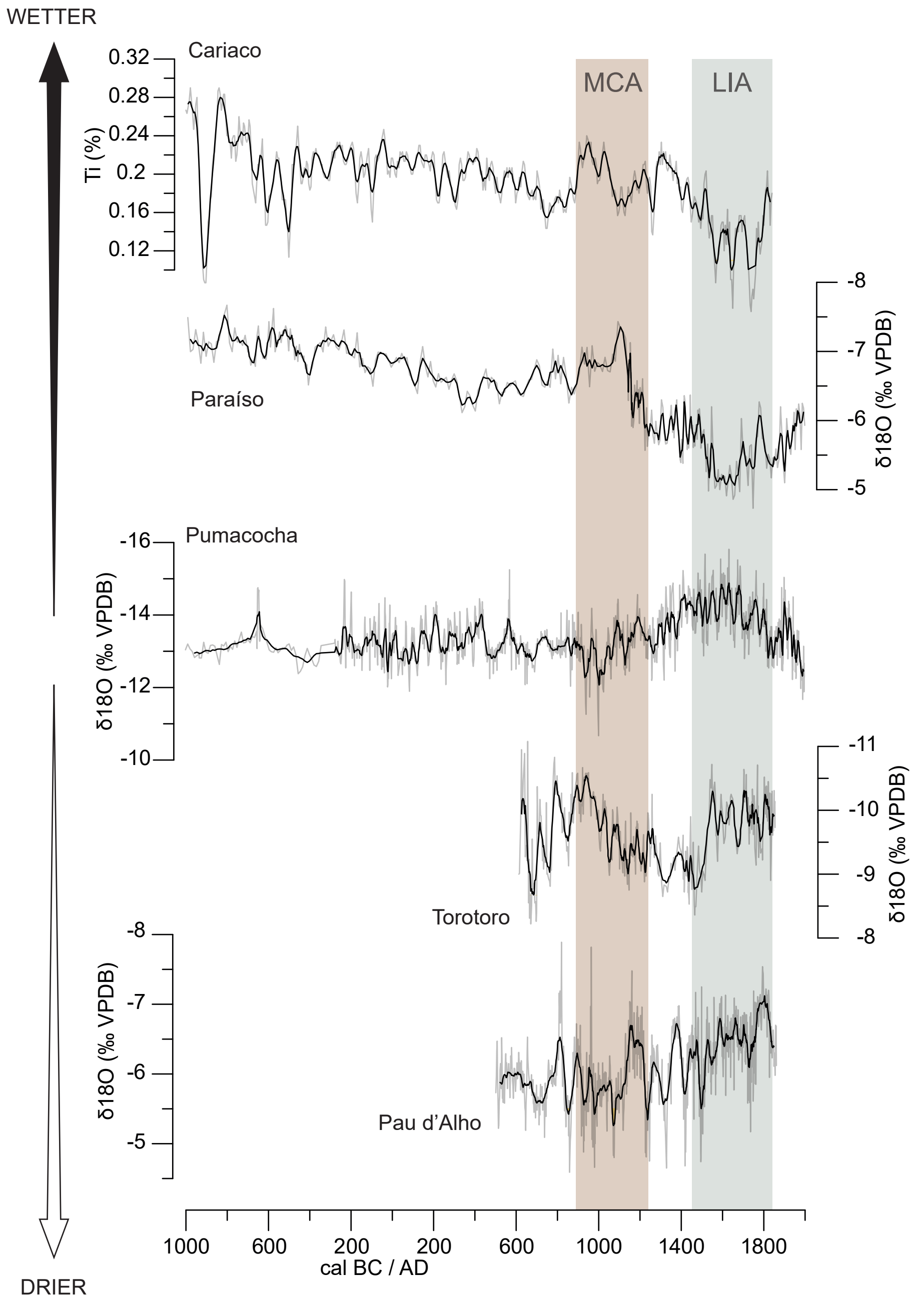
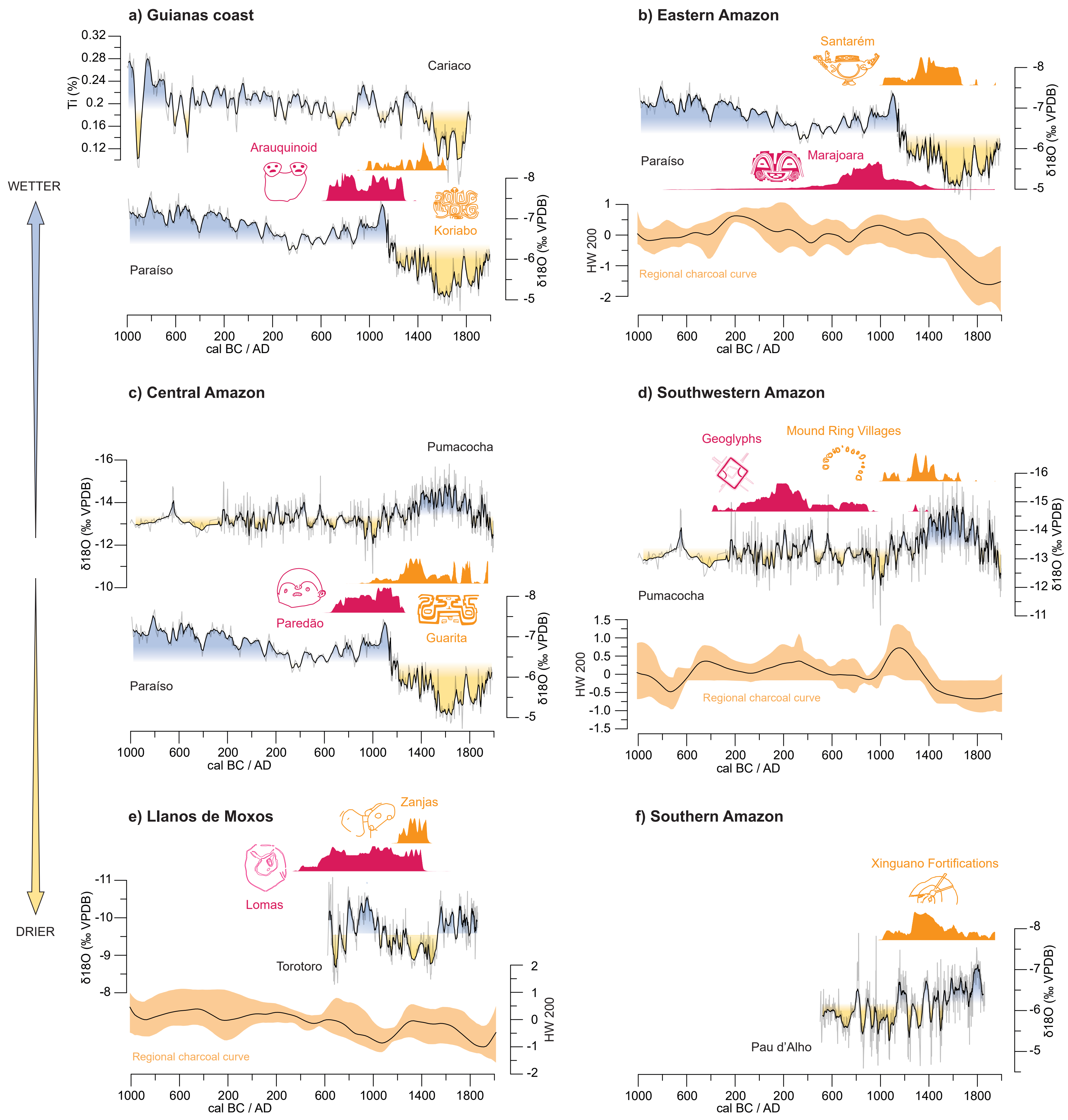


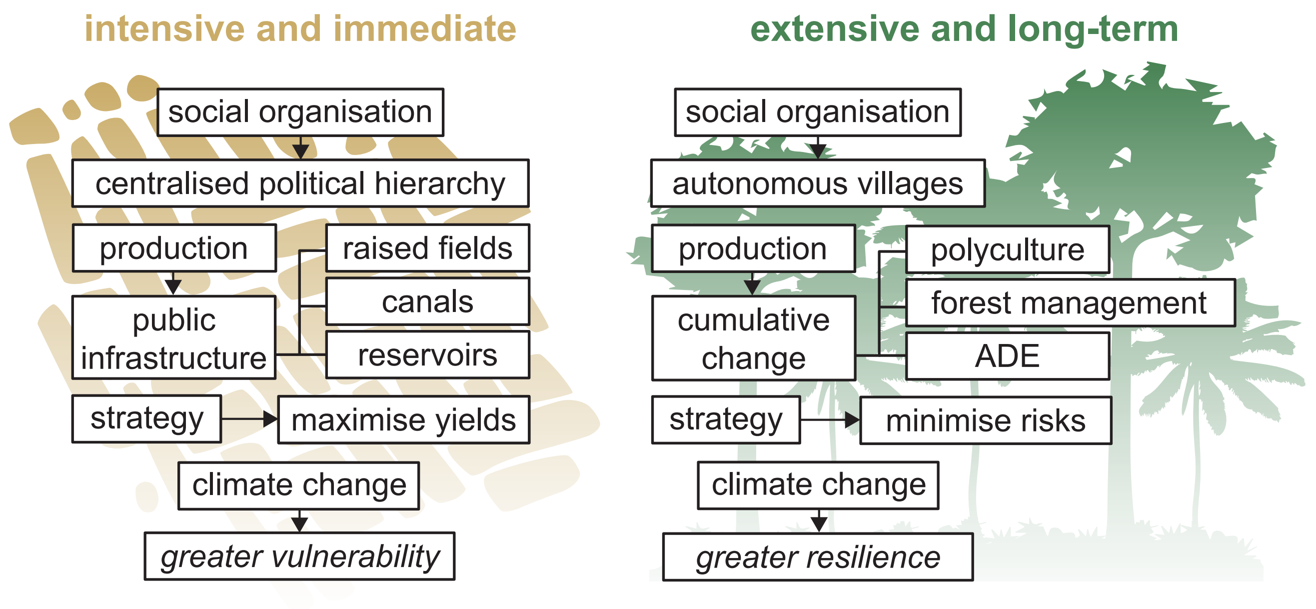
80°W
75°W
70°W
65°W
60°W
55°W
50°W
45°W
10°N
5°N
0°
5°S
10°S
15°S
Archaeological sites
Dated sites
Palaeoclimate records
CAR
Koriabo
Arauquinoid
Guianas Coast
Eastern Amazon
Santarém
Marajoara
Paredão
Guarita
PAR
Central Amazon
Southwestern Amazon
Geoglyphs
Mound villages
Southern Amazon
Xinguano
PMA
Lomas
Zanjas
Llanos de Moxos
PDA
TOR



WETTER
DRIER
Cariaco
Ti (%)
0.32
0.28
0.24
0.2
0.16
0.12
MCA
LIA
Paraíso
δ18O (‰ VPDB)
-8
-7
-6
-5
Pumacocha
δ18O (‰ VPDB)
-16
-14
-12
-10
Torotoro
δ18O (‰ VPDB)
-11
-10
-9
-8
Pau d'Alho
δ18O (‰ VPDB)
-8
-7
-6
-5
1000
600
200
200
600
1000
1400
1800
cal BC / AD



a) Guianas coast
Cariaco
Ti (%)
0.32
0.28
0.24
0.2
0.16
0.12
Arauquinoid
Koriabo
Paraíso
δ18O (‰ VPDB)
cal BC / AD
b) Eastern Amazon
Santarém
Marajoara
Paraíso
HW 200
Regional charcoal curve
c) Central Amazon
Pumacocha
Paredão
Guarita
Paraíso
d) Southwestern Amazon
Geoglyphs
Mound Ring Villages
Pumacocha
HW 200
Regional charcoal curve
e) Llanos de Moxos
Zanjas
Lomas
Torotoro
Regional charcoal curve
HW 200
f) Southern Amazon
Xinguano Fortifications
Pau d'Alho
WETTER
DRIER


intensive and immediate
social organisation
centralised political hierarchy
production
public infrastructure
raised fields
canals
reservoirs
strategy
maximise yields
climate change
greater vulnerability
extensive and long-term
social organisation
autonomous villages
production
cumulative change
polyculture
forest management
ADE
strategy
minimise risks
climate change
greater resilience