Research paper

The Holocene
22(2) 131–141

DOI: 10.1177/0959683611414932
hol.sagepub.com
SAGE

Spatial and temporal scales of pre-Columbian disturbance associated with western Amazonian lakes

Crystal H. McMichael,[1] Mark B. Bush,[1] Dolores R. Piperno,[2,3] Miles R. Silman,[4] Andrew R. Zimmerman[5] and Christina Anderson[1]

Abstract

The history of landscape alteration in Amazonia by humans prior to the arrival of Europeans remains poorly understood. Estimates of human population size at the time of European contact vary by several million, and the trajectories of cultural and agricultural development are equally uncertain. The extent to which human populations altered Amazonian ecosystems is a function of population size, land management style, radius of influence of each subpopulation, and the temporal development of settlements. Here we report evidence that relates to the temporal and spatial scales of human disturbance in western Amazonia. Three lake sediment records and 94 terrestrial soil cores located 0–12 km from the adjacent lake were used to examine scales of pre-Columbian human impacts at two sites in western Amazonian forests. Lake sediment and soil charcoal records indicate discontinuous and localized burning around the study areas. Terrestrial soil phytolith and nutrient analyses reveal a range in disturbance intensity between the two sites but contain no evidence of large-scale forest clearing or anthropogenic soil enrichment. Our data suggest that while all of the settings examined were occupied or used, the halo of influence around each was limited. It should not be assumed that intensive landscape transformations by prehistoric human populations occurred throughout Amazonia or that Amazonian forests were resilient in the face of heavy historical disturbance.

Keywords

charcoal, disturbance, fire history, phytoliths, pre-Columbian agriculture, western Amazonia

Introduction

Friar Gaspar de Carvajal provided an eyewitness account of the first European passage down the Napo River of modern Ecuador and the main Amazon channel in 1541–1542 (Medina, 1934). Carvajal's description includes such observations as dense settlements along a 180-mile portion of the river, and other settlements that 'stretched for 5 leagues (*c.* 17 miles) without there intervening any space from house to house', and the warrior women for which the river was named (Mann, 2005; Smith, 1990). Discounted as a self-serving and unreliable account that exaggerated the value of Amazonia to the King of Spain, Carvajal's account was ignored by generations of scholars. However, as evidence for complexes of roads and structures in the Xingu of southern Amazonia (Heckenberger et al., 2007, 2008), large-scale earthworks in the Bolivian Beni (Erickson, 2000, 2006), and large settlements at Marajó Island and Santarém in eastern and central Amazonia have emerged (Neves and Petersen, 2006, Roosevelt, 1999, Roosevelt et al., 1991, 1996), de Carvajal's writings have recently been revisited and seriously considered.

Despite their weaknesses, the friar's record remains a frequently cited piece of evidence for pre-Contact human populations and social organization in Amazonia. The resulting estimates of pre-Contact population size are between 1 and 5 million for the lowland Amazon (e.g. Bush and Silman, 2007; Denevan, 1996; Mann, 2005). Similarly, a wide range of opinion exists as to whether this population manipulated Amazonian forests on a local or wholesale basis. If Amazonian farming primarily involved relatively small-scale food production by inhabitants living in shorter-term settlements at low population densities (Meggers, 1971, 1984, 2003), their influence would have been small. However, at the other extreme, long-term settlement and the wholesale conversion of landscapes for agriculture, fruit production, and cultivation of species with recognized utility, e.g. palms for thatching, could have led to a 'parkland' or 'manufactured landscape'. Here again, the predicted spatial scale of such modification ranges from influences concentrated along high river bluffs and adjacent wetlands (e.g. Denevan, 1996) to a manipulation of most of the forested region (Balee and Erickson, 2006).

[1]Florida Institute of Technology, USA
[2]Smithsonian National Museum of Natural History, USA
[3]Smithsonian Tropical Research Institute, Panama
[4]Wake Forest University, USA
[5]University of Florida, USA

Received 17 December 2010; revised manuscript accepted 10 April 2011

Corresponding author:
Crystal H. McMichael, Department of Biological Sciences, Florida Institute of Technology, 150 W. University Blvd, Melbourne FL 32901, USA.
Email: cmcmicha@my.fit.edu

A huge amount has been learned of past human activity through archaeological and anthropological studies, yet the spatial and temporal scales of human impacts remain poorly understood for much of Amazonia. We do not know these impacts at the scale of the basin, and we need to know much more about them at the scale of individual settlements. Most evidence of large-scale landscape transformations comes from riverine or seasonal floodplain/savanna settings (Denevan, 1992, 1996, 2001; Erickson, 2000, 2006; Heckenberger et al., 1999, 2007; Kern et al., 2003; McKey et al., 2010; Neves and Petersen, 2006; Neves et al., 2004; Roosevelt et al., 1991, 1996). That these populations accessed the forest interior for hunting is a given, but their penetration was probably limited by walking distance (Glanz, 1991). But what of disturbance in the interfluvial terra firme rainforests, which constitute the greatest proportion of Amazonian landscapes, and where resource availability is considerably lower; were people manipulating these settings in the same way?

Bush and Silman (2007) reported that 13 of 22 fossil pollen records from Amazonian lakes exhibited a signature of human activity. These data suggest that lakes were preferred settlement sites, and one avenue to provide more precise information on the scale of past disturbances around settlements is by comparing lake sediment records with independent proxies for adjacent land use; in this case soil charcoal, phytoliths, and chemistry. Macroscopic charcoal particles (> 0.5 mm) recovered from soils indicate local fire events (Ohlson and Tryterud, 2000) and can be ^{14}C dated to give temporal frameworks of fire. Similarly, phytoliths, the silica bodies produced by many neotropical plant species, are deposited locally and can be used to identify different vegetational formations such as old-growth tropical forest and early successional growth typical of human disturbance and farming, along with domesticated plants such as maize and squash (Piperno, 2006a, b, 2007). Repeated cycles of burning also leave diagnostic records in the form of charred but still morphologically identifiable phytoliths (Piperno, 2006b). Soil geochemistry, including black carbon, total organic carbon, phosphorus, and calcium levels can also indicate anthropogenic soil enrichments, such as settlement sites or enriched anthropogenic soil (*terra preta*) formation (Glaser and Woods, 2004).

Here, we report on 94 soil cores collected around three western Amazonian lakes with sediment records containing known pre-Columbian disturbance. We compared charcoal and phytolith data from soil core records with one another and with the corresponding lake sediment records to determine whether periods of fire and agriculture recorded in the lake sediment records were generated from spatially limited or widespread landscape modifications.

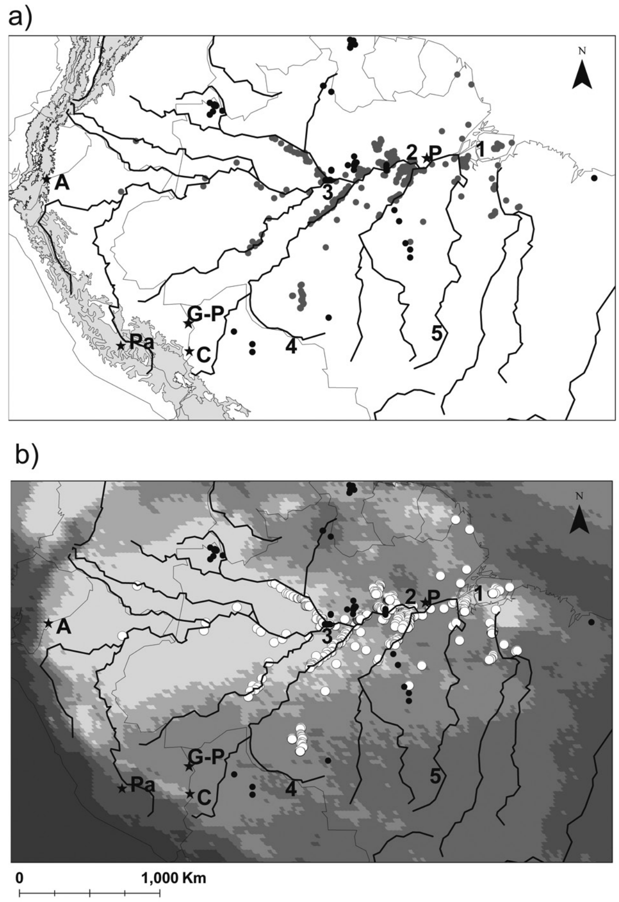

Figure 1. Map of northern South America showing locations of Lakes Ayauch[i] (A) and Gentry/Parker (G-P) along with the major archaeological sites of (1) Marajó Island, (2) Santarém, (3) Manacapuru, (4) the Beni, (5) the upper Xingu, major Amazonian riverways (thick black lines), published records of soil charcoal (black circles), terra preta (grey circles in (a), white circles in (b)), and locations of other lakes discussed in the text: Lago Consuelo (C) and the Prainha watershed (P), Lake Pacucha (Pa). Andean regions are shaded in light gray in (a); political boundaries are demarcated with thin black lines. (b) The seasonality gradient for the same area, with light colors representing aseasonal forests and dark colors representing seasonal forests. Seasonality data are from the TRMM 1998–2004 data set (modified from Silman, 2007)

Methods

Study sites and field methods

Sites used include Lake Ayauchi (3°2'42.93"S, 78°2'4.32"W) in southeastern Ecuador and Lakes Gentry (12°10'41.06", 69°5'54.91"W), and Parker (12°8'31.47"S, 69°1'16.64"W) located in the same watershed in the Madre de Dios region of southeastern Peru (Figure 1). Detailed site descriptions can be found in Bush and Colinvaux (1988) for Ayauchi, and Bush et al. (2007) for Gentry and Parker.

Ayauchi lies at 330 m above sea level on the eastern flank of the Andes, and is located above the floodplain within 2 km of Rio Santiago (Figure 2a). The region receives 2000–3000 mm/yr of rainfall with 0–2 months of dry season and supports dense tropical rain forest. Members of the Shuar nation inhabit the area, and they cultivate manioc, plantains, and papayas near the lake (Figure 2a). The lake was first cored in 1983 with a modified Livingstone piston-corer, and re-cored in 2007 to obtain sediment for high-resolution charcoal analysis. Terrestrial soil cores (N = 15) were randomly collected around a 1.5 km radius of the lake with a 10 cm diameter AMS Soil Sampling hand auger in 2007 (Figure 2a). Four cores were taken at or near sites with modern agriculture, and two sites on the south and western sides of the lake were located within 100 m of a modern farmhouse. Additional soil cores were located in secondary forest dominated by *Cecropia*, with no sign of very recent disturbance. For all cores, leaf litter and rootlets were cleared from the soil surface prior to augering to prevent modern contamination. Samples were recovered in incremental segments of typically 3–20 cm, while total core depths ranged from 30 to 100 cm depending on abundances of rocks, density of roots, and total depth of soils. Any surface debris falling into the soil core between drives of the auger was removed by hand. Generally, the

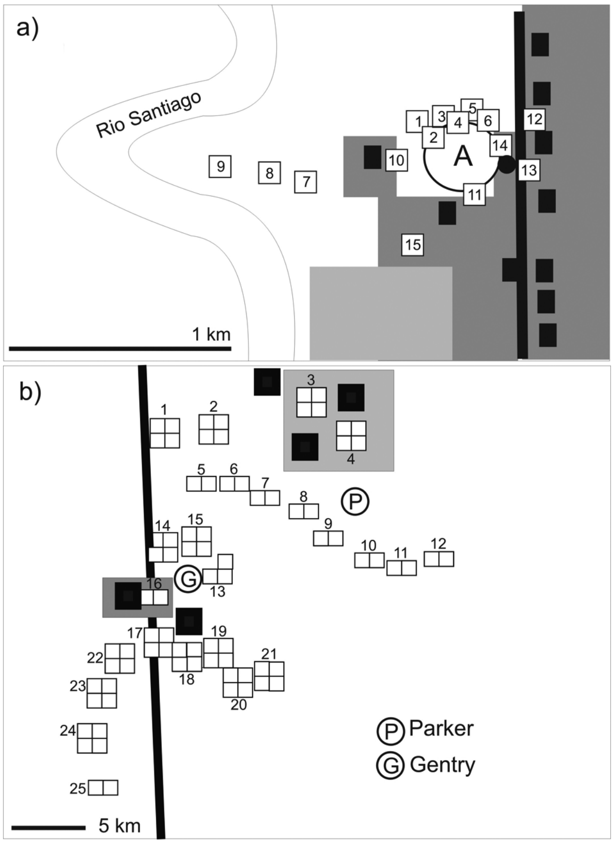

Figure 2. Soil core locations and site numbers (white squares) around Lake Ayauchi[i] (a) and Lakes Gentry and Parker (b) shown in relation to modern land usage. Location of the lake is indicated with a white circle with A, G, or P for Ayauchi, Gentry, and Parker, respectively. Agricultural land (dark grey), pastures (light grey), farmhouses (black squares), community houses (black circles), and roads (black lines) are shown. Subdivided squares at Gentry and Parker indicate replicate cores collected within 100 m of each other

soils in the area were wet clay entisols, approximately 50 cm deep, especially immediately around the lake, which is believed to be volcanic in origin (Colinvaux et al., 1985).

Gentry and Parker are located at elevations of 200–300 m, lie > 200 km from the Andes, and are located > 20 km away from the Madre de Dios River. The region consists of typical upper Amazonian forests, with a local abundance of *Bertholletia* and *Couratari* species (e.g. Pitman et al., 1999). A precipitation gradient extends across the Madre de Dios watershed, ranging from *c.* 2000 mm/yr in the south to *c.* 1700 mm/yr in the north. The duration of the dry season is typically 2 to 4 months. A small cluster of approximately four families lived on a knoll beside a non-navigable stream within 4 km of Lake Gentry. Accessibility around Parker was extremely limited, but several farmhouses were noted within 3–5 km of the lake. The Trans-Amazon highway (completed 2009) was located within 1 km of Gentry and 11 km of Parker, but was a less-traveled dirt road at the time of lake coring and soil sampling. Gentry and Parker were cored in 1998 and 2001 (respectively) with a Colinvaux-Vohnout coring rig (Colinvaux et al., 1999). Soil cores were collected in 2008, and locations were chosen in randomly located but accessible sites (numbered 1–25), with each site composed of two to four replicate cores (Figure 2b). Sites (n = 25) and cores (N = 79) were located at distances from 100 m to 12 km from either one or both lakes. A further constraint was to place soil cores > 100 m from any sign of modern disturbance or agriculture to avoid potential problems with churned soils, although two sites were sampled in pasture areas. Depth intervals of samples at Gentry and Parker were typically from 10 to 30 cm, and total core depths ranged between 50 cm and 130 cm in the rather dry, friable entisols.

Laboratory methods

All lake cores were volumetrically sampled for charcoal at 1 cm intervals. Both the original lake core (old core) from 1983 and the 2007 core (new core) from Ayauchi were used for analyses. Cores were cross-correlated using changes in stratigraphy, ^{14}C dates (Table 1), marked changes in diatom composition (Reidinger, 1993), and prominent charcoal abundance spikes. Sediment samples were deflocculated using 10% potassium hydroxide and sodium pyrophosphate then sieved to 180 µm. Charcoal particles were identified with a stereoscope, and surface area of particles per sample was calculated using Image J software. The published charcoal data for Gentry and Parker (Bush et al., 2007) were used, and sediment samples were processed in the same manner as described for Ayauchi. All radiocarbon dates were calibrated using the Fairbanks et al. (2005) calibration curve. Age-models for all cores were calculated with the PaleoMAS package for R statistical software (Correa Metrio et al., 2010).

Terrestrial soils were volumetrically measured in water, deflocculated with detergent, wet sieved to 1 mm and 500 µm and analyzed for charcoal particle surface area (mm^2/cm^3) using Image J software. Surface area of charcoal was converted to volume (mm^3/cm^3) to down-weight the smaller fragments (Weng, 2005). Total charcoal abundance was measured in each depth interval of each core. Selected fragments were ^{14}C AMS dated and the ages calibrated using the Fairbanks et al. (2005) calibration curve. Black carbon (n = 12, N = 24), phosphorus, and calcium levels (mg/g soil) (n = 8 at Ayauchi, 5 at Gentry; N = 13) and total organic carbon percentages (TOC%) (n = 12, N = 24) were measured in randomly selected depth intervals of selected soil cores. Descriptive statistics for each hole were calculated, and Mann-Whitney U tests were performed for each proxy to compare between locations.

Phytoliths were extracted from soils using standard laboratory techniques (Piperno, 2006b), and used to determine the degree of forest modification at our sites. Identification was based on Piperno's modern reference collection comprised of over 2000 species of tropical plants. Phytolith content was high in virtually all soil samples studied from around the three lakes. Percentages of forest taxa, Arecaceae, early successional herbaceous taxa (grasses, *Heliconia*, sedges), and burned phytoliths were calculated for each depth interval of randomly selected soil cores (N = 57 at Ayauchi; N = 58 at Gentry/Parker). The category forest taxa included phytoliths from families such as Annonaceae and Chrysobalanaceae along with other presently unidentified phytoliths that are characteristic of old growth forests in modern phytolith assemblages studied (Piperno, 2006b, 2007). Arecaceae (palm phytoliths) were quantified separately from forest taxa in order to assess whether human disturbances were associated with palm increases, possibly from deliberate management and manipulation of palms, as some researchers have suggested (Balee, 1989; Balee and Erickson, 2006). Presence of cultivars provided direct evidence of agriculture, and increases of grass phytoliths from the sub-families Panicoideae and Chloridoideae grasses (hereafter

Table 1. ^{14}C AMS dates obtained from lake sediment, soil phytoliths, and soil charcoal fragments from Ayauch[i], Gentry and Parker

Location	Site	Depth (cm)	Age group	^{14}C age	Std dev	Cal. age	Std dev	Weight (mg)
Ayauch[i] (nc)		13.5		1480	30	1359	27	
Ayauch[i] (nc)		90.25		1800	30	1725	41	
Ayauch[i] (nc)		111		1910	30	1855	31	
Ayauch[i] (nc)		145		2340	35	2346	22	
Ayauch[i] (nc)		178.5		2580	35	2725	31	
Ayauch[i] (oc)		146		2440	80	2949	146	
Ayauch[i] (oc)		192.5		3310	80	3536	95	
Ayauch[i] (oc)		230		4570	70	5273	115	
Ayauch[i] (oc)		286.5		7010	130	7838	127	
Ayauch[i] (s)	7	30–33	D	2600	30	2736	15	5
Ayauch[i] (s)	8	32–39	A	modern				4.7
Ayauch[i] (s)	9	32–39.5	D	2120	25	2099	42	1.6
Ayauch[i] (s)	9	39.5–47	C	1670	25	1560	28	2.1
Ayauch[i] (s)	10	35–43	A	modern				40.4
Ayauch[i] (s)	10	52–60	D	2300	30	2328	25	27
Ayauch[i] (s)	10	68–72	A	modern				2.5
Ayauch[i] (s)	11	12–19	C	1940	35	1883	35	2
Ayauch[i] (s)	11	19–26	C	1720	35	1624	51	0.8
Ayauch[i] (s)	11	26–34	E	2910	35	3044	62	1.2
Ayauch[i] (s)	12	32–37	A	modern				29.1
Ayauch[i] (s)	13	13–25	C	1250	25	1191	40	N/A
Ayauch[i] (s)	13	37–42	A	modern				6.7
Gentry/Parker (s)	2(3)	51–69	G	5310	30	6087	63	24.6
Gentry/Parker (s)	2(3)	89–108	G	5360	50	6162	74	75.7
Gentry/Parker (s)	3(1)	20–40	C	1260	25	1205	39	3.5
Gentry/Parker (s)	3(1)	80–97	E	3580	35	3877	44	4.5
Gentry/Parker (s)	3(1)	97–117	D	2510	25	2636	79	2.8
Gentry/Parker (s)	10(1)	24–38	B	845	30	745	31	2
Gentry/Parker (s)	16(1)	54–71	G	7610	40	8403	25	2
Gentry/Parker (s)	16(2)	12–25	A	modern				13.8
Gentry/Parker (s)	17(1)	17–33	E	3570	40	3865	51	22.2
Gentry/Parker (s)	17(1)	47–69	D	2490	25	2599	81	13.1
Gentry/Parker (s)	17(3)	86–97	G	7590	40	8392	21	21.7
Gentry/Parker (s)	18(1)	19–30	C	1260	25	1205	39	26.3
Gentry/Parker (s)	18(2)	22–44	G	4790	30	5544	43	3.4
Gentry/Parker (s)	19(1)	39–55	D	2540	25	2694	55	69.8
Gentry/Parker (s)	19(2)	95–110	G	5920	35	6733	41	2.1
Gentry/Parker (s)	21(1)	52–65	A	modern				2.3
Gentry/Parker (s)	21(4)	92–108	G	8050	35	8987	40	5.7
Gentry/Parker (s)	23(4)	44–64	G	5160	30	5914	22	27.1
Gentry/Parker (s)	23(4)	64–76	A	modern				3.2
Gentry/Parker (s)	24(1)	34–55	A	modern				0.7
Gentry/Parker (s)	24(2)	69–93	G	4960	30	5675	35	66.8
Gentry/Parker (p)	17(1)	0–17	d	2680	40	2770	20	
Gentry/Parker (p)	17(1)	17–33	d	2470	40	2680	50	
Gentry/Parker (p)	17(1)	47–69	e	2930	40	3070	70	
Gentry/Parker (p)	17(1)	89–95	g	4590	40	5311	66	
Gentry/Parker (p)	18(1)	0–19	e	2920	40	3070	80	
Gentry/Parker (p)	18(1)	19–30	c	1830	40	1740	30	
Gentry/Parker (p)	18(1)	42–61	e	3270	40	3484	50	
Gentry/Parker (p)	18(1)	98–110	g	4680	50	5409	75	
Gentry/Parker (p)	23(4)	0–17	c	1740	40	1660	60	
Gentry/Parker (p)	23(4)	17–29	d	2090	40	2050	50	

Lake sediment data: nc, from 2007 core; oc, from 1983 core. Site number corresponds with soil core sites listed in Figure 2. Depths from lake sediments and intervals of dated soil charcoal fragments and phytoliths are listed. Weights (mg) of individual charcoal fragment submitted for dating is given. Age groups are used in Figure 5. Dates from the new core and soils were processed by NOSAMS Laboratory, and old core and phytolith dates by Beta Analytic. All dates were calibrated using Fairbanks (2005) calibration curve to the one sigma level.

PC grasses) along with *Heliconia* and sedges provided indirect evidence for forest clearance associated with human activities, as these taxa are typical of regrowth vegetation in and on the edge of cultivated fields. Phytoliths in selected cores and depths were directly dated by ^{14}C at Beta Analytic Laboratory, Miami, Florida using techniques explained in Piperno (Piperno, 2006b).

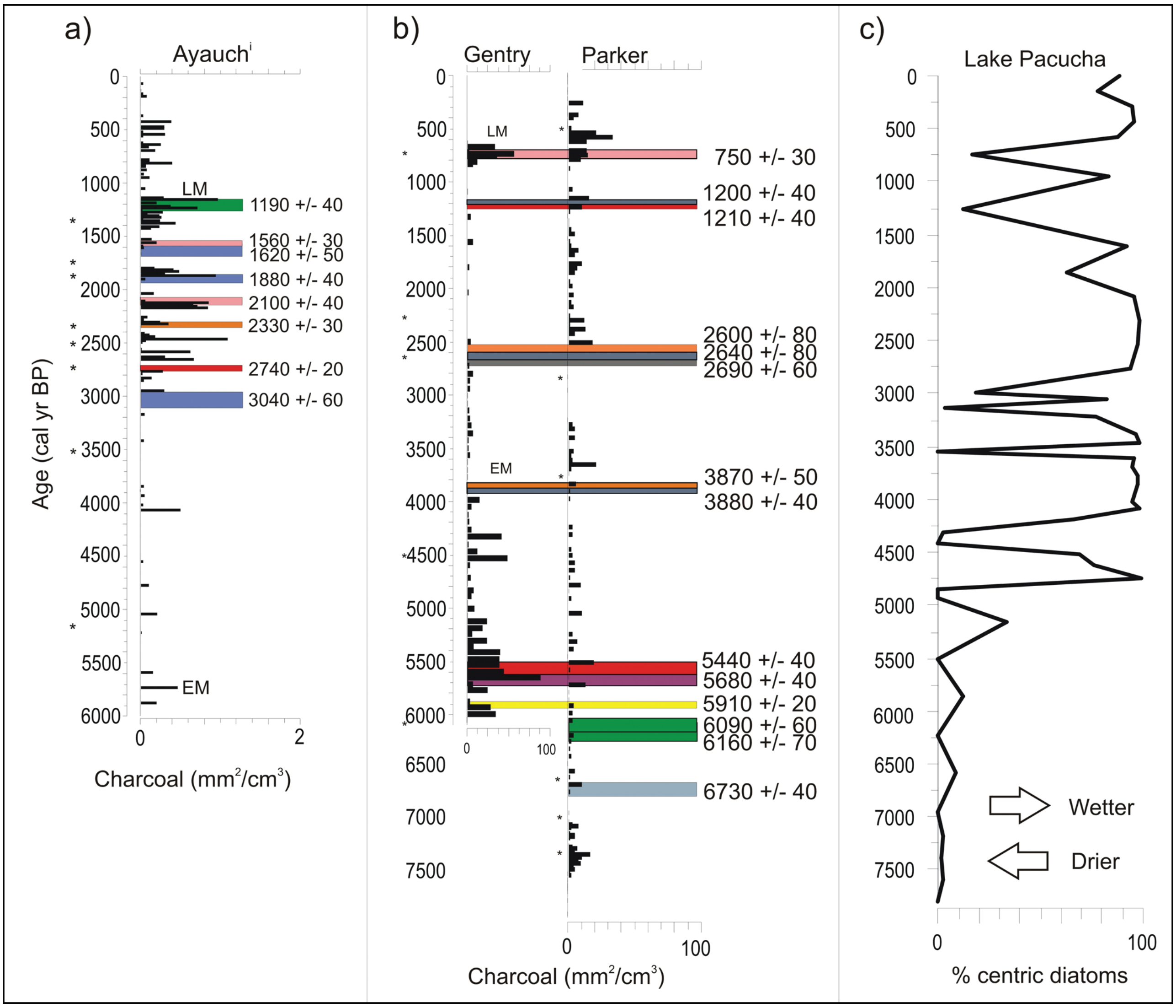

Figure 3. Lake sediment charcoal records (black bars) from Ayauch[i] (a) and Gentry and Parker (b) compared with dated soil charcoal fragments (listed to the right of colored bars – see Figure 4 for locations). EM marks the first sign of maize pollen or phytoliths and LM marks the last presence of maize. Asterisks (*) denote where ^{14}C dates were obtained from the lake sediment cores.
Note: values of soil core ^{14}C ages have been rounded to the nearest 10. See Table 1 for exact values. (c) Lake sediment diatom record from Lake Pacucha, Peru that recorded Amazonian wet and dry periods in the Holocene through changes in lake level (modified from Hillyer et al., 2009)

C2 software was used for creating stratigraphic diagrams of lake sediment records and soil core records. ArcGIS version 9.3 was used to create site maps.

Results

Lake Ayauchi, Ecuador

Four ^{14}C dates on the 2007 lake core, plus four on the 1983 record provide a robust chronology spanning the last 6000 cal. yr BP (Table 1). Lake sediment charcoal showed a temporally discontinuous fire history, with distinct peaks of sedimentary charcoal separated by periods with very little to none. Fire activity increased *c*. 3000 cal. yr BP and declined around 450 cal. yr BP (Figure 3a). The main fire events recorded in the lake sediment were reflected in the charcoal ages obtained from the soil survey (Figure 3a). The congruency of lake and terrestrial soil records revealed that fires within 1 km of the lake were represented in the lake sediment record.

The terrestrial cores revealed spatially heterogeneous patterns of charcoal abundances and phytolith percentages indicating patchy land usage. Charcoal abundances varied markedly between depth intervals and between holes, but most subsurface charcoal and maize phytoliths were located just south of the lake and to the west closer to Rio Santiago (Figures 4a, b, 5a). Absence of charcoal does not necessarily indicate the absence of fire (Ohlson and Tryterud, 2000), and the presence of charred phytoliths (Sites 2 and 6) in the absence of charcoal provided a more refined spatial fire history. Burned phytoliths occurred even where charcoal did not, indicating that the fuel was primarily herbaceous. Indeed, in soil core 5, where no charcoal was detected, 13–30% of herbaceous phytoliths had been burned at the soil depths where maize phytoliths were recovered. Presence of maize (Sites 2, 5, 8–11) and squash (Site 9) phytoliths, and increased percentages of subsurface PC grass phytoliths, often with burned *Heliconia* phytoliths (Sites 2, 9–11) revealed agricultural activity occurring at several sites around the lake (Figures 4b, 5a). During periods of agricultural activity, forest phytoliths continued to be much more frequent than the early successional growth indicators, often maintaining frequencies above 70%.

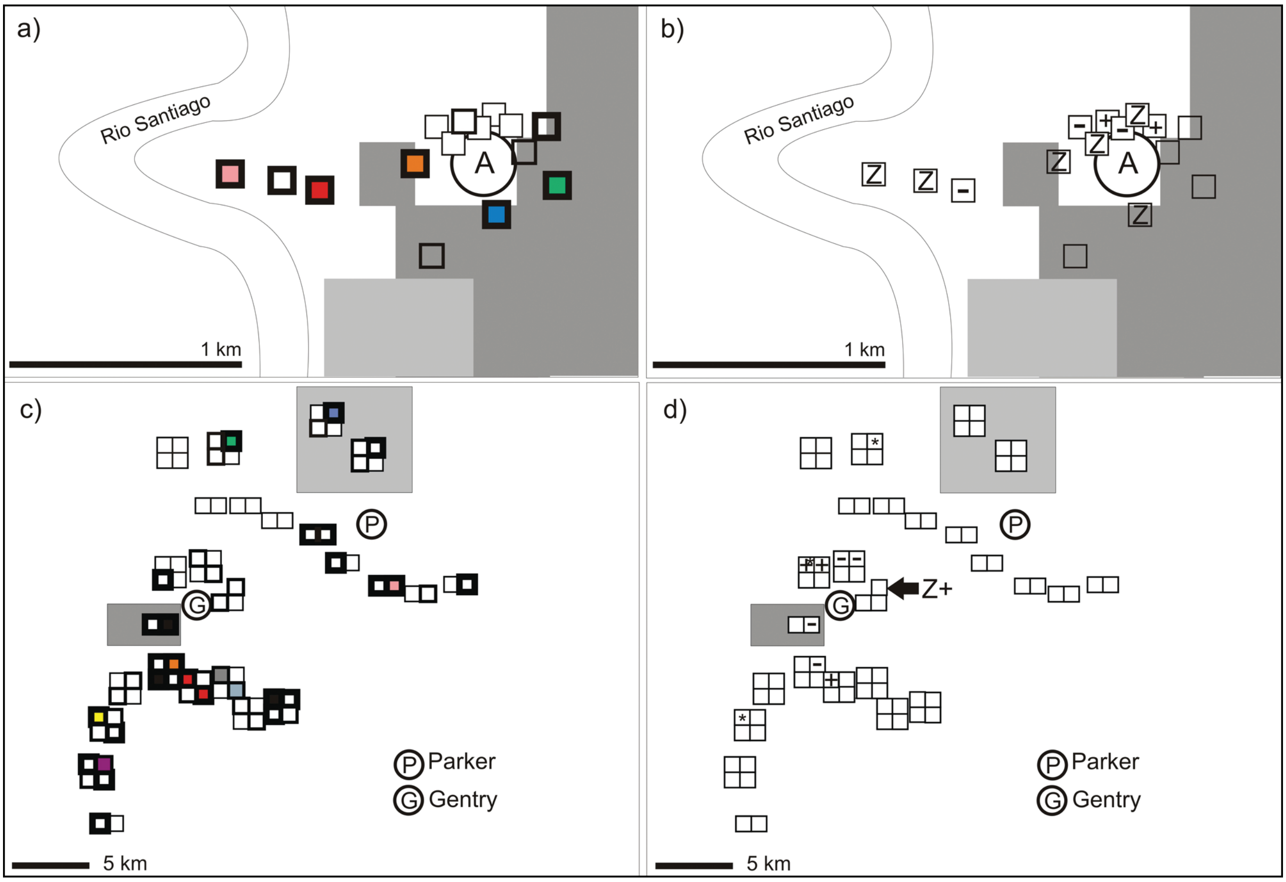

Figure 4. Soil charcoal and phytolith distributions around Ayauch[i] (a and b) and Gentry/Parker (c and d). In (a) and (c) black outlines around core sites indicate total charcoal abundances (thickest outlines > 1 mm^3/cm^3; medium outlines < 1 mm^3/cm^3; light outlines = no charcoal). ^{14}C dated charcoal fragments spatially represent colored bars seen in Figure 3, and black sites at Gentry indicate fires prior to lake formation. In (b) and (d) vegetation changes and disturbance indicators, including subsurface *Zea* phytoliths (Z), high levels (> 10%) of Panicoid grass indicators (+), high levels of closed forest grasses (*), and forest indicators (–) throughout individual soil cores

The phytolith record indicated that very little disturbance through time occurred in six of the sites studied (Sites 3–8), which included sampling locales only *c*. 200 m from sites where persistent cultivar presence and forest clearings are evidenced (e.g. Sites 7 and 8). Additionally, no increase of palm phytoliths was seen when disturbance indicators were present in significant frequencies, suggesting that inhabitants were not artificially increasing palm densities. There is, then, no suggestion from the phytolith record that the vegetation of most of the lake's watershed was significantly disrupted by human occupation and agriculture or that farming was associated with clear-cutting of forest areas. Supporting these conclusions is the absence of ceramic sherds in the sampled sub-surface soils.

No extraordinarily enriched layers of charcoal within the clay-rich soils around Ayauch[i] were found at any site, except for surface samples from Site 10, which was located within 100 m of a farmhouse (Figure 5a). Extremely abundant charcoal was only found at three sites (Sites 7, 10, and 13, Figure 5a). In only four holes, charcoal was found at multiple levels within the profile that would suggest repeated fires at that site (Sites 7, 10, 11, and 13).

Modern agricultural sites always included charcoal in the uppermost level of the profile, although usually in low quantities, and contained a mixture of both modern and pre-Columbian (2000–4000 cal. yr BP) charcoal fragments in sub-surface levels (Figure 5a, Table 1). That modern charcoal was found at depth in these disturbed settings indicates that stratigraphic integrity is uncertain on recently disturbed sites. Downward percolation of modern charcoal in two agricultural sites (Sites 12 and 13) and one site located within 100 m of a modern farmhouse on the western side of the lake (Site 10) was indicated (Figure 5a).

Soil nutrient data revealed that neither *terra preta* formation nor other anthropogenic soil enrichment practices had likely occurred around Lake Ayauch[i]. Black carbon averages per hole ranged from 0.41 to 12.43 mg/g soil, with a median of 6.50 mg/g soil. Total organic carbon ranged from 0.42 to 10.16%, with a median of 3.61%. The average phosphorus measurements per hole ranged from 5.86 to 84.43 mg/kg P, with a median of 10.36. Average calcium measurements per hole ranged from 68.58 to 2075.87 mg/kg Ca, with a median of 497.91.

Lakes Gentry and Parker, Peru

Fossil pollen and charcoal sequences from these lakes displayed evidence of episodes of burning at both lakes, the cultivation of *Zea* at Gentry from 3700 cal. yr BP to 500 cal. yr BP, and *Manihot* pollen at Gentry *c*. 2400 cal. yr BP (Figure 3b) (Bush et al., 2007). The amplified signals of agriculture and fire frequency around 3000 cal. yr BP observed at Ayauch[i] were not seen at Gentry or Parker. Parker had a more consistent record of charcoal than Gentry, but it was a much smaller water body and would be expected to have higher macrofossil inputs to the lake center. The peaks of charcoal deposition in Gentry aligned to times of regional drying that would have reduced lake surface area (Figure 3c). Samples containing *Zea* and *Manihot* pollen at Gentry contained relatively

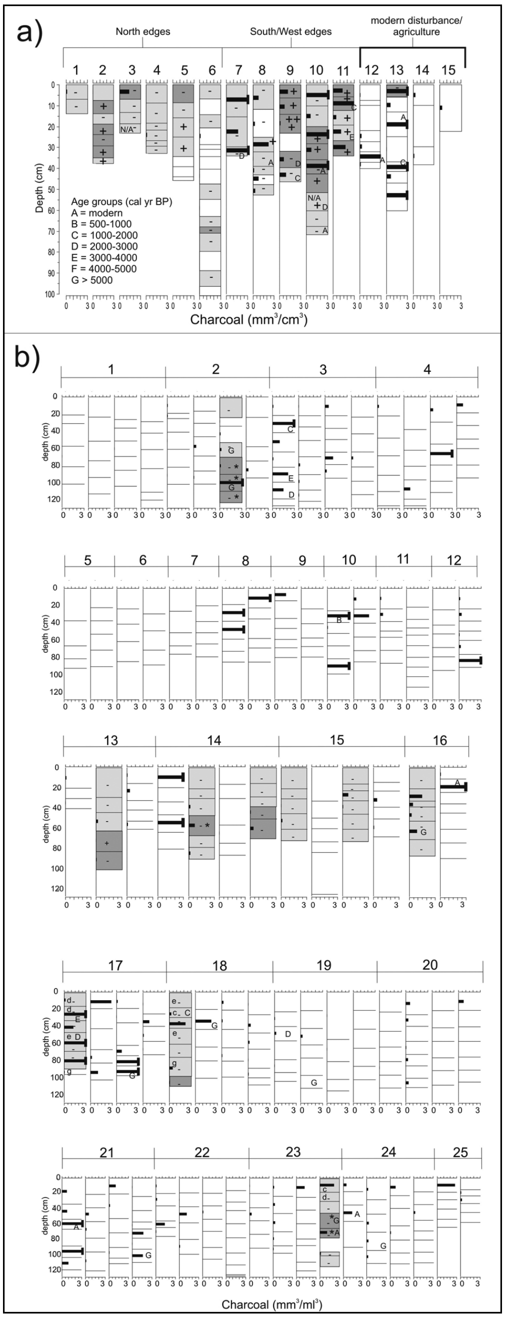

Figure 5. Individual soil core records with charcoal abundances, maize presence/absence, and changes in forest structure through time around Lakes Ayauchi (a) and Gentry and Parker (b). Site numbers correspond to numbers shown in Figure 2, and replicates of all sites are shown for Gentry and Parker. Charcoal abundances (black bars) are shown in mm^3/cm^3 for each soil core (x-axis) and for each depth interval within each core (y-axis), and exceed scale of the x-axis when intersected with a perpendicular bar at 3 mm^3/cm^3. Depth intervals of soil cores are separated by grey lines, which also illustrate the maximum core depth. Intervals colored light grey contain forest dominated phytoliths, and intervals colored dark grey contain increased levels of herbaceous taxa (>10 %). Percentages of successional herbaceous phytoliths (grasses, *Heliconia*, and sedges) in the levels colored dark grey ranged from 12 to 28% at Ayauchi, with all values but three between 15 and 28%. At Gentry and Parker, herbaceous phytolith values ranged between 11 and 32% and three levels had values greater or equal to 15%. Dark grey intervals marked with an asterisk (*) indicates that increased grass phytoliths were bamboos. Grasses accounted for most of the herbaceous phytoliths at every site. ^{14}C dates from soil charcoal are indicated by capital letters and phytolith dates by lowercase letters, which correspond with the same age groups (cal. yr BP) legend as seen in Table 1 and (a). Plus (+) signs indicate maize presence; minus (–) signs absence of maize

little charcoal compared with portions of the core during dry periods of the mid Holocene (Figure 3b and c). Charcoal abundance declined to zero at *c*. 650 cal. yr BP at Gentry, coinciding with the last record of *Zea* in the sediment record. At Parker, charcoal continued to be present until *c*. 250 cal. yr BP.

Charcoal recovered and dated from the soil cores around Lakes Gentry and Parker showed some concordance with peaks of charcoal in the lake cores, but fire events recorded at *c*. 3870 cal. yr BP and between 2600 and 2690 cal. yr BP in the soil records had no corresponding charcoal in the lacustrine data (Figures 3b and 4c). These sites all lie 3.5–5 km from the lake edge, but concordance between lake and soil records was seen in other soil cores at greater distances (Sites 23 and 24). Of 21 dated soil charcoal fragments, 13 indicated an increased fire frequency during periods of drought prior to 5000 cal. yr BP, as did charcoal peaks in the lake sediment (Figure 3b, c). Several dated fragments of charcoal recorded fires *c*. 8000–9000 cal. yr BP, which was prior to lake formation (Figure 4c, Table 1).

Evidence of fire history from soil cores was sporadic and localized around both lakes, with many sites showing no evidence of any historical disturbance (Figures 4c, d, 5b). Soil cores on the south and east side of Lake Gentry contained the highest charcoal abundances, along with a few cores scattered around Lake Parker. Charcoal abundances appeared to be unrelated to proximity to the lake (Figure 4c). Many sites had no sign of charcoal in any replicate, but when charcoal was present, it usually occurred in only one or two of the four replicate cores collected within 100 m of each other.

Soil phytolith records in tandem with radiocarbon determinations carried out directly on the soil phytoliths from selected depth intervals indicated a predominantly forest-dominated system over the last several thousand years throughout the sampling area (Figure 5b), which was concordant with the > 70% pollen of arboreal taxa found throughout the lake core (Bush et al., 2007). The phytolith records span at least the last half of the Holocene, and phytolith dates also demonstrated stratigraphic trends in the assemblages through time, with the oldest phytoliths occurring with depth in the soil cores. *Zea* phytoliths were only found in a single soil sample that was located approximately 1 km from the lake edge (site 13, core 2, Figure 4b). This sample also contained high levels of PC grasses. PC grass assemblages (> 10%) without *Zea* occurred in three of the ten soil cores analyzed for phytoliths. Bamboos, which may occur in the understory of mature forest and are not typically weeds of agricultural fields, accounted for the increased grass percentages in two other cores, and were found alongside charcoal > 5000 cal. yr BP (Figures 4c, d, 5b). In all cores containing evidence of historical disturbance, the uppermost sections returned to a forest-dominated system (Figure 5b). As at Ayauchi, no patterns could be seen in the palm phytolith records, suggesting humans were not artificially increasing palm densities.

Although samples around Gentry/Parker were not collected near current agricultural sites, modern charcoal was often found at depths less than 25 cm or when fragments submitted for dating were smaller than 4 mg (Table 1, Figure 5b).

Black carbon levels per hole ranged from 0.28 to 0.95 mg/g soil, with a median of 0.47. Total organic carbon percentages per hole ranged from 0.25 to 0.78%, with a median of 0.37%. Average phosphorus per hole ranged from 1.96 to 419.50 mg/kg P, with a median of 15.50. Average calcium per hole ranged from 49.34 to 1124.44 mg/kg Ca, with a median of 173.02. Again, these data suggested no intentional anthropogenic soil organic enrichments. Both total organic carbon and black carbon concentrations were significantly lower than those found at Ayauch[i] (for TOC: U = 4.00, $p < 0.0001$) (for BC: U = 17.00, $p = 0.001$). Phosphorus and calcium values were not significantly different between locations (for P: U = 18.00, $p = 0.770$; for Ca: U = 13.00, $p = 0.306$).

Discussion

Spatial and temporal scales of disturbance

No pottery sherds, *terra preta*, evidence of anthropogenic soil modifications or stone tools were found in any of our samples, and many soil cores showed little to no sign of vegetational disturbance for several thousand years (Figures 4 and 5). The low to moderate degrees of disturbance recorded at our sites were considerably smaller than those found in the savannah–forest transition areas of Bolivia (Erickson, 2000, 2006), the savannahs of French Guiana (McKey et al., 2010) or along the Amazon River and its major tributaries (Heckenberger et al., 1999, 2003, 2007; Neves and Petersen, 2006; Roosevelt et al., 1991, 1996).

Temporally discontinuous and spatially patchy disturbances have occurred around all three lakes since 6000–7000 cal. yr BP (Figure 3). At Ayauch[i], the decline of some mature forest indicators from the lake pollen and phytolith records and increases in herbaceous taxa and agricultural intensification occur after 3000 cal. yr BP, and subsequent decreases in herbaceous taxa coincide with the disappearance of agricultural indicators (Bush et al., 1989; Piperno, 1990). These patterns are also reflected in the terrestrial soil records that provided evidence for charcoal, crops, and forest clearings at some of the sites from 3000 to 1000 cal. yr BP. Old-growth forest indicators dominated the entire span of the Gentry and Parker lake records (Bush et al., 2007), although fire frequency was increased during dry periods of the middle Holocene (Figure 3b, c). Signs of human disturbance in all three lake records and corresponding soil records decreased or disappeared around 500 cal. yr BP, coincident with the arrival of Europeans to the Americas and the subsequent native population collapse (e.g. Cook and Lovell, 2001). Lake charcoal abundances cannot be directly compared *between* lakes because of differences in lake drainage and size, but relative changes *within* each of the sediment records point to Ayauch[i] as a more intensively used area compared with Gentry and Parker, a result corroborated by the soil phytolith and charcoal records.

Large-scale human disturbances have generally, though not exclusively, been associated with major rivers. Denevan (1996) suggested that as much as 90% of occupations would have occurred on river bluffs. In a later paper we will test this hypothesis, but here we refer to such river bluff or lake margin settings as being ‘preferred’ occupation sites. The increased levels of pre-Columbian disturbance found at Ayauch[i] are probably, in part, due to its closer proximity to a ‘preferred’ riverine bluff setting than at Gentry or Parker. Ayauch[i] soil cores closest to Rio Santiago were the most heavily disturbed from that site (Figures 4a, b, 5a). The disturbed settings of Ayauch[i] lay *c*. 40 m in elevation above the Rio Santiago negating the possibility of flooding contributing to soil fertility. Nevertheless, total organic carbon and black carbon percentages were significantly greater around Ayauch[i] than Parker or Gentry. While both of these have been associated with soils of greater fertility, the macronutrients (P, Ca) concentrations were not significantly greater and there was no evidence suggesting anthropogenic alteration of the soils.

Around all of our studied lakes, fire and agriculture were concentrated in specific areas. Slash and burn or slash and mulch agriculture occurred within a 1.5 km radius around Ayauch[i], but there was no evidence of wholesale clearance of the landscape around the lake and about half of the sites showed little to no evidence for vegetational disturbance at all. No sign of slash and burn agriculture was found around the Peruvian lakes, only very low impact cultivation within 1 km of the lake. Disturbance indicators within the 12 km radius studied suggested minimal impacts. At distances of 5–12 km from the lake some increases in bamboo frequency was observed in intervals containing charcoal dated at 6162 ± 70 cal. yr BP, but there is no firm link between this vegetation type and human activity.

A spectrum of pre-Columbian disturbance therefore existed even within watersheds. The low levels of disturbance found in both lake and soil records at Gentry and Parker were greater than at two other lakes located less than 50 km away (Lakes Vargas and Werth), which contained little to no evidence of fire and no sign of agriculture in lake sediment records (Bush et al., 2007). Similar patterns were also recorded near Prainha, Brazil, with one lake containing evidence of pre-Columbian human activity and the others showing only an increase in fire frequency during the mid Holocene (Bush et al., 2007; Piperno and Pearsall, 1998) (Figure 1). Lake Consuelo, lying to the south of Gentry and Parker but in a different watershed, also contained no sign of fire or human activity during the Holocene (D. Urrego, personal communication, 2007; Figure 1).

Silence and noise in the record

Distinguishing natural from anthropogenic prehistoric landscape modifications in western Amazonian forests is not always possible. During the known dry periods of the middle Holocene (Figure 3c) fire activity may have resulted from natural ignition, and other proxies, such as direct evidence of agriculture, are necessary to confirm human activity. However, paleoecological and ecosystem studies suggest that fire is not natural in western Amazonia under modern climate conditions (Malhi et al., 2009; Nepstad et al., 2004; Ray et al., 2005). The end of the mid-Holocene drought *c*. 4400 cal. yr BP (e.g. Hillyer et al., 2009; Mayle and Power, 2008) marks the onset of near-modern precipitation regimes (Figure 3c). Therefore, we infer that western Amazonian fires after 4400 cal. yr BP were probably due to anthropogenic activities. Regardless of origin, disturbances at our sites did not occur in the past frequently or intensely enough to cause widespread landscape transformations.

The proxies used in this study are sensitive to fire (charcoal), canopy gap openings (PC grass, *Heliconia*, and sedge phytoliths), and agriculture (maize and squash phytoliths and pollen); however, some types of disturbance would be ‘silent’. Some cultivars that were probably very important in pre-Columbian Amazonian agriculture, such as *Manihot* and *Ipomoea* (sweet potato), and most fruit and ‘orchard’ species in the Annonaceae family produce few to no recognizable phytoliths and little pollen. Consequently, detecting an enrichment of native forest with fruit trees and shade cultivation of some crops are beyond the methodological possibilities of this study.

Negative evidence often goes unreported, and yet is a valuable source of information. Recording abundance of burned and charred phytoliths in soil profiles can refine spatial patterns of fire history and determine the type of vegetation burned when

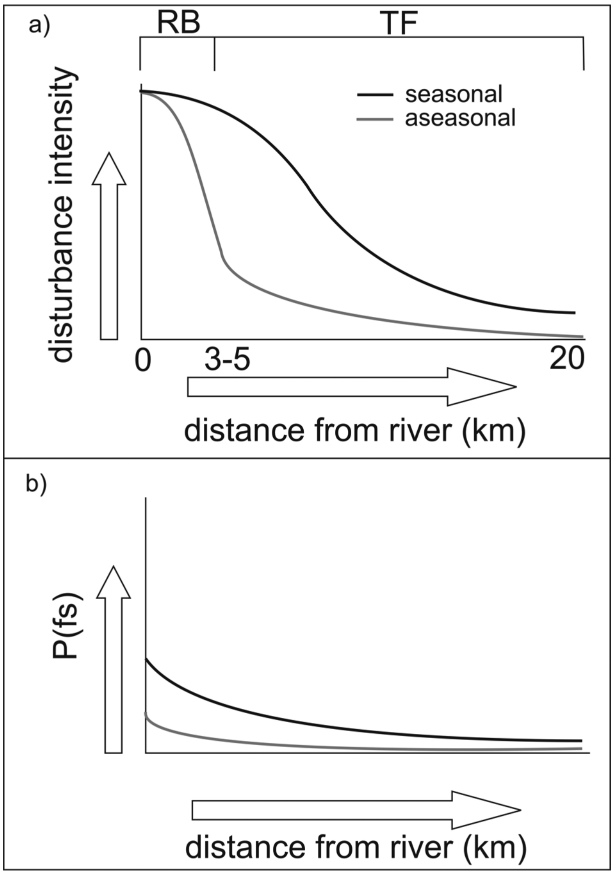

Figure 6. Predictions of pre-Columbian disturbance patterns in Amazonia. (a) Disturbance intensity as a function of distance from river and forest seasonality, and (b) probability of finding a human disturbance site (P(fs)) from randomized surveys. Predictions are shown for both aseasonal and seasonal forests in river bluff settings (RB) and in terra firme forests (TF)

charcoal is absent. High proportions of burned grass phytoliths at Site 5 at Ayauch[i] revealed historical fires in areas with increased grass composition with no indication of macroscopic charcoal. However, repeated sampling producing negative results argues strongly against widespread burning. These important negative data have so far been missing from the discussion of human impacts on Amazonia (Bush and Silman 2007).

Chronologies of soil records were provided by radiocarbon dating of both charcoal fragments and phytolith assemblages, and the two fire proxies differed in dates from the same depth interval by about 700 years (Table 1). It is unrealistic to expect closer dating conformity between charcoal and phytoliths, as a ^{14}C phytolith age represents the mean age of all the phytoliths present in a particular soil level and may represent a mixture of phytoliths of somewhat different ages. This can be contrasted to dating a single piece of charcoal that records a more discrete moment of time. Nevertheless, it is apparent that the phytolith records from depths of between 17 and about 70 cm are recording at least the last 3000 years of vegetational history.

Downward mixing of younger soil charcoal into soil profiles, perhaps due to entrainment by infiltrating water or soil overturn (Table 1, Figure 5) creates a potential overestimation of the frequency of historical disturbance. Although most published records of soil charcoal at depths greater than 20 cm are of pre-Columbian age (Bush et al., 2008), when all dates are reported, charcoal with modern ages can also appear at these depths (Table 1). Making generalizations about depth–age relationships in soils at our sites was not possible, as has happened in soil charcoal studies (e.g. Fesenmyer and Christensen, 2010). Applying thresholds to size and depth of fragments analyzed, and avoiding sample collection near areas of modern disturbance could help reduce noise seen in the samples. However, despite this potential error, neither soil nor lake data show evidence of regional or landscape-scale historical disturbance.

Testable predictions

The studied western Amazonian lakes containing evidence of human impact have occupation histories that last millennia, but radii of disturbance measured only a few kilometers. We find that the halos of disturbance in these western Amazonian forests are much less than in central and southern Amazonian sites of Santarém, the Xingu or the Bolivian Beni (e.g. Erickson, 2006; Heckenberger et al., 2008; Roosevelt et al., 1996), which are in much more seasonal areas (Figure 1b). When examining our data in the context of these other settings, a prediction arises that disturbance intensity in interior forests, composed of temporal frequency and spatial extent, is a function of proximity to bluffs along the major rivers (Denevan, 1996) and forest seasonality (Figure 1b). Generalized diffusion models are often used to explain population spread (e.g. Levin, 1992), and may also describe how disturbance intensity declines away from riverine bluffs (Figure 6a). The seasonal forests of the central and eastern Amazon burn more readily, are not as prone to flooding, and published records contained more evidence of fire and *terra preta* than in the aseasonal forests of western Amazonia (Figure 1). If seasonal forests are more preferred settings than aseasonal forests, the halo of disturbance would extend farther away from rivers (Figure 6a). As optimal riverine bluff settings are a relatively small portion of the entire riverine forest (Denevan, 1996), and meandering river complexes and erosion destroy evidence of settlements through time, we predict a low probability of finding evidence of pre-Columbian human disturbance, even along the rivers (Figure 6b). Other local factors, including distance to freshwater lakes, edaphic variation, topography, microclimate, and distance to nearest other human settlement also probably influences these relationships. With further data collection and analysis, hierarchical Bayesian modeling should prove to be a useful tool in recreating high-resolution spatial and temporal patterns of pre-Columbian landscape modifications.

Conclusions

Lake sediment records containing evidence of pre-Columbian disturbance cannot be assumed to have resulted from temporally and spatially extensive landscape transformations. Our data highlight the need to avoid suggesting vast expanses of pre-Columbian Amazonia were 'manufactured landscapes' based on evidence collected at a few major archaeological sites (Balee, 1989; Erickson, 2003; Mann, 2005). We suggest that with the exception of a few major archaeological sites studied in Amazonia, large-scale pre-Columbian disturbances may turn out to be the exception rather than the norm, particularly in aseasonal terra firme forests (Figure 6). Upon analysis of more field data collected in western Amazonia and more reporting of negative data, we can refine our generalized predictions into testable models of pre-Columbian disturbances. Until such models are tested, conservation policy makers should not assume Amazonian forests are resilient to heavy historical disturbance.

Acknowledgements

We thank Robert van Woesik and Nicole Sublette Mosblech for comments on the manuscript, and Benjamin McMichael, Luis Immunda, and Bryan Rado for field assistance. We are grateful to the Shuar community near lake Ayauch[i] and the small cluster of families around Lakes Gentry and Parker for allowing us to conduct fieldwork on their land. We thank Dr Francis Mayle and an anonymous reviewer for their inputs.

Funding

Field work and ^{14}C dating of charcoal fragments was funded by NSF Ecology Program: award DEB 0742301. Other funding was provided by Florida Institute of Technology, Smithsonian National Museum of Natural History, including a Restricted Endowment and Small Grant Award, and Smithsonian Tropical Research Institute.

References

Balee W (1989) The culture of Amazonian forests. In: Posey DA and Balee W(eds) *Resource Management in Amazonia: Indigenous and Folk Strategies*. New York: New York Botanical Garden.

Balee W and Erickson CL (2006) *Time, Complexity, and Historical Ecology*. New York: Columbia University Press.

Bush MB and Colinvaux PA (1988) A 7,000-year pollen record from the Amazon lowlands, Ecuador. *Vegetation* 76: 141–154.

Bush MB and Silman MR (2007) Amazonian exploitation revisited: Ecological asymmetry and the policy pendulum. *Frontiers in Ecology and the Environment* 5: 1–9.

Bush MB, Piperno DR and Colinvaux PA (1989) A 6,000 year history of Amazonian maize cultivation. *Nature* 340: 303–305.

Bush MB, Silman MR, De Toledo MB, Listopad C, Gosling WD, Williams C et al. (2007) Holocene fire and occupation in Amazonia: Records from two lake districts. *Philosophical Transactions of the Royal Society B* 362: 209–218.

Bush MB, Silman MR, McMichael C and Saatchi S (2008) Fire, climate change, and biodiversity in Amazonia: A late-holocene perspective. *Philosophical Transactions of the Royal Society B* 363: 1795–1802.

Colinvaux P, Miller M, Liu K, Steinitz-Kannan M and Frost I (1985) Discovery of permanent Amazon lakes and hydraulic disturbance in the upper Amazon basin. *Nature* 313: 42–45.

Colinvaux PA, De Oliveira PE and Moreno JE (1999) *Amazon Pollen Manual and Atlas*. New York: Hardwood Academic Press.

Cook N and Lovell W (2001) *Secret Judgments of God: Old World Disease in Colonial Spanish America*. University of Oklahoma Press.

Correa Metrio A, Cabrera K and Bush M (2010) Quantifying ecological change through discriminant analysis: A paleoecological example from the Peruvian Amazon. *Journal of Vegetation Science* 21: 695–704.

Denevan WM (1992) The pristine myth: The landscape of the Americas in 1492. *Annals of the Association of American Geographers* 82: 369–385.

Denevan WM (1996) A bluff model of riverine settlement in prehistoric Amazonia. *Annals of the Association of American Geographers* 86: 654–681.

Denevan WM (2001) *Cultivated Landscapes of Native Amazonia and the Andes*. Oxford: Oxford University Press.

Erickson CL (2000) An artificial landscape-scale fishery in the Bolivian Amazon. *Nature* 408: 190–193.

Erickson CL (2003) Historical ecology and future explorations. In: Lehmann J, Kern DC, Glaser B and Woods WI (eds) *Amazonian Dark Earths: Origin, Properties, Management*. Dordrecht: Kluwer Academic Publishers.

Erickson CL (2006) The domesticated landscapes of the Bolivian Amazon. In: Balee W and Erickson CL (eds) *Time and Complexity in Historical Ecology*. New York: Columbia Press.

Fairbanks R, Mortlock R, Chiu T, Cao L, Kaplan A, Guilderson T et al. (2005) Radiocarbon calibration curve spanning 0 to 50,000 years bp based on paired $^{230}TH/^{234}U/^{238}U$ and ^{14}C dates on pristine corals. *Quaternary Science Reviews* 24: 1781–1796.

Fesenmyer K and Christensen N Jr (2010) Reconstructing holocene fire history in a southern Appalachian forest using soil charcoal. *Ecology* 91: 662–670.

Glanz WE (1991) Mammalian densities at protected versus hunted sites in central panama. In: Robinson JG and Redford KH (eds) *Neotropical Wildlife Use and Conservation*. Chicago: University of Chicago Press.

Glaser B and Woods WI (2004) *Amazonian Dark Earths: Explorations in Space and Time*. Berlin: Springer-Verlag.

Heckenberger M, Russell J, Fausto C, Toney J, Schmidt M, Pereira E et al. (2008) Pre-Columbian urbanism, anthropogenic landscapes, and the future of the Amazon. *Science* 321: 1214–1217.

Heckenberger MJ, Kuikuro A, Kuikuro UT, Russell JC, Schmidt MJ, Fausto C et al. (2003) Amazonia 1492? Pristine forest or cultural parkland. *Science* 301: 1710–1714.

Heckenberger MJ, Petersen JB and Neves EG (1999) Village size and permanence in Amazonia: Two archaeological examples from Brazil. *Latin American Antiquity* 10: 353–376.

Heckenberger MJ, Russell JC, Toney JR and Schmidt MJ (2007) The legacy of cultural landscapes in the Brazilian Amazon: Implications for biodiversity. *Philosophical Transactions of the Royal Society B* 362: 197–208.

Hillyer R, Valencia B, Bush M, Silman M and Steinitz-Kannan M (2009) A 24,700-yr paleolimnological history from the Peruvian Andes. *Quaternary Research* 71: 71–82.

Kern DC, Aquino GD, Rodrigues TE, Frazao FJL, Sombroek W, Myers TP et al. (2003) Distribution of Amazonian dark earths in the Brazilian Amazon. In: Lehmann J, Kern DC, Glaser B and Woods WI (eds) *Amazonian Dark Earths: Origins, Properties, Management*. Dordrecht: Kluwer Academic Publishers.

Levin S (1992) The problem of pattern and scale in ecology: The Robert H. Macarthur award lecture. *Ecology* 73: 1943–1967.

Malhi Y, Aragão LEOC, Galbraith D, Huntingford C, Fisher R, Zelazowski S et al. (2009) Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences 106: 20 610–20 615. Mann CC (2005) 1491: New Revelations of the Americas Before Columbus*. New York: Alfred A. Knopf.

Mayle FE and Power MJ (2008) Impact of a drier early–mid-Holocene climate upon Amazonian forests. *Philosophical Transactions of the Royal Society B* 363(1498): 1829–1838.

McKey D, Rostain S, Iriarte J, Glaser B, Birk J, Holst I et al. (2010) Pre-Columbian agricultural landscapes, ecosystem engineers, and self-organized patchiness in Amazonia. *Proceedings of the National Academy of Sciences* 107: 7823–7828.

Medina J (1934) *The Discovery of the Amazon According to the Account of Friar Caspar de Carvajal and Other Documents*. New York: American Geographical Society.

Meggers BJ (1971) *Amazonia: Man and Culture in a Counterfeit Paradise*. Chicago: Aldine-Atherton.

Meggers BJ (1984) The indigenous peoples of Amazonia, their cultures, land use patterns and effects on the landscape and biota. In: Sioli H (ed.) *The Amazon. Limnology and Landscape Ecology of a Mighty Tropical River and its Basin*. Dordrecht: Dr W. Junk Publishers.

Meggers BJ (2003) Revisiting Amazonia circa 1492. *Science* 302: 2067.

Nepstad D, Lefebver P, Silva ULD, Tomasella J, Schlesinger P, Solorzano L et al. (2004) Amazon drought and its implications for forest flammability and tree growth: A basin-wide analysis. *Global Change Biology* 10: 704–717.

Neves E and Petersen J (2006) Political economy and pre-columbian landscape transformation in central Amazonia. In: Balee W and Erickson CL (eds) *Time and Complexity in Historical Ecology: Studies in the Neotropical Lowlands*. New York: Columbia University Press.

Neves EG, Petersen JB, Bartone RN and Heckenberger MJ (2004) The timing of terra preta formation in the central Amazon: Archaeological data from three sites. In: Glaser B and Woods WI (eds) *Amazonian Dark Earths: Explorations in Space and Time*. Berlin: Springer.

Ohlson M and Tryterud E (2000) Interpretation of the charcoal record in forest soils: Forest fires and their production and deposition of macroscopic charcoal. *The Holocene* 10: 519–525.

Piperno DR (1990) Fitalitos, arquealogia y cambias prehistoricas el la historia vegetal de una parcela de cincuenta hectores en la isla de barro colorado, Panama. In: Leigh E, Rand AS and Windsor D (eds) *The Ecology of a Tropical Forest: Seasonal Rhythms and Long-term Changes (Spanish Edition)*. Washington DC: Smithsonian Institution Press.

Piperno DR (2006a) The origins of plant cultivation and domestication in the neotropics. In: Kennett D and Winterhalder B (eds) *Foraging Theory and the Transition to Agriculture*. Berkeley: University of California Press.

Piperno DR (2006b) *Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists*. Lanham MD: Altamira.

Piperno DR (2007) Preshistoric human occupation and impacts on neotropical forest landscapes during the late pleistocene and early/middle holocene. In: Bush MB and Flenley JR (eds) *Tropical Rainforest Response to Climatic Change*. Chichester: Springer.

Piperno DR and Pearsall DM (1998) *The Origins of Agriculture in the Lowland Neotropics*. San Diego: Academic Press.

Pitman NCA, Terborgh J, Silman MR and Nuñez P (1999) Tree species distributions in an upper amazonian forest. *Ecology* 80: 2651–2661.

Ray D, Nepstad D and Moutinho P (2005) Micrometeorological and canopy controls of fire susceptibility in a forested amazon landscape. *Ecological Applications* 15: 1664–1678.

Reidinger MA (1993) The application of fossil diatom assemblages in reconstructing mid to late holocene climate in the neotropics: The paleolimnology of huarmicocha and lake ayauchi, ecuador. Ph.D. Thesis, Ohio State University.

Roosevelt A (1999) The development of prehistoric complex societies: Amazonia, a tropical forest. *Archeological Papers of the American Anthropological Association* 9: 13–33.

Roosevelt AC, Housley RA, Imazio Da Siveira M, Maranca S and Johnson R (1991) Eighth millenium pottery from a prehistoric shell midden in the brazilian amazon. *Science* 254: 1621–1624.

Roosevelt AC, Lima Da Costa M, Lopes Machado C, Michab M, Mercier N, Valladas H et al. (1996) Paleoindian cave dwellers in the Amazon: The peopling of the Americas. *Science* 272: 373–384.

Smith A (1990) *Explorers of the Amazon*. Chicago: University of Chicago Press.

Weng C (2005) An improved method for quantifying sedimentary charcoal via a volume proxy. *The Holocene* 15: 298.