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Human versus climatic influences on late-Holocene fire regimes in southwestern Nicaragua

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Abstract

Fire regimes in the lowland Neotropics are affected both by anthropogenic land use practices and natural climate variability. In Central America it is widely recognized that fire has been used as an agricultural tool for thousands of years, but the role of anthropogenic ignition as a determinant of past biomass burning frequency and magnitude has been debated. Little is known about the effects of short-term climate variability on fire regimes in this region of the world because of both the low temporal resolution of the available charcoal records and the obfuscating effects of anthropogenic burning throughout the late Holocene. Here we reconstruct 1400 years of fire history and environmental change on Ometepe Island, Lake Nicaragua, and perform statistical wavelet analysis on multiple proxy records to identify natural cycles of environmental variability possibly related to climate forcing. Our results indicate that extensive indigenous burning and landscape modification largely mask any climate signal in the paleo-fire record from AD 580 to 1400, with the exception of the period AD 775–1000 where high wavelet power exists at scales of 2–24 years. This time period coincides with a severe, two-century long regional drought that has been identified at other locations in Central America. High wavelet power at climate-relevant scales after ~AD 1400 in the Ometepe fire record suggests that periodic drought possibly caused by the El Niño Southern Oscillation and/or high-frequency solar cycles may have played a significant role in influencing the post-contact fire regime – a role that is largely concealed in the pre-European strata because of the overriding effects of anthropogenic burning.

Keywords

biomass burning, late Holocene, Nicaragua, paleoecology, pre-Hispanic land use, wavelet analysis

Introduction

The relative influences of climatic versus human factors in shaping historical fire regimes have long been debated by researchers working on temperate forest systems (Vale, 2002; Veblen et al., 1999, 2000). High-resolution late-Quaternary macroscopic charcoal records from temperate North and South America show that fire frequency and magnitude throughout the Holocene have largely been determined by climate variability in these mid-latitude forests, and that human activities played a relatively minor role until the nineteenth century (Kitzberger et al., 2001; Veblen et al., 1999; Whitlock et al., 2007). The history of wildfires in Neotropical forests, however, is not as well understood (Carcaillet et al., 2002; Nevle and Bird, 2008). Efforts to characterize the Holocene history of tropical fire regimes have been hampered by a general lack of data density, both geographic and temporal. Nonetheless, several competing theses regarding the fundamental causes of Holocene fire patterns in the Neotropics have been proposed, ranging from climate change (Marlon et al., 2008) to land use history (Nevle and Bird, 2008) to anthropogenic–climatic synergisms (Bush et al., 2008; Mayle and Power, 2008).

The tropical dry forest (TDF) biome in Central America is particularly prone to wildfires today because of annual forest fuel load desiccation during the dry season, and because humans are a ubiquitous ignition source: over 79% of the inhabitants of Central America presently live in the TDF biome (Janzen, 1988). While human-set fires in TDFs are a common disturbance mechanism during the dry season today (Murphy and Lugo, 1986), it has been argued that the *pre-human* role of fire in the ecology and biogeography of the TDF biome was negligible (Janzen, 1988).

Bimodal (wet and dry) annual precipitation patterns in Central America are caused by the annual migration of the Intertropical Convergence Zone (ITCZ). Perturbations in ITCZ movement occur during the El Niño phase of the El Niño Southern Oscillation (ENSO), during which the ITCZ is deflected south toward unusually warm sea surface temperatures in the tropical Pacific. The lack of atmospheric moisture over Central America during El Niño summer months results in severe drought in many parts of the region (Glantz, 2001; Koonce and Caban-Gonzalez, 1990). Cyclical fluctuations in solar irradiance, which in turn affect sea surface temperatures and ITCZ migration, may also generate regional drought conditions at decadal and centennial scales (Haug et al., 2003; Hodell et al., 2001; Schimmelmann et al., 2003).

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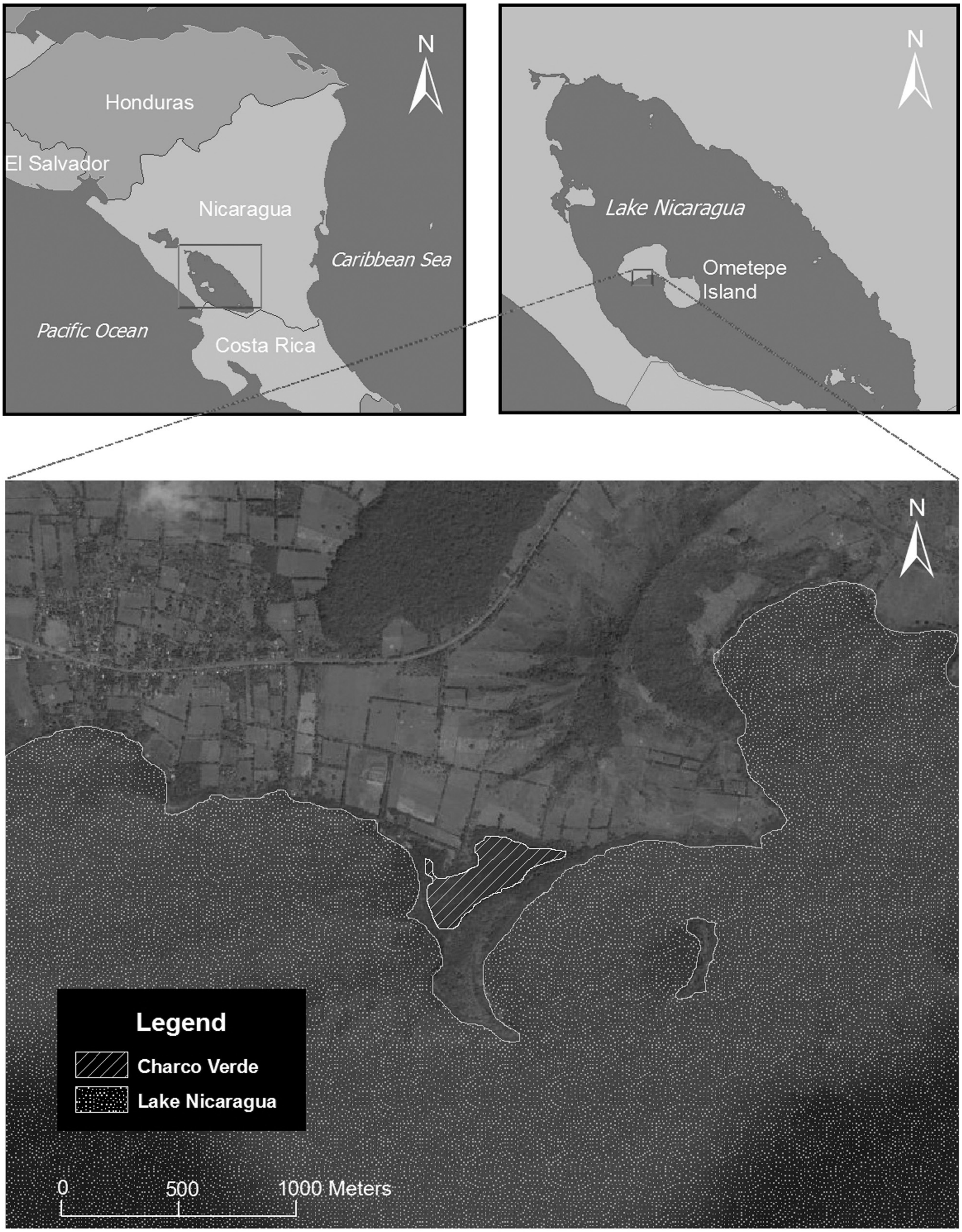

Figure 1. Site map depicting Laguna Charco Verde located on Ometepe Island within Lake Nicaragua: (1) regional map of Nicaragua (top left); (2) Lake Nicaragua blow up depicting the position of Ometepe Island (top right); and (3) close up of the southern side of Volcán Concepción on Ometepe Island, with Laguna Charco Verde indicated by hash marks

Although the largest expanse of Central American tropical dry forest stretches across Nicaragua's southern Pacific coast (Sabogal, 1992), few investigations of historic fire regimes in this region of the world exist, particularly at temporal resolutions that foster analyses of interannual- to interdecadal-scale changes in fire frequencies and their relation to short-term climate variability (i.e. Suman, 1991). Here we present a high-resolution record of biomass burning and local erosion patterns reconstructed from a lake sediment core in Laguna Charco Verde, located on Ometepe Island (11°0′24″N, 85°0′30″W) within Lake Nicaragua (Figure 1). This record is unique

Table 1. Radiocarbon sampling and age calibration results for the Charco Verde lake sediment core obtained from the WM Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California at Irvine

Sample ID	Depth (cm)	UCIAMS[a] Number	Age – median probability ± error (^{14}C years BP)	Lower – upper 1σ range (years AD)	Lower – upper 2σ range (years AD)	Calibrated age – median probability (years AD)
Charco Verde 314	314	32318	705 ± 25	1274–1292	1264–1301	1284
Charco Verde 372	372	11792	865 ± 25	1163–1212	1151–1225	1183
Charco Verde 421	421	32319	1010 ± 15	1013–1027	993–1030	1018
Charco Verde 498	498	11793	1190 ± 20	811–848	777–888	835
Charco Verde 586	586	11794	1230 ± 20	788–819	765–876	789
Charco Verde 622	622	32320	1420 ± 15	622–648	606–653	633

Dates were calibrated using the Calib program version 5.0 (Stuiver and Reimer, 1993) and the INTCAL04 calibration data set (Reimer et al., 2004). All materials dated consisted of terrestrial plant macrofossils.

[a] University of California at Irvine Accelerator Mass Spectrometry Facility.

in both location (the first published paleoenvioronmental record from Lake Nicaragua) and resolution (subdecadal sampling interval). Ometepe Island was inhabited by indigenous populations who employed typical Mesoamerican agricultural strategies – including the use of fire as a land management tool – for at least three millennia prior to Spanish arrival (Haberland, 1986). Because of the introduction of epidemic diseases and forced slavery, western Nicaragua suffered a 75%+ population decline over the three decades that followed the arrival of the Spanish in 1524 (exceeding 90% at the nadir point in the early seventeenth century) (Newson, 1987).

We use wavelet transform analysis to identify both natural (including paleo-El Niño events and/or cyclical variations in solar irradiance) and anthropogenic sources of biomass burning over the past 1400 years. Because proxy dynamics can be driven by both anthropogenic and climatic factors, wavelet transforms are a powerful means of analysis due to their ability to localize in time the different spectral signatures likely associated with human land use dynamics verses those of many periodic climate mechanisms (e.g. Daubechies, 1992; Jevrejeva et al., 2003; Keitt, 2008; Mallat, 1999; Soon, 2005; Torrence and Compo, 1998; Wang and Wang, 1996; Zhang et al., 2007). While wavelets have been utilized in a variety of geophysical applications over the last few decades, to our knowledge they have not been employed to isolate natural signals in paleoproxy records that may otherwise be obfuscated by anthropogenic activity. The macroscopic charcoal record, a proxy for biomass burning, is one such indicator in which natural and human sources of change are greatly intertwined. We additionally conduct wavelet analysis on two other paleoenvironmental proxies – loss on ignition and magnetic susceptibility – in order to examine potential correlations between fire, fuel load, and erosion at different temporal scales. Results from this analysis, combined with our knowledge of general population trends on Ometepe Island, afford a rare assessment of anthropogenic versus natural (i.e. climate) forcing of biomass burning and associated environmental change in the tropical dry forest biome.

Methods

We present macroscopic (>150 μm) charcoal (MC), loss on ignition (LOI), and magnetic susceptibility (MS) proxies at 2 cm resolution to reconstruct fire and related land-use regimes before and after the European arrival. For charcoal analysis, 1.2 cc (1/2 tsp) of lake sediment was extracted from each sampled core level and placed into a 250 ml beaker. Samples were soaked overnight in a 5% solution of sodium hexametaphosphate, and then rinsed through a 150 μm sieve with distilled water. The sieved residue was removed to a petri dish and suspended in water. Charcoal particles were counted with a dissecting microscope at 20 × magnification and converted to charcoal concentrations per cc, as well as charcoal accumulation rates (CHAR) in order to account for variations in the core's sedimentation rate (Whitlock and Larsen, 2001).

Organic matter was determined by the loss on ignition technique, where dried samples were subjected to 550°C in a Barnstead muffle furnace for 2 h (Heiri et al., 2001). Magnetic susceptibility readings were taken using a Barrington MS2 magnetic susceptibility meter and an MS2B sensor. The average of three magnetic susceptibility readings is reported as volume magnetic susceptibility (k).

Six radiocarbon (^{14}C) dates were obtained from terrestrial plant macrofossils in the 6.38 m Charco Verde core from the WM Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California at Irvine. Dates were calibrated using the Calib program version 5.0 (Stuiver and Reimer, 1993) and the INTCAL04 calibration data set (Reimer et al., 2004). Table 1 details radiocarbon sampling and age calibration results. Our age model is based on linear interpolation between sampled depths. The time period of analysis spans the past 1420 years, corresponding with a core bottom age of AD 580. Sedimentation rates vary between 0.23 and 1.91 cm/yr (0.52–4.35 yr/cm), with an average sedimentation rate of 0.62 cm/yr (1.60 yr/cm) and a mean sampling resolution of 3.20 yr. Although some discreet laminated sections are evident in the core, we do not suppose that this lake was ever anoxic or that it contains annual laminations.

We implement wavelet transform analysis to determine the dominant frequencies, localized in time, embedded within the MC, CHAR, LOI, and MS records. Because cyclic climate mechanisms such as ENSO are assumed to have a different time-frequency signature than more aperiodic human activity (e.g. Bradshaw and McIntosh, 1994; Keitt, 2008; Keitt and Fischer, 2006; Keitt and Urban, 2005; Nakken, 1999; Oh et al., 2003; Stanley et al., 2000), wavelet analysis of paleoenvironmental proxies may help extricate natural from anthropogenic sources of change in time series data when the two contribution sources are intertwined. High wavelet power, indicating similarity between the time series data and the cyclic wavelet mother function, suggests potential periods of strong climate forcing, while periods of low power may indicate signal dominance by less-periodic anthropogenic disturbance.

We use the Morlet wavelet transform for our analysis because of its ability to localize time and frequency both sufficiently and relatively evenly compared with other mother functions. Preliminary analysis of raw time series data (not shown) indicated that significant wavelet peaks primarily occurred at scales less than ~64 years with the most prominent periodicities at less than ~32 years, thus precluding analysis of centennial-scale climate forcing of the Charco Verde records. We log-transformed the raw data in order to reduce the potential for heteroskedastic biases in our results (i.e. the concentration of wavelet power at higher scales as a response to overall time series trends rather than a periodic signature) and applied a 2–32 year bandpass filter to focus wavelet power at the interannual and decadal scales of interest. The Charco Verde proxy data were interpolated at a constant time-step of 1 year to account for differences in sedimentation rates. Based on sedimentation rates, the shortest period capable of extraction by wavelet analysis ranges between 1.04 and 8.70 years, with an average of 6.40 years; this period corresponds with the upper range of ENSO variability.

Two types of significance tests were performed on the wavelet power spectra. The first test assumes a red noise background spectrum for the null hypothesis and tests, for every point in the time/scale plane (i.e. pointwise test), whether wavelet power exceeds the critical value corresponding to the chosen significance level estimated by Monte Carlo simulations (Torrence and Compo, 1998). Because pointwise significance testing always leads to the problem of multiple testing (false positive significant patches of wavelet power), we also implement an areawise test that utilizes information about the size and shape of patches to determine significance (see Maraun and Kurths, 2004, for further details). The latter test is considered to be more conservative, as it eliminates possible spurious peaks caused by multiple testing (Maraun and Kurths, 2004). Both tests were performed at a significance level of 0.05; wavelet power peaks are therefore considered significant at the 95% confidence level. All analyses were implemented using the R statistical software package (Ihaka and Gentleman, 1996) with supporting packages Rwave (Carmona et al., 1998) and Sowas (Maraun and Kurths, 2004; Maraun et al., 2007).

Results

Figure 2 illustrates (a) MC, (b) CHAR, (c) LOI, and (d) MS at Charco Verde over the period of record. High MC values (~600 particles/cm^3) at the beginning of the record fall dramatically through AD 900, after which values climb to their peak at ~AD 1100. MC rapidly declines after AD 1300, with values <~200 particles/cm^3 after ~AD 1400 (Figure 2a). The CHAR record indicates generally low and declining accumulation rates (from over 100 to ~30 particles/cm^2 per yr) from AD 580 to 700, after which CHAR slowly increases and then rises sharply at AD 775. CHAR drops dramatically at ~AD 850, after which the record mirrors the fluctuations of the MC data with a reduced overall magnitude (Figure 2b). Both the charcoal and CHAR records thus indicate that biomass burning decreased after ~AD 1400 on Ometepe Island, with peak fire activity occurring between ~AD 580–900 and AD 1100–1300 AD.

The LOI and MS time series indicate an expectedly inverse correlation, with low sediment organic content (~5%) and high erosion (> ~100 k) persisting from AD 580 through AD 1000 (Figure 2c, d). At this point, MS values drop and remain low throughout the record (< ~50 k), with the least magnetic responses occurring between AD 1000–1150 and AD 1300–1400 (Figure 2d). LOI values, by contrast, abruptly rise to 30% organic content at AD 1000 with sustained values through ~AD 1150. LOI subsequently declines and remains relatively stable (~10–20%) until AD 1750, after which organic content rapidly fluctuates through a 100 yr period (up to 58% organic content) before returning to reduced levels around AD 1850 (Figure 2c).

Figure 3 illustrates wavelet power spectrum (WPS) for each time series record. The MC and CHAR WPS (Figure 3a,b) exhibit similar spectral patterns with small differences in the timing and periodicities of significant wavelet power peaks. The MC WPS (Figure 3a) displays high power after ~AD 1400 at scales of 2–8 and 10–28 years. Particularly noteworthy is the prevalence of power at <7-, 11-, and 22-yr periodicities (dashed lines) corresponding with ENSO variability and two important and related solar cycles (the Schwabe and Hale cycles, respectively), suggesting a possible relationship between short-term climate forcing and fire regimes. Peak power at a scale of ~15 years may be due to variability within or the interference between these climate forcing mechanisms. Additionally significant peaks occur at AD 850–1000 at a scale of 8–24 years, AD 775–850 at 2–8 years, and AD 600–750 at 21–32 years. The most notable difference between the MC and CHAR WPS is that significant power patches are present at slightly lower periodicities in the CHAR record, with peak power at ~11 years after AD 1400 (Figure 3b). In addition, significant peaks are absent after ~ AD 1850 in the CHAR WPS, whereas patches of power exist through the end of the MC record.

The LOI WPS demonstrates periods of significant wavelet power at similar, climate-relevant scales (Figure 3c): AD 1750–1850 at scales of 16–22 years and AD 850–1000 at scales of 20–32 years. The MS WPS (Figure 3d) additionally exhibits periods of significant wavelet power from AD 1600 to 1800 at scales of 8–12 and 20–32 years, AD 850 to 1000 at 11–16 and 22–32 years, and AD 775 to 850 at 2–11 years. The vertically elongated regions of wavelet power in the MS and LOI WPS (i.e. between AD 775 and 850 in the LOI WPS and AD 1300 and 1450 in the MS WPS, Figure 3c, d) must be interpreted cautiously, as they imply high variability but not necessarily periodicity (a segment of high variability white noise embedded in a signal will show up as a vertical stripe of significant values). Although the MS and LOI WPS have fewer wavelet power peaks, the most significant features of these records include: (1) the coeval incidence of power at scales suggestive of climate forcing between AD 775–1000, and (2) the greater presence of peak power at climate-relevant scales after ~ AD 1400 as compared with the period AD 1000–1400, similar to the MC and CHAR WPS.

Discussion

When the charcoal time series data are considered with the MC and CHAR WPS results, where significant power is notably absent between ~ AD 1000 and 1400 (the period of greatest fire activity according to the charcoal record (Figure 2a)), our results appear to suggest three phases of different degrees of natural versus anthropogenic dominance of fire regimes on Ometepe Island: a period of combined anthropogenic and climatic influence from AD 580 becomes dominated by anthropogenic activity at AD 1000, which finally transitions to a naturally forced record at ~ AD 1400. These dates roughly correspond with the cultural history of Ometepe Island. The pinnacle of cultural development is believed to have occurred by the year AD 950 (Haberland, 1986), which is reflected in the paleoecological record by high charcoal concentrations, low sediment organic content, and high magnetic

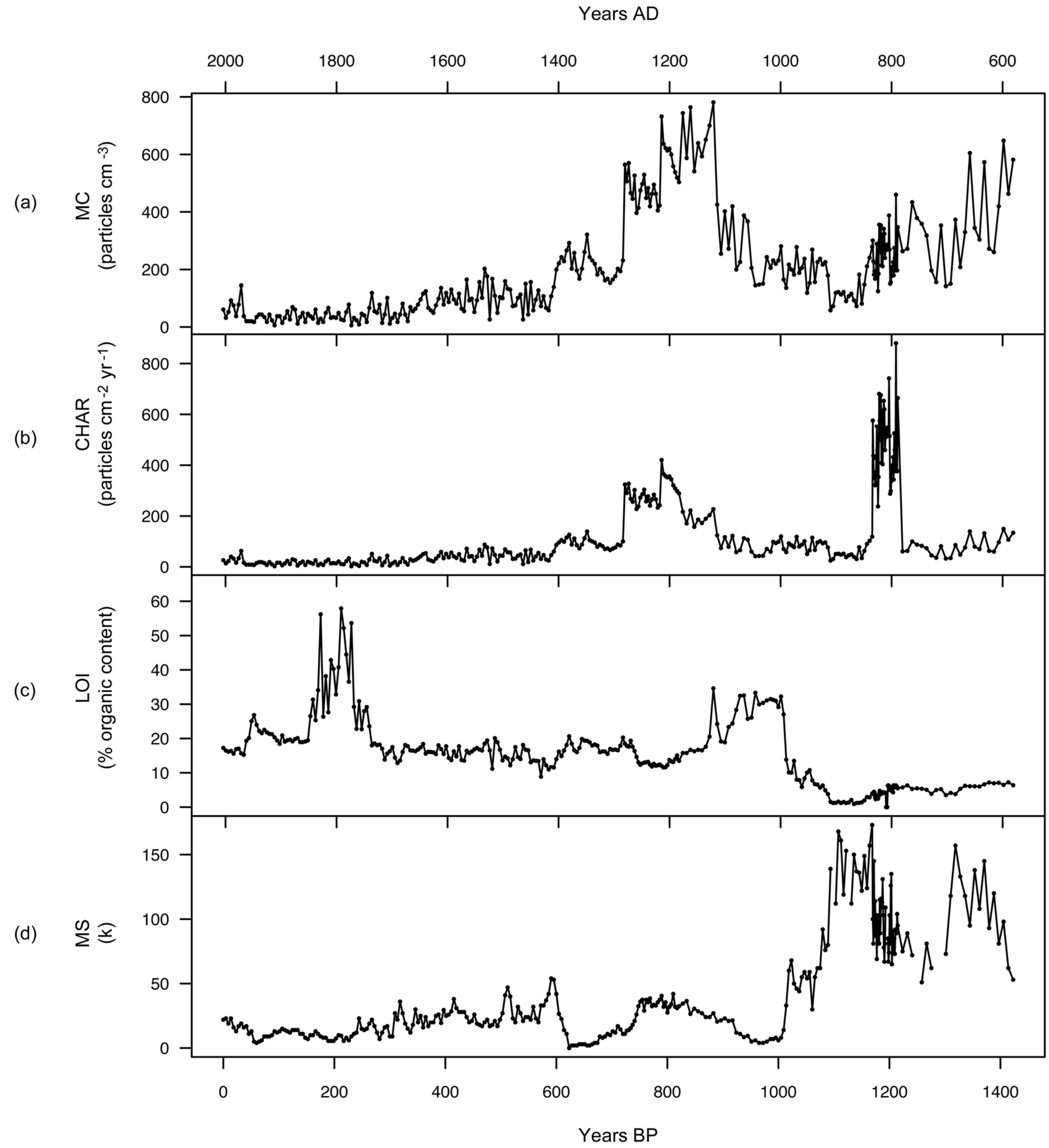

Figure 2. Time series results of the Charco Verde lake sediment core: (a) macroscopic charcoal (MC); (b) charcoal accumulation rates (CHAR); (c) loss on ignition (LOI); and (d) magnetic susceptibility (MS)

susceptibility values suggesting that the Ometepe population actively burned their landscape for agricultural and other purposes, decreasing natural vegetation abundance and increasing watershed erosion rates.

Island populations are believed to have risen after ~ AD 950, with high charcoal concentrations suggesting greater indigenous burning activities until the arrival of the Spanish in ~ AD 1524, at which time indigenous populations began to plummet. Strong wavelet power at scales of 2–32 years after ~ AD 1400 in the paleoproxy records (and particularly the MC and CHAR records) may therefore be indicative of a natural fire regime on Ometepe Island forced by short-term climate variability, which becomes manifest in the charcoal record once the anthropogenic burning signal is diminished. The approximate 100-year discrepancy between the arrival of the Europeans and the onset of significant wavelet power (Figure 3a,b) as well as the decline in biomass burning (Figure 2a,b) may be due to uncertainties arising from radiocarbon dating and the constructed age–depth model, but is also consistent with the progressive nature of the post-contact native population collapse which took about a century to reach its nadir point (Newson, 1987).

Although charcoal concentrations steadily decline in the Charco Verde record from AD 580 to 900 and might be interpreted as a period of increased precipitation and curtailed fire frequencies on Ometepe Island, wet conditions are not consistent with the other Charco Verde proxies (i.e. high erosion rates combined with extremely low sediment organic content). Rather than a consequence of a higher precipitation, declining charcoal concentrations during this period may have been in part caused by reduced non-agricultural plant fuel loads (i.e. the scrubby secondary vegetation that was presumably burned to make way for new plantings) and overall reduced farming activities connected to

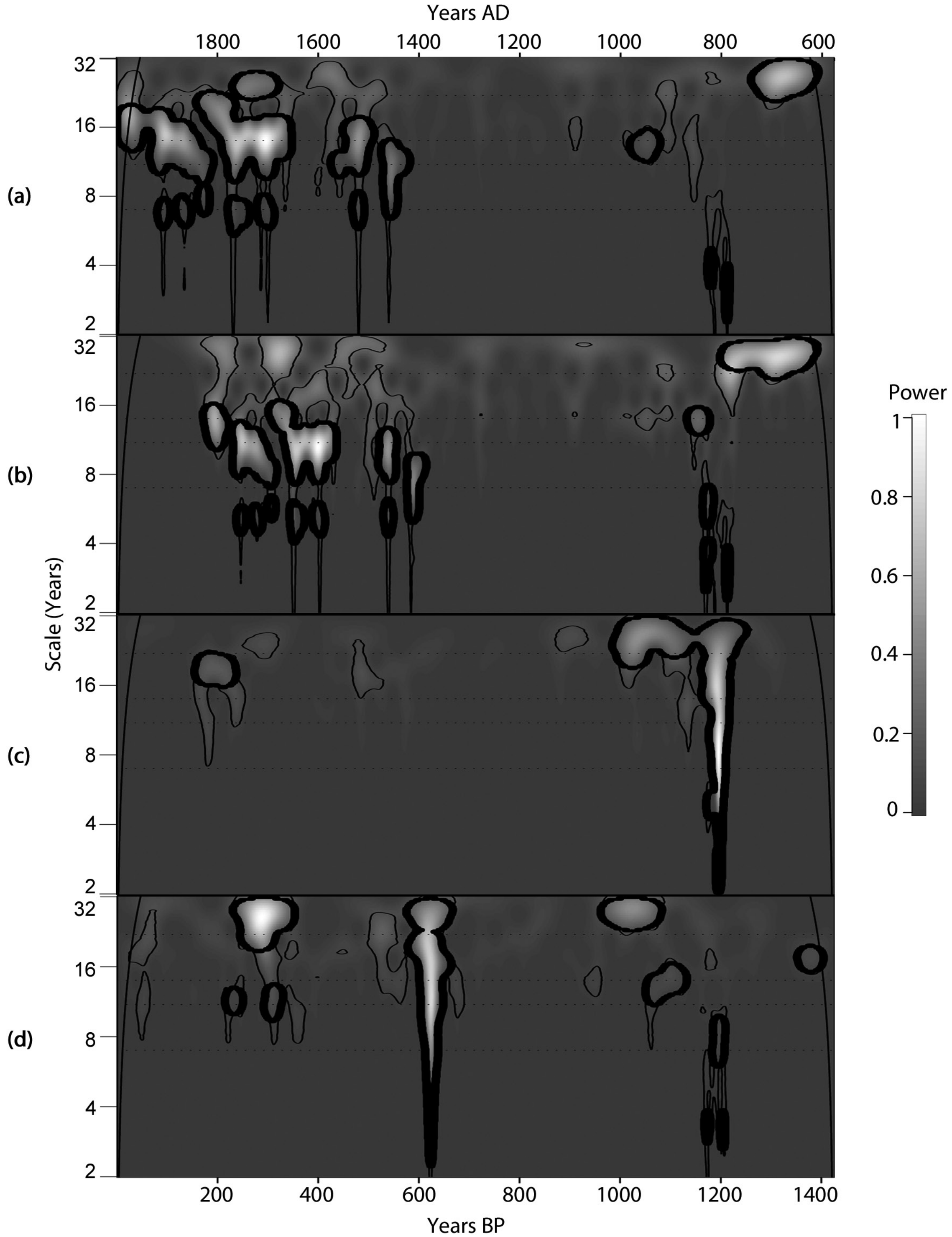

Figure 3. Wavelet power spectra plots of the Charco Verde paleoproxies: (a) macroscopic charcoal (MC); (b) charcoal accumulation rate (CHAR); (c) loss on ignition (LOI); and (d) magnetic susceptibility (MS). Significant wavelet power peaks at the 95% confidence level are delineated by (1) point-wise (thin black lines) and (2) areawise testing (thick black lines), where the latter significance test is considered to be more conservative (Maraun and Kurths, 2004)

persistent drought conditions during the ninth and tenth centuries AD. Hodell and co-authors (1995, 2001, 2005) have shown that the period from AD 800 to 1000 was the driest of the late Holocene in the Peten and Yucatan Peninsula, a drought that they have connected to the Classic Period Mayan 'collapse' and to centennial-scale solar forcing. These drought periods have also been identified in the Cariaco Basin, Venzuela record (Haug et al., 2003) and in ice cores from the Peruvian Andes (Thompson et al., 1985). Evidence of coeval climate forcing in each of the Charco Verde proxies is demonstrated by wavelet power at scales of 2–32 years between AD 775 and 1000 (Figure 3). Declining charcoal concentrations and charcoal accumulation rates (after a short period of extremely high values between AD 775 and 850) during this time together with high erosion rates and the lowest organic content values of the record (Figure 2) provide additional evidence of changing land use practices and/or agricultural activity on Ometepe Island during this time, potentially related to widespread drought conditions.

Conclusions

The charcoal record indicates that contemporary burning on Ometepe Island is almost an order of magnitude lower than peak pre-European anthropogenic burning. Paleoecological analyses of sediments from Guatemala, Costa Rica, El Salvador, the Amazon, and the Eastern Pacific off the coast of Nicaragua document similar environmental histories, with the highest concentrations of charcoal and disturbance pollen species occurring from AD 200 to 900 and reduced biomass burning and environmental disturbance after European contact (Anchukaitis and Horn, 2005; Brenner et al., 1990; Bush et al., 2008; Dull, 2004, 2007; Nevle and Bird, 2008; Suman; 1991; Tsukada and Deevey, 1967). The post-industrial anthropogenic fire increase found in many places throughout the world (Marlon et al., 2008) is not present in the Charco Verde record. Wavelet analysis of the Charco Verde proxies further suggest that fire regimes on Ometepe Island may respond to cycles of drought possibly induced by severe ENSO events and/or the 11- and 22-year solar cycles, a signal that is largely concealed by anthropogenic burning prior the arrival of the Spanish. The only significant evidence of climate forcing of fire regimes evident in the pre-European strata at Charco Verde occurs during a period of widespread and persistent drought in the ninth and tenth centuries AD.

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