Vegetation History and Archaeobotany (2020) 29:477–492
https://doi.org/10.1007/s00334-019-00755-0

ORIGINAL ARTICLE

Stable isotope analysis of vegetation history and land use change at Laguna Santa Elena in southern Pacific Costa Rica

Matthew T. Kerr[1] · Sally P. Horn[1] · Chad S. Lane[2]

Received: 30 January 2019 / Accepted: 8 October 2019 / Published online: 18 October 2019

Abstract
Laguna Santa Elena (8.9290° N, 82.9257° W, 1055 m a.s.l.) is a small lake in the Diquís archaeological sub-region of southern Pacific Costa Rica. Previous analyses of pollen and charcoal in a sediment core from Santa Elena revealed a nearly 2,000 year history of vegetation change, maize cultivation and site occupation that is consistent with the archaeological record from the lake basin and surrounding area. Here we present the results of new loss-on-ignition, geochemical and bulk stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope analyses of the Santa Elena sediments that supplement and refine the previous reconstruction. Like many lakes in Central America and the Caribbean, Laguna Santa Elena was a magnet for humans throughout its history. As a result, the lake experienced vegetation modification by humans and maize cultivation at varying intensities over a long duration. The Santa Elena sediments provide a record of palaeoenvironmental change during times of major culture change and increasing cultural complexity in the Diquís region, which occurred during intervals of broader changes driven by external forcing mechanisms, including the Terminal Classic Drought (TCD), the Little Ice Age (LIA) and the Spanish Conquest. Our high resolution lake sediment study from Santa Elena reveals details of these events at the local scale that are unobtainable by other means, including the timing of the initial intensification of maize cultivation at ca. 1,570 cal BP (AD 380) and two intervals of population decline coinciding with the TCD at ca. 1,085 cal BP (AD 865) and near the start of the LIA at ca. 683 cal BP (AD 1267).

Keywords Carbon · Nitrogen · Stable isotopes · Costa Rica · Archaeology · Palaeoenvironments

Introduction

The study of lake sediments as archives of palaeoenvironmental history involves analyzing microfossil and geochemical proxy evidence preserved in the sediments and producing stratigraphic reconstructions of both natural and human change with time. A variety of microfossils preserved in sediments provides evidence of prehistoric human activity around lakes. For example, the presence of *Zea mays* ssp. *mays* L. (maize) pollen is used as a marker for human activity (Goman and Byrne 1998; Clement and Horn 2001; Dull 2007; Wahl et al. 2007), while abundances of macroscopic and microscopic charcoal are used as indicators of local and regional biomass burning (Whitlock and Larsen 2001).

In small neotropical lake basins, bulk stable carbon isotope ($\delta^{13}C$) analysis can enhance evidence of land use history revealed by pollen and charcoal and allow researchers to reconstruct high resolution records of the scale and intensity of prehistoric agriculture and land use (Lane et al. 2004, 2008, 2009; Taylor et al. 2013a, b, 2015). Analyses of organic carbon (%C) and nitrogen (%N) abundances, carbon/nitrogen (C/N) ratios and stable nitrogen isotope ratios ($\delta^{15}N$) can provide additional geochemical evidence of vegetation change and agricultural activity (Meyers and Teranes 2001; Talbot 2001; Taylor et al. 2015).

Communicated by L. Newsom.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00334-019-00755-0) contains supplementary material, which is available to authorized users.

✉ Matthew T. Kerr
mkerr6@vols.utk.edu

[1] Department of Geography, University of Tennessee Knoxville, 1000 Phillip Fulmer Way, Knoxville, TN 37996, USA

[2] Department of Earth and Ocean Sciences, University of North Carolina Wilmington, 601 South College Road, Wilmington, NC 28403, USA

Carbon isotope ratios are an effective proxy for reconstructing the history of land cover change and the scale of maize cultivation from sediments of small lakes in tropical settings in which the conversion of wild vegetation to cultivated land involves a shift in dominant photosynthetic pathways. Most plants in wet tropical locales use the C_3 photosynthetic pathway, producing organic matter with $\delta^{13}C$ values from −35 to −20‰ VPDB (Bender 1971; O'Leary 1981; Brown 1999; Sage et al. 1999). Maize and some agricultural weeds use the C_4 photosynthetic pathway, producing organic matter with $\delta^{13}C$ values between −14 and −10‰ VPDB (Bender 1971; O'Leary 1981). Forest clearance by humans and replacement of native vegetation by maize and agricultural weeds causes a positive shift in $\delta^{13}C$ values in lake sediments due to changing organic inputs from the surrounding land. This shift in $\delta^{13}C$ can be detected through stable isotope analysis and used together with pollen and charcoal evidence to reconstruct the history of changing prehistoric land use (Lane et al. 2004, 2008, 2009).

Nitrogen isotope ratios are less straightforward to interpret. While $\delta^{15}N$ analyses can be useful for building multi-proxy palaeoenvironmental reconstructions, $\delta^{15}N$ values often reflect a complex synergy of causes. Changes in $\delta^{15}N$ of lake sediments can be driven by forces both internal and external to lakes, including aridity, phytoplankton and microbial activity, changes in water depth, sudden pulses of sediment input, natural changes in trophic state, human alteration of the landscape, fire and deforestation, among others (Hassan et al. 1997; Meyers and Teranes 2001; Talbot 2001; Tepper and Hyatt 2011; Torres et al. 2012). Another complicating factor for nitrogen analysis is that no modern analogue exists that would allow us to extrapolate from present knowledge of nitrogen cycling and fractionation to understand processes in the distant past, because the modern nitrogen cycle has been severely altered by human activities, including agriculture, fossil fuel combustion and urbanization (Schlesinger 1997; Vitousek et al. 1997; Talbot 2001; McLauchlan et al. 2013). Although interpreting shifts in $\delta^{15}N$ can be difficult because of the number of biogeochemical processes possible, these data can provide valuable palaeoenvironmental information when carefully combined with other data, such as from diatoms, $\delta^{13}C$, C/N and other geochemical indicators (Talbot 2001; McLauchlan et al. 2013). For example, Talbot and Johannessen (1992) used sedimentary $\delta^{13}C$ and $\delta^{15}N$ to reconstruct a 27,500 year palaeoclimate record at Bosumtwi, a lake in Ghana. More recently, Pessenda et al. (2010) combined pollen, elemental, $\delta^{13}C$ and $\delta^{15}N$ data to reconstruct palaeoenvironmental change over the past millennium at Lagoa Grande in Brazil and demonstrated that the site experienced warm and wet conditions there during the Little Ice Age (LIA).

Carbon/nitrogen ratios (C/N) of bulk sedimentary organic matter serve as a proxy for organic matter sources in lake systems (Meyers and Ishiwatari 1993; Tyson 1995; Meyers and Lallier-Vergès 1999; Talbot 2001). Ratios of sediments with high terrestrial input are generally > 20, sediments with high aquatic productivity have lower C/N ratios ranging ca. 3–9, while C/N ratios of 10–20 indicate mixed aquatic and terrestrial input (Meybeck 1982; Hedges et al. 1986; Tyson 1995; Meyers 1997; Sharp 2017).

Loss-on-ignition (LOI; Dean 1974) is a simple and inexpensive technique for estimating the organic, inorganic and carbonate content of sediments and soils. Changes to the input of organic matter and inorganic sediments into a lake can indicate disturbances and changes in land use. For example, forest clearance and agricultural activities destabilize soil and increase inorganic contributions to sediments (Oldfield et al. 2003; Enters et al. 2006; Lane et al. 2008; Bookman et al. 2010), which can drive temporal shifts in $\delta^{13}C$ and $\delta^{15}N$ values, providing evidence of human impacts in catchment areas.

Southern Pacific Costa Rica and adjacent western Panama have been places of extensive research on signals of prehistoric human activity preserved in lake sediments. Researchers have reconstructed long histories of human landscape disturbance and maize agriculture through analyses of pollen and charcoal (Behling 2000; Clement and Horn 2001; Anchukaitis and Horn 2005; Horn 2006), pollen and stable carbon isotopes (Lane et al. 2004; Horn and Haberyan 2016; Johanson et al. 2019), carbon and nitrogen isotopes (Taylor et al. 2015), diatoms (Haberyan and Horn 2005), phosphorous (Filippelli et al. 2010) and chironomids (Wu et al. 2017) preserved in lake sediments. Owing to the relative ease and cost-effectiveness of bulk isotope and geochemical analyses, robust multi-proxy studies have become the norm for reconstructing models of palaeoenvironmental change and for researching the history of vegetation change and land use. Studies using these lines of evidence complement earlier studies of pollen and charcoal by filling information gaps and providing details at temporal resolutions not otherwise achievable. For example, stable isotope analyses of sediments from Laguna Zoncho (Taylor et al. 2013a, 2015) refined the timeline of agricultural decline in the lake basin. These researchers demonstrated that a decline previously linked to the Spanish Conquest (Clement and Horn 2001) began two centuries earlier, likely caused by drought. They also showed that the lake sediments recorded an earlier episode of agricultural decline that corresponded in time to the Terminal Classic Drought (TCD), a series of severe droughts over many decades that affected the Yucatan Peninsula and wider circum-Caribbean region between ca. 1,200 and 850 cal BP (AD 750 and 1100) (Hodell et al. 2005; Lane et al. 2014).

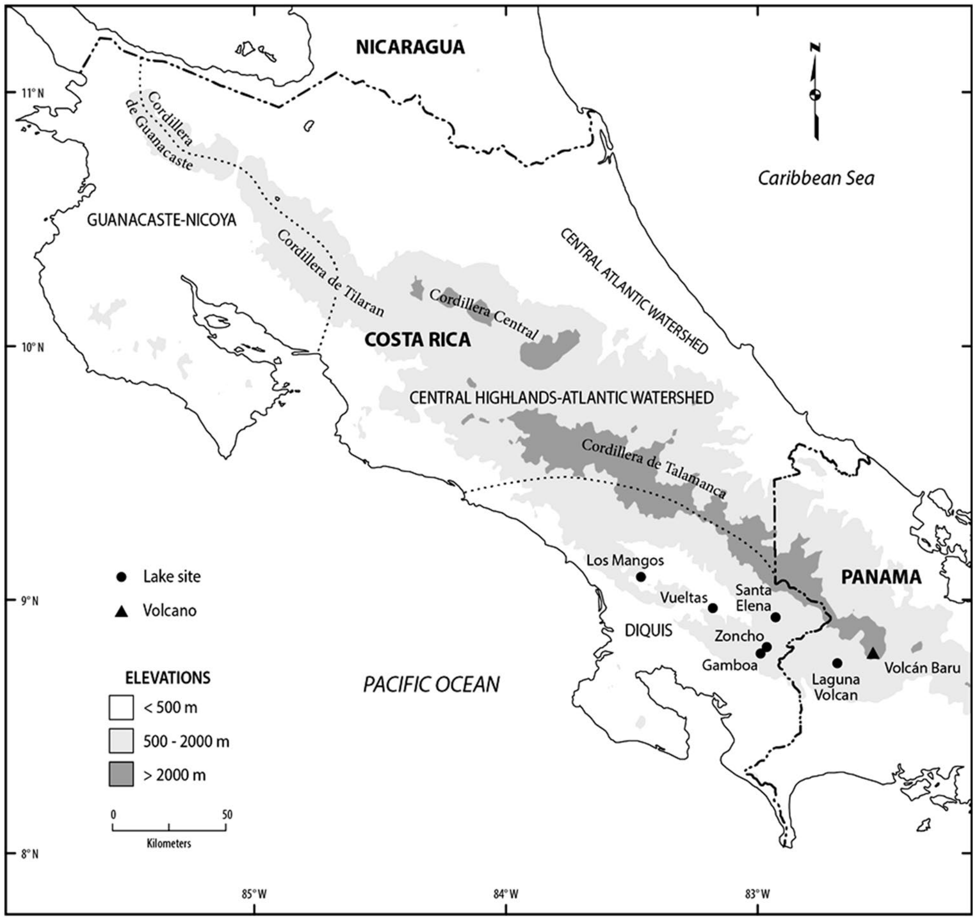


Fig. 1 Location of Laguna Santa Elena and other sites in Costa Rica and Panama mentioned in the text. Archaeological region boundaries follow Snarskis (1981). Map modified from Horn (2006, Fig. 27-1)

Anchukaitis and Horn (2005) conducted pollen and charcoal analyses on a sediment core from Laguna Santa Elena, located 13.5 km north of Laguna Zoncho (Fig. 1). Their work showed the establishment and near-continuous cultivation of maize as well as changing vegetation and land use through almost two millennia, including a possible short hiatus in maize growing and site abandonment around the time of the Spanish Conquest. Those data and interpretations roughly coincide with the limited archaeological information available for the Santa Elena site (for example, Sánchez and Rojas 2002) and with evidence of maize cultivation and palaeoenvironmental change at other lake sites in the region (Behling 2000; Clement and Horn 2001; Taylor et al. 2013a, 2015; Horn and Haberyan 2016; Johanson et al. 2019).

We carried out loss-on-ignition, geochemical and bulk stable isotope analyses on the original Santa Elena sediment core to supplement and refine the previous reconstruction from pollen and charcoal by Anchukaitis and Horn (2005). Laguna Santa Elena, like many lakes in the wider region of Central America and the Caribbean, was attractive for humans throughout its history. As a result, the lake experienced human vegetation modification and maize cultivation at varying intensities near the lake over a long duration through prehistory. Importantly, lake sites like Santa Elena provide records of palaeoenvironmental change during times of major culture change and increasing cultural complexity. All these changes in subsistence patterns, culture and complexity are overlain by much broader external mechanisms forcing change, including the TCD ca. 1,200–850 cal BP (AD 750–1100), the LIA ca. 550–100 cal BP (AD 1400–1850) and the Spanish Conquest beginning ca. 458 cal BP (AD 1492). High resolution lake sediment studies can reveal details of these events at a local scale that are unobtainable by other means. Our new work at Laguna Santa Elena contributes both a new level of detail there and broader insights that can improve interpretations at other sites.

Background

Archaeological setting

Laguna Santa Elena (8.9290° N, 82.9257° W, 1,055 m a.s.l.) is a small (0.13 ha), shallow (3.8 m) lake occupying a landslide-truncated stream channel in the Puntarenas Province in southern Pacific Costa Rica (Fig. 1; Horn and Haberyan 2016). Santa Elena is situated in the Diquís archaeological sub-region, which is part of the broader Greater Chiriquí archaeological region that includes southern Pacific Costa Rica and western Panama. Humans have occupied the area continuously for thousands of years (Barrantes et al. 1990; Constenla 1991; Lange 1992, 1993; Barrantes 1993; Corrales 2000; Palumbo 2009).

The cultural chronology for the area surrounding Laguna Santa Elena is dated mainly from archaeological contexts and pottery comparisons (Corrales et al. 1988; Drolet 1992; Hoopes 1996; Corrales 2000; Palumbo 2009), rather than by radiocarbon. The earliest settlement in the Diquís sub-region dates to ca. 3,450 BP (1500 BC), in the Curré period, but the chronology remains poorly established (Corrales 2000). The Aguas Buenas period, dated by ceramic typology, may have begun sometime between 2,450 and 1,750 BP (500 BC and AD 200) (Drolet 1984; Haberland 1984a, b; Hoopes 1996; Corrales 2000; Palumbo 2009). Hoopes (1996) postulated that populations in the Aguas Buenas period were small and dispersed, while Linares et al. (1975) reported chiefdom-level societies in western Panama. Ceramics from the Bugaba phase in western Panama, which have been dated to ca. 1,750–1,350 BP (AD 200–600), overlap and correspond stylistically to typologies from the Aguas Buenas period in Costa Rica. Archaeological investigations at nearby Laguna Zoncho yielded radiocarbon dates later than 1,750 BP (AD 200) for Aguas Buenas materials (Soto and Gómez 2002). The Chiriquí period followed the Aguas Buenas, spanning ca. 1,150–450 BP (AD 800–1500) (Quilter and Blanco 1995; Baudez et al. 1996; Corrales 2000). Considerable debate continues over the timing, chronology and connections between cultural phases, periods and traditions in the Greater Chiriquí region (Soto and Gómez 2002; Palumbo 2009; Sánchez 2013).

Several archaeological sites have been identified in the area around Laguna Santa Elena. Sánchez and Rojas (2002; Sánchez 2013, personal communication) identified several house sites on the hilltops surrounding the lake from which they recovered stone artefacts and Aguas Buenas pottery, but none from the later Chiriquí period. A larger site named Fila Tigre ca. 2 km east of Laguna Santa Elena contained predominantly Aguas Buenas ceramics, but also had a minor presence of Chiriquí artefacts. Sánchez and Rojas (2002) argued that Fila Tigre was probably a significant regional centre and that the area conforms to expected settlement patterns of large centres associated with dispersed hamlet sites for the Diquís sub-region (Linares and Sheets 1980; Drolet 1992; Palumbo et al. 2013; Brodie et al. 2016).

Lake sediment studies have revealed a long history of maize cultivation in the Greater Chiriquí region, with *Zea* pollen dated to ca. 1,800 cal BP (AD 150) at Laguna Volcán in the Chiriquí sub-region of western Panama (Behling 2000) and to ca. 2,500 cal BP (550 BC) at Laguna Gamboa in Costa Rica near the Panamanian border (Horn 2006), ca. 3,400 cal BP (1450 BC) at Laguna Los Mangos (Johanson et al. 2019), ca. 3,200 cal BP (1250 BC) at Laguna Zoncho (Clement and Horn 2001) and ca. 1,780 cal BP (AD 170) at Laguna Santa Elena (Fig. 1; Anchukaitis and Horn 2005). These studies show that maize was cultivated in southern Costa Rica and western Panama before the Aguas Buenas period and they confirm its presence in both the Diquís and Chiriquí sub-regions during the Aguas Buenas and Chiriquí periods. The earliest identified maize macrofossils in the region are from highland Panama and date to 1,750 BP (AD 200) (Galinat 1980). Although no earlier macrofossils have been found, Galinat (1980) and Smith (1980) argued that maize was introduced prior to 1,750 BP (AD 200) in the region, which is consistent with sedimentary pollen records (Horn 2006). Macrobotanical remains and stone grinding implements from the Chiriquí region of western Panama show a change to maize and bean subsistence following Archaic occupations (Haberland 1984b); however, Drolet (1992) claimed that similar evidence does not exist for the Diquís sub-region. While charred maize and bean remains have been reported for the area (Blanco and Mora 1994), Hoopes (1991, 1996) argued that maize may not have been a staple then, but may have been a special-use crop instead, possibly for ritual feasting.

Beyond debate over the archaeological chronology for the Diquís sub-region and the cultural and dietary role of maize in the broader area, disagreement also exists over subsistence strategies and the intensity of cultivation (Anchukaitis and Horn 2005; Palumbo 2009). Linares and Sheets (1980) argued that the inhabitants were intensive cultivators, while Drolet (1988) emphasized the role of gathered wild resources. Focusing on the wider region, Iltis (2000) and Iltis and Benz (2000) proposed that maize was not initially cultivated in tropical America for its grain, but for its sugary stems. Smalley and Blake (2003) argued that alcohol produced from maize may have played a role in developing complexity.

Despite these many uncertainties, researchers have argued that the development of social complexity in Central and Mesoamerica, including our research area, may have been linked to a transition to subsistence-based maize cultivation. For example, Corrales et al. (1988) suggested that the increased importance of maize may be directly tied to major cultural changes toward political, economic and social complexity in the Chiriquí period. However, Hoopes (1996) noted that disentangling the effects of maize intensification and increasing complexity is difficult. Analysis of palaeoenvironmental proxy evidence contained in lake sediments, including pollen, charcoal, geochemical signals and stable isotopes of carbon and nitrogen, has the potential to make important contributions to scientific knowledge regarding prehistoric land use, changes in subsistence patterns and understanding of cultural complexity in these regions.

Previous work at Laguna Santa Elena

Horn and students recovered a 7.13 m long sediment core from Laguna Santa Elena using a Colinvaux-Vohnout locking piston corer (Colinvaux et al. 1999) and a plastic tube fitted with a rubber piston for the uppermost, watery sediments (Anchukaitis and Horn 2005). The core sections were returned to the Laboratory of Paleoenvironmental Research at the University of Tennessee where they were opened, photographed and described. The core comprises ca. 6 m of lake sediments underlain by ca. 1 m of soil. Six AMS ^{14}C dates were obtained from wood and plant macrofossils, five from the lacustrine section of the core and one from the underlying soil.

Samples were taken from 29 stratigraphic levels of the core at intervals of ca. 16–32 cm for pollen and microscopic charcoal analyses. Microfossil data are available for 25 samples from the lacustrine portion of the core in which pollen was well preserved, but the lowest four samples were not counted due to poor preservation. Additional samples for macroscopic charcoal were processed, concentrated on the intervals also sampled for pollen and microscopic charcoal (Anchukaitis and Horn 2005). Loss-on-ignition analysis was carried out at each level sampled for pollen to estimate the organic, inorganic and carbonate content of the sediments (Anchukaitis 2002).

The Laguna Santa Elena record supports archaeological evidence of a long human presence on the landscape. *Zea mays* pollen evidence is consistent with that from nearby Lagunas Zoncho (Clement and Horn 2001; Taylor et al. 2013a, b, 2015), Vueltas (Horn and Haberyan 2016) and Los Mangos (Johanson et al. 2019) and with Laguna Volcán in western Panama (Behling 2000). At Santa Elena, *Zea* pollen is absent in the level dated to ca. 540 cal BP (AD 1410), which may represent a temporary abandonment of the site near the time of Spanish arrival, but earlier evidence of forest recovery starting ca. 700 cal BP (AD 1250) suggests declining settlement before the conquest (Anchukaitis and Horn 2005). From analysis of multiple sediment cores from Laguna Zoncho, Taylor et al. (2013a, 2015) found that maize decline and site abandonment there also appears to precede the Spanish Conquest, occurring some 200 years earlier than that found by Clement and Horn (2001) in a single, central core. These results demonstrate the need for additional research on the timing of population movement and maize cultivation in the area.

Materials and methods

We recalibrated the AMS radiocarbon dates in Anchukaitis and Horn (2005), produced an updated age-depth model and generated point estimates for the dates of our sampled levels using Clam v. 2.3.2 (Blaauw 2019) for the R Statistical Environment v. 3.5.2 (R Core Team 2018) and the IntCal13 radiocarbon calibration curve (Reimer et al. 2013). Anchukaitis and Horn (2005) originally used linear interpolation to develop an age model for the Santa Elena core and this is also used here. We experimented with Bayesian methods of creating an age model using Rbacon v. 2.3.6 (Blaauw and Christen 2019), but given the strong and varying human impacts on the site previously noted and for which we report new evidence here, we believe that the assumptions of gradual shifts in sedimentation rates when using this software are unwarranted. Likewise, other modelling options in Clam such as spline and polynomial regression produced age-depth curves that were too smooth for the depositional history of Santa Elena. In small tropical lakes in basins with major, clearly defined episodes of forest clearance, land use and site abandonment, we expect sedimentation to vary over time in ways that are not captured by Bayesian and other smoothing models. We are aware of the limitations of linear interpolation, primarily that it forces unrealistic breakpoints on the radiocarbon dates in the age-depth curve; nevertheless, we find this method to be the best model for site history at Laguna Santa Elena.

We re-sampled the same 25 levels in the lacustrine portion of the core collected by Anchukaitis and Horn (2005), plus an additional 40 intervening levels for loss-on-ignition (LOI), bulk geochemical (%C, %N, C/N) and bulk stable isotope ($\delta^{13}C$, $\delta^{15}N$) analyses to fill gaps and to increase the sampling resolution, corresponding to ca. 8-16 cm intervals between samples.

Following Dean (1974), samples for LOI were weighed into porcelain crucibles, oven dried at 100 °C for 24 h and reweighed. They were then heated to 550 °C in a muffle furnace for 1 h, cooled and reweighed. The mass lost during this first burn provided an estimate of organic matter content in the samples, with the remaining mass corresponding to the total inorganic fraction. Following the 550 °C burn, the samples were heated to 1,000 °C for 1 h, cooled and reweighed. The mass lost in this second burn provided an estimate of the carbonate content of the sediments; however, when sediments are low in carbonate with values < 5%, such as throughout the Santa Elena core, these estimates should be interpreted with caution, as part or all of the mass lost through ignition above 550 °C may represent the loss of lattice water bound in clays, rather than carbonates (Dean 1974).

Preparation for bulk %C, %N, $\delta^{13}C$ and $\delta^{15}N$ analyses followed Lane et al. (2013) and the standard laboratory protocol of the University of North Carolina Wilmington (UNCW) Stable Isotope Facility. Sediment samples were oven dried at 50 °C, then ground to a fine powder and homogenized with a mortar and pestle. The ground samples were split roughly into two aliquots, with one ready for $\delta^{15}N$ analysis as the non-acidified fraction (Brodie et al. 2011). The other samples, being analysed for $\delta^{13}C$, were placed in pre-combusted ceramic crucibles, moistened with distilled water, fumigated with 12 N hydrochloric acid for 2 h in a glass desiccator and then vented for 24 h. Following acidification, the samples were dried on a hotplate at ca. 60 °C for 48 h to remove water and residual acid, and then reground.

We calculated target masses for isotope samples using the organic content estimated by LOI and an assumption of 40% carbon content for organic matter. Subsamples for $\delta^{13}C$ and $\delta^{15}N$ were loaded into tin capsules and sent to the UNCW Stable Isotope Facility for analysis. All samples were analysed in duplicate and data from the replicate runs were averaged to produce single values for each datum. Analysis was done with a Costech 4010 elemental analyser coupled to a Thermo Delta V Plus mass spectrometer. Carbon and nitrogen isotope compositions are reported in standard δ per mil notation, with carbon values relative to the Vienna Pee Dee Belemnite (VPDB) marine carbonate standard and nitrogen values relative to atmospheric nitrogen (AIR), where:

$$R = {}^{13}C/{}^{12}C \text{ or } {}^{15}N/{}^{14}N \quad (1)$$

and:

$$\delta^{13}C \text{ or } \delta^{15}N(‰) = 1,000\left[\left(\left(R_{sample} - R_{standard}\right)/R_{standard}\right) - 1\right] \quad (2)$$

Repeated analyses of USGS 40 glutamic acid standard indicated that instrument precision for our samples averaged ± 0.15‰ for C and ± 0.13‰ for N.

We plotted our new results for LOI, geochemical composition (%C, %N, C/N) and bulk stable isotopes ($\delta^{13}C$, $\delta^{15}N$) along with original LOI, selected pollen and spores, and charcoal data using C2 v. 1.7.7 (Juggins 2007). C/N ratios were calculated as the ratio of carbon content (%C) to nitrogen content (%N) from the acidified fraction. Pollen percentages for all taxa except Cyperaceae were calculated from a pollen sum that excluded Cyperaceae. Hornwort spores are expressed as a percentage of total pollen plus fern and hornwort spores. *Zea* pollen is reported as percentages and as presence or absence based on low magnification scans of up to five microscope slides per level sampled. Some pollen and spore types are grouped by vegetation type or habitat in the pollen diagram. Cyperaceae counts, excluded from the pollen sum used for other types, may reflect land disturbance directly (terrestrial sedges in cultivated fields) and indirectly (aquatic sedges increasing with infilling and the growth of a fringing herbaceous mat around the lake during times of increased erosion) (Bush 2002; Anchukaitis and Horn 2005).

We plotted the data by calibrated age and divided our stratigraphic diagram into informal zones based on major changes in the data and according to the cultural chronology of the Diquís sub-region. Our zones, based on our new, larger data set, differ slightly from the original ones by Anchukaitis and Horn (2005), but they are close enough to allow comparison with these interpretations of the pollen and charcoal results.

Results

The upper ca. 6 m of the Laguna Santa Elena core consisted of lake silts and clays with organic matter content of ca. 15–45.6% and total inorganic content of ca. 54.4–84.9% as estimated by loss-on-ignition. Carbonate content is ca. 2–5.5% (average 3.4%) based on LOI, but these low values may be overestimates owing to the loss of interstitial waters in clays (Dean 1974). The core contained three volcanic tephra layers at 538, 417–415 and 314–312 cm that have been interpreted to represent the three most recent eruptions of the nearby Volcán Barú in Panama (Anchukaitis and Horn 2005; Sherrod et al. 2007; Holmberg 2009, 2016).

Our recalibration of the six Santa Elena radiocarbon dates confirmed a normal stratigraphic sequence from 1,950 to 1,825 cal BP (AD 1–125) to the present (Table 1, Fig. 2). All 65 of our isotope samples yielded signals sufficient for palaeoenvironmental interpretation and comparison with the original results (Fig. 3). Here we present our new LOI, geochemical and isotope analyses in the context of the major trends in botanical data originally documented in the Santa Elena core (see also ESM).

Zone 3—ca. 1,780 to 1,590 cal BP (AD 170–360)

Zone 3, corresponding to the earliest phase of lake sedimentation, is characterized by relatively high organic carbon and nitrogen contents, low $\delta^{15}N$ values and the lowest $\delta^{13}C$ values in the record. Organic carbon and nitrogen contents begin to decrease at the top of zone 3, while both $\delta^{15}N$ and $\delta^{13}C$ values begin to increase. Pollen counts show intact mature tropical premontane forest with a high diversity of pollen taxa, with tree pollen typical of moist lowland forests in Costa Rica, including *Quercus*, *Alnus*, *Hedyosmum*,

Table 1 Radiocarbon determinations for the Laguna Santa Elena sediment core

Lab code	Material dated	Depth (cm)	^{14}C age (BP)	Age, 2σ range (cal BP)	Age, 2σ range (cal BC/AD)	Probability
B-158436	Wood	156.5	150 ± 40	42–(-1)	AD 1908–1951	16.6
				154–59	AD 1796–1891	32.3
				234–167	AD 1716–1783	28.7
				284–236	AD 1666–1714	17.2
B-150706	Leaf fragments	312.0	640 ± 60	677–539	AD 1273–1411	95.0
B-145347	Wood	434.5	1,240 ± 40	1,270–1,070	AD 680–880	95.0
B-145348	Charcoal	530.5	1,510 ± 40	1,424–1,315	AD 526–635	66.1
				1,443–1,429	AD 507–521	3.3
				1,521–1,455	AD 429–495	25.4
B-141242	Wood	580.5	1,880 ± 30	1,883–1,730	AD 67–220	95.0
B-141243	Wood	682.5	1,950 ± 30	1,950–1,825	AD 1–125	91.6
				1,970–1,960	20–10 BC	2.6
				1,983–1,980	33–30 BC	0.8

All analyses were performed by Beta Analytic Inc. Dates were calibrated using Clam v. 2.3.2 (Blaauw 2019) for the R Statistical Environment v. 3.5.2 (R Core Team 2018) and the IntCal13 radiocarbon calibration curve (Reimer et al. 2013)

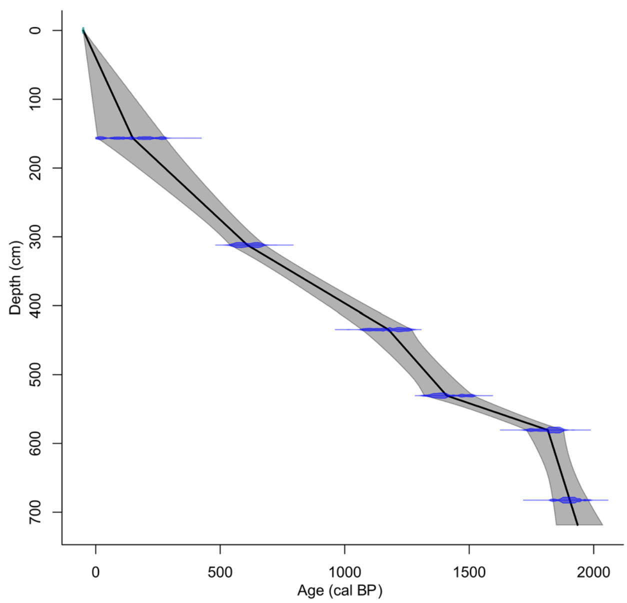


Fig. 2 Age-depth graph for the Laguna Santa Elena sediment core. The model was created using linear interpolation with Clam (Blaauw 2019) for the R Statistical Environment (R Core Team 2018). Blue lines are the probability distributions of the AMS ^{14}C dates. Grey shading shows the 95% confidence interval. The black curve is the line of best fit

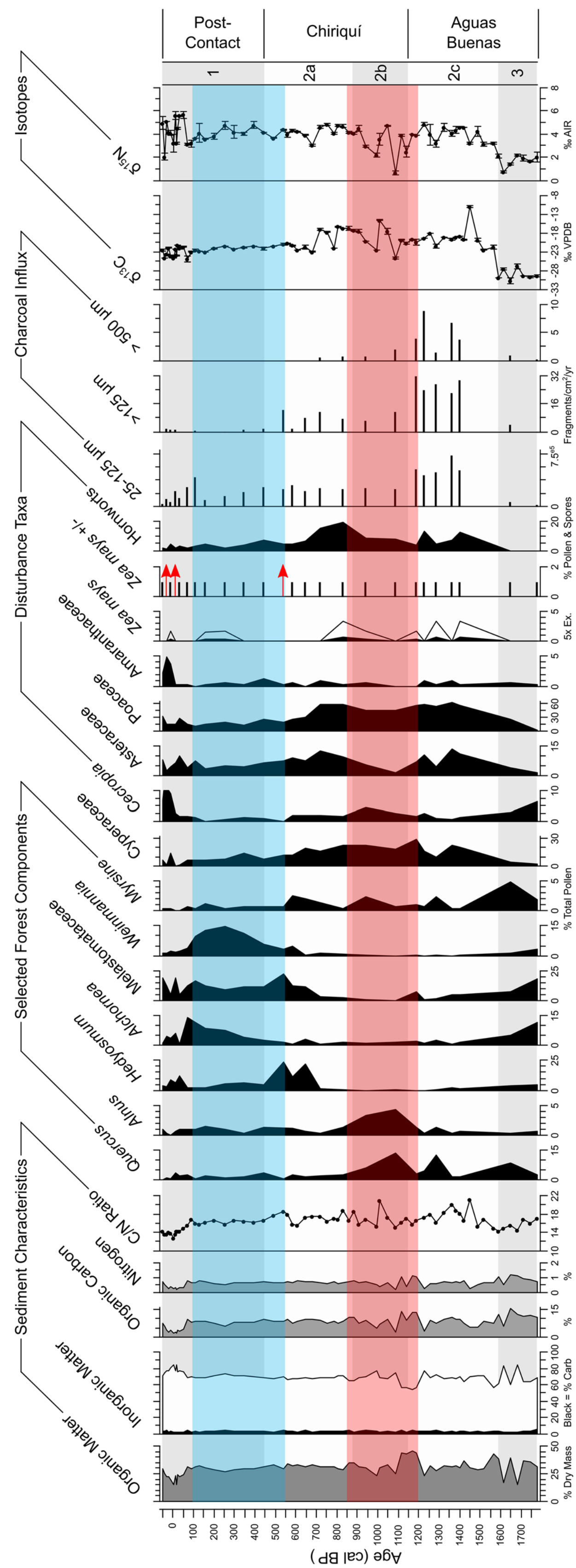
Alchornea, Melastomataceae, *Weinmannia* and *Myrsine* (Hartshorn 1983; Graham 1987; Rodgers and Horn 1996; Anchukaitis and Horn 2005) and rare occurrences of taxa indicating disturbance. Minor presence of *Zea* pollen, coupled with the lowest levels of charcoal in the core, indicates human presence but with relatively slight impact at this time. High organic matter, along with high organic carbon content and relatively low δ^{13}C values, support an interpretation of low disturbance and predominantly intact, native C_3 tropical vegetation in the surroundings during the initial period of sedimentation following formation of the lake. Relatively low δ^{15}N values indicate low terrestrial nutrient delivery, while C/N ratios indicate mixed terrestrial and aquatic inputs.

Zone 2c—ca. 1,590 to 1,150 cal BP (AD 360–800)

Zone 2c shows a marked expansion of land clearance and cultivation in the Santa Elena basin beginning no later than 1,568 cal BP (AD 382). Organic carbon and nitrogen contents are lower than in the preceding zone 3, while δ^{13}C and δ^{15}N ratios increase substantially in response to forest clearance and intensified maize cultivation. C/N ratios increase toward the middle of zone 2c at ca. 1,450 cal BP (AD 500), indicating an increase in the contribution of terrestrial plant matter to the organic sediment. LOI data indicate increased inorganic composition of the sediments at the beginning of zone 2c, perhaps from erosion caused by people clearing forest to establish or expand fields. The δ^{13}C value of − 10.3‰ at 1,450 cal BP (AD 500) is the highest in the record, supporting an interpretation of accelerated or more spatially extensive forest clearance and increased or intensified cultivation of maize at that time.

The pollen results indicate replacement of forest by grasses and other taxa indicating disturbance (*Cecropia*, Asteraceae, Poaceae, Amaranthaceae, Cyperaceae). Higher percentages of hornwort spores, possibly the genus *Phaeomegaceros*, may also relate to disturbance (Anchukaitis 2006, personal communication). This zone shows increased *Zea* pollen percentages and the highest charcoal influx in the profile. Zone 2c also has abundant micro- and macroscopic charcoal fragments, including in the > 500 µm size class, which are found only sporadically in other parts of the core, indicating an increase in fires near the site.

Fig. 3 Laguna Santa Elena proxy data diagram, including sediment ▶ characteristics determined by loss-on-ignition and geochemical analyses, pollen and spore percentages for selected forest components and disturbance taxa, charcoal influx and bulk stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes. Pollen and charcoal data from Anchukaitis and Horn (2005) are re-plotted here by age using our new age-depth model. *Zea mays* refers to *Zea mays* ssp. *mays* L. Red arrows in the presence/absence graph indicate three samples with no maize pollen. Zones in the diagram were informally defined by major changes in the data and the cultural chronology of the region (on the right). The red band represents the Terminal Classic Drought ca. 1,200–850 cal BP (AD 750–1100) and the blue band represents the Little Ice Age ca. 550–100 cal BP (AD 1400–1850). The grey bands correspond to the zones on the right. See text for additional details



A change at the top of zone 2c indicates a transition in human activity, including reduced maize cultivation and a period of forest regrowth. This change, just below the zone 2c/2b boundary at ca. 1,150 cal BP (AD 800), represents the time of transition between the Aguas Buenas and Chiriquí cultural periods in the area and also corresponds to the start of the Terminal Classic Drought (TCD) ca. 1,200–850 cal BP (AD 750–1100) that more broadly affected Central America and the Caribbean region (Lane et al. 2014).

The sample from 1,170 cal BP (AD 780) shows the highest organic content in the core and continued high charcoal influx. The low inorganic content at that time indicates a decline in soil disturbance due to decreased forest clearance in the basin. A decrease in $\delta^{13}C$ and $\delta^{15}N$ values continues through the top of zone 2c, indicating decreasing maize cultivation and an increasing C_3 vegetation signal as the Aguas Buenas period ended.

Zone 2b—ca. 1,150 to 880 cal BP (AD 800–1070)

Zone 2b shows changes in the pattern of human activity in the catchment beginning at ca. 1,115 cal BP (AD 835). Importantly, zone 2b and the timing of those shifts coincide with the beginning and duration of the TCD and our data indicate major changes in maize cultivation in the Santa Elena basin then. This may reflect significant reorganization of culture in the region at the beginning of the Chiriquí period.

The lowering of isotope values that started in zone 2c continues into the beginning of 2b, paralleled by decreases in organic carbon and nitrogen content. The trend in $\delta^{13}C$ values indicates a shift towards more C_3 vegetation, and $\delta^{15}N$ reaches its lowest values in the core at ca. 1,085 cal BP (AD 865), early in zone 2b. The influx of microscopic and macroscopic charcoal decreases across the zone 2c/2b boundary. These changes point to reduced cultivation activity, an interpretation supported by increased pollen percentages of forest taxa (*Quercus*, *Alnus*, *Myrsine*) and a decrease in disturbance taxa (Asteraceae, Poaceae, Amaranthaceae).

Toward the middle of zone 2b, $\delta^{13}C$ and $\delta^{15}N$ values increase sharply, with $\delta^{13}C$ reaching the second highest value in the profile, likely representing increased maize cultivation beginning ca. 1,045 cal BP (AD 905). C/N ratios increase toward the middle of zone 2b, indicating increased terrestrial input to the lake, probably caused by renewed cultivation in the area. Charcoal influx indicates continued burning at the site.

Following a peak of cultivation at 1,011 cal BP (AD 939), $\delta^{13}C$ and $\delta^{15}N$ values decrease sharply, indicating a temporary reduction in maize growing and a period of relatively rapid change in human activity that was not apparent at the resolution of the original pollen sampling. This is supported by a decrease in inorganic matter and reduced carbon and nitrogen contents in the sediments.

At the top of zone 2b, pollen values of disturbance taxa increase along with $\delta^{13}C$ and $\delta^{15}N$ values, while pollen from forest taxa declines. *Zea* pollen begins to increase again, and abundant charcoal influx continues, indicating a return to cultivation at the site as the TCD came to an end ca. 850 cal BP (AD 1100).

Zone 2a—ca. 880 to 450 cal BP (AD 1070–1500)

Zone 2a opens with a century of sustained, intensive maize cultivation following the TCD, indicated by reduced pollen from forest taxa, increased pollen from disturbance taxa, a spike in *Zea* pollen, moderate charcoal influx and relatively high $\delta^{13}C$ and $\delta^{15}N$ values. However, within this zone, at 683 cal BP (AD 1267), $\delta^{13}C$ values shift strongly toward a C_3 vegetation signal, indicating decreased maize and increased forest regrowth. This interpretation is supported by changes in pollen percentages which include increases in forest taxa (*Hedyosmum*, *Alchornea*, Melastomataceae, *Myrsine*), decreases in grasses and other disturbance taxa, and decreased *Zea* pollen.

Absence of *Zea* pollen at ca. 540 cal BP (AD 1410) led Anchukaitis and Horn (2005) to propose a possible brief hiatus in maize cultivation at Santa Elena, but this interpretation is not supported by the $\delta^{13}C$ values. Rather, data in the upper part of zone 2a indicate a period of stability in maize cultivation and human activity at the site that was not seen before this. This is shown by relatively constant $\delta^{13}C$ and $\delta^{15}N$ values, organic carbon and nitrogen contents, and continued presence of *Zea* pollen, albeit in relatively low values compared to earlier amounts. Influx of large charcoal particles (> 500 µm) ends in zone 2a, while influx of smaller charcoal particles continues, indicating reductions in both forest clearance and local fires. C/N ratios throughout the zone are typical of mixed terrestrial and aquatic inputs. Taken together, data in the upper part of zone 2a establish a constant background and indicate a time of prolonged stability during the transition from the Chiriquí period into Post-Contact times.

Zone 1—ca. 450 to – 50 cal BP (AD 1500–2000)

Zone 1 begins with the Post-Contact period and the data show continued low-intensity maize cultivation and human land use, but with increased forest taxa (*Alchornea*, Melastomataceae, *Weinmannia*) relative to previous levels, consistent with increased forest cover. *Zea* pollen increases slightly from 253 to 158 cal BP (AD 1697–1792), but $\delta^{13}C$ values indicate no significant increase. Signals remain relatively stable across all types of data until modern time. Beginning at 111 cal BP (AD 1839), pollen values of forest taxa begin declining and charcoal influx increases, indicating renewed forest clearance and the beginning of modern agriculture. Inorganic input increases, as do $\delta^{13}C$ and $\delta^{15}N$ values. *Zea* pollen increases once again, along with pollen percentages for disturbance taxa. Relatively low C/N and higher $\delta^{15}N$ values indicate increased delivery of terrestrial nutrients and productivity in the lake, likely from the establishment of modern settlements, maize farming and landscape disturbance at the site. The data then become highly variable at 50 cal BP (AD 1900) and remain so, with maize farming and landscape disturbance continuing to the top of the core.

Interpretation and discussion

Vegetation change and land use history

Our high-resolution reconstruction of prehistoric land use and maize cultivation in the Laguna Santa Elena catchment supplements earlier interpretations from pollen and charcoal, and reveals new details of land use history including the timing of land abandonments that were not clearly visible in previous work. Data from the lowest lake sediments of zone 3 show the presence of low-intensity maize cultivation in the basin from the formation of the lake at ca. 1,780 cal BP (AD 170). The presence of *Zea* pollen, combined with pollen percentages indicating intact native vegetation and almost no charcoal are consistent with a minor human presence on the landscape, with a few people engaged in small-scale subsistence cultivation. Two phases of increased inorganic content in the sediments at 1,682 and 1,613 cal BP (AD 268 and 337), as well as the appearance of microscopic and macroscopic charcoal in the sediments at 1,649 cal BP (AD 301), indicate an initial change toward more broad-scale or intensive cultivation, although pollen percentages still indicate relatively intact forest at this time (Fig. 3).

Our data indicate rapid forest clearance and increased maize cultivation shortly after 1,592 cal BP (AD 358). Pollen values for forest taxa decline, while those for disturbance taxa increase, indicating replacement of forest by cultivated land. Stable carbon isotope ratios indicate intensive maize cultivation throughout zone 2c, with the highest $\delta^{13}C$ value in the core at 1,450 cal BP (AD 500). Following this high peak, $\delta^{13}C$ values fall slightly and establish a regular pattern of C_4 plant dominance throughout the upper half of zone 2c from 1,422 cal BP (AD 528) onwards. High charcoal influx rates indicate extensive biomass burning between 1,403 and 1,189 cal BP (AD 547 and 761). Paired with increased $\delta^{13}C$ values and decreased pollen of forest taxa, this suggests regular burning of fields. The inorganic content of sediments throughout zone 2c is high, but relatively steady following the start of intensive maize cultivation, providing further evidence that cultivation was high and continuous throughout the top half of zone 2c. We interpret these signals, together with relatively high *Zea* pollen percentages, to indicate a strong human presence in the Santa Elena area with people engaged in considerable maize cultivation throughout the latter part of the Aguas Buenas period.

Zone 2b has sharply decreasing values of $\delta^{13}C$ and $\delta^{15}N$ from 1,115 cal BP (AD 835). Inorganic content also declines and is accompanied by increases in organic matter, organic carbon and nitrogen content in the sediments. Charcoal influx decreases along with pollen percentages for disturbance taxa, including maize, while pollen percentages of forest taxa increase. Taken together, the data indicate a strong decrease in the scale or intensity of land use and maize cultivation beginning no later than 1,228 cal BP (AD 722) and continuing through the zone 2c/2b transition until finally reaching its lowest point at ca. 1,085 cal BP (AD 865). We interpret this record as indicating nearly a century and a half of land abandonment, the timing of which corresponds to the cultural transition from the Aguas Buenas to the Chiriquí period in the region. Importantly, the Santa Elena area appears to have been largely abandoned during the TCD. While the continued presence of *Zea* pollen through the 2c/2b transition indicates low intensity human presence in the area, the abrupt decline in signals of land use beginning at 1,189 cal BP (AD 761) likely indicate a population collapse at Santa Elena, as discussed below.

The data for zone 2b indicate major swings in patterns of land use and cultivation of maize, which are overlain at the local to regional scale by the effects of cultural transition and at a broader scale by those of the TCD. After ca. 1,085 cal BP (AD 865), the area was reoccupied and maize was once more grown at the site, indicated by relatively high $\delta^{13}C$ and $\delta^{15}N$ values, increased inorganic input, declining forest pollen and increasing pollen from disturbance taxa. The scale and intensity of maize cultivation reaches its peak in zone 2b at 1,011 cal BP (AD 939), only to fall again to its lowest levels at 995 cal BP (AD 955). Following this low point in the middle of zone 2b, the data reveal that maize was being grown again from around 942 cal BP (AD 1008), indicated by increasing inorganic content, $\delta^{13}C$ and $\delta^{15}N$ values, pollen of *Zea* and disturbance taxa, and charcoal, and by declining abundances of forest taxa. This second reestablishment of maize cultivation may reflect stabilization of Chiriquí culture and climate improvement toward the end of the TCD. These findings are not evident from the pollen and charcoal data alone, partly due to the lower resolution of those data.

In the lower part of zone 2a, the record again indicates some variability in land cultivation and maize from 831 to 720 cal BP (AD 1119–1230), but not of the same magnitude as in zone 2b. Values for $\delta^{13}C$ and $\delta^{15}N$ remain relatively high through this time, as does charcoal influx. Pollen of forest taxa remains low and values of disturbance taxa and maize are relatively high. However, following the final signal of expansive C_4 vegetation around 720 cal BP (AD 1230), values for $\delta^{13}C$ and $\delta^{15}N$ decline. The LOI results indicate that inorganic input to the lake stabilized, and organic carbon and nitrogen content are both also steady. Pollen of disturbance taxa decreases and forest recovery begins, while *Zea* pollen percentages fall. Charcoal continues to be deposited in the sediments in zone 2a but in reduced amounts and fragment sizes compared with lower in the core. Taken together, we interpret these data as a major shift in subsistence patterns in the Laguna Santa Elena basin beginning no later than 683 cal BP (AD 1267). The evidence indicates a greatly reduced human presence in the landscape and a major reduction in the scale and intensity of maize cultivation.

Continued but reduced charcoal deposition, combined with a minor presence of *Zea* pollen from 683 cal BP (AD 1267) onward, indicates low levels of cultivation and landscape disturbance. Anchukaitis and Horn (2005) reported an absence of *Zea* pollen in the Santa Elena sediments at ca. 540 cal BP (AD 1410) that roughly coincides with the arrival of Spaniards (within the margins of ^{14}C error), but also noted that pollen percentages indicate a period of forest regrowth that began much earlier. Our values for $\delta^{13}C$ fall sharply beginning at 720 cal BP (AD 1230), and coincide with the beginning of forest recovery identified by Anchukaitis and Horn (2005). While the area was never completely abandoned, it did undergo a substantial change in patterns or modes of subsistence cultivation beginning around 720 cal BP (AD 1230) and a new, but regular, signal emerged that persisted until modern times. Interestingly, Taylor et al. (2013a, 2015) demonstrated that the nearby Laguna Zoncho basin, which had been intensively cultivated for thousands of years, was abandoned a few centuries before Spanish arrival. They attributed this to climate deterioration due to the early effects of the LIA, which was beginning then. The pattern and timing of this decline at Santa Elena matches what Taylor and colleagues found at Laguna Zoncho, suggesting the intriguing possibility of a regional population decline and/or a fundamental shift in lifeways and subsistence, although more evidence is needed to support these conclusions at the local scale. Future palaeoclimate studies, combined with additional archaeological investigations, could provide that supporting evidence.

The Santa Elena sediments record an extended period of stable but low intensity maize cultivation beginning no later than 683 cal BP (AD 1267), from the middle of zone 2a and continuing into zone 1 up to modern times at 111 cal BP (AD 1839). This nearly six century period of low intensity maize cultivation is also reflected in stability in $\delta^{13}C$ and $\delta^{15}N$ values and charcoal influx, increased values for select forest taxa and relatively lower ones for disturbance taxa. *Zea* pollen remains present in the record except for the sample at ca. 540 cal BP (AD 1410). Organic and inorganic matter, organic carbon and nitrogen and C/N ratios are all steady during this period. *Zea* pollen increases in abundance in the middle of zone 1, but the sediments do not record a corresponding response in $\delta^{13}C$. Importantly, the zone 2a/1 transition coincides with the beginning of Spanish Conquest in the broader region, although colonization began relatively late in our area. Additionally, the majority of zone 1 coincides with the LIA, which lasted from ca. 550 to 100 cal BP (AD 1400–1850). Whether or not the human population in the Laguna Santa Elena area was affected by climate deterioration during the LIA is unclear from our dataset, but large-scale, intensive prehistoric maize cultivation had finished by 683 cal BP (AD 1267) at the latest, long before the beginning of the Spanish Conquest.

The evidence from the uppermost sediments of the core at the top of zone 1 shows the arrival of modern agriculture in the area, beginning around 91 cal BP (AD 1859). Inorganic matter input to the lake increases, diluting the organic carbon and nitrogen pools. Pollen values for forest taxa decrease and those for disturbance taxa increase along with *Zea* pollen. Charcoal influx also increases then, indicating renewed burning in the surrounding area. Values for $\delta^{13}C$ and $\delta^{15}N$ show significant change, with $\delta^{15}N$ values increasing to the highest in the core, beginning around 51 cal BP (AD 1899). These relatively high values likely reflect modern agricultural practices, including the introduction of livestock and runoff from manure or fertilizer. This is further supported by decreased C/N values, indicating greater productivity in the lake resulting from increased terrestrial nitrogen input from modern agriculture. *Zea* pollen is absent from the uppermost pollen samples, but this may result from modern sediment dynamics or increased distance between cultivated land and the lakeshore, rather than from an actual absence of maize. There is also an increase in charcoal influx near the top of the profile at ca. 111 cal BP (AD 1839). Based on Manger's (1992) study of the colonization of the area, this extrapolation from radiocarbon is probably earlier than the actual date of settlement by non-indigenous people, which probably occurred no earlier than about AD 1927.

Isotope ratios as proxies for vegetation change, cultivation and human activity

Values for $\delta^{13}C$ in the Santa Elena sediments range between ca. –30‰ and –10‰ VPDB, a range which is much wider than found at many other lakes in Costa Rica and around the Caribbean, including from nearby Laguna Zoncho (Taylor et al. 2013a, 2015). These values show that periods of both maize cultivation and forest recovery were quite pronounced in the Santa Elena catchment, resulting in strong signals of vegetation change and land use in the sediments. These $\delta^{13}C$ values are within the expected range for C_3 and C_4 vegetation and conversion of native C_3 forest to cultivated fields with C_4 crops and weeds; however, the value of –10.33‰ at 1,450 cal BP (AD 500) is at the extreme high end of what would be expected from vegetation change alone. A portion of isotopic shifts toward relatively higher $\delta^{13}C$ values in the sediments may be attributable to increased aquatic productivity, particularly if the supply of available carbon became depleted to the point at which aquatic and emergent plants began using inorganic bicarbonate as a source of carbon. However, C/N values indicate well-mixed terrestrial and aquatic contributions to sedimentary matter in the prehistoric portion of the core, with a C/N value of 21.13 at 1,450 BP (AD 500) indicating increased importance of terrestrial matter at the same time as the high $\delta^{13}C$ value of –10.33‰. Another possibility is that the isotope sample at 535.5 cm in the core contained some residual inorganic carbonate following acid fumigation during sample preparation, which could have resulted in an artificially high value. We consider this unlikely, however, as the Santa Elena sediments contain small amounts of carbonate in general (min = 2.0%, max = 5.5%, av = 3.4%) and the sample from 535.5 cm contains lower than average carbonate for the core at 2.7%. Nevertheless, the range of $\delta^{13}C$ values in the sediments and the interpretation of large shifts in vegetation and land use patterns are noteworthy.

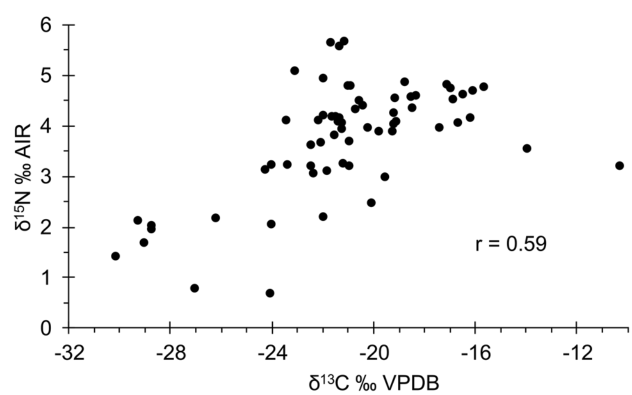


Fig. 4 Correlation plot comparing bulk stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope ratios in the Santa Elena sediments

The stable isotope signal also reveals an unusual pattern in which $\delta^{15}N$ values closely track $\delta^{13}C$ values (Fig. 3). Indeed, $\delta^{15}N$ values are correlated with $\delta^{13}C$ ($r = 0.59$; Fig. 4), suggesting that the same factors controlled composition of both isotopes in the sediments. Shifts in $\delta^{15}N$ in lake sediments are difficult to interpret because they can be driven by a variety of factors, both internal and external, such as aridity, primary productivity, changes in water depth, sudden pulses of sediment input, natural changes in trophic state, vegetation change, landscape disturbance and others (Hassan et al. 1997; Meyers and Teranes 2001; Talbot 2001; Tepper and Hyatt 2011; Torres et al. 2012). Additionally, we have no generalized modern analogues from which to interpret prehistoric changes in $\delta^{15}N$. However, shifts in $\delta^{13}C$ are easier to interpret, and in small neotropical catchments that experienced broad scale vegetation change and intensive maize cultivation, $\delta^{13}C$ composition of lake sediments is primarily driven by changes in C_3 versus C_4 terrestrial vegetation (Lane et al. 2004, 2008, 2011).

The relationship between $\delta^{15}N$ and $\delta^{13}C$ at Santa Elena, in which $\delta^{15}N$ values parallel closely the $\delta^{13}C$ signals of forest clearance, C_4 maize cultivation and forest recovery, suggests that both signals are responding to similar changes in human activity and land use in the area. During periods of increased cultivation, such as at 1,450 and 1,011 cal BP (AD 500 and 939), corresponding C/N ratios are 21.13 and 20.86, respectively, indicating increased importance of the terrestrial component of the sedimentary organic matter pool. High $\delta^{15}N$ values around these times may indicate preferential volatilization and removal of the lighter ^{14}N isotope of nitrogen resulting from fire used by people to clear and maintain fields (Dunnette et al. 2014; Szpak 2014). The result would be increased $\delta^{15}N$ values in the remaining terrestrial organic matter. Continued cultivation would have resulted in transport of terrestrial matter into the lake, contributing to relatively higher $\delta^{15}N$ values in the sedimentary record. Conversely, at times of lower maize cultivation, such as 1,189–1,141 cal BP (AD 761–809), reduced inorganic input, *Zea* pollen percentages and charcoal influx indicate reduced importance of terrestrial matter in the lake sediments. Decreased $\delta^{13}C$ and $\delta^{15}N$ values at these times likely reflect increased importance of C_3 phytoplankton fractionating nitrogen isotopes closer to the $\delta^{15}N$ values of atmospheric N_2 (Talbot 2001). In the case of Laguna Santa Elena, $\delta^{15}N$ values are responding to and signalling changes in the scale and intensity of land use for growing maize. This hypothesis could be further strengthened by additional analysis of sedimentary charcoal at an increased sampling resolution, together with analysis of diatoms and algae present in the sediments at key times through the site history.

Population collapse(s)

The cultural transition from the Aguas Buenas to the Chiriquí period in this area is marked by large shifts in signals across the zone 2c/2b transition at ca. 1,228–1,185 cal BP (AD 722–765), indicating major changes in the pattern, scale, or intensity of land use and maize cultivation in the Santa Elena basin (Fig. 3). Archaeological investigations near the coring site have found Aguas Buenas type artefacts at house sites along the ridges surrounding the lake, but none diagnostic of the later Chiriquí period (Sánchez and Rojas 2002; Sánchez 2013, personal communication). Maize cultivation returned to the area following this transition at a scale and intensity matching that of the earlier Aguas Buenas period, yet it appears that people were no longer living nearby. Instead, during the Chiriquí period, people may have been concentrated in larger regional population centres such as at nearby Fila Tigre, while maintaining sites like Santa Elena as outposts for growing crops. Shifts in settlement patterns such as these match expectations in the published literature (Linares and Sheets 1980; Drolet 1992). Additionally, this major change in agriculture and lifeways in the Diquís sub-region broadly coincides with the TCD (Hodell et al. 2005), including local manifestations of the TCD in Costa Rica (Horn and Sanford 1992; Wu et al. 2019). Our evidence indicates a major decline in maize cultivation during this time. That, combined with available archaeological evidence, leads us to conclude that a population collapse took place in the Santa Elena area, coinciding with evidence of regional and broad scale drought around the Caribbean. Further understanding of the relationship between this collapse and climate change will require additional study of local conditions.

A second decline in maize took place at Santa Elena beginning ca. 720 cal BP (AD 1230) that may be related to early climate deterioration from the beginning of the LIA. The LIA was globally asynchronous and resulting climate changes were not uniform across time or space, yet the effect was widespread and apparently reached southern Pacific Costa Rica (Wu et al. 2017). Anchukaitis and Horn (2005) noted from pollen and charcoal analyses that this decline in maize cultivation occurred close to the time of Spanish arrival. Our new analyses, however, show that it happened much earlier and that the pattern of land use and maize cultivation that was in place from 683 cal BP (AD 1267) and which persisted until 111 cal BP (AD 1839) was already established by the time of Spanish arrival in the 16th century. Archaeological literature does not show evidence of this major shift in subsistence patterns and maize cultivation, nor does the literature note a period of cultural change in the region prior to the Spanish Conquest. Indeed, the cultural chronology of the Diquís sub-region progresses from the Chiriquí period through the Conquest and into the Post-Contact period at ca. 450 cal BP (AD 1500). While the Santa Elena area was not completely abandoned during this time, we interpret the sedimentary record as indicating a second population collapse there around 683 cal BP (AD 1267), before Spanish arrival and coinciding with the findings of Taylor et al. (2013a, 2015) at nearby Laguna Zoncho.

Conclusions: Santa Elena in a broader perspective

Our data have yielded a high-resolution reconstruction of vegetation change and land use history that agrees well with evidence from nearby Laguna Zoncho. Taylor et al. (2013a, 2015) reported two periods of agricultural decline there between ca. 1,150–970 and 860–640 cal BP (AD 800–980 and 1090–1310), that correspond to severe droughts throughout the circum-Caribbean region (Haug et al. 2001; Hodell et al. 2005; Peterson and Haug 2006; Black et al. 2007). They also suggested that population history and intensity of maize cultivation at Laguna Zoncho and in the wider area, including at our site, were controlled by climate change and precipitation variability. The scale and intensity of land use and maize cultivation declined at Santa Elena after ca. 1,115 and 720 cal BP (AD 835 and 1230), which coincides with the periods of decline recognized at Laguna Zoncho. Anchukaitis and Horn (2005) reported a brief hiatus in *Zea* pollen at Santa Elena at ca. 540 cal BP (AD 1410), but that finding is not well supported by our new geochemical and isotope analyses. Instead, the absence of *Zea* pollen at 288 cm may simply represent the chance failure of *Zea* pollen to be captured in that sample.

Taylor et al. (2013a, 2015) reported that maize cultivation, and presumably also people, were nearly absent at Laguna Zoncho ca. 220 years before the arrival of the Spanish. In contrast, stable carbon isotope ratios and the presence of *Zea* pollen in the Santa Elena sediments indicate that this area was never completely abandoned, despite population declines after ca. 1,115 and 720 cal BP (AD 835 and 1230), at the latest. There were also shifts toward relatively negative carbon isotope values during these periods following peaks in C_4 vegetation signals, along with decreased *Zea* pollen percentages and charcoal influx, and increased pollen indicating forest recovery. Continued charcoal influx and the presence of *Zea* pollen, however, indicate that low-intensity maize cultivation continued in the area despite these declines.

Archaeological evidence from southern Pacific Costa Rica and western Panama shows population movement, increasing social complexity and culture change across the transition from the Aguas Buenas to the Chiriquí period ca. 1,150 cal BP (AD 800) (Corrales et al. 1988; Drolet 1992; Hoopes 1996). Excavations near Laguna Santa Elena revealed the presence of house sites on hilltops surrounding the basin which contained Aguas Buenas period artefacts, but no Chiriquí material (Sánchez and Rojas 2002; Sánchez 2013, personal communication). Archaeological evidence suggests that the area was abandoned, and our data lead us to conclude that a population collapse took place in the area beginning at 1,115 cal BP (AD 835). Seventy years later, pollen and $\delta^{13}C$ signals of maize cultivation again increase, indicating a strong C_4 signature of maize at Santa Elena at 1,046 cal BP (AD 904), but the archaeological record does not show evidence that the area was settled again (Sánchez 2013, personal communication).

Some major questions remain for Laguna Santa Elena. If archaeological and sedimentary evidence indicates that people moved out of the area at the end of the Aguas Buenas period, but data show that maize cultivation continued and later intensified, where did the people go, and why? Were people aggregating into larger regional population centres, such as Fila Tigre, and maintaining sites like Laguna Santa Elena and Laguna Zoncho as agricultural outposts? Considered in the context of archaeological theory and geographical reality, Fila Tigre would have been a likely location for initial population aggregation during periods of environmental stress and collapse in the hinterlands.

The minor presence of Chiriquí period artefacts at Fila Tigre indicates that the site was not occupied for long following the Aguas Buenas to Chiriquí transition. Considering severe regional drought in the Caribbean area, population movement and decline, and increasing hierarchy and social complexity in our area, a logical conclusion is that people were relocating from the hinterlands to population centres larger yet than Fila Tigre and were maintaining smaller sites like Laguna Santa Elena and Laguna Zoncho for maize cultivation. Conversations with local residents in the Diquís sub-region during our 2013 field work revealed that other sites exist in the area that are known to local people but have yet to be investigated by professional archaeologists. Future archaeological and palaeoenvironmental research here may help to resolve the nature and chronology of activities and movements of the people who occupied the Laguna Santa Elena basin and the wider area through nearly two millennia of prehistory.

Acknowledgements Core recovery, radiocarbon dating and previous pollen and charcoal analyses were funded by a grant from The A.W. Mellon Foundation to Sally Horn and Robert Sanford Jr., and by a STAR Fellowship from the U.S. Environmental Protection Agency awarded to Kevin Anchukaitis. A 2013 field visit and our new results reported here were supported by the University of Tennessee, the Center for Marine Science and College of Arts and Sciences at the University of North Carolina Wilmington, and NSF Grant #1660185 awarded to Sally Horn, Chad Lane, and Doug Gamble. We thank Maureen Sánchez for sharing her knowledge on the archaeology of the Santa Elena site and surrounding area, and Paul Lemieux and Sarah Bleakney for laboratory assistance.

References

Anchukaitis KJ (2002) A 2000-year history of forest disturbance in southern Pacific Costa Rica: pollen, spore, and charcoal evidence from Laguna Santa Elena. MS Thesis, University of Tennessee Knoxville

Anchukaitis KJ, Horn SP (2005) A 2000-year reconstruction of forest disturbance from southern Pacific Costa Rica. Palaeogeogr Palaeoclimatol Palaeoecol 221:35–54

Barrantes R (1993) Evolución en el trópico: los Amerindios de Costa Rica y Panamá. Editorial de la Universidad de Costa Rica, San José

Barrantes R, Smouse PE, Mohrenweiser HW et al (1990) Microevolution in lower Central America: genetic characterization of the Chibcha-speaking groups of Costa Rica and Panama, and consensus taxonomy based on genetic and linguistic affinity. Am J Hum Genet 46:63–84

Baudez CL, Borgnino N, Laligant S et al (1996) A ceramic sequence for the lower Diquís area, Costa Rica. In: Lange FW (ed) Paths to Central American prehistory. University Press of Colorado, Niwot, pp 79–92

Behling H (2000) A 2860-year high-resolution pollen and charcoal record from the Cordillera de Talamanca in Panama: a history of human and volcanic forest disturbance. Holocene 10:387–393

Bender MM (1971) Variations in the $^{13}C/^{12}C$ ratios of plants in relation to the pathway of photosynthetic carbon dioxide fixation. Phytochemistry 10:1239–1244

Blaauw M (2019) Clam: classical age-depth modelling of cores from deposits. R package version 2.3.2. https://CRAN.R-project.org/package=clam. Accessed 23 Jan 2019

Blaauw M, Christen JA (2019) Rbacon: age-depth modelling using Bayesian statistics. R package version 2.3.6. https://CRAN.R-project.org/package=rbacon. Accessed 23 Jan 2019

Black DE, Abahazi MA, Thunell RC et al (2007) An 8-century tropical Atlantic SST record from the Cariaco Basin: baseline variability, twentieth-century warming, and Atlantic hurricane frequency. Paleoceanography 22:PA4204

Blanco A, Mora G (1994) Plantas silvestres y cultivadas segun la evidencia arqueobotanica en Costa Rica. Vínculos 20:53–77

Bookman R, Driscoll CT, Effler SW, Engstrom DR (2010) Anthropogenic impacts recorded in recent sediments from Otisco Lake, New York, USA. J Paleolimnol 43:449–462

Brodie CR, Leng MJ, Casford JSL et al (2011) Evidence for bias in C and N concentrations and $\delta^{13}C$ composition of terrestrial and aquatic organic materials due to pre-analysis acid preparation methods. Chem Geol 282:67–83

Brodie LJ, Palumbo SD, Corrales F (2016) Early social complexity at Bolas, Costa Rica: first year southern Costa Rica archaeological project (SCRAP) results. Arqueología 22:409–418

Brown RH (1999) Agronomic implications of C_4 photosynthesis. In: Sage RF, Monson RK (eds) C_4 plant biology. Academic Press, San Diego, pp 473–507

Bush MB (2002) On the interpretation of fossil Poaceae pollen in the lowland humid tropics. Palaeogeogr Palaeoclimatol Palaeoecol 177:5–17

Clement RM, Horn SP (2001) Pre-Columbian land use history in Costa Rica: a 3000-year record of forest clearance, agriculture and fires from Laguna Zoncho. Holocene 11:419–426

Colinvaux P, De Oliveira PE, Moreno JE (1999) Amazon pollen manual and atlas. Hardwood Academic Publishers, Amsterdam

Constenla A (1991) Las lenguas del Área Intermedia: introducción a su estudio areal. Editorial de la Universidad de Costa Rica, San José

Corrales F (2000) An evaluation of long-term cultural change in southern Central America: the ceramic record of the Diquís archaeological subregion, southern Costa Rica. Dissertation, University of Kansas

Corrales F, Quintanilla I, Barrantes O (1988) Historia precolombina y de los siglos XVI y XVII del sureste de Costa Rica. Proyecto investigación y promoción de la cultura popular y tradicional del Pacifico sur OEA/MCJD. Ministerio de Cultura, Juventud y Deportes. Organización de los Estados Americanos, San José

Dean WE Jr (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J Sediment Petrol 44:242–248

Drolet RP (1984) Community life in a late phase agricultural village, southeastern Costa Rica. In: Lange FW (ed) Recent developments in Isthmian archaeology: advances in the prehistory of lower Central America (BAR International Series 212). Archaeopress, Oxford, pp 123–152

Drolet RP (1988) The emergence and intensification of complex societies in Pacific southern Costa Rica. In: Lange FW (ed) Costa Rican art and archaeology: essays in honor of Frederick R. University of Colorado, Boulder, Mayer, pp 163–188

Drolet RP (1992) The house and the territory: the organizational structure for chiefdom art in the Diquis subregion of greater Chiriqui. In: Lange FW (ed) Wealth and hierarchy in the Intermediate Area: a symposium at Dumbarton Oaks 10th and 11th October 1987. Dumbarton Oaks Research Library and Collection, Washington, DC, pp 207–241

Dull RA (2007) Evidence for forest clearance, agriculture, and human-induced erosion in Precolumbian El Salvador. Ann Assoc Am Geogr 97:127–141

Dunnette PV, Higuera PE, McLauchlan KK et al (2014) Biogeochemical impacts of wildfires over four millennia in a Rocky Mountain subalpine watershed. New Phytol 203:900–912

Enters D, Lücke A, Zolitschka B (2006) Effects of land-use change on deposition and composition of organic matter in Frickenhauser See, northern Bavaria, Germany. Sci Total Environ 369:178–187

Filippelli GM, Souch C, Horn SP et al (2010) The pre-Colombian footprint on terrestrial nutrient cycling in Costa Rica: insights from phosphorus in a lake sediment record. J Paleolimnol 43:843–856

Galinat WC (1980) The archaeological maize remains from Volcan, Panama—a comparative perspective. In: Linares OF, Ranere AJ (eds) Adaptive radiations in prehistoric Panama. (Peabody Museum Monographs 5). Harvard University, Cambridge, pp 175–180

Goman M, Byrne R (1998) A 5000-year record of agriculture and tropical forest clearance in the Tuxtlas, Veracruz, Mexico. Holocene 8:83–89

Graham A (1987) Miocene communities and paleoenvironments of southern Costa Rica. Am J Bot 74:1501–1518

Haberland W (1984a) The Valle de General and Panamanian Chiriquí: temporal and regional differences. In: Skirboll E, Creamer W (eds) Inter-regional ties in Costa Rican prehistory: papers presented at a symposium at Carnegie Museum of Natural History, Pittsburgh, April 27, 1983 (BAR International Series 226). Archaeopress, Oxford, 261–276

Haberland W (1984b) The archaeology of Greater Chiriqui. In: Lange FW, Stone DZ (eds) The archaeology of lower Central America. University of New Mexico Press, Albuquerque, pp 233–262

Haberyan KA, Horn SP (2005) Diatom paleoecology of Laguna Zoncho, Costa Rica. J Paleolimnol 33:361–369

Hartshorn GS (1983) Plants. In: Janzen DH (ed) Costa Rican natural history. University of Chicago Press, Chicago, pp 118–350

Hassan KM, Swinehart JB, Spalding RF (1997) Evidence for Holocene environmental change from C/N ratios, and $\delta^{13}C$ and $\delta^{15}N$ values in Swan Lake sediments, western Sand Hills, Nebraska. J Paleolimnol 18:121–130

Haug GH, Hughen KA, Sigman DM et al (2001) Southward migration of the Intertropical Convergence Zone through the Holocene. Science 293:1304–1308

Hedges JI, Clark WA, Quay PD et al (1986) Compositions and fluxes of particulate organic material in the Amazon River. Limnol Oceanogr 31:717–738

Hodell DA, Brenner M, Curtis JH (2005) Terminal Classic Drought in the northern Maya lowlands inferred from multiple sediment cores in Lake Chichancanab (Mexico). Q Sci Rev 24:1413–1427

Holmberg K (2009) Nature, material, culture, and the volcano: the archaeology of the Volcán Barú in highland Chiriquí, Panamá. Dissertation, Columbia University

Holmberg K (2016) The cultural nature of tephra: 'problematic' ecofacts and artifacts and the Barú volcano, Panamá. Q Int 394:133–151

Hoopes JW (1991) The Isthmian alternative: reconstructing patterns of social organization in formative Costa Rica. In: Fowler WR Jr (ed) The formation of complex society in southeastern Mesoamerica. CRC Press, Boca Raton, pp 171–192

Hoopes JW (1996) Settlement, subsistence, and the origins of social complexity in Greater Chiriquí: a reappraisal of the Aguas Buenas tradition. In: Lange FW (ed) Paths to Central American prehistory. University Press of Colorado, Niwot, pp 15–47

Horn SP (2006) Pre-Columbian maize agriculture in Costa Rica: pollen and other evidence from lake and swamp sediments. In: Staller J, Tykot R, Benz B (eds) Histories of maize: multidisciplinary approaches to the prehistory, linguistics, biogeography, domestication, and evolution of maize. Academic Press, Amsterdam, pp 368–376

Horn SP, Haberyan KA (2016) Lakes of Costa Rica. In: Kappelle M (ed) Costa Rican ecosystems. University of Chicago Press, Chicago, pp 656–682

Horn SP, Sanford RL Jr (1992) Holocene fires in Costa Rica. Biotropica 24:354–361

Iltis HH (2000) Homeotic sexual translocations and the origin of maize (*Zea mays*, Poaceae): a new look at an old problem. Econ Bot 54:7–42

Iltis HH, Benz BF (2000) *Zea nicaraguensis* (Poaceae), a new teosinte from Pacific coastal Nicaragua. Novon 10:382–390

Johanson EJ, Horn SP, Lane CS (2019) Pre-Columbian agriculture, fire, and Spanish contact: a 4200-year record from Laguna Los Mangos, Costa Rica. Holocene 29:1743–1757

Juggins S (2007) C2: software for ecological and palaeoecological data analysis and visualization, user guide version 1.5. University of Newcastle, Newcastle upon Tyne

Lane CS, Horn SP, Mora CI (2004) Stable carbon isotope ratios in lake and swamp sediments as a proxy for prehistoric forest clearance and crop cultivation in the Neotropics. J Paleolimnol 32:375–381

Lane CS, Mora CI, Horn SP et al (2008) Sensitivity of bulk sedimentary stable carbon isotopes to prehistoric forest clearance and maize agriculture. J Archaeol Sci 35:2119–2132

Lane CS, Horn SP, Taylor ZP et al (2009) Assessing the scale of prehistoric human impact in the Neotropics using stable carbon isotope analyses of lake sediments: a test case from Costa Rica. Lat Am Antiq 20:120–133

Lane CS, Horn SP, Mora CI et al (2011) Sedimentary stable carbon isotope evidence of late Quaternary vegetation and climate change in highland Costa Rica. J Paleolimnol 45:323–338

Lane CS, Clark JJ, Knudsen A et al (2013) Late-Holocene paleoenvironmental history of bioluminescent Laguna Grande, Puerto Rico. Palaeogeogr Palaeoclimatol Palaeoecol 369:99–113

Lane CS, Horn SP, Kerr MT (2014) Beyond the Mayan Lowlands: impacts of the Terminal Classic Drought in the Caribbean Antilles. Q Sci Rev 86:89–98

Lange FW (1992) The intermediate area: an introductory overview of wealth and hierarchy issues. In: Lange FW (ed) Wealth and hierarchy in the intermediate area: a symposium at Dumbarton Oaks 10th and 11th October 1987. Dumbarton Oaks Research Library and Collection, Washington, DC, pp 1–14

Lange FW (1993) The conceptual structure in lower Central American studies: a Central American view. In: Graham MM (ed) Reinterpreting prehistory of Central America. University Press of Colorado, Niwot, pp 277–324

Linares OF, Sheets PD (1980) Highland agricultural villages in the Volcan Baru region. In: Linares OF, Ranere AJ (eds) Adaptive radiations in prehistoric Panama. (Peabody Museum Monographs 5). Harvard University, Cambridge, pp 44–55

Linares OF, Sheets PD, Rosenthal EJ (1975) Prehistoric agriculture in tropical highlands. Science 187:137–145

Manger WF (1992) Colonization on the southern frontier of Costa Rica: a historical-cultural landscape. Memphis State University, Thesis

McLauchlan KK, Williams JJ, Craine JM, Jeffers ES (2013) Changes in global nitrogen cycling during the Holocene epoch. Nature 495:352–355

Meybeck M (1982) Carbon, nitrogen, and phosphorus transport by world rivers. Am J Sci 282:401–450

Meyers PA (1997) Organic geochemical proxies of paleoceanographic, paleolimnologic, and paleoclimatic processes. Org Geochem 27:213–250

Meyers PA, Ishiwatari R (1993) Lacustrine organic geochemistry—an overview of indicators of organic matter sources and diagenesis in lake sediments. Org Geochem 20:867–900

Meyers PA, Lallier-Vergès E (1999) Lacustrine sedimentary organic matter records of Late Quaternary paleoclimates. J Paleolimnol 21:345–372

Meyers PA, Teranes JL (2001) Sediment organic matter. In: Last WM, Smol JP (eds) Tracking environmental change using lake sediments, vol 2. Physical and geochemical methods. Kluwer, Dordrecht, pp 239–269

O'Leary MH (1981) Carbon isotope fractionation in plants. Phytochemistry 20:553–567

Oldfield F, Wake R, Boyle J et al (2003) The late-Holocene history of Gormire Lake (NE England) and its catchment: a multiproxy reconstruction of past human impact. Holocene 13:677–690

Palumbo SD (2009) The development of complex society in the Volcán Barú region of western Panama. Dissertation, University of Pittsburgh

Palumbo SD, Brodie L, Locascio WA et al (2013) Early social complexity in southern Costa Rica: new evidence from Bolas. Antiquity 87(337). http://antiquity.ac.uk/projgall/palumbo337/. Accessed 23 January 2019

Pessenda LCR, Saia SEMG, Gouveia SEM et al (2010) Last millennium environmental changes and climate inferences in the Southeastern Atlantic forest, Brazil. An Acad Bras Ciênc 82:717–729

Peterson LC, Haug GH (2006) Variability in the mean latitude of the Atlantic Intertropical Convergence Zone as recorded by riverine input of sediments to the Cariaco Basin (Venezuela). Palaeogeogr Palaeoclimatol Palaeoecol 234:97–113

Quilter J, Blanco A (1995) Monumental architecture and social organization at the Rivas Site, Costa Rica. J Field Archaeol 22:203–221

R Core Team (2018) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. https://www.r-project.org. Accessed 23 January 2019

Reimer PJ, Bard E, Bayliss A et al (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55:1,869-1,887

Rodgers JC III, Horn SP (1996) Modern pollen spectra from Costa Rica. Palaeogeogr Palaeoclimatol Palaeoecol 124:53–71

Sage RF, Wedin DA, Li M (1999) The biogeography of C_4 photosynthesis: patterns and controlling factors. In: Sage RF, Monson RK (eds) C_4 plant biology. Academic Press, San Diego, pp 313–373
Sánchez M (2013) Las sociedades de rango y distribución territorial en el Pacífico sur de Costa Rica. Revista de Arqueología Americana 31:59–80
Sánchez M, Rojas P (2002) Asentamientos humanos antiguos en las tierras intermedias del Cantón de Coto Brus. Cuadernos de Antropología 12:87–106
Schlesinger WH (1997) Biogeochemistry: an analysis of global change, 2nd edn. Academic Press, San Diego
Sharp Z (2017) Principles of stable isotope geochemistry, 2nd edn. https://doi.org/10.5072/fk2gb24s9f
Sherrod DR, Vallance JW, Tapia A, McGeehin JP (2007) Volcán Barú—eruptive history and volcano-hazards assessment, open-file report 2007-1401. US Geological Survey, Reston
Smalley J, Blake M (2003) Sweet beginnings: stalk sugar and the domestication of maize. Curr Anthropol 44:675–703
Smith CE (1980) Plant remains from the Chiriqui sites and ancient vegetational patterns. In: Linares OF, Ranere AJ (eds) Adaptive radiations in prehistoric Panama (Peabody Museum Monographs 5). Harvard University, Cambridge, pp 151–174
Snarskis MJ (1981) The archaeology of Costa Rica. In: Benson EP (ed) Between continents/between seas: Precolumbian art of Costa Rica. Harry N Abrams, New York, pp 15–84
Soto K, Gómez L (2002) Sitio arqueologico el Zoncho (CAT. U.C.R. N°168): una manifestación de los agricultores especializados en las Tierra Intermedias de San Vito, Cantón de Coto Brus, Puntarenas. Tesis de Licenciatura, Universidad de Costa Rica
Szpak P (2014) Complexities of nitrogen isotope biogeochemistry in plant-soil systems: implications for the study of ancient agricultural and animal management practices. Front Plant Sci 5, Article 298:1–19
Talbot MR (2001) Nitrogen isotopes in paleolimnology. In: Last WM, Smol JP (eds) Tracking environmental change using lake sediments, vol 2. Physical and geochemical methods. Kluwer, Dordrecht, pp 401–439
Talbot MR, Johannessen T (1992) A high resolution palaeoclimatic record for the last 27,500 years in tropical West Africa from the carbon and nitrogen isotopic composition of lacustrine organic matter. Earth Planet Sci Lett 110:23–37
Taylor ZP, Horn SP, Finkelstein DB (2013a) Pre-Hispanic agricultural decline prior to the Spanish Conquest in southern Central America. Q Sci Rev 73:196–200
Taylor ZP, Horn SP, Finkelstein DB (2013b) Maize pollen concentrations in Neotropical lake sediments as an indicator of the scale of prehistoric agriculture. Holocene 23:78–84
Taylor ZP, Horn SP, Finkelstein DB (2015) Assessing intra-basin spatial variability in geochemical and isotopic signatures in the sediments of a small Neotropical lake. J Paleolimnol 54:395–411
Tepper JH, Hyatt JA (2011) Holocene trophic state history of a subtropical blackwater lake, South Georgia, USA. J Paleolimnol 45:9–22
Torres IC, Inglett PW, Brenner M, Kenney WF, Reddy KR (2012) Stable isotope ($\delta^{13}C$ and $\delta^{15}N$) values of sediment organic matter in subtropical lakes of different trophic status. J Paleolimnol 47:693–706
Tyson RV (1995) Sedimentary organic matter: organic facies and palynofacies. Chapman and Hall, London
Vitousek PM, Aber JD, Howarth RW et al (1997) Human alteration of the global nitrogen cycle: sources and consequences. Ecol Appl 7:737–750
Wahl D, Schreiner T, Byrne R, Hansen R (2007) A paleoecological record from a Late Classic Maya reservoir in the North Petén. Lat Am Antiq 18:212–222
Whitlock C, Larsen C (2001) Charcoal as a fire proxy. In: Smol JP, Birks HJB, Last WM (eds) Tracking environmental change using lake sediments, vol 3. Terrestrial, algal, and siliceous indicators. Kluwer, Dordrecht, pp 75–97
Wu J, Porinchu DF, Horn SP (2017) A chironomid-based reconstruction of late-Holocene climate and environmental change for southern Pacific Costa Rica. Holocene 27:73–84
Wu J, Porinchu DF, Horn SP (2019) Late Holocene hydroclimate variability in Costa Rica: signature of the terminal classic drought and the Medieval Climate Anomaly in the northern tropical Americas. Quat Sci Rev 215:144–159