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]

[1]Department of Geography, University of Tennessee Knoxville

[2]Department of Earth and Ocean Sciences, University of North Carolina Wilmington

[*]Corresponding author; email: mkerr6@vols.utk.edu

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Abstract

Laguna Santa Elena (8.9290 °N, 82.9257 °W, 1055 m elevation) 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 2000-year history of vegetation change, maize agriculture, and site occupation that is consistent with the archaeological record from the watershed 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 anthropogenic vegetation modification and maize agriculture at varying intensities over a long duration. The Santa Elena sediments provide a record of paleoenvironmental 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 agriculture at ca. 1570 cal B.P. (AD 380) and two intervals of population decline coincident with the TCD at ca. 1085 cal B.P. (AD 865) and with the onset of the LIA at ca. 683 cal B.P. (AD 1267).

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Introduction

The study of lake sediments as archives of paleoenvironmental history involves analyzing microfossil and geochemical proxies preserved in the sediments and producing stratigraphic time-series reconstructions of both natural and anthropogenic change in watersheds. A variety of microfossils preserved in sediments provide evidence of prehistoric human activity around lakes. For example, the presence of *Zea mays* subsp. *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 watersheds, 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).

Carbon isotope ratios are an effective proxy for reconstructing timelines of land-cover change and the scale of maize agriculture from sediments of small lakes in tropical settings in which conversion of wild vegetation to agriculture involves a shift in dominant photosynthetic pathways. The majority of 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). Anthropogenic forest clearance 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 terrestrial organic inputs. This shift in $\delta^{13}C$ can be detected through stable isotope analysis and paired with pollen and charcoal evidence to reconstruct timelines 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 paleoenvironmental reconstructions, $\delta^{15}N$ values often reflect a complex synergy of driving factors. 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 watershed, 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 researchers to extrapolate from present knowledge of nitrogen cycling and fractionation to understand nitrogen processes in the distant past because the modern nitrogen cycle has been severely altered by anthropogenic 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, $\delta^{15}N$ can provide valuable paleoenvironmental information when carefully combined with other proxies, such as 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 paleoclimate record at Lake Bosumtwi in Ghana. More recently, Pessenda et al. (2010) combined pollen, elemental, $\delta^{13}C$, and $\delta^{15}N$ data to reconstruct paleoenvironmental change over the past millennium at Lagoa Grande in Brazil and demonstrated that the site experienced warm and wet conditions during the Little Ice Age.

Carbon/nitrogen ratios (C/N) of bulk sedimentary organic matter serve as a proxy for organic matter source in lake systems (Meyers and Ishiwatari 1993; Tyson 1995; Meyers and Lallier-Vergés 1999; Talbot 2001). C/N 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 watershed 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 anthropogenic impacts in watersheds.

Southern Pacific Costa Rica and adjacent western Panama have been sites of extensive research on signals of prehistoric human activity preserved in lake sediments. Researchers have documented long histories of anthropogenic 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 2016; Johanson et al. forthcoming), 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 paleoenvironmental change and for building timelines of vegetation change and agricultural history. Studies using these proxies complement earlier studies of pollen and charcoal by filling in 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 watershed. These researchers demonstrated that a decline previously linked to Spanish Conquest (Clement and Horn 2001) began two centuries earlier, likely triggered 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, multi-decadal droughts that affected the Yucatan Peninsula and wider circum-Caribbean region between ca. 1200 and 850 cal B.P. (AD 750 and 1100; Hodell et al. 2005; Lane et al. 2014).

Anchukaitis and Horn (2005) conducted pollen and charcoal analyses on a sediment core from Laguna Santa Elena (Fig. 1), located 13.5 km north of Laguna Zoncho. Their work documented the establishment and near-continuous cultivation of maize and changing vegetation and land use across almost two millennia, including a possible short hiatus in maize farming 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 (e.g., Sánchez and Rojas 2002) and with evidence of maize farming and paleoenvironmental 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. forthcoming).

We carried out loss-on-ignition, geochemical, and bulk stable isotope analyses on the Santa Elena sediment core to supplement and refine the previous reconstruction from pollen and charcoal developed by Anchukaitis and Horn (2005). Laguna Santa Elena, like many lakes in the wider region of Central America and the Caribbean, was a magnet for humans throughout its history. As a result, the lake experienced anthropogenic vegetation modification and maize agriculture at varying intensities over a long duration across prehistory. Importantly, lake sites like Santa Elena provide records of paleoenvironmental change during times of major culture change and increasing cultural complexity. All of those changes in subsistence patterns, culture, and complexity are overlain by much broader external forcing mechanisms, including the Terminal Classic Drought ca. 1200–850 cal B.P. (AD 750–1100), the Little Ice Age ca. 550–100 cal B.P. (AD 1400–1850), and the Spanish Conquest beginning ca. 458 cal B.P. (AD 1492). High-resolution lake-sediment studies can reveal details of these events at the local scale that are unobtainable by other means. Our new work at Laguna Santa Elena contributes both a new level of detail from one site and broader insights that can improve interpretations at other sites.

Background

Archaeological Setting

Laguna Santa Elena (8.9290 °N, 82.9257 °W, 1055 m elevation) (Fig. 1) is a small (0.13 ha), shallow (3.8 m) lake occupying a landslide-truncated stream channel in southern Pacific Costa Rica (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; Barrantes 1993; Lange 1992, 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 radiocarbon. The earliest sedentary habitation of the Diquís sub-region dates to ca. 3450 B.P. (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 2450 and 1750 B.P. (500 BC and AD 200; Drolet 1984; Haberland 1984a, b; Hoopes 1996; Corrales 2000; Palumbo 2009). The Chiriquí period followed the Aguas Buenas, spanning ca. 1150 to 450 B.P. (AD 800 to 1500; Quilter and Blanco 1995; Baudez et al. 1996; Corrales 2000). 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. 1750–1350 B.P. (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 1750 B.P. (AD 200) for Aguas Buenas materials (Soto and Gómez 2002). Considerable debate continues over the timing, chronology, and connections between cultural phases, periods, and traditions in the Greater Chiriquí region (Soto and Gomez 2002; Palumbo 2009; Sánchez 2013).

Several archaeological sites have been identified in the area around Laguna Santa Elena. Sánchez and Rojas (2002; M. Sánchez, personal communication, 2013) identified several house sites on the hilltops surrounding the lake from which they recovered lithic artifacts and Aguas Buenas period ceramics, but no artifacts from the later Chiriquí period. A larger site named Fila Tigre ca. 2 km east of Laguna Santa Elena contained predominantly Aguas Buenas period ceramics, but also had a minor presence of Chiriquí period artifacts. Sánchez and Rojas (2002) argued that Fila Tigre was likely a significant regional center and that the area conforms to expected settlement patterns of large centers 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 agriculture in the Greater Chiriquí region, with maize pollen dated to ca. 1800 cal B.P. (AD 150) at Laguna Volcán (Fig. 1) in the Chiriquí sub-region of western Panama (Behling 2000), and to ca. 2500 cal B.P. (550 BC) at Laguna Gamboa in Costa Rica near the Panamanian border (Horn 2006), ca. 3400 cal B.P. (1450 BC) at Laguna Los Mangos (Johanson et al. forthcoming), ca. 3200 cal B.P. (1250 BC) at Laguna Zoncho (Clement and Horn 2001), and ca. 1780 cal B.P. (AD 170) at Laguna Santa Elena (Anchukaitis and Horn 2005). These studies showed that maize was cultivated in southern Costa Rica and western Panama prior to the Aguas Buenas period and confirmed 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 1750 B.P. (AD 200; Galinat 1980). Although no earlier macrofossils have been found, Galinat (1980) and Smith (1980) argued that maize was introduced prior to 1750 B.P. (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 shift 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 carbonized 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, but may have instead been a special-use crop, 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 agriculture (Anchukaitis and Horn 2005; Palumbo 2009). Linares and Sheets (1980) argued that the inhabitants were intensive farmers, 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 corn 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 southern Pacific Costa Rica, may have been linked to a transition to subsistence-based maize agriculture. For example, Corrales et al. (1988) suggested that the increased importance of maize agriculture may be directly tied to major cultural shifts 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 paleoenvironmental proxies 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 trajectories of cultural complexity in these regions.

Previous Proxy 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 Santa Elena sediment core comprises ca. 6 m of lacustrine sediments underlain by ca. 1 m of soil. Anchukaitis and Horn (2005) reported six AMS ^{14}C dates on wood and plant macrofossils, five from the lacustrine section of the core and one from underlying soil.

Anchukaitis and Horn (2005) sampled 29 stratigraphic levels of the core at intervals of ca. 16–32 cm for pollen and microscopic charcoal analyses. They reported microfossil data for 25 samples from the lacustrine portion of the core in which pollen was well preserved, but did not count the lowest four samples due to poor preservation. They processed additional samples for macroscopic charcoal centered on the intervals sampled for pollen and microscopic charcoal. 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. Maize pollen at Santa Elena is consistent with sediment records 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. forthcoming), and with Laguna Volcán in western Panama (Behling 2000). At Santa Elena, maize pollen is absent in the level dated to ca. 540 cal B.P. (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 B.P. (AD 1250) suggested declining agricultural use 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 at Laguna Zoncho also appears to precede the Spanish Conquest, occurring some 200 years earlier than found by Clement and Horn (2001) in a single core. These results demonstrate the need for additional research on the timing of population movement and maize agriculture in the area.

Materials and Methods

We recalibrated the AMS radiocarbon dates reported by Anchukaitis and Horn (2005), produced an updated age-depth model, and generated point estimates for our sampled levels using the 'clam' package (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. Here we also use linear interpolation. We experimented with Bayesian methods of creating an age model using the 'rbacon' package for R (v. 2.3.6; Blaauw and Christen 2019) but given the strong and varying human impacts on the site previously documented and for which we report new evidence here, we believe that Bacon assumptions of gradual shifts in sedimentation rates are unwarranted. Likewise, other modeling options in 'clam' (e.g., 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, punctuated episodes of forest clearance, agricultural 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 linear interpolation to be the best model for site history at Laguna Santa Elena.

We sampled the same 25 levels in the lacustrine portion of the Santa Elena core sampled 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 in gaps and to tighten the sampling resolution, corresponding to ca. 8–16 cm between samples.

Following Dean (1974), samples for LOI were weighed into porcelain crucibles, oven-dried at 100 °C for 24 h to remove water, and reweighed. They were then combusted at 550 °C in a muffle furnace for 1 h, cooled, and reweighed. The mass lost during this first burn provides 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 combusted at 1000 °C for 1 h, cooled, and reweighed. The mass lost in this second burn provides an estimate of the carbonate content of the sediments; however, carbonate content of sediments that are low in carbonate (e.g., <5%), such as throughout the Santa Elena core, 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 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 aliquot ready for $\delta^{15}N$ analysis as the non-acidified fraction (Brodie et al. 2011). Samples analyzed for $\delta^{13}C$ were placed in pre-combusted ceramic crucibles, moistened with distilled water, fumigated with 12 N hydrochloric acid for 2 hours in a glass desiccator, and then vented for 24 hours. Following acidification, the samples were dried on a hotplate at ca. 60 °C for 48 hours 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 shipped to the UNCW Stable Isotope Facility for analysis. All samples were analyzed in duplicate and data from the replicate runs were averaged to produce single values for each datum. Samples were analyzed on a Costech 4010 Elemental Analyzer 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:

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

and:

$$\delta^{13}C \text{ or } \delta^{15}N(‰) = 1000[((R_{sample} - R_{standard}) / R_{standard}) - 1] \qquad \text{(Eq. 2)}$$

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 ($\delta^{13}C$ and $\delta^{15}N$) along with original LOI, selected pollen and spores, and charcoal data using C2 (v. 1.7.7; Juggins 2007). C/N ratios are calculated as the ratio of carbon content (%C) to nitrogen content (%N) from the acidified fraction. Pollen percentages for all taxa except Cyperaceae are calculated based on a pollen sum that excludes Cyperaceae. Anthocerotophyta (hornwort) spores are expressed as a percentage of total pollen plus fern and hornwort spores. Maize pollen is reported as percentages and as presence or absence based on low power 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, tallied outside of the pollen sum used for other types, may reflect agricultural disturbance directly (terrestrial sedges in agricultural fields) and indirectly (aquatic sedges increasing with infilling and the growth of a fringing herbaceous mat around the lake during times of enhanced erosion) (Bush 2002; Anchukaitis and Horn 2005).

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

Results

The upper ca. 6 m of the Laguna Santa Elena core consists of lacustrine silts and clays with organic matter content of ca. 15.0–45.6% and total inorganic content of ca. 54.4–84.9% as estimated by loss-on-ignition. Carbonate content is ca 2.0–5.5% (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 contains three volcanic tephra layers at 538, 417–415, and 314–312 cm that have been interpreted to represent the three most recent eruptions of nearby Volcán Barú in Panama (Anchukaitis and Horn 2005; Sherrod et al. 2007; Holmberg 2009, 2016).

Our recalibration of six Santa Elena radiocarbon dates confirmed a normal stratigraphic sequence dating to 1950–1825 cal B.P. (AD 0–125; Table 1 and Fig. 2). All 65 of our isotope samples yielded signals in abundances adequate for paleoenvironmental interpretation and comparison with original proxies (Fig. 3). Here we present our new LOI, geochemical, and isotope analyses in the context of the major trends in botanical proxies originally documented in the Santa Elena core.

Zone 3 – ca. 1780 to 1590 cal B.P. (AD 170 to 360)

Zone 3, corresponding to the earliest interval of lacustrine sedimentation, is characterized by relatively high organic carbon and nitrogen content, 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, tree pollen typical of moist lowland forests in Costa Rica, including *Quercus*, *Alnus*, *Hedyosmum*, *Alchornea*, Melastomataceae, *Weinmannia*, and *Myrsine* (Hartshorn 1983; Graham 1987; Rodgers and Horn 1996; Anchukaitis and Horn 2005), and rare occurrences of disturbance taxa. Minor presence of maize pollen, coupled with the lowest levels of charcoal in the core, indicates human presence but relatively slight impacts at this time. High organic matter, along with high organic carbon content and relatively low $\delta^{13}C$ values, support an interpretation of low disturbance and predominantly intact, native C_3 tropical vegetation in the watershed during the initial interval of sedimentation following formation of the lake. Relatively low $\delta^{15}N$ values indicate low terrestrial nutrient delivery. C/N ratios indicate mixed terrestrial and aquatic inputs.

Zone 2c – ca. 1590 to 1150 cal B.P. (AD 360 to 800)

Zone 2c shows marked expansion of agriculture and land clearance in the Santa Elena watershed beginning no later than 1568 cal B.P. (AD 382). Organic carbon and nitrogen contents drop between zone 3 and zone 2c, while $\delta^{13}C$ and $\delta^{15}N$ ratios increase substantially in response to forest clearance and intensified maize agriculture. C/N ratios increase toward the middle of zone 2c at ca. 1450 cal B.P. (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 moving into zone 2c, perhaps from erosion caused by people clearing forest to establish or expand agricultural fields. The $\delta^{13}C$ value of –10.3‰ at 1450 cal B.P. (AD 500) is the highest value in the record, supporting an interpretation of accelerated or more spatially extensive forest clearance and increased or intensified maize agriculture at that time.

Pollen counts indicate clearance of tropical forest and replacement by grasses and other disturbance taxa (*Cecropia*, Asteraceae, Poaceae, Amaranthaceae, Cyperaceae). Higher percentages of hornwort spores, possibly the genus *Anthoceros*, may also relate to disturbance (Anchukaitis and Horn 2005). This zone shows increased maize pollen percentages and the highest charcoal influx in the profile. Zone 2c also has abundant microscopic and macroscopic charcoal fragments, particularly in the >500 µm size class, which is found only sporadically in other parts of the core, indicating an increase in local fires at the site.

A shift in proxy data at the top of zone 2c indicates a transition in human activity, including reduced maize agriculture and a period of forest regrowth. This shift just below the zone 2c/2b boundary at ca. 1150 cal B.P. (AD 800) took place at a time of cultural transition between the Aguas Buenas and Chiriquí periods in southern Pacific Costa Rica that also corresponds to the onset of the Terminal Classic Drought ca. 1200–850 cal B.P. (AD 750–1100) that more broadly affected Central America and the circum-Caribbean (Lane et al. 2014).

The sample from 1170 cal B.P. (AD 780) shows the highest organic content in the core and continued high charcoal influx. The low inorganic content at this time indicates a decline in soil disturbance due to decreased forest clearance in the basin. A negative excursion of $\delta^{13}C$ and $\delta^{15}N$ values continues through the top of zone 2c, indicating decreasing maize agriculture and an increasing C_3 vegetation signal as the Aguas Buenas period ends.

Zone 2b – ca. 1150 to 880 cal B.P. (AD 800 to 1070)

Zone 2b exhibits changes in proxy signals that indicate shifts in the pattern of human activity in the watershed beginning ca. 1115 cal B.P. (AD 835). Importantly, zone 2b and the timing of those shifts coincide with the onset and duration of the Terminal Classic Drought and the proxy record indicates major changes in maize agriculture in the Santa Elena watershed. This may reflect significant reorganization of culture in the region at the beginning of the Chiriquí period.

The negative excursion 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 toward more C_3 vegetation, and $\delta^{15}N$ reaches the lowest values in the core at ca. 1085 cal B.P. (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 agricultural activity, an interpretation supported by increased pollen percentages for 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 values in the profile, likely representing increased maize agriculture beginning ca. 1045 cal B.P. (AD 905). C/N ratios increase toward the middle of zone 2B, indicating increased terrestrial input to the lake, likely caused by renewed agricultural activity in the watershed. Charcoal influx indicates continued burning at the site.

Following a peak of agricultural activity at 1011 cal B.P. (AD 939), $\delta^{13}C$ and $\delta^{15}N$ values decrease sharply, indicating a temporary reduction in maize farming at the site and a period of relatively rapid change in human activity that was not apparent at the resolution of pollen sampling. This is supported by a decrease in inorganic matter and reduced carbon and nitrogen content in the sediments.

At the top of zone 2b, pollen counts from disturbance taxa increase along with $\delta^{13}C$ and $\delta^{15}N$ values, while pollen counts from forest taxa decline. Maize pollen begins to increase again and abundant charcoal influx continues, indicating a return to agriculture in the watershed as the Terminal Classic Drought comes to an end ca. 850 cal B.P. (AD 1100).

Zone 2a – ca. 880 to 450 cal B.P. (AD 1070 to 1500)

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

Absence of maize pollen at ca. 540 cal B.P. (AD 1410) led Anchukaitis and Horn (2005) to propose a possible brief hiatus in maize agriculture at Santa Elena, but this interpretation is not supported by $\delta^{13}C$ values. Rather, proxy data in the upper part of zone 2a indicate a period of stability in maize agriculture and human activity at the site that was not seen prior. This is indicated by relatively constant $\delta^{13}C$ and $\delta^{15}N$ values, organic carbon and nitrogen content, and continued presence of maize pollen, albeit in relatively low abundances compared to earlier signals. 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 across the zone are typical of mixed terrestrial and aquatic inputs. Taken together, proxy 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.

Zone 1 – ca. 450 to –50 cal B.P. (AD 1500 to 2000)

Zone 1 begins the Post-Contact period and proxy data show continued low-intensity maize agriculture and human land use, but with increased forest taxa (*Alchornea*, Melastomataceae, *Weinmannia*) relative to previous levels, consistent with increased forest cover. Maize pollen increases slightly from 253–158 cal B.P. (AD 1697–1792), but $\delta^{13}C$ values indicate no significant increase. Signals remain relatively stable across all proxies until modern time. Beginning at 111 cal B.P. (AD 1839), pollen percentages 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. Maize 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 signaling establishment of modern settlements, maize agriculture, and landscape disturbance at the site. Proxy signals then become highly variable at 50 cal B.P. (AD 1900) and remain so, with maize agriculture and landscape disturbance continuing to the top of the core.

Interpretation and Discussion

Vegetation Change and Land-Use History at Laguna Santa Elena

Our high-resolution reconstruction of prehistoric land use and maize agriculture in the watershed of Laguna Santa Elena supplements prior interpretations from pollen and charcoal and reveals new details of land use history, including the timing of watershed abandonments that were not clearly visible in previous work. Proxy data in the lowest lacustrine sediments of zone 3 show the presence of low-intensity maize farming in the watershed from the lake's inception ca. 1780 cal B.P. (AD 170). The presence of maize pollen, combined with pollen percentages indicating intact native vegetation and almost no charcoal are consistent with a minor human presence on the landscape, with small numbers of people engaged in small-scale subsistence farming. Two intervals of increased inorganic content in the sediments at 1682 and 1613 cal B.P. (AD 268 and 337), plus the appearance of microscopic and macroscopic charcoal in the sediments at 1649 cal B.P. (AD 301), indicate an initial shift toward more broad-scale or intensive agriculture at Laguna Santa Elena, although pollen percentages still indicate relatively intact forest at this time (Fig. 3).

Proxy evidence indicates rapid forest clearance and increased maize agriculture shortly after 1592 cal B.P. (AD 358). Pollen percentages for forest taxa drop, while percentages for disturbance taxa increase, indicating replacement of forest by agricultural fields. Stable carbon isotope ratios signal intensive maize agriculture throughout zone 2c, with the highest $\delta^{13}C$ value in the core appearing at 1450 cal B.P. (AD 500). Following this high peak, $\delta^{13}C$ values fall slightly and establish a regular pattern of C_4 plant dominance through the upper half of zone 2c from 1422 cal B.P. (AD 528) onward. High charcoal influx rates indicate extensive biomass burning between 1403 and 1189 cal B.P. (AD 547 and 761). Paired with increased $\delta^{13}C$ values and decreased pollen of forest taxa, this suggests regular burning of agricultural fields. The inorganic content of sediments across zone 2c is high, but relatively steady following initial establishment of intensive maize agriculture, providing further evidence that maize agriculture was high and continuous through the top half of zone 2c. We interpret these signals, together with relatively high maize pollen percentages in zone 2c, to indicate a strong human presence in the Santa Elena watershed with people engaged in considerable maize agriculture throughout the latter part of the Aguas Buenas period.

Moving into zone 2b, values for $\delta^{13}C$ and $\delta^{15}N$ decline sharply beginning at 1115 cal B.P. (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 proxy data indicate a strong decrease in the scale or intensity of land use and maize agriculture beginning no later than 1228 cal B.P. (AD 722) and continuing across the zone 2c/2b transition until finally bottoming out at ca. 1085 cal B.P. (AD 865). We interpret the proxy record as indicating nearly a century and a half of watershed abandonment at Laguna Santa Elena. The timing of this abandonment corresponds to the cultural transition from the Aguas Buenas to the Chiriquí period in southern Pacific Costa Rica. Importantly, the Santa Elena site appears to have been largely abandoned during the Terminal Classic Drought. While the continued presence of maize pollen across the 2c/2b transition indicates a low-intensity human presence in the watershed, the abrupt decline in proxy signals of land use beginning at 1189 cal B.P. (AD 761) likely indicate a population collapse at Santa Elena (see below).

Proxy data in zone 2b indicate major swings in patterns of land use and maize agriculture, which are overlain at the local to regional scale by cultural transition and at a broader scale by the Terminal Classic Drought. After ca. 1085 cal B.P. (AD 865), the Santa Elena watershed was reoccupied and maize agriculture was reestablished 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 agriculture peak in zone 2b at 1011 cal B.P. (AD 939), only to fall again and bottom out at 995 B.P. (AD 955). Following this low point in the middle of zone 2b, proxy data reveal yet another reestablishment of maize agriculture beginning around 942 B.P. (AD 1008), indicated by increasing inorganic content, $\delta^{13}C$ and $\delta^{15}N$ values, pollen of maize and disturbance taxa, and charcoal, and by declining abundances of forest taxa. This second reestablishment of maize agriculture may reflect stabilization of Chiriquí culture and climate amelioration toward the end of the Terminal Classic Drought. These findings are not visible from the pollen and charcoal data alone, partly due to the lower temporal resolution of those data.

Moving into the lower part of zone 2a, the proxy record again indicates some variability in land use and maize agriculture from 831 to 720 cal B.P. (AD 1119 to 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 pollen of disturbance taxa and maize are relatively high. However, following the final signal of expansive C_4 vegetation around 720 cal B.P. (AD 1230), values for $\delta^{13}C$ and $\delta^{15}N$ decline. The LOI results indicate that inorganic input to the lake stabilizes. Organic carbon and nitrogen content are also steady. Pollen of disturbance taxa decreases and forest recovery begins, while maize pollen percentages fall. Charcoal continues to be deposited in the sediments in zone 2a but at reduced amounts and fragment sizes relative to lower in the core. Taken together, we interpret this as a major shift in subsistence patterns in the Laguna Santa Elena watershed beginning no later than 683 cal B.P. (AD 1267) The proxy evidence indicates a greatly reduced human presence on the landscape and a major reduction in the scale and intensity of maize agriculture.

Continued, but reduced charcoal deposition combined with a minor presence of maize pollen from 683 cal B.P. (AD 1267) onward indicates low levels of agricultural activity and landscape disturbance. Anchukaitis and Horn (2005) reported an absence of maize pollen in the Santa Elena sediments at ca. 540 cal B.P. (AD 1410) that roughly coincides with the arrival of Spaniards (within ^{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 B.P. (AD 1230) coincident with the beginning of forest recovery identified by Anchukaitis and Horn (2005). While the Santa Elena watershed was never completely abandoned, the area did undergo a substantial shift in patterns or modes of subsistence agriculture beginning around 720 cal B.P. (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 watershed, which had been intensively farmed for thousands of years, was abandoned a few centuries before Spanish arrival. They attributed that abandonment to climate deterioration due to early effects from the onset of the Little Ice Age. 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 farming, although more evidence is needed to support those conclusions at the local scale. Future paleoclimate 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 agriculture beginning no later than 683 cal B.P. (AD 1267) in the middle of zone 2a that crosses the zone 2a/1 transition and continues until modern times at 111 cal B.P. (AD 1839). This nearly six century time of low-intensity maize agriculture is reflected in the proxy record by stability in $\delta^{13}C$ and $\delta^{15}N$ values and charcoal influx and is marked by increased pollen percentages for select forest taxa and relatively lower percentages of pollen representing disturbance taxa. Maize pollen remains present in the record except for the sample at ca. 540 cal B.P. (AD 1410). Organic and inorganic matter, organic carbon and nitrogen, and C/N ratios are all steady across this period. Maize 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 represents the beginning of Spanish Conquest in the broader region, although colonization began relatively late in southern Pacific Costa Rica. Additionally, the majority of zone 1 is overprinted by the Little Ice Age, lasting ca. 550–100 cal B.P. (AD 1400–1850). Whether or not the human population of the Laguna Santa Elena watershed was affected by climate deterioration during the Little Ice Age is unclear from our dataset, but large-scale, intensive prehistoric maize agriculture was finished by 683 cal B.P. (AD 1267) at the latest, long before the beginning of Spanish Conquest.

Proxy markers in the uppermost sediments of the core corresponding to the top of zone 1 record the arrival of modern agriculture in the Santa Elena watershed beginning around 91 cal B.P. (AD 1859). Inorganic matter input to the lake increases, diluting the organic carbon and nitrogen pools. Pollen percentages for forest taxa decrease and pollen representing disturbance taxa increases along with maize pollen. Charcoal influx also increases at this time, indicating renewed burning in the area surrounding Santa Elena. Values for $\delta^{13}C$ and $\delta^{15}N$ show significant change at this time, with $\delta^{15}N$ values increasing to the highest values in the core beginning around 51 cal B.P. (AD 1899). These relatively high $\delta^{15}N$ 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 increased productivity in the lake resulting from increased terrestrial nitrogen input related to modern agriculture. Maize pollen is absent from the uppermost pollen samples, but that absence likely results from modern sediment dynamics or increased distance between crops and the lakeshore, rather than from an actual absence of maize agriculture. The arrival of modern agriculture at Santa Elena corresponds to an increase in charcoal influx near the top of the profile. Our age model suggests a date of 111 cal B.P. (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 likely occurred no earlier than about AD 1927.

Isotope Ratios as Proxies for Vegetation Change, Agriculture, and Human Activity

Values for $\delta^{13}C$ in the Santa Elena sediments range between ca. –30‰ and –10‰ VPDB. This range is much wider than many other lakes in Costa Rica and the circum-Caribbean, including nearby Laguna Zoncho (Taylor et al. 2013a, 2015). This wide range of $\delta^{13}C$ values shows that periods of both maize agriculture and forest recovery were quite pronounced in the Santa Elena watershed, 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 agricultural fields with C_4 crops and weeds; however, the $\delta^{13}C$ value of –10.33‰ at 1450 cal B.P. (AD 500) is at the extreme high end of what should 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 that aquatic and emergent plants began using bicarbonate as a source of carbon. However, C/N values indicate well-mixed terrestrial and aquatic contributions to sedimentary matter across the prehistoric portion of the core, with a C/N value of 21.13 at 1450 B.P. (AD 500) indicating an increased importance of terrestrial matter coeval with 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 $\delta^{13}C$ value. We consider this unlikely, however, as the Santa Elena sediments contain low amounts of carbonate in general (min = 2.0%, max = 5.5%, avg = 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 Santa Elena sediments and the interpretation of large shifts in vegetation and land-use patterns are noteworthy.

The stable isotope signal at Laguna Santa Elena 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 factors controlling $\delta^{13}C$ composition of the sediments are also controlling $\delta^{15}N$. Shifts in $\delta^{15}N$ in lake sediments are difficult to interpret because they can be driven by a variety of factors, both allochthonous and autochthonous, 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 generalizable modern analogues from which to interpret prehistoric changes in $\delta^{15}N$. Shifts in $\delta^{13}C$ are easier to interpret, and in small neotropical watersheds that experienced broad scale vegetation change and intensive maize agriculture, $\delta^{13}C$ composition of lake sediments is primarily driven by changes in C_3 vs. 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 track closely with $\delta^{13}C$ signals of forest clearance, C_4 maize agriculture, and forest recovery, suggests that both proxy signals are responding to changes in human activity and land use in the watershed. During periods of increased agricultural activity, such as at 1450 and 1011 cal B.P. (AD 500 and 939), corresponding C/N ratios are 21.13 and 20.86, respectively, indicating an increased importance in 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 anthropogenic fire used to clear and maintain agricultural fields (Dunnette et al. 2014; Szpak 2014). The result would be increased $\delta^{15}N$ values in the remaining terrestrial organic matter. Continued agricultural activity would have resulted in transport of terrestrial matter into the lake, incorporating the relatively higher $\delta^{15}N$ signal into the sedimentary record. Conversely, at times of lower maize agriculture, such as 1189–1141 cal B.P. (AD 761–809), reduced inorganic input, maize pollen percentages, and charcoal influx indicate a reduced importance of terrestrial matter to the lake sediments. Decreased $\delta^{13}C$ and $\delta^{15}N$ values at this time likely reflect an increased importance of allochthonous 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 signaling changes in the scale and intensity of land use and maize agriculture. This hypothesis could be further strengthened by additional analysis of sedimentary charcoal to increase the sampling resolution and analysis of diatoms and algae present in the sediments at key times through the site history.

Population Collapse(s) at Laguna Santa Elena

The cultural transition from the Aguas Buenas to the Chiriquí period in southern Pacific Costa Rica is marked by large shifts in proxy signals across the zone 2c/2b transition in the Laguna Santa Elena sediments ca. 1228–1185 cal B.P. (AD 722–765), indicating major changes in the pattern, scale, or intensity of land use and maize agriculture in the Santa Elena watershed (Fig. 3). Archaeological investigations at the site have revealed Aguas Buenas type artifacts from house sites along the ridges surrounding Laguna Santa Elena, but no artifacts diagnostic of the later Chiriquí period (Sánchez and Rojas 2002; M. Sánchez, personal communication 2013). Maize agriculture returned to Santa Elena 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 at the Santa Elena site. Instead, during the Chiriquí period, people may have been concentrated in larger regional population centers such as nearby Fila Tigre and maintaining sites like Santa Elena as agricultural outposts. 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 is overlain broadly by the Terminal Classic Drought (Hodell et al. 2005), including local manifestations of the TCD in Costa Rica (Horn and Sanford 1992; Wu et al. 2019). Paleoenvironmental signals from the Laguna Santa Elena sediment core indicate a major decline in maize agriculture during this time. That, combined with available archaeological evidence, leads us to conclude that a population collapse took place in the Santa Elena watershed, coincident with evidence of regional and broad scale circum-Caribbean drought. Further understanding of the relationship between this collapse and climate change will require additional proxy analyses of local conditions.

A second decline in maize agriculture took place at Santa Elena beginning ca. 720 cal B.P. (AD 1230) that may be related to early climate deterioration from the onset of the Little Ice Age. The LIA was globally asynchronous and resulting climate changes were not uniform across time or space, yet the effect was widespread and may have reached southern Pacific Costa Rica (Wu et al. 2017). Anchukaitis and Horn (2005) noted from pollen and charcoal analysis that this decline in maize agriculture occurred close to the time of Spanish arrival. Our new analyses, however, show that the decline happened much earlier and that the pattern of land use and maize agriculture that was in place from 683 cal B.P. (AD 1267) and that persisted until 111 B.P. (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 agriculture, nor does the literature note a period of culture change in the region prior to Spanish Conquest. Indeed, the cultural chronology of the Diquí sub-region progresses from the Chiriquí period through Conquest and into the Post-Contact period at ca. 450 cal B.P. (AD 1500). While the Santa Elena watershed was not completely abandoned during this time, we interpret the sedimentary proxy record to indicate a second population collapse at Laguna Santa Elena centered on 683 cal B.P. (AD 1267) prior to Spanish arrival and coinciding with the findings of Taylor et al. (2013a, 2015) at nearby Laguna Zoncho.

Conclusions – Santa Elena in a Broader Perspective

Proxy data from the Laguna Santa Elena sediments yielded a high-resolution reconstruction of vegetation change and land-use history that coincides well with evidence from nearby Laguna Zoncho. Taylor et al. (2013a, 2015) reported two periods of agricultural decline in the Zoncho watershed between ca. 1150–970 and 860–640 cal B.P. (AD 800–980 and 1090–1310) that correspond to severe droughts throughout the circum-Caribbean (Haug et al. 2001; Hodell et al. 2005; Peterson and Haug 2006; Black et al. 2007). Taylor et al. (2013a, 2015) suggested that population history and maize agriculture intensity at Laguna Zoncho and in the wider area – including the Santa Elena site – were controlled by climate change and precipitation variability. The scale and intensity of land use and maize agriculture declined at Santa Elena after ca. 1115 and 720 cal B.P. (AD 835 and 1230) These times fall within the intervals of agricultural decline recognized at Laguna Zoncho. Anchukaitis and Horn (2005) reported a brief hiatus in maize agriculture in the Santa Elena watershed at ca. 540 cal B.P. (AD 1410), but that finding is not well-supported by our new geochemical and isotope analyses. Instead, the absence of maize pollen at 288 cm in the Santa

Elena sediment core may simply represent the chance failure of maize pollen to be captured in that particular sample.

Taylor et al. (2013a, 2015) reported that maize agriculture, 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 maize pollen in the Santa Elena sediments indicate that the Laguna Santa Elena watershed was never completely abandoned, despite population declines after ca. 1115 and 720 cal B.P. (AD 835 and 1230), at the latest. The Santa Elena sediments show shifts toward relatively negative carbon isotope values at ca. 1115 and 720 cal B.P. (AD 835 and 1230) following peaks in C_4 vegetation signals, along with decreased maize pollen percentages and charcoal influx and increased pollen percentages indicating forest recovery. Continued charcoal influx and the presence of maize pollen, however, indicate that low-intensity maize agriculture continued in the Santa Elena watershed 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. 1150 cal B.P. (AD 800; Corrales et al. 1988; Drolet 1992; Hoopes 1996). Excavations at Laguna Santa Elena revealed the presence of house sites on hilltops surrounding the basin (Sánchez and Rojas 2002; M. Sánchez, personal communication, 2013). These sites contained Aguas Buenas period artifacts, but no Chiriquí materials. Archaeological evidence suggests that the Santa Elena watershed was abandoned and proxy evidence from lake sediments leads us to conclude that a population collapse took place at Santa Elena beginning at 1115 cal B.P. (AD 835). Seventy years later, pollen and $\delta^{13}C$ signals of maize agriculture again increase, indicating a strong C_4 signature of maize agriculture at Santa Elena at 1046 cal B.P. (AD 904), but the archaeological record does not show evidence that residences returned to the watershed (M. Sánchez, personal communication, 2013).

Some major questions remain for Laguna Santa Elena. If archaeological and sedimentary evidence indicate that people moved out of the Santa Elena watershed at the end of the Aguas Buenas period, but proxy data from lake sediments show that maize agriculture continued and later intensified, where did the people go, and why? Were people aggregating into larger regional population centers, 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 artifacts at Fila Tigre indicates that the site was not occupied for a long duration following the Aguas Buenas to Chiriquí transition. Considering severe regional and circum-Caribbean drought, population movement and decline, and increasing hierarchy and social complexity in southern Pacific Costa Rica and western Panama, a logical conclusion is that people were relocating from the hinterlands to population centers larger yet than Fila Tigre and were maintaining smaller sites like Laguna Santa Elena and Laguna Zoncho for maize agriculture. Conversations with local residents in the Diquí sub-region during 2013 field work revealed that other sites exist in the area that are known to locals, but have yet to be investigated by professional archaeologists. Future archaeological and paleoenvironmental research in the area may help to resolve the nature and timeline of activities and movements of the people who occupied the Laguna Santa Elena watershed and the wider area across nearly two millennia of prehistory.

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Table 1. Radiocarbon determinations for the Laguna Santa Elena sediment core.[a]

Lab Number[b]	Material Dated	Depth (cm)	Uncalibrated ^{14}C Age (^{14}C yr B.P.)	±2σ Age Range (cal B.P.)	±2σ Age Range (BC/AD)	Area Under Probability Curve
B-158436	wood	156.5	150 ±40	42–(–1) 154–59 234–167 284–236	AD 1908–1951 AD 1796–1891 AD 1716–1783 AD 1666–1714	16.6 32.3 28.7 17.2
B-150706	leaf fragments	312.0	640 ±60	677–539	AD 1273–1411	95.0
B-145347	wood	434.5	1240 ±40	1270–1070	AD 680–880	95.0
B-145348	charcoal	530.5	1510 ±40	1424–1315 1443–1429 1521–1455	AD 526–635 AD 507–521 AD 429–495	66.1 3.3 25.4
B-141242	wood	580.5	1880 ±30	1883–1730	AD 67–220	95.0
B-141243	wood	682.5	1950 ±30	1950–1825 1970–1960 1983–1980	AD 0–125 20–10 BC 33–30 BC	91.6 2.6 0.8

[a] Dates were calibrated using the 'clam' package (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).
[b] All analyses were performed by Beta Analytic, Inc.

Figure Captions

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 Fig. 27-1 in Horn (2006)

Fig. 2 Age-depth model for the Laguna Santa Elena sediment core. The model was created using linear interpolation with the 'clam' package (Blaauw 2019) for the R Statistical Environment (R Core Team 2018). Blue marks are the probability distributions of the AMS ^{14}C dates. Gray outline is the 95% confidence interval. Black curve is the line of best fit

Fig. 3 Laguna Santa Elena proxy 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 were originally presented in Anchukaitis and Horn (2005) and are replotted here by age using our new age-depth model. *Zea mays* refers to *Zea mays* subsp. *mays* L. Longer lines with arrowheads in the presence/absence graph indicate three samples with no maize pollen. Zones in the diagram were informally delineated using major changes in proxy data and informed by the cultural chronology of the region, which is presented at the right. The red band represents the Terminal Classic Drought ca. 1200–850 cal B.P. (AD 750–1100) and the blue band represents the Little Ice Age ca. 550–100 cal B.P. (AD 1400–1850)). See text for additional details

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

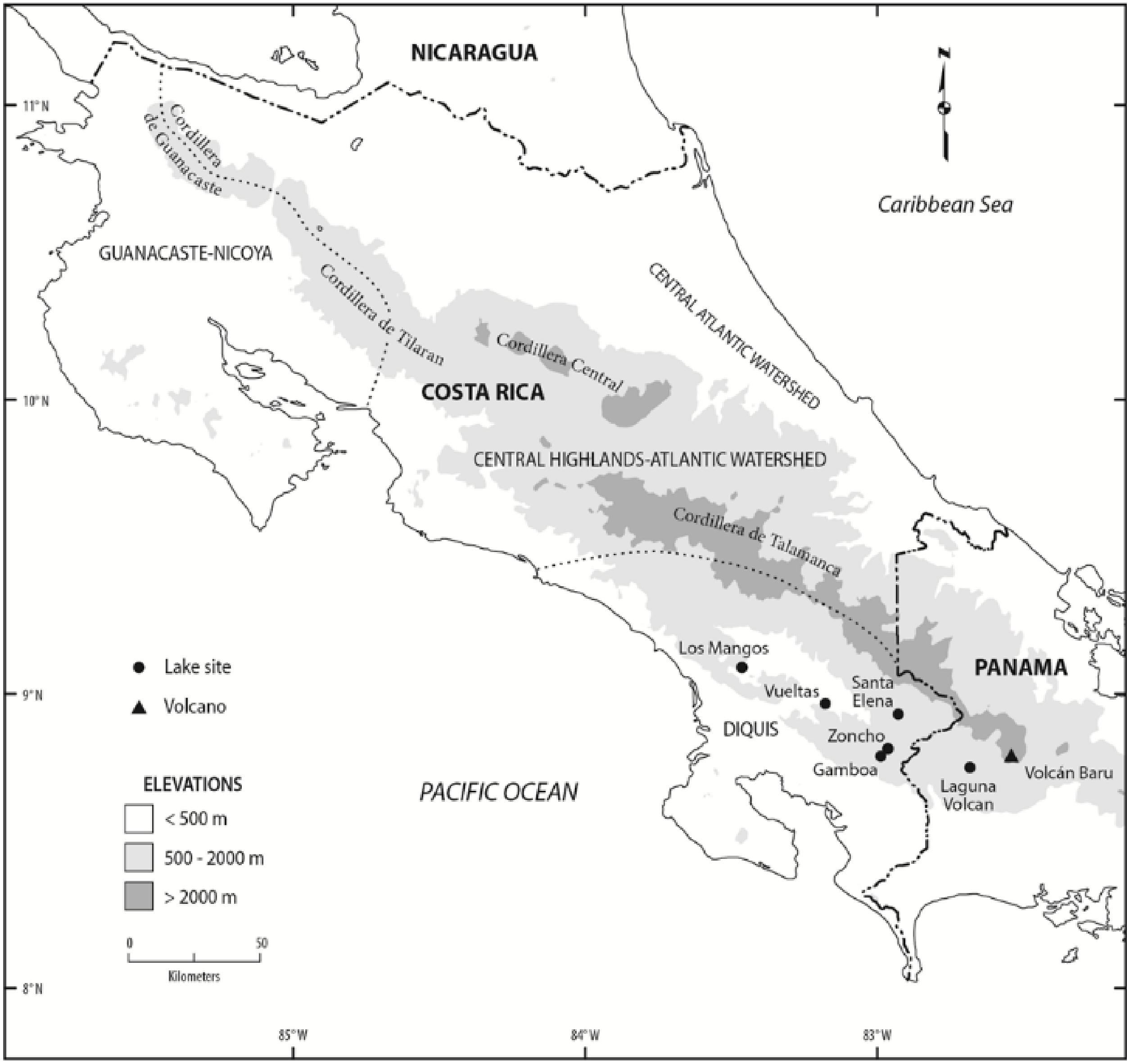
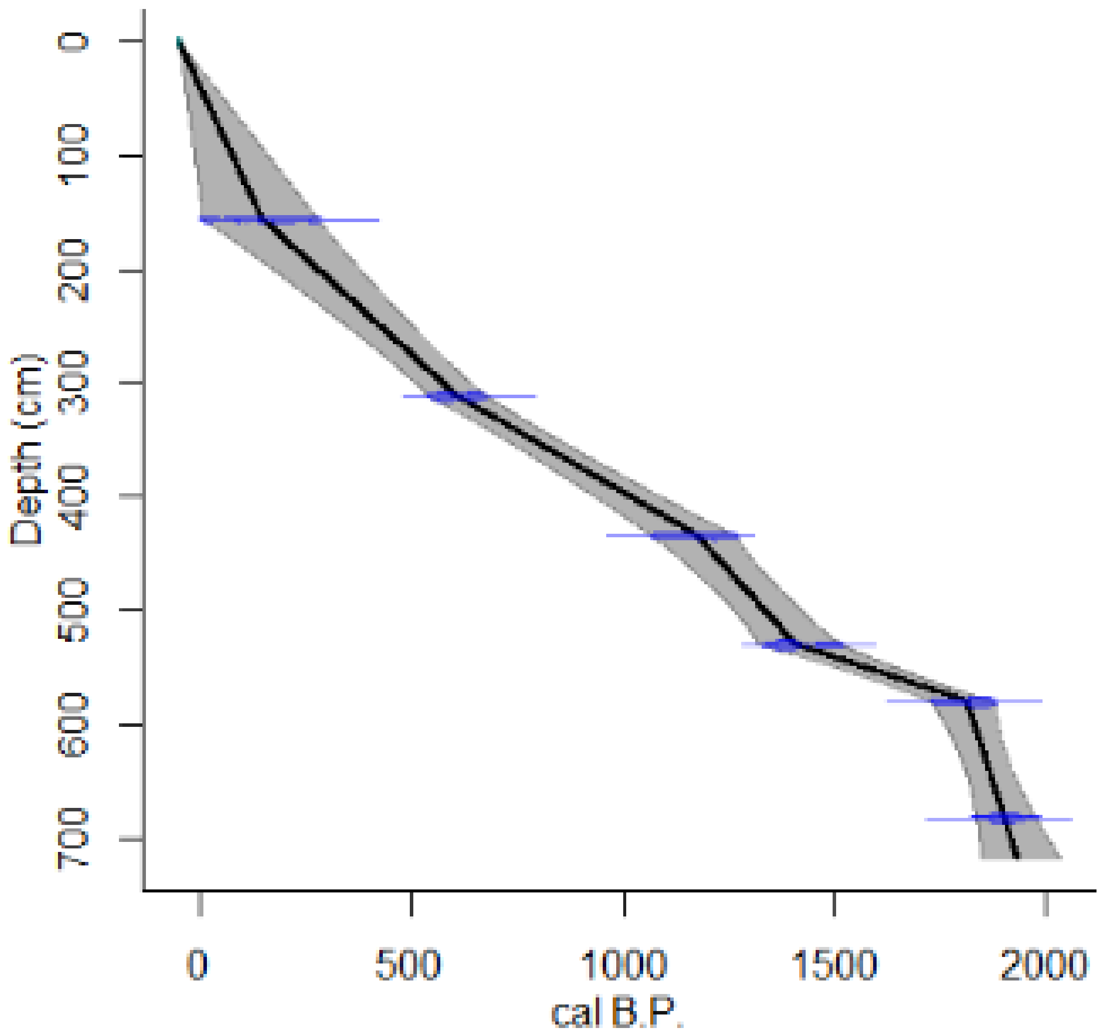
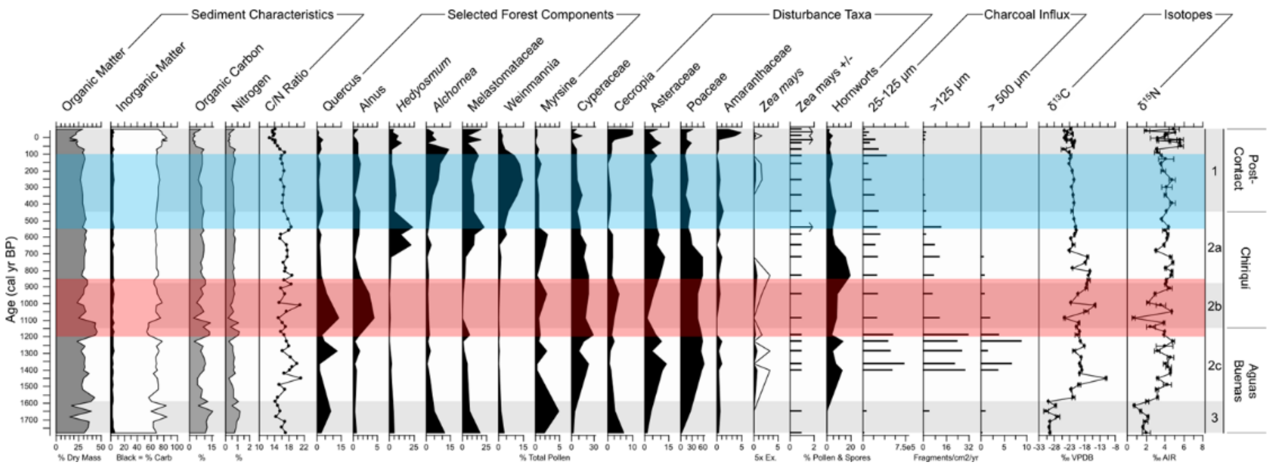

NICARAGUA
11° N
10° N
9° N
8° N
85° W
84° W
83° W
Caribbean Sea
Cordillera de Guanacaste
GUANACASTE-NICOYA
Cordillera de Tilaran
Cordillera Central
COSTA RICA
CENTRAL ATLANTIC WATERSHED
CENTRAL HIGHLANDS-ATLANTIC WATERSHED
Cordillera de Talamanca
PANAMA
Los Mangos
Vueltas
Santa Elena
DIQUIS
Zoncho
Gamboa
Laguna Volcan
Volcán Baru
Lake site
Volcano
ELEVATIONS
< 500 m
500 - 2000 m
> 2000 m
0
50
Kilometers
PACIFIC OCEAN

Figure 1.



Depth (cm)
0
100
200
300
400
500
600
700
0
500
1000
1500
2000
cal B.P.

Figure 2.



Sediment Characteristics
Selected Forest Components
Disturbance Taxa
Charcoal Influx
Isotopes
Organic Matter
Inorganic Matter
Organic Carbon
Nitrogen
C/N Ratio
Quercus
Alnus
Hedyosmum
Alchornea
Melastomataceae
Weinmannia
Myrsine
Cyperaceae
Cecropia
Asteraceae
Poaceae
Amaranthaceae
Zea mays
Zea mays +/-
Hornworts
25-125 µm
>125 µm
> 500 µm
δ13C
δ15N
Age (cal yr BP)
Post-Contact
Chiriquí
Aguas Buenas
1
2a
2b
2c
3
% Dry Mass
Black = % Carb
% Total Pollen
5x Ex.
% Pollen & Spores
Fragments/cm2/yr
‰ VPDB
‰ AIR

Figure 3.

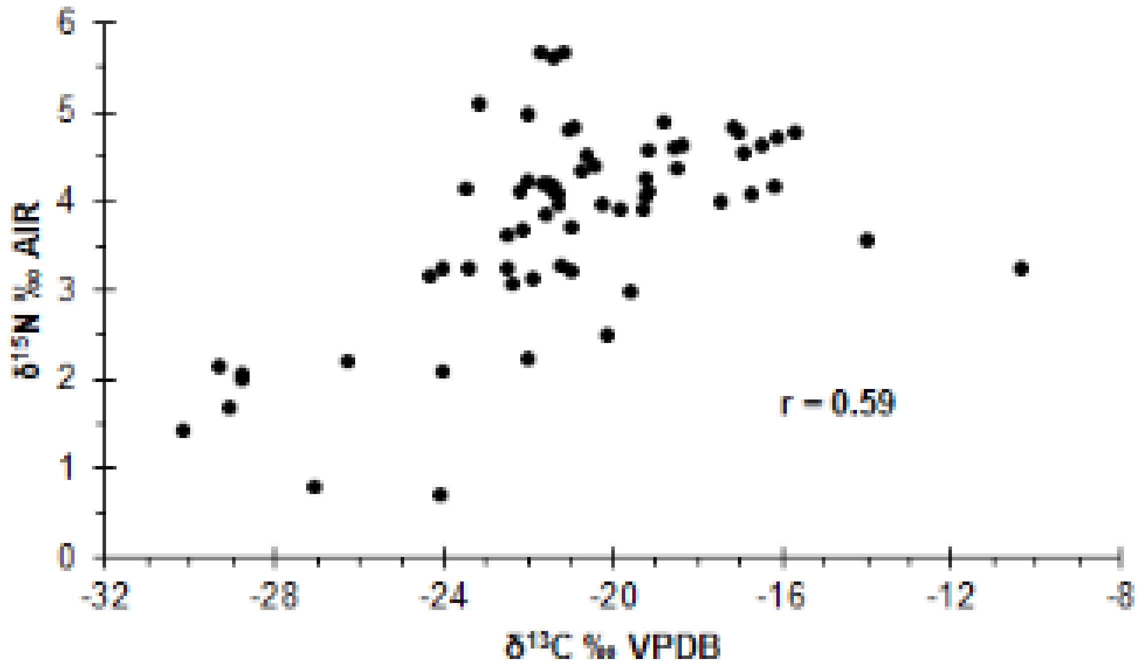


Figure 4.