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Sensitivity of bulk sedimentary stable carbon isotopes to prehistoric forest clearance and maize agriculture

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Abstract

The stable carbon isotope compositions ($\delta^{13}C$) of tropical lake sediments and soils have been used to reconstruct the occurrence of prehistoric maize cultivation and its relative importance through time. This study assesses some of the possible variables affecting the response of lake sediment bulk organic carbon isotope ($\delta^{13}C_{TOC}$) values to variations in the scale of prehistoric maize cultivation and the potential of this proxy to yield quantitative estimates of the scale of prehistoric maize agriculture in small tropical watersheds. High resolution analyses of $\delta^{13}C_{TOC}$ values, maize pollen concentrations, and mineral influx were conducted on sediments deposited during a ~220 year period of prehistoric maize agriculture in the watershed of Laguna Castilla, a small lake in the mid-elevations of the Cordillera Central, Dominican Republic. Close correspondence between $\delta^{13}C_{TOC}$ values and maize pollen concentrations in the Laguna Castilla sediment record indicates a close relationship between the isotopic values and the scale of prehistoric maize cultivation. Correlations between the $\delta^{13}C_{TOC}$ signature and mineral influx indicate that the isotope record is also sensitive to variations in allochthonous carbon delivery. This study establishes that sedimentary $\delta^{13}C_{TOC}$ values can provide a highly sensitive proxy of the spatial scale of prehistoric maize agriculture in small tropical watersheds, but emphasizes the need for a better understanding of sediment dynamics and carbon cycling in anthropogenically modified landscapes before this proxy can be widely employed in diverse archaeological settings.

Keywords: Lake sediments; Pollen; Dominican Republic; Tropics; Mineral influx; Erosion

1. Introduction

Much of what we currently know about the environmental impacts of prehistoric human populations has come from lake sediment records of paleoenvironmental change. Lake sediment records from around the world have been used to document a variety of prehistoric human impacts including deforestation (Burney et al., 1994; Clement and Horn, 2001; Fisher et al., 2003; Goman and Byrne, 1998; Islebe et al., 1996; Northrop and Horn, 1996; Rosenmeier et al., 2002a,b; Wahl et al., 2006), soil degradation (Beach, 1998; Conserva and Byrne, 2002; Jacob and Hallmark, 1996; Lucke et al., 2003; O'Hara et al., 1994), water pollution (Davies et al., 2004; Ekdahl et al., 2004; Oldfield et al., 2003), and agriculture (Dull, 2006; Horn, 2006; Leyden et al., 1998; Sluyter, 1997). The majority of these studies have taken a qualitative approach, documenting the occurrence and timing, but not attempting to quantify the spatial scale, of these activities.

In recent studies, Lane et al. (2004 in press-a) documented prehistoric forest clearance and crop cultivation in the neotropics using the stable carbon isotope composition of total organic carbon ($\delta^{13}C_{TOC}$) in lake sediments and proposed that relative shifts in the $\delta^{13}C_{TOC}$ values of lake sediments through time reflected the relative spatial scale of prehistoric forest clearance and agriculture at a particular site. These studies raised the possibility of quantitatively reconstructing the spatial scale of these activities at high temporal resolutions using the stable carbon isotope proxy.

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Stable carbon isotope analyses of lake sediments (Lane et al., 2004, in press-a) and soils (Johnson et al., 2007; Webb et al., 2004, 2007) have been used to document the prehistoric cultivation of maize. This proxy is effective because maize (*Zea mays* subsp. *mays*) and many associated agricultural weeds use the C_4 photosynthetic pathway (Brown, 1999), whereas mesic neotropical forest ecosystems are dominated by trees and shrubs that use the C_3 photosynthetic pathway (Sage et al., 1999a,b). Plants that use the C_3 photosynthetic pathway produce tissues with $\delta^{13}C$ values ranging between −35‰ and −20‰ V-PDB, but plants that use the C_4 photosynthetic pathway produce tissues with $\delta^{13}C$ values ranging between −14‰ and −10‰ V-PDB (Bender, 1971; O'Leary, 1981). Thus, the deforestation of a C_3-dominated ecosystem, such as a neotropical forest, and its replacement by C_4 cultigens and weeds, produces a positive shift in the carbon isotope values of the plant biomass at the site.

This shift in carbon isotope composition can be recorded in lake sediments or soils as organic matter from terrestrial plants is input to those systems (Aucour et al., 1999; Huang et al., 2001; Johnson et al., 2007; Street-Perrott et al., 1997, 2004; Webb et al., 2004, 2007). Isotopic analyses of lake sediments provide stratigraphic records that are often superior to soil isotope records, which are complicated by the addition of carbon below the surface by plant roots, and by mixing of profiles through bioturbation. However, lake sediments include organic matter produced within the lakes as well as the terrestrial organic matter of interest in the reconstruction of human impacts on terrestrial ecosystems (Meyers, 1994; Meyers and Ishiwatari, 1993; Meyers and Lallier-vergés, 1999). This autochthonous carbon from aquatic macrophytes and algae can complicate the isotopic signal of deforestation and prehistoric agriculture. These organisms may use bicarbonate as a carbon source when dissolved CO_2 concentrations in lakes become limiting (Lucas, 1983; Smith and Walker, 1980), a shift that can lead to an increase in the $\delta^{13}C$ composition of their tissues, despite the fact that they photosynthesize primarily using the C_3 plants pathway (Mook et al., 1974; Smith and Walker, 1980). For example, Huang et al. (1999) documented $\delta^{13}C$ values as high as −16.9‰ in cultured colonies of the alga *Botryococcus braunii* as a result of bicarbonate photosynthesis. Thus, a positive excursion in the $\delta^{13}C_{TOC}$ record resulting from bicarbonate photosynthesis could be misinterpreted as an increase in terrestrial C_4 plant dominance if autochthonous carbon sources are dominating the sedimentary organic pool.

Shifts in the trophic state of a lake can also impact $\delta^{13}C_{TOC}$ values (Brenner et al., 2000; Meyers and Teranes, 2001). As nutrient availability and biological productivity increase there is typically a decrease in the amount of dissolved CO_2 available for photosynthesis. This decrease in dissolved CO_2 can result in a general increase in the $\delta^{13}C$ values of organic tissues produced by aquatic organisms even if C_3 photosynthesis is being used, thereby increasing $\delta^{13}C_{TOC}$ values. This increase in $\delta^{13}C_{TOC}$ values can also be misinterpreted as an increase in terrestrial C_4 plant abundance.

In addition to carbon source dynamics, sedimentary $\delta^{13}C_{TOC}$ values can also be influenced by post-depositional diagenetic processes such as biological reworking. Typically, sediments affected by such diagenetic alterations will display a consistent, monotonic increase in $\delta^{13}C_{TOC}$ values throughout the depth of the core (Talbot and Johannessen, 1992). Lake sediments are also prone to ^{13}C enrichment during methanogenesis. Degassing of ^{12}C-enriched methane can leave residual organics highly enriched in ^{13}C and increase $\delta^{13}C_{TOC}$ values (Ogrinc et al., 2002).

Isolating the purely allochthonous carbon isotope signal in lake sediments through compound-specific analyses would eliminate many of these complications (Brincat et al., 2000; Cayet and Lichtfouse, 2001; Ficken et al., 2002; Hayes et al., 1990; Meyers and Lallier-vergés, 1999), but such analyses require relatively large samples, and are time intensive and expensive — and thus less than ideal for high-resolution studies. For this reason, it is useful to identify other criteria for establishing that sediments are primarily of terrestrial origin, and hence appropriate for more routine bulk stable carbon isotopes that can be performed at high resolution.

In this study, we use mineral influx as a proxy of allochthonous sediment delivery. While autochthonous sources such as diatoms, sponge spicules, and biogenic carbonates can contribute to the mineral content of lake sediments, sediments with low calcite and aragonite concentrations, such as those analyzed here, primarily contain allochthonous mineral matter that originates from the physical and chemical breakdown of surrounding rocks and soils and subsequent delivery of that material to the lake through erosion and sediment transport (Cohen, 2003). We suggest that mineral influx can be used as a proxy of the relative importance of allochthonous sediment delivery through time at lakes such as our study site where there is strong evidence that the majority of mineral material is not autochthonous.

Previous analyses of the sedimentary $\delta^{13}C_{TOC}$ proxy of prehistoric forest clearance and agriculture only allowed assessment of the relative importance of these activities through time (Lane et al., 2004, in press-a). To develop a more quantitative assessment of the environmental impacts of prehistoric human populations on the environment, based on the isotope proxy, it is necessary to develop a more in-depth understanding of how the sedimentary $\delta^{13}C_{TOC}$ record responds to numerous and complex watershed variables. Two critical variables are variations in the abundance of C_4 plants, most notably maize, in the watershed and variations in the contribution of allochthonous carbon to the lake sediments. In this study, we attempt to assess the influence of these variables on $\delta^{13}C_{TOC}$ values of lake sediments from Laguna Castilla, a small lake in the Dominican Republic, over a period of ∼220 years using a multi-proxy approach at high temporal resolution.

The most established technique for reconstructing the abundance of C_4 plants within a watershed is a mass balance approach in which the relative contributions of C_3 and C_4 plants to the bulk carbon isotope compositions of lake sediments and soils are estimated based on their end-member isotopic compositions (Cerling, 1999; Phillips and Gregg, 2003). Tropical forest ecosystems are dominated by C_3 plants; any increase in C_4 plant abundance in these ecosystems is typically linked to agricultural activities and will be proportional in scale to agriculture within the watershed. However, the sensitivity of the $\delta^{13}C_{TOC}$ proxy to variations in C_4 plant abundance is, in essence, what we are seeking to study.

An alternative approach to establishing the relative abundance of C_4 plants through time in the mesic neotropics is to use maize pollen concentrations in sediments as a proxy. Pollen produced by cultivated maize is relatively large, and is generally dispersed only short distances (Aylor et al., 2005; Luna et al., 2001; Raynor et al., 1972). Maize pollen in lake sediments provides key evidence of prehistoric maize cultivation (Staller et al., 2006), almost certainly within the lake watershed and potentially on the very shore of the lake (Islebe et al., 1996). Maize pollen may occur only in low percentages in pollen assemblages, but its large size makes it possible to scan multiple pollen slides at low magnification to increase the count of this important cultigen so as to be certain of its presence or absence, and to chart its changing abundance in sediment profiles (Horn, 2006). Changes in maize percentages in standard pollen counts or in concentrations calculated from extended counts are interpreted to indicate shifts in maize abundance (Leyden et al., 1998; Dull, 2004, 2007). Because of the short dispersal distances of maize pollen, we can be certain that these increased maize populations are local to the site, particularly in small watersheds. In the mesic neotropics, forest clearance for prehistoric agriculture and the maintenance of agriculture fields is likely to provide habitat for C_4 plants in addition to maize that are rare or absent in closed canopy forests. (Some of these other C_4 species may also contribute pollen to sediments, but it is not possible using routine light microscopy to distinguish their pollen from C_3 species in the same families.) In sediment records with enough maize pollen to reliably estimate concentrations, we hypothesize that these maize pollen concentrations will track, at least semi-quantitatively, changes in the relative abundance of maize and closely associated agricultural weeds in the watershed through time.

In this study we have conducted high resolution analyses of sedimentary $\delta^{13}C_{TOC}$ values, maize pollen concentrations, and mineral influx in a sub-section of sediment core collected from a lake with a small watershed, a high sedimentation rate, and abundant maize pollen to assess the sensitivity of lake sediment $\delta^{13}C_{TOC}$ values to variations in the abundance of C_4 cultigens and associated weeds on the surrounding landscape, as well as variations in allochthonous sediment delivery. Because agricultural activities are typically based on an annual cycle of field clearance and crop cultivation, it is essential that the $\delta^{13}C_{TOC}$ record be responsive at a high temporal resolution if we hope to use this proxy to quantitatively estimate these past activities.

2. Methods

2.1. Study site

Laguna Castilla (18°47′51″ N, 70°52′33″ W, 976 m) is located on the Caribbean slope of the Cordillera Central in the Dominican Republic (Fig. 1), near the small community of Las Lagunas, in the province of Azua. The lithology of the Cordillera Central dates back some 60 million years and includes Cretaceous volcanic, metamorphic, and plutonic rocks (Bolay, 1997). In the province of Azua, which includes the Laguna Castilla watershed, much of the plutonic core of the Cordillera Central is covered with deeply incised soft marine sediments. Based on aerial photographs and topographic maps of the area, the Laguna Castilla watershed appears to be less than 25 ha in total area (Fig. 1). Laguna Castilla itself is a fairly small lake with a surface area of approximately 1.5 ha. In June 2002, the lake was 4.5 m deep, water temperature was ∼21 °C, and lake waters were slightly alkaline (pH 7.9). The most abundant ions were Ca (32.9 ppm), Na (20.8 ppm), Si (18.3 ppm), Mg (14.5 ppm), and Cl (10 ppm).

The landscape around Laguna Castilla (Fig. 1) is presently used for a wide range of agricultural activities including cattle and goat ranching and the cultivation of a variety of crops including pigeon peas, beans, corn, and coffee. Vegetation of nearby areas with similar climate conditions, but with less human impact, has been classified as lower montane moist forest (Holdridge life zone designation; Tolentino and Peña, 1998). Lower montane moist forest in the Dominican Republic is a C_3-dominated ecosystem consisting of pines (*Pinus occidentalis* Schwartz) mixed with a wide variety of evergreen and deciduous broadleaved trees and shrubs (Liogier, 1981). Emergent and aquatic plants currently growing in Laguna Castilla include *Typha domingensis* Pers., *Eleocharis interstincta* (Vahl) R&S, and a variety of other species in the Cyperaceae and Poaceae families. We have also identified microremains of the algae *Botryococcus braunii* Kützing, *Pediastrum* sp., and *Spirogyra* sp. in near surface sediments of the lake.

No archaeological surveys have been undertaken in the Las Lagunas area and the only evidence we have found of prehistoric human occupation of the lake basins is the maize pollen preserved in our sediment cores from Laguna Castilla and nearby Laguna de Salvador (Lane et al., in press-b). The radiocarbon chronologies from both lake sediment records place the interval of prehistoric maize agriculture around Las Lagunas within the regional Ostionoid archaeological period (∼ A.D. 500 to A.D. 1500) as described by Wilson (1997). This time period has been associated with an intensification of horticultural production throughout much of the Caribbean region (Krieger, 1930; Newsom, 2006; Newsom and Deagan, 1994; Ortiz Aguilu et al., 1991; Rouse, 1992; Wilson, 1997).

Very little is known about the relative importance of maize in the diets of Ostionoid populations on Hispaniola. Botanical evidence of maize agriculture has been found only at four sites on Hispaniola (Lane et al., in press-b). Newsom (2006) suggested that maize played a minor role in the diets of prehistoric Hispaniolans, based on the rarity of ethnobotanical

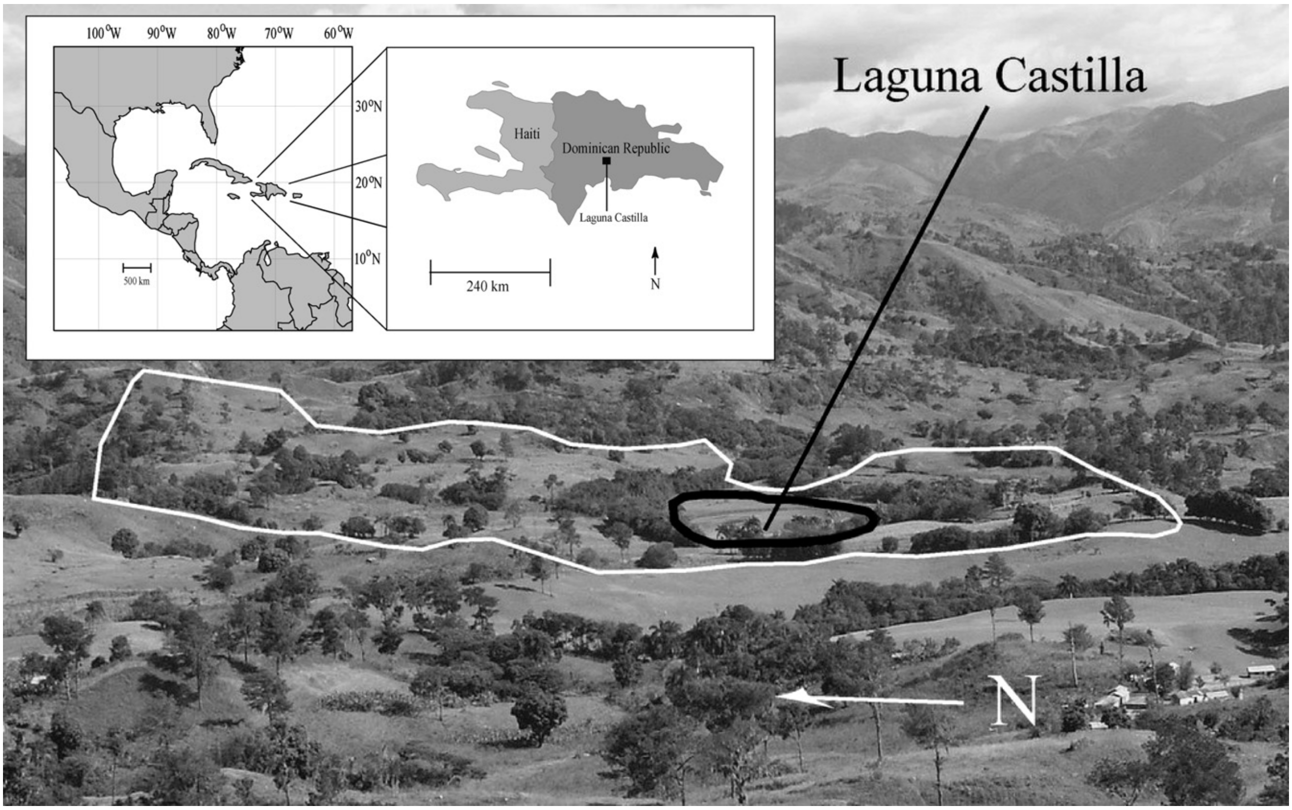

Fig. 1. Location of the Dominican Republic and Laguna Castilla and a photograph of the Laguna Castilla watershed and the surrounding landscape. Note the small size of the Laguna Castilla watershed (highlighted in white). The shore of Laguna Castilla has been highlighted in black. For scale, the width of Laguna Castilla is approximately 100 m.

evidence of maize cultivation and agriculture on the island. Diets of many populations were apparently centered on root-crops, such as cassava, or on marine resources. However, the vast majority of archaeological sites on the island of Hispaniola are coastal. Stokes (1998) and Lane et al. (in press-b) suggested that maize may have played a greater role in the diets of prehistoric Caribbean populations living in the interior of islands where ocean resources could not be accessed on a daily basis. More archaeological investigations of inland sites in the Caribbean are required to fully understand the importance of maize in prehistoric Hispaniola and the Caribbean region as a whole.

2.2. Sediment core recovery and chronology

A 7.8 m sediment core was collected from near the center of Laguna Castilla in 2002. Sediments >40 cm below the sediment/water interface were retrieved in aluminum core tubes in 1 m sections using a Colinvaux–Vohnaut (C-V) locking piston corer (Colinvaux et al., 1999). After opening the C-V core sections in our lab, the cores were promptly photographed and the sediment stratigraphy described. This study focuses on sediments from 3 to 6 m below the sediment/water interface, which span the period of prehistoric human occupation of the watershed (Lane et al., in press-b). A chronology for the Laguna Castilla sediment core was constructed by obtaining accelerator mass spectrometry (AMS) radiocarbon dates from Beta Analytic Laboratory, Inc., in Miami, Florida. Radiocarbon determinations were made on a variety of organic materials including charcoal, non-carbonized organic macrofossils, and bulk sediment. The AMS radiocarbon dates were calibrated using the CALIB 5.0 computer program (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004a). A single calibrated age was assigned to each AMS sample by calculating the weighted mean of the calibrated age probability distribution. These assigned ages were used to calculate sedimentation rates (Telford et al., 2004a,b) and linearly interpolated calendar ages of lake sediment horizons between radiocarbon dated materials.

2.3. Stable carbon isotope analysis

The stable carbon isotope ratios of bulk sedimentary organic carbon ($\delta^{13}C_{TOC}$) were measured on Laguna Castilla sediments sampled at intervals of 4–16 cm (5–15 years). Carbonates were removed from the sediment samples by reacting the sediment with 10% HCl. Following neutralization with distilled water, the sediment was dried overnight at 50 °C, any large organic macrofossils were removed, and the dried samples were ground to a fine powder with a mortar and pestle to ensure the samples were homogenized and representative of the organic carbon fraction of the bulk sediment. The sediment sub-samples were combusted at 800 °C under vacuum in quartz tubes in the presence of 500 mg copper, 500 mg copper oxide, and a small platinum wire. The rendered CO_2 was purified cryogenically and analyzed using a dual-inlet Finnigan MAT Delta-plus mass spectrometer at the University of Tennessee. All carbon isotopic compositions are reported in standard δ-per mil notation relative to the Vienna-Pee Dee belemnite (V-PDB) marine-carbonate standard, where $R = {}^{13}C/{}^{12}C$ and:

$$\delta^{13}\mathrm{C}\ (\text{per mil}) = 1000\left[\left(R_{\text{sample}}/R_{\text{standard}}\right) - 1\right] \quad (1)$$

Repeated analyses of the USGS 24 graphite standard indicate that the precision of these offline carbon isotopic determinations is better than ±0.05‰ V-PDB. Duplicate sample runs indicate that the precision of sample measurements is better than ±0.20‰ V-PDB.

2.4. Pollen, maize pollen concentration, and microscopic charcoal analyses

A detailed description of the pollen sampling and processing procedures, along with the criteria used to identify maize (*Zea mays* subsp. *mays*) pollen, can be found in Lane et al. (in press-b). Briefly, 0.5 cm^3 of sediment was sub-sampled from the Laguna Castilla core for pollen analysis at the same depth intervals that were sub-sampled for isotope analysis. Pollen samples were processed using standard techniques (Faegri and Iverson, 1989). Tablets containing *Lycopodium* spores were added as controls (Stockmarr, 1971) and the pollen residues were mounted on slides in silicone oil. Pollen was identified at 400× magnification based on comparisons with pollen reference slides and keys. Two slides from each sample level were scanned in their entirety for maize pollen. Concentration of maize pollen grains (grains/cm^3) were calculated using the following equation:

$$\text{Maize grain concentration}\ (\text{grains}/\text{cm}^3) = \left\{\left[\text{Controls}_{\text{sample}} * \text{Maize}_{\text{slides}}\right]/\text{Controls}_{\text{slides}}\right\}/ \times \text{sample volume}\left(\text{cm}^3\right) \quad (2)$$

where $\text{Controls}_{\text{sample}}$ represents the total number of controls (*Lycopodium* spores) added to each 0.5 cm^3 sediment sample processed (approximately 13,911 for the batch we used), $\text{Maize}_{\text{slides}}$ represents the total number of *Zea mays* subsp. *mays* pollen grains counted on two slides, and $\text{Controls}_{\text{slides}}$ represents the number of controls on two slides. The number of controls on two slides was estimated based on the extrapolation of the number of controls counted during full pollen counts that covered a known area of the slides.

Microscopic charcoal was tallied during the regular pollen counts. Charcoal was identified as black, opaque, angular fragments with no signs of discoloration. All fragments over 50 μm in length were tallied in two size classes: 50–125 μm or >125 μm.

2.5. Loss on ignition and mineral influx analysis

Duplicate 0.5 cm^3 sediment samples for loss on ignition (LOI) were taken from the same intervals of the Laguna Castilla sediment core sampled for isotope and pollen analysis. After desiccation the pre-weighed sub-samples were combusted at 550 °C for 1 h to estimate the organic carbon content of the sediment and at 1000 °C for 1 h to estimate the carbonate content of the sediment (Dean, 1974). Any material remaining after the 550 °C burn was assumed to be mineral. The mineral influx for each sample was calculated using the following equation:

$$\text{Mineral Influx}\ (\text{mg}/\text{cm}^2/\text{yr}) = \text{Mineral Bulk Density}\ (\text{mg}/\text{cm}^3)/\text{Sedimentation Rate}\ (\text{cm}/\text{yr}) \quad (3)$$

Sedimentation rates were calculated using linear interpolation of the weighted means of the probability distributions of the calibrated radiocarbon ages bracketing the positions of the two adjacent sub-samples.

3. Results

3.1. Sediment stratigraphy and chronology

The stratigraphy and chronology of the Laguna Castilla sediment core are presented in Figs. 2 and 3. Between 5.2 and 6.0 m, the Laguna Castilla sediments consist of organic silts and clays with fine fibrous organics. An abrupt transition to faintly banded organic and mineral clays occurs at 5.2 m. These sediment laminations indicate a lack of post-depositional mixing of the sediments and associated fossils. Based on the appearance of maize pollen in the sediment record around this time, Lane et al. (in press-b) hypothesized that this transition represents the initial occupation of the Laguna Castilla watershed by prehistoric humans. The laminated sediments have very low carbonate contents, averaging around 2% by mass. At a depth of 4.1 m, the sediments become mineral rich. Within the overlying 50 cm, the proportion of mineral content to organic material gradually decreases. At 325 cm depth, an abrupt transition occurs from gyttja to a relatively small lens (5.5 cm) of mineral clay. Based on the disappearance of maize pollen from the sediment record at this time, Lane et al. (in press-b) inferred that these sediments coincide with a period of prehistoric human abandonment of the watershed. Following deposition of this clay lens, total organic content and the abundance of fine fibrous organics increase. The small particle size and lack of evidence of pedogenesis in the sediments deposited after lake formation indicates that the lake has never dried completely since formation (Lane, 2007).

The radiocarbon chronology for Laguna Castilla includes one date reversal in underlying landslide debris near the bottom of the core (Table 1). We chose to reject this date because

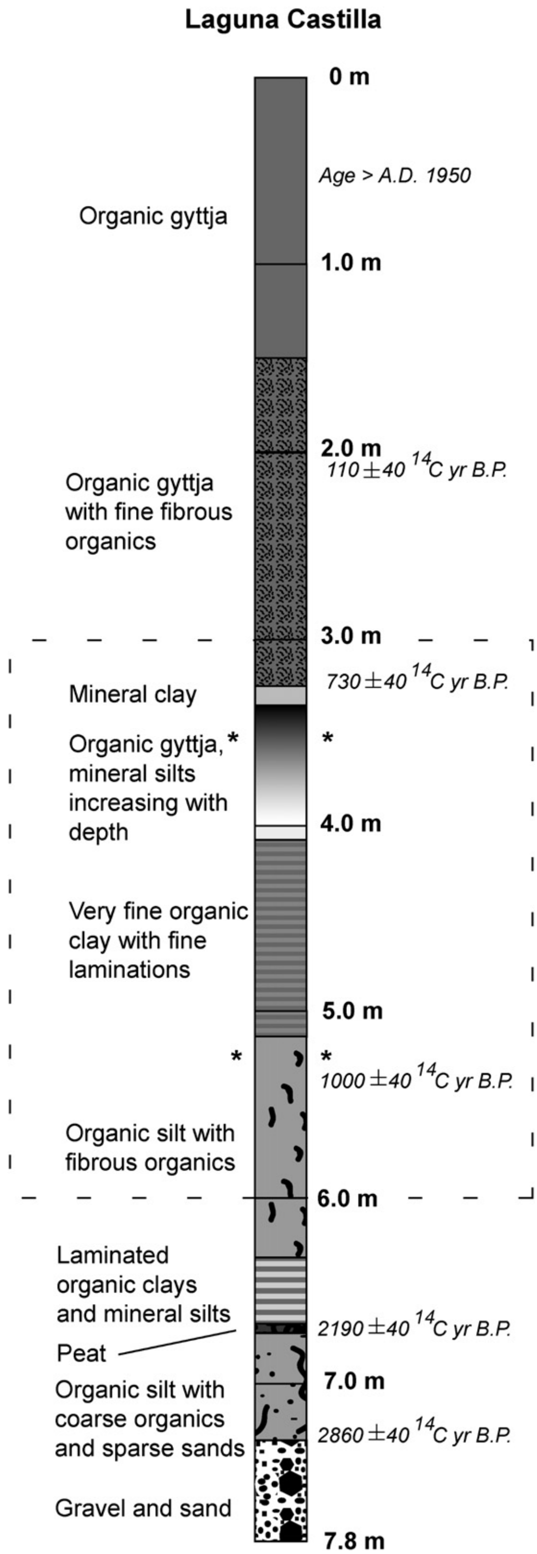

Fig. 2. Stratigraphy and radiocarbon chronology of the entire Laguna Castilla sediment core. This study focuses on the sediments located between 300 and 600 cm (dashed line). The asterisks designate the uppermost and lowermost positions of pollen grains of prehistoric maize (*Zea mays* subsp. *mays*) in the Laguna Castilla sediment record.

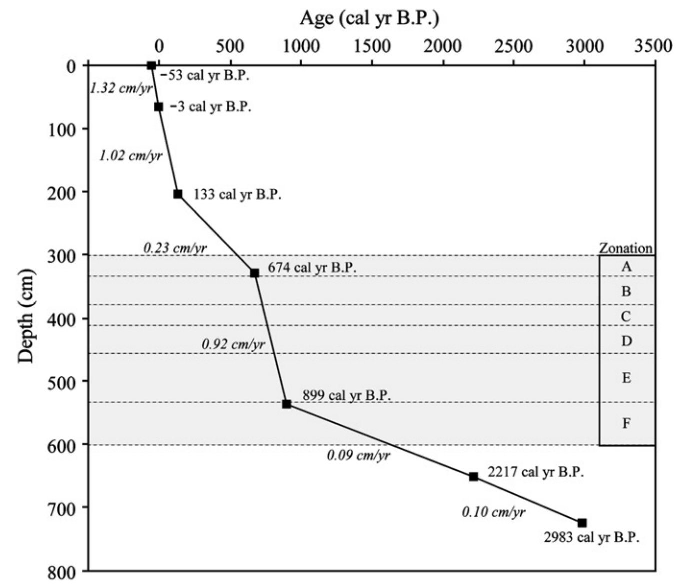

Fig. 3. Age-depth graph for the Laguna Castilla sediment core based on weighted means of the probability distributions for radiocarbon dates (Table 1). Sediment accumulation rates (italics) are reported in cm/calendar year. The highlighted section of the stratigraphic profile is that analyzed in this study and the zonation refers to the stratigraphic zones discussed in Sections 2 and 4.

it appears that the organic material dated may have been root material that grew down through the Castilla sediments and is anomalously young compared to the surrounding sediment. Radiocarbon sample β-171500 consisted of charcoal and is likely to be a more reliable date for estimating the timing of the formation of Laguna Castilla (Table 1). Based on this date, it appears that Laguna Castilla formed around 2980 cal yr B.P. Sedimentation rates in Laguna Castilla vary between 0.09 cm/yr and 1.32 cm/yr, with the highest sedimentation rates occurring during periods of prehistoric and modern human occupation (Fig. 3).

3.2. Stable carbon isotopes, maize pollen concentrations, and mineral influx

The Castilla 3–6 m sediment sub-section can be divided into six zones (A–F) based on the interrelationships of $\delta^{13}C_{TOC}$, maize pollen concentrations, and mineral influx (Fig. 4). No monotonic trends are apparent in the $\delta^{13}C_{TOC}$ record that would indicate diagenetic alteration of the sediments (Lane, 2007), and the negative average $\delta^{13}C_{TOC}$ values indicate that these values were not significantly affected by methanogenesis. Starting at the base the six zones delineated are as follows.

3.2.1. Zone F (600–535 cm; ∼1635–900 cal yr B.P.)

Zone F represents a period when conditions in and around Laguna Castilla favored low mineral influx (2–8 mg/cm^2/yr). No maize pollen is present and stable carbon isotope values increase from −27 to −24‰, decreasing briefly at ∼570 cm to approximately −25‰, before increasing again to −24‰ at ∼535 cm.

Table 1
Radiocarbon determinations and calibrations for Laguna Castilla

Lab number[a]	Depth (cm)	$\delta^{13}C$ (‰)	Uncalibrated ^{14}C age (^{14}C yr BP)	Calibrated age range[b] ± 2σ (cal yr B.P.)	Area under probability curve	Weighted mean[c] (cal yr B.P.)
β-196817	66–68	−25.6	103.9% of Modern	−1.5 to −4.5[d]	1.000[d]	−3[d]
β-204702	204–207	−24.5	110 ± 40	−1 to −4	0.008	133
				150–10	0.651	
				178–174	0.007	
				273–185	0.333	
β-196818	329–331	−25.9	730 ± 40	585–567	0.063	674
				732–647	0.937	
β-171499	536–537	−24.2	1000 ± 40	975–795	1.000	899
β-192641	651–653	−23.8	2190 ± 40	2077–2070	0.009	2217
				2332–2113	0.991	
β-171500	724–725	−23.2	2860 ± 40	3080–2862	0.970	2983
				3109–3093	0.016	
				3140–3127	0.014	
β-171501	758–761	−25.3	2470 ± 40	2419–2363	0.118	2552
				2623–2428	0.600	
				2713–2628	0.282	

[a] Analyses were performed by Beta Analytic Laboratory. Samples β-196817, β-196818, and β-171499 consisted of bulk sediment; samples β-192641 and β-204702 consisted of a mixture of plant macroremains, insect parts, and charcoal; sample β-171501 consisted of plant macroremains; and sample β-171500 consisted of charcoal.
[b] Calibrations were calculated using Calib 5.0 (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004a).
[c] Weighted mean of the calibrated age probability distribution curve.
[d] Dates were calibrated using the CALIBomb program (Reimer et al., 2004b).

3.2.2. Zone E (535–460 cm; ∼900–815 cal yr B.P.)

Zone E contains the first appearance of maize in the Laguna Castilla watershed. Concentrations of maize pollen range from 0 to 118 grains/cm^3. Maximum $\delta^{13}C_{TOC}$ values (−21‰) occur early in Zone E, decreasing abruptly at ∼500 cm to −25‰, and then increasing again to −22.5‰ above 480 cm. There appears to be a good correspondence between $\delta^{13}C_{TOC}$ values and maize pollen concentrations in Zone E, with a slight lag in the response of the $\delta^{13}C_{TOC}$ values to changes in maize pollen concentrations. The $\delta^{13}C_{TOC}$ and mineral influx records display similar patterns through Zone E, with mineral influx values slightly leading shifts in the $\delta^{13}C_{TOC}$ record. Mineral influx values reach some of the highest values in the entire sediment record in Zone E, ranging from a minimum of 32 mg/cm^2/yr to a maximum of 356 mg/cm^2/yr.

3.2.3. Zone D (460–414 cm; ∼815–765 cal yr B.P.)

Average mineral influx values and maize pollen concentrations decrease significantly in Zone D. Mineral influx values drop to ∼160 mg/cm^2/yr, but still remain high compared to Zone F where mineral influx values are less than 10 mg/cm^2/yr. The $\delta^{13}C_{TOC}$ values decrease steadily in the lowermost

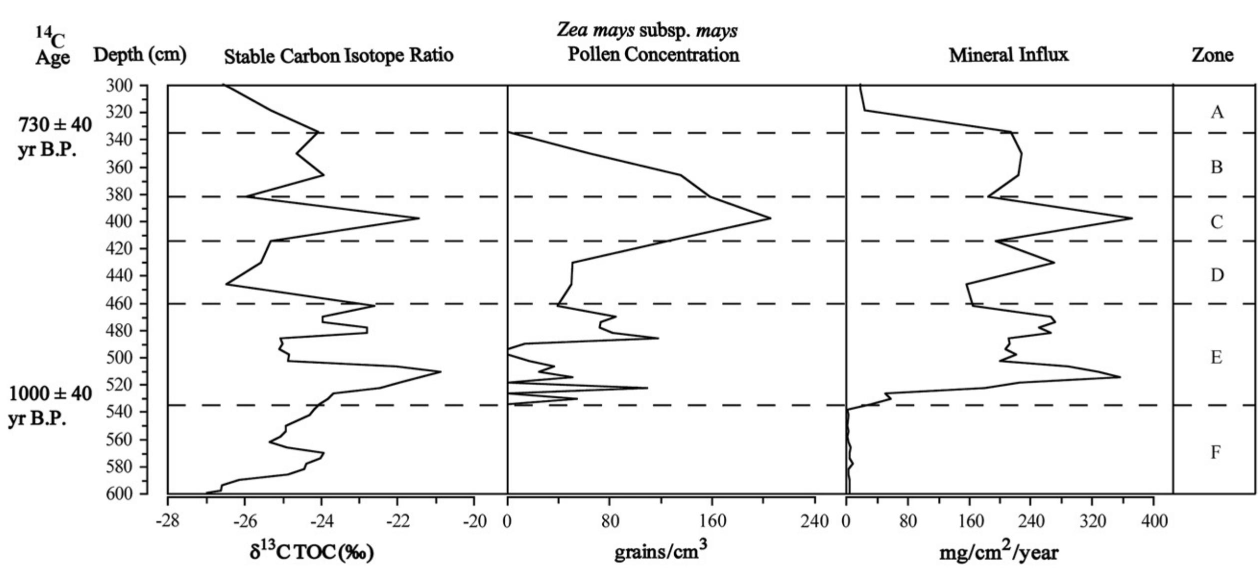

Fig. 4. Summary diagram of Laguna Castilla sedimentary $\delta^{13}C_{TOC}$ values, maize pollen concentrations, and mineral influx variation. Radiocarbon dates (^{14}C yr B.P.) at left are uncalibrated.

portion of Zone D to −26.5‰, but then increase slightly to −25.3‰ in conjunction with a sharp increase in mineral influx, which increases to ∼270 mg/cm^2/yr, from 446 to 430 cm.

3.2.4. Zone C (414–382 cm; ∼765–730 cal yr B.P.)

Zone C contains the highest maize pollen concentrations in the entire sediment record (206 grains/cm^3). Along with this increase in maize pollen concentration is an increase in $\delta^{13}C_{TOC}$ values to around −21‰, and the highest mineral influx in the entire sediment record (370 mg/cm^2/yr). Following these increases, all three proxy indicators decline toward the top of Zone C.

3.2.5. Zone B (382–335 cm; ∼730–680 cal yr B.P.)

Zone B is characterized by a steady decline in maize pollen and its eventual disappearance from the sediment record. Mineral influx and $\delta^{13}C_{TOC}$ values remain relatively steady at ∼220 mg/cm^2/yr and −24‰, respectively.

3.2.6. Zone A (335–300 cm; ∼680–550 cal yr B.P.)

Mineral influx values in Zone A approach the very low pre-occupational levels (20 mg/cm^2/yr). Stable carbon isotope ratios progressively decrease from approximately −24‰ to around −27‰. There is no maize pollen present in Zone A.

4. Discussion

4.1. Mineral influx as a proxy of allochthonous material delivery to Laguna Castilla

The mineral component of lake sediments can originate from both allochthonous and autochthonous sources. Using mineral influx as a proxy for allochthonous material delivery requires establishing that the autochthonous fraction is minor. Within lakes the greatest potential sources of autochthonous minerals are biogenic carbonates (produced by such organisms as ostracods, gastropods, and charophytes), authigenic carbonates (marl), and biogenic silica (produced primarily by diatoms).

The carbonate content of the 300–600 cm section of the Laguna Castilla core is nearly constant, based on LOI results, with values ranging from 1% to 5% dry mass, except for two samples at 566 and 570 cm that reach 15% dry mass. The consistently low carbonate content of these sediments indicates variations in carbonate content are not driving variations in mineral influx. Initial diatom analyses reveal low diatom concentrations in samples from this subsection of the Laguna Castilla sediment core (K. Haberyan, pers. commun.), indicating that diatom productivity is not a major control on mineral influx. It is frankly hard to imagine how silica deposition from diatom productivity could drive the 300% increase in mineral influx that followed prehistoric occupation of the watershed (Fig. 4). For diatom productivity to be responsible for such a large increase in mineral influx would require high nutrient availability and eutrophic conditions in Laguna Castilla, but the LOI data indicate decreasing organic carbon content during this interval (Fig. 5). Thus, the majority of mineral material deposited in Laguna Castilla at this time appears to be originating from allochthonous sources.

4.2. Potential carbon sources contributing to Laguna Castilla

For the $\delta^{13}C_{TOC}$ proxy of agricultural activity to be effective, the organic matter in the lacustrine sedimentary organic pool must be primarily terrestrial in origin. Carbon/nitrogen (C/N) ratios are often used to determine dominant carbon sources in lacustrine settings, based on the finding that aquatic plants and algae typically produce organic tissues with C/N ratios of less than 10, while terrestrial plants produce C/N ratios greater than 10 (Meyers and Ishiwatari, 1993). Sediments with low C/N ratios (<10) have typically been interpreted as originating from aquatic sources and sediments with high C/N (>10) have been interpreted as originating from terrestrial sources. However, recent studies have found that some algae, such as *Botryococcus braunii*, are capable of producing organic tissues with C/N ratios as high as 30 (Huang et al., 1999). Because *B. braunii* microremains are present in the Laguna Castilla sediments we did not analyze C/N ratios as a proxy for the relative contribution of autochthonous vs. allochthonous carbon sources.

More recently, researchers have turned to compound-specific isotopic analyses to isolate allochthonous carbon isotope signals from autochthonous signals. These techniques are highly effective, but are time intensive, material intensive, and expensive compared to bulk carbon isotope analyses, and are not currently appropriate for high-resolution analyses. In separate work we have begun alkane extractions and compound-specific isotope analysis of the Laguna Castilla sediment core, but at a much lower resolution than required to meet the objectives of the present study.

Although we do not have compound-specific isotope data to support our interpretations, several lines of evidence indicate that the $\delta^{13}C_{TOC}$ values in the 3–6 m section of the Laguna Castilla core reflect terrestrial vegetation change. First, as outlined above, the rapid increase in sedimentation rates, mineral influx rates, and inorganic content suggests a predominantly allochthonous source of sediment, most likely from increased erosion in the watershed. A general increase in allochthonous sediment delivery should also result in an increase in allochthonous carbon delivery. The relatively low organic content of the sediment and sparse occurrence of diatoms indicate that nutrient availability and aquatic productivity are not driving the $\delta^{13}C_{TOC}$ record (Fig. 5). Second, the close correlation between $\delta^{13}C_{TOC}$ values and mineral influx values (Fig. 4) suggests that the $\delta^{13}C_{TOC}$ record is being controlled largely by allochthonous carbon sources. Third, preliminary n-alkane extractions and gas chromatography–mass spectrometry (GCMS) analyses conducted on six samples from this section of the Laguna Castilla core indicate a predominantly terrestrial source of aliphatic lipids in the sediments (unpublished data). Samples from 369, 400, 444, 479, 496, and 520 cm contain n-alkane distributions with strong odd over even

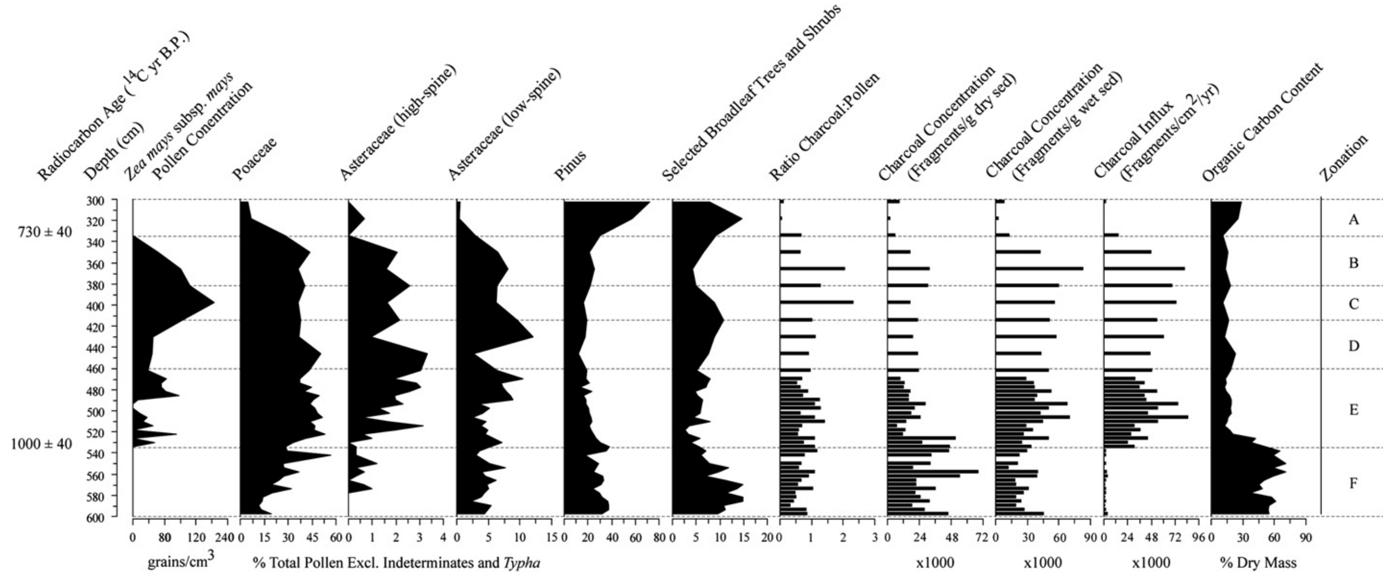

Fig. 5. Pollen percentage diagram for selected arborescent and herbaceous taxa in the Laguna Castilla sediment core. The "Selected Broadleaf Trees and Shrubs" group includes *Cecropia*, *Ficus*, *Garrya*, *Myrsine*, Rubiaceae, *Trema*, and *Weinmannia*. This diagram also includes microscopic charcoal fragments (50–125 μm and >125 μm size classes combined) expressed as charcoal:pollen. Concentrations of microscopic charcoal fragments >50 μm are also expressed as fragments per g dry sediment and fragments per g wet sediment. The influx of microscopic charcoal fragments >50 μm is expressed as fragments per cm^2 per year. Also included is the organic carbon content (% dry mass) of the sediments. Radiocarbon ages are uncalibrated.

predominance, high average chain lengths (average ~28), and high carbon preference index values (~4.5–5.5) all of which are typical of sedimentary organic carbon derived from terrestrial carbon sources (Huang et al., 1999; Ficken et al., 2000).

4.3. Stable carbon isotopes, maize pollen concentrations, and mineral influx

4.3.1. Zone F (600–535 cm; ~1635–900 cal yr B.P.): pre-settlement conditions

Prior to the settlement of the Laguna Castilla watershed by prehistoric humans, mineral influx was low, indicating a small contribution of allochthonous materials to the lake sediments, and $\delta^{13}C_{TOC}$ values were low, indicating that organic carbon that originated from terrestrial vegetation in the watershed was most likely being produced by C_3 plants (average $\delta^{13}C_{TOC}$ value = −25‰), typical of mesic tropical forest ecosystems. This is supported by the relatively high percentages of pine and other arborescent pollen types deposited in the sediments at this time (Fig. 5). A period of increasing $\delta^{13}C_{TOC}$ values through Zone F may indicate increasing regional aridity. A steady increase in Poaceae pollen at the expense of arborescent pollen types through Zone F is indicative of increasingly arid conditions around the lake (Fig. 5). An increase in regional aridity could result in a slight increase in $\delta^{13}C_{TOC}$ values as a result of increased local dominance of C_4 plants. Hypothetically, the increase in $\delta^{13}C_{TOC}$ values of ~2–3‰ would only require a ~15% increase in the amount of organic matter originating from C_4 plants. A similar $\delta^{13}C_{TOC}$ excursion could result from drought stress in C_3 plants, which can also cause an increase in the $\delta^{13}C$ composition of C_3 organic tissues of ~2–3‰ (e.g. Stewart et al., 1995). It seems unlikely that the increase in $\delta^{13}C_{TOC}$ values was the result of prehistoric deforestation because we observed no concurrent increase in mineral influx that would be expected with deforestation and increased soil erosion (Figs. 4 and 5).

4.3.2. Zone E (535–460 cm; ~900–815 cal yr B.P.): initial settlement

The most striking aspects of Zone E are the sudden appearance of maize pollen, the steep increases in mineral influx and carbon isotope ratios, and the abrupt transition to faintly laminated, mineral-rich sediments. Mineral influx increases by two orders of magnitude compared to pre-settlement conditions and is most likely associated with significant land clearance during initial human settlement of the watershed. This hypothesis is supported by very low percentages of arborescent pollen types and sharp increases in charcoal concentrations and influx at this time that likely resulted from forest clearance that involved the use of fire (Fig. 5). The lack of a negative excursion in the $\delta^{13}C_{TOC}$ record at this time indicates that some of the cleared material may not have been C_3 plant matter. This would support the hypothesis that there was a natural increase in terrestrial C_4 plant dominance in the watershed in Zone F (Fig. 5).

That the $\delta^{13}C_{TOC}$ data in Zone E correspond very well with both maize pollen concentrations and mineral influx indicates that the bulk organic carbon in the watershed likely includes a significant component of organic matter produced by cultivated maize or C_4 agricultural weeds. There is a slight lag in the response of the $\delta^{13}C_{TOC}$ record to changes in maize abundance as indicated by the pollen concentrations. Peaks in maize pollen concentrations around 520, 485, and 470 cm match well with peaks in $\delta^{13}C_{TOC}$ values around 510, 480, and 462 cm, respectively. In addition, a conspicuous drop in maize pollen concentration around 495 cm is accompanied by a decrease in $\delta^{13}C_{TOC}$ values around 490 cm. This temporal relationship between the $\delta^{13}C_{TOC}$ record and the maize pollen concentration record appears to exist throughout the 300–600 cm subsection of the Laguna Castilla sediment record.

The close relationship between the $\delta^{13}C_{TOC}$ and maize pollen concentration curves is clearly evident when the depths of carbon isotope data are shifted downward by 4 cm (Fig. 6). The magnitude of this depth shift is arbitrary and is merely intended to clarify the relationships between these two datasets. Realistically, the temporal response of $\delta^{13}C_{TOC}$ values is unlikely to be linear through time, as it will depend upon numerous, and quite complex, environmental variables including, among many other possibilities, precipitation variability (a primary control on sediment transport efficiency), watershed topography and agricultural field position (how are watershed drainage patterns and agricultural fields linked spatially?), and agricultural practices (are fields being fallowed and then re-cleared activating the erosion of soil carbon deposited when the field was last cultivated?). Despite the simplistic nature of this linear shift, the close correspondence between $\delta^{13}C_{TOC}$ values and maize pollen concentrations is quite clear.

If the maize pollen concentrations in the Laguna Castilla sediment record reflect the abundance of maize being cultivated on the landscape in a relatively narrow window of time, then a slight lag in the response of the $\delta^{13}C_{TOC}$ record should be expected. This section of the Castilla sediment record has very high sedimentation rates (Fig. 3; 1 cm/yr) and we have analyzed proxies at high temporal resolution (approximately 5–15 years between samples). We may actually be seeing in these datasets the time lag between pollen

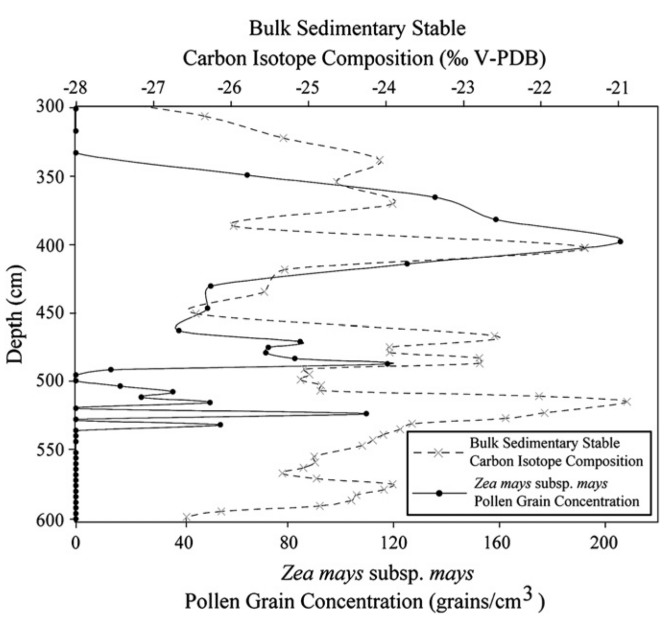

Fig. 6. Comparison of Laguna Castilla sedimentary $\delta^{13}C_{TOC}$ values and maize pollen concentrations, with $\delta^{13}C_{TOC}$ data graphed 4 cm higher in the profile than actual depths to capture the inherent time lag between the two proxies.

production by living maize plants and the decomposition and delivery of maize tissues to Laguna Castilla and the incorporation of that carbon into the sedimentary carbon pool.

Taking into account the slight lag in the response of $\delta^{13}C_{TOC}$ values to shifting maize pollen concentrations, the close correspondence between $\delta^{13}C_{TOC}$ values and the maize pollen concentrations in Zone E indicate that the sedimentary $\delta^{13}C_{TOC}$ values may be quite sensitive to the abundance of maize in the watershed (Fig. 5). Despite the fact that maize pollen is very poorly dispersed and typically under-represented in pollen assemblages, the correspondence between the two proxies is quite strong. Based on this strong correspondence, we suggest that the majority of sedimentary carbon produced by C_4 plants and entering Laguna Castilla originated either from maize itself, or from C_4 weeds associated with maize agriculture.

The strong correspondence between the $\delta^{13}C_{TOC}$ record and mineral influx data indicates that the $\delta^{13}C_{TOC}$ record is also sensitive to variations in allochthonous sediment delivery. Unlike the relationship between the $\delta^{13}C_{TOC}$ record and maize pollen concentrations, there is virtually no lag in the relationship between the $\delta^{13}C_{TOC}$ and mineral influx records. Conceptually, this relationship suggests the $\delta^{13}C_{TOC}$ record is largely driven by the delivery of allochthonous C_4 carbon to the lake. In other words, the co-variation of the $\delta^{13}C_{TOC}$ and maize pollen concentration records indicates that the $\delta^{13}C_{TOC}$ record is sensitive to variations in the abundance of maize being cultivated within the watershed, but it appears that the efficiency of transport of the organic carbon produced by these terrestrial sources ultimately controls the response of the $\delta^{13}C_{TOC}$ record.

4.3.3. Zone D (460–414 cm; ∼815–765 cal yr B.P.): decreased prehistoric human impact

We interpret the decrease in $\delta^{13}C_{TOC}$ values, maize pollen concentrations, and mineral influx values in Zone D to represent a period of decreased human impact in the Laguna Castilla watershed, compared to the previous time interval encompassed by Zone E. Although $\delta^{13}C_{TOC}$ values and maize pollen concentrations are relatively low throughout Zone D, mineral influx varies significantly, spiking from a minimum of 156 mg/cm^2/yr to a maximum of 270 mg/cm^2/yr at a depth of ∼430 cm. The correspondence between the $\delta^{13}C_{TOC}$ and maize pollen concentration data, and the lack of a response in the $\delta^{13}C_{TOC}$ data to the spike in mineral influx around 430 cm, seem to indicate that the $\delta^{13}C_{TOC}$ record is more responsive to variations in the abundance of maize on the landscape than it is to variations in the amount of allochthonous sedimentary material delivered throughout Zone D.

The exact mechanisms responsible for the departure between the $\delta^{13}C_{TOC}$ record, maize pollen concentration data, and mineral influx data in Zone D cannot be resolved with the limited analyses conducted here. One possibility is that increased allochthonous sediment delivery around 430 cm was coincident with more mesic environmental conditions, a slight increase in the dominance of C_3 plants in the watershed, and an increase in the contribution of C_3

organic matter to the lake. A consistent increase in the abundance of arborescent pollen types through Zone D offers some support for this hypothesis (Fig. 5).

4.3.4. Zone C (414–382 cm; ~765–730 cal yr B.P.): maximum human impact

Zone C includes very high concentrations of maize pollen and some of the highest $\delta^{13}C_{TOC}$ and mineral influx values in the entire sediment record. All three proxies indicate that the period encompassed by Zone C may have been the period of most severe prehistoric human impacts in the Laguna Castilla watershed.

As in Zone E, we found a close correspondence between the $\delta^{13}C_{TOC}$ record and the mineral influx data. Perhaps more importantly, a comparison of the isotopic shift ($\Delta^{13}C_{TOC}$) in Zone E to that of Zone C reveals the impact of allochthonous sediment delivery on the $\delta^{13}C_{TOC}$ record. In Zone E, a shift was found in $\delta^{13}C_{TOC}$ values from −24‰ to −21‰ ($\Delta^{13}C_{TOC} = 3$‰) between 515 and 535 cm. Taking into account the slight lag in the response of the $\delta^{13}C_{TOC}$ record (Figs. 4 and 6), this shift is associated with a peak in maize pollen concentrations of approximately 110 grains/cm^3. In Zone C there is a shift in $\delta^{13}C_{TOC}$ values from −25.5‰ to −22.5‰ ($\Delta^{13}C_{TOC\,=}$ 3‰) between 390 and 420 cm. Again taking into account the slight lag in the response of the $\delta^{13}C_{TOC}$ record (Figs. 4 and 6), this shift is associated with a peak in maize pollen concentrations of approximately 205 grains/cm^3. This shift in maize pollen concentrations from 110 to 205 grains/cm^3 corresponds to a three-fold increase in the raw number of maize grains observed on two pollen slides. If the concentration of maize pollen in the sediments is a good proxy for maize abundance in the watershed, and if the $\delta^{13}C_{TOC}$ record was primarily responding to the abundance of maize being cultivated within the watershed, then there should hypothetically be a larger isotopic shift in Zone C than that observed in Zone E, but the isotopic shifts are quite similar. However, the peak mineral influx values for Zone C and Zone E are also quite similar. The similarity between the response of the $\delta^{13}C_{TOC}$ record in Zones C and E to the mineral influxes during those periods indicates that allochthonous sediment delivery is potentially the primary control on the amplitude of change observed in the $\delta^{13}C_{TOC}$ record. Again, this is not surprising considering the fact that the amount of C_4 organic matter that enters the lake is not only controlled by the size of the carbon source area, but also by the efficiency of allochthonous organic matter delivery.

This finding is important because it indicates that the $\delta^{13}C_{TOC}$ value of the sediment alone may not be an accurate representation of the exact amount of maize being cultivated within the watershed without taking into account variations in allochthonous sediment delivery. This does not mean that the $\delta^{13}C_{TOC}$ record cannot provide a reliable estimate of the *relative* extent of maize cultivation in the watershed through time (Lane et al., in press-b), only that developing an accurate estimate of the extent of these activities at any one moment in time may not be as simple as only analyzing variations in the $\delta^{13}C_{TOC}$ record.

4.3.5. Zone B (382–335 cm; ~730–680 cal yr B.P.): decreased human impact

Compared to Zone C, Zone B marks the beginning of a different relationship between $\delta^{13}C_{TOC}$ values, maize pollen concentrations, and mineral influx in the Laguna Castilla sediment record. Maize pollen concentrations decrease steadily throughout Zone B, but the $\delta^{13}C_{TOC}$ and mineral influx data display little change. The similarity in the $\delta^{13}C_{TOC}$ record and the mineral influx data seems to indicate that the $\delta^{13}C_{TOC}$ record in Zone B is more sensitive to variations in allochthonous sediment delivery than it is to variations in the abundance of maize on the landscape.

Based on our limited analyses, it is difficult to explain why the $\delta^{13}C_{TOC}$ record appears to be more sensitive to variations in allochthonous sediment delivery than to maize abundance at this time. It is possible that prehistoric human impacts in the Laguna Castilla watershed were so severe through the period encompassed by Zone C that they had an effect on the available terrestrial carbon pool that lasted through the period encompassed by Zone B. If the majority of the Laguna Castilla watershed was deforested and under cultivation during the period encompassed by Zone C, an abundance of C_4 organic matter would have been available for transport into the lake. Thus, even with a decrease during Zone B in the abundance of maize being cultivated, there may still have been a large fraction of C_4 organic material in the terrestrial carbon pool available for transport to the lake. Also, we cannot discount the possibility that some fraction of the C_4 vegetation that became established in Zone C persisted on the landscape, perhaps due to the apparent severity of landscape impacts by these prehistoric agriculturalists at this time. Percentages of pollen from the Poaceae and Asteraceae plant families, which include weedy taxa associated with agricultural fields (Brown, 1999) and numerous C_4 species (Sage et al., 1999a), do remain relatively high throughout Zone B despite the apparent decrease in maize cultivation (Fig. 5).

4.3.6. Zone A (335–300 cm; ~680–550 cal yr B.P.): land abandonment

Maize pollen deposition in Laguna Castilla terminates at the Zone B/Zone A boundary, indicating the cessation of maize agriculture around the lake and apparent abandonment of the watershed around 730 cal yr B.P. (Table 1). Mineral influx and $\delta^{13}C_{TOC}$ values nearly drop to pre-settlement levels, indicating decreased watershed erosion and the recovery of C_3-dominated lower montane moist forest. Pollen percentages of arborescent taxa also increase in Zone A, further suggesting forest recovery around Laguna Castilla. The proxy evidence currently available from Laguna Castilla, the immediate area, and the region as a whole, provides no clear indication of why the watershed was abandoned at this time (Lane, 2007). The lack of archaeological research in the immediate area, and for the interior of the island as a whole, leaves room only for speculation as to why humans would have abandoned the watershed at this time.

5. Conclusions

The stable carbon isotope composition of lake sediments is an effective proxy of prehistoric forest clearance and agriculture in the neotropics, but the development of quantitatively robust reconstructions of these activities will require a more in-depth understanding of the sensitivity of sedimentary $\delta^{13}C_{TOC}$ values to factors such as shifts in the relative dominance of C_3 and C_4 plants and variations in allochthonous carbon delivery. The Laguna Castilla data we present here indicate that sedimentary $\delta^{13}C_{TOC}$ values are temporally sensitive to rapid variations in C_3 and C_4 plant dominance, but the isotopic changes tend to lag vegetation shifts by a few years. The close correspondence between sedimentary $\delta^{13}C_{TOC}$ and mineral influx values in Zones E, C, and B of the Laguna Castilla record highlights the sensitivity of sedimentary $\delta^{13}C_{TOC}$ values to variations in allochthonous carbon delivery. More importantly, comparisons between the $\delta^{13}C_{TOC}$ record and the mineral influx data indicate that the amplitudes of shifts in the $\delta^{13}C_{TOC}$ record are intimately linked with variations in allochthonous sediment delivery.

The sensitivity of the sedimentary $\delta^{13}C_{TOC}$ record to the limited number of watershed variables analyzed here further reinforces the need for an increased understanding of carbon dynamics and cycling in lake watersheds. Despite the complexity of the exact response of the sedimentary $\delta^{13}C_{TOC}$ record to numerous watershed variables, the close correspondence between the $\delta^{13}C_{TOC}$ record and maize pollen concentrations indicates that the $\delta^{13}C_{TOC}$ record can be used to reliably assess the *relative* extent of these activities through time. We also believe that this proxy has enormous potential for the eventual quantitative reconstruction of the areal extent of anthropogenic forest clearance and crop cultivation in tropical watersheds.

Future studies that utilize high-resolution compound-specific isotopic analyses could further refine this technique by providing a purely allochthonous stable carbon isotope record, thereby eliminating any complications arising from autochthonous carbon dynamics (Brincat et al., 2000; Ficken et al., 1998; Huang et al., 1999). This approach is likely to become more common as biomarker isolation and compound specific isotope analyses become less expensive and more efficient. In addition, the development of watershed-scale studies of prehistoric agriculture combining lake sediment and soil (Johnson et al., 2007; Webb et al., 2004, 2007) stable carbon isotope proxies of maize cultivation could provide more quantitative estimates of the scale of such activities and their environmental impacts.

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References

Aucour, A.M., Bonnefille, R., Hillaire-Marcel, C., 1999. Sources and accumulation rates of organic carbon in an equatorial peat bog (Burundi, East Africa) during the Holocene: carbon isotope constraints. Palaeogeography Palaeoclimatology Palaeoecology 150 (3–4), 179–189.

Aylor, D.E., Baltazar, B., Schoper, J., 2005. Some physical properties of teosinte (*Zea mays* subsp. *parviglumis*) pollen. Journal of Experimental Botany 56 (419), 2401–2407.

Beach, T., 1998. Soil catenas, tropical deforestation, and ancient and contemporary soil erosion in the Peten, Guatemala. Physical Geography 19 (5), 378–405.

Bender, M.M., 1971. Variations on the 13C ratios of plants in relation to the pathway of photosynthetic carbon dioxide fixation. Phytochemistry 10, 1239–1244.

Bolay, E., 1997. The Dominican Republic: A Country Between Rain Forest and Desert; Contributions to the Ecology of a Caribbean Island. Margraf Verlag, Weikersheim.

Brenner, M., Whitmore, T.J., Lasi, M.A., Cable, J.E., Cable, P.H., 2000. A multi-proxy trophic state reconstruction for shallow Orange Lake, Florida, USA: possible influence of macrophytes on limnetic nutrient concentrations. Journal of Paleolimnology 21, 215–233.

Brincat, D., Yamada, K., Ishiwatari, R., Uemura, H., Naraoka, H., 2000. Molecular-isotopic stratigraphy of long-chain n-alkanes in Lake Baikal Holocene and glacial age sediments. Organic Geochemistry 31 (4), 287–294.

Brown, R.H., 1999. Agronomic implications of C_4 photosynthesis. In: Sage, R.F., Monson, R.K. (Eds.), C_4 Plant Biology. Academic Press, San Diego, pp. 473–509.

Burney, D.A., Burney, L.P., MacPhee, R.D.E., 1994. Holocene charcoal stratigraphy from Laguna Tortuguero, Puerto Rico, and the timing of human arrival on the island. Journal of Archaeological Science 21 (2), 273–281.

Cayet, C., Lichtfouse, E., 2001. $\delta^{13}C$ of plant-derived *n*-alkanes in soil particle-size fractions. Organic Geochemistry 32 (2), 253–258.

Cerling, T.E., 1999. Paleorecords of C_4 plants and ecosystems. In: Sage, R.F., Monson, R.K. (Eds.), C_4 Plant Biology. Academic Press, San Diego, pp. 445–473.

Clement, R.M., Horn, S.P., 2001. Pre-Columbian land-use history in Costa Rica: a 3000-year record of forest clearance, agriculture and fires from Laguna Zoncho. Holocene 11 (4), 419–426.

Cohen, A.S., 2003. Paleolimnology: The History and Evolution of Lake Systems. Oxford University Press.

Colinvaux, P.A., De Oliveira, P.E., Moreno, J.E., 1999. Chapter 3: Guide to piston coring of lake sediments. Amazon Pollen Manual and Atlas. Hardwood Academic Publishers, Amsterdam.

Conserva, M.E., Byrne, R., 2002. Late Holocene vegetation change in the Sierra Madre Oriental of central Mexico. Quaternary Research 58 (2), 122–129.

Davies, S.J., Metcalfe, S.E., MacKenzie, A.B., Newton, A.J., Endfield, G.H., Farmer, J.G., 2004. Environmental changes in the Zirahuen Basin, Michoacan, Mexico, during the last 1000 years. Journal of Paleolimnology 31 (1), 77–98.

Dean, W.E., 1974. Determinations of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. Journal of Sedimentary Petrology 44, 242–248.

Dull, R.A., 2004. A Holocene record of Neotropical savanna dynamics from El Salvador. Journal of Paleolimnology 32, 219–231.

Dull, R.A., 2006. The maize revolution: A view from El Salvador. In: Staller, J., Tykot, R., Benz, B. (Eds.), Histories of Maize: Multidisciplinary Approaches to the Prehistory, Biogeography, Domestication, and Evolution of Maize. Elsevier Press, San Diego, pp. 357–365.

Dull, R.A., 2007. Evidence for forest clearance, agriculture, and human-induced erosion in Precolumbian El Salvador. Annals of the Association of American Geographers 97 (1), 127–141.

Ekdahl, E.J., Teranes, J.L., Guilderson, T.P., Turton, C.L., McAndrews, J.H., Wittkop, C.A., Stoermer, E.F., 2004. Prehistorical record of cultural eutrophication from Crawford Lake, Canada. Geology 32 (9), 745–748.

Faegri, K., Iverson, J., 1989. Textbook of Pollen Analysis, fourth ed. Wiley, New York.

Ficken, K.J., Li, B., Swain, D.L., Eglinton, G., 2000. An n-alkane proxy for the sedimentary input of submerged/floating freshwater aquatic macrophytes. Organic Geochemistry 31, 745–749.

Ficken, K.J., Street-Perrott, F.A., Perrott, R.A., Swain, D.L., Olago, D.O., Eglinton, G., 1998. Glacial/interglacial variations in carbon cycling revealed by molecular and isotope stratigraphy of Lake Nkunga, Mt. Kenya, East Africa. Organic Geochemistry 29 (5–7), 1701–1719.

Ficken, K.J., Wooller, M.J., Swain, D.L., Street-Perrott, F.A., Eglinton, G., 2002. Reconstruction of a subalpine grass-dominated ecosystem, Lake Rutundu, Mount Kenya: a novel multi-proxy approach. Palaeogeography, Palaeoclimatology, Palaeoecology 177 (1–2), 137–149.

Fisher, E., Oldfield, F., Wake, R., Boyle, J., Appleby, P., Wolff, G.A., 2003. Molecular marker records of land use change. Organic Geochemistry 34 (1), 105–119.

Goman, M., Byrne, R., 1998. A 5000-year record of agriculture and tropical forest clearance in the Tuxtlas, Veracruz, Mexico. Holocene 8 (1), 83–89.

Hayes, J.M., Freeman, K.H., Popp, B.N., Hoham, C.H., 1990. Compound-specific isotopic analyses: a novel tool for reconstruction of ancient biogeochemical processes. Organic Geochemistry 16 (4–6), 1115–1128.

Horn, S.P., 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, Biogeography, Domestication, and Evolution of Maize. Elsevier Press, San Diego, pp. 367–380.

Huang, Y.S., Street-Perrott, F.A., Perrot, R.A., Metzger, P., Eglinton, G., 1999. Glacial-interglacial environmental changes inferred from molecular and compound-specific delta C-13 analyses of sediments from Sacred Lake, Mt. Kenya. Geochimica Et Cosmochimica Acta 63 (9), 1383–1404.

Huang, Y., Street-Perrott, F.A., Metcalfe, S.E., Brenner, M., Moreland, M., Freeman, K.H., 2001. Climate change as the dominant control on glacial-interglacial variations in C-3 and C-4 plant abundance. Science 293 (5535), 1647–1651.

Islebe, G.A., Hooghiemstra, H., Brenner, M., Curtis, J.H., Hodell, D.A., 1996. A Holocene vegetation history from lowland Guatemala. Holocene 6 (3), 265–271.

Jacob, J.S., Hallmark, C.T., 1996. Holocene stratigraphy of Cobweb Swamp, a Maya wetland in northern Belize. Geological Society of America Bulletin 108 (7), 883–891.

Johnson, K.D., Wright, D.R., Terry, R.E., 2007. Application of carbon isotope analysis to ancient maize agriculture in the Petexbatun region of Guatemala. Geoarchaeology—an International Journal 22 (3), 313–336.

Krieger, H.W., 1930. The aborigines of the ancient island of Hispaniola, Annual Report of the Board of Regents of the Smithsonian Institution for 1929. Government Printing Office, Washington D.C., 473-556 pp.

Lane, C.S., 2007. Late-Holocene Environmental History in the Northeastern Caribbean: Multi-Proxy Evidence from Two Small Lakes on the Southern Slope of the Cordilleran Central, Dominican Republic. Ph.D. Dissertation. University of Tennessee, Knoxville, 226 p.

Lane, C.S., Horn, S.P., Mora, C.I., 2004. Stable carbon isotope ratios in lake and swamp sediments as a proxy for prehistoric forest clearance and crop cultivation in the Neotropics. Journal of Paleolimnology 32 (4), 375–381.

Lane, C.S., Horn, S.P., Taylor, Z.P., Mora, C.I., in press-a. Assessing the scale of prehistoric human impact in the Neotropics using stable carbon isotope analyses of lake sediments. Latin American Antiquity.

Lane, C.S., Horn, S.P., Orvis, K.H., Mora, C.I., in press-b. The earliest evidence of Ostionoid maize agriculture from the interior of Hispaniola. Caribbean Journal of Science.

Leyden, B.W., Brenner, M., Dahlin, B.H., 1998. Cultural and climatic history of Coba, a lowland Maya city in Quintana Roo, Mexico. Quaternary Research 49 (1), 111–122.

Liogier, A.H., 1981. Ecosistemas de montañas en la República Dominicana. Anuario 5, 87–102.

Lucas, W.J., 1983. Photosynthetic assimilation of exogenous HCO_3^- by aquatic plants. Annual Review of Plant Physiology 34, 71–104.

Lucke, A., Schleser, G.H., Zolitschka, B., Negendank, J.F.W., 2003. A Lateglacial and Holocene organic carbon isotope record of lacustrine palaeoproductivity and climatic change derived from varved lake sediments of Lake Holzmaar, Germany. Quaternary Science Reviews 22 (5-7), 569–580.

Luna, S., Figueroa, J., Baltazar, M., Gomez, R., Townsend, R., Schoper, J., 2001. Maize pollen longevity and distance isolation requirements for effective pollen control. Crop Science 41, 1551–1557.

Meyers, P.A., 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. Chemical Geology 114, 289–302.

Meyers, P.A., Ishiwatari, R., 1993. Lucustrine organic geochemistry—an overview of indicators of organic-matter sources and diagenesis in lake-sediments. Organic Geochemistry 20 (7), 867–900.

Meyers, P.A., Lallier-vergés, E., 1999. Lacustrine sedimentary organic matter records of late Quaternary paleoclimates. Journal of Paleolimnology 21, 345–372.

Meyers, P.A., Teranes, J.L., 2001. Sediment organic matter. In: Last, W.M., Smol, J. (Eds.), Tracking Environmental Change Using Lake Sediments. Physical and Geochemical Methods, vol. 2. Kluwer Academic Publishers, Dordrecht, pp. 239–268.

Mook, W.G., Bommerson, J.C., Staberman, W.J., 1974. Carbon isotope fractionation between dissolved bicarbonate and gaseous carbon dioxide. Earth and Planetary Science Letters 22, 169–176.

Newsom, L.A., 2006. Caribbean maize: Current research on the archaeology, history, and biogeography. In: Staller, J., Tykot, R.H., Benz, B. (Eds.), Histories of Maize: Multidisciplinary Approaches to the Prehistory, Linguistics, Biogeography, Domestication, and Evolution of Maize. Elsevier, San Diego, pp. 325–335.

Newsom, L.A., Deagan, K.A., 1994. *Zea mays* in the West Indies: the archaeological and early historic record. In: Johannessen, S., Hastorf, C.A. (Eds.), Corn and Culture in the Prehistoric New World. Westview Press, Boulder, CO, pp. 203–217.

Northrop, L.A., Horn, S.P., 1996. PreColumbian agriculture and forest disturbance in Costa Rica: Palaeoecological evidence from two lowland rainforest lakes. Holocene 6 (3), 289–299.

Ogrinc, N., Lojen, S., Faganeli, J., 2002. A mass balance of carbon stable isotopes in an organic-rich methane-producing lacustrine sediment (Lake Bled, Slovenia). Global and Planetary Change 33, 57–72.

O'Hara, S.L., Metcalfe, S.E., Street-Perrott, F.A., 1994. On the arid margin - the relationship between climate, humans and the environment—a review of evidence from the highlands of Central Mexico. Chemosphere 29 (5), 965–981.

Oldfield, F., Wake, R., Boyle, J., Jones, R., Nolan, S., Gibbs, Z., Appleby, P., Fisher, E., Wolff, G., 2003. The late-Holocene history of Gormire Lake (NE England) and its catchment: a multiproxy reconstruction of past human impact. Holocene 13 (5), 677–690.

O'Leary, M.H., 1981. Carbon isotope fractionation in plants. Phytochemistry 20, 553–567.

Ortiz Aguilu, J.J., Melendez, J.R., Jacome, A.P., Maiz, M.M., Colberg, M.L., 1991. Intensive agriculture in pre-Columbian West Indies: The case for terraces. In: Cummins, A., King, P. (Eds.), Proceedings of the Fourteenth Congress of the International Association for Caribbean Archaeology. Barbados Museum and Historical Society, Barbados, pp. 278–285.

Phillips, D.L., Gregg, J.W., 2003. Source partitioning using stable isotopes: coping with too many sources. Oecologia 136 (2), 261–269.

Raynor, G.S., Ogden, E.C., Hayes, K.V., 1972. Dispersion and deposition of corn pollen from experimental sources. Agronomy Journal 64, 420–427.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004a. IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. Radiocarbon 46 (3), 1029–1058.

Reimer, P.J., Brown, T.A., Reimer, P.J., 2004b. Discussion: Reporting and calibration of post-bomb C-14 data. Radiocarbon 46, 1299–1304.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.H., Guilderson, T.P., 2002a. A 4000-year lacustrine record of environmental change in the southern Maya lowlands, Peten, Guatemala. Quaternary Research 57 (2), 183–190.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.H., Martin, J.B., Anselmetti, F.S., Ariztegui, D., Guilderson, T.P., 2002b. Influence of vegetation change on watershed hydrology: implications for paleoclimatic interpretation of lacustrine delta O-18 records. Journal of Paleolimnology 27 (1), 117–131.

Rouse, I., 1992. The Tainos: Rise and Decline of the People who Greeted Columbus. Yale University Press, New Haven.

Sage, R.F., Li, M., Monson, R.K., 1999a. The taxonomic distribution of C_4 photosynthesis. In: Sage, R.F., Monson, R.K. (Eds.), C_4 Plant Biology. Academic Press, San Diego, pp. 551–584.

Sage, R.F., Wedin, D.A., Li, M., 1999b. The biogeography of C_4 photosynthesis: patterns and controlling factors. In: Sage, R.F., Monson, R.K. (Eds.), C_4 Plant Biology. Academic Press, San Diego, pp. 313–377.

Sluyter, A., 1997. Regional, Holocene records of the human dimension of global change: Sea-level and land-use change in prehistoric Mexico. Global and Planetary Change 14 (3-4), 127–146.

Smith, F.A., Walker, N.A., 1980. Photosynthesis by aquatic plants: effects of unstirred layers in relation to assimilation of CO_2 and HCO_3^- and to carbon isotope discrimination. New Phytology 86, 245–259.

Staller, J., Tykot, R., Benz, B. (Eds.), 2006. Histories of Maize: Multidisciplinary Approaches to the PrehistoryLinguistics, Biogeography, Domestication, and Evolution of Maize. Elsevier, San Diego.

Stewart, G.R., Turnbull, J., Schmidt, S., Erskine, P.D., 1995. ^{13}C natural abundance in plant communities along a rainfall gradient: A biological integrator of rainfall availability. Functional Plant Biology 22, 51–55.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores 13, 615–621.

Stokes, A.V., 1998. A Biogeographic Survey of Prehistoric Human Diet in the West Indies Using Stable Isotopes. Ph.D. Dissertation. University of Florida, Gainesville, FL.

Street-Perrott, F.A., Huang, Y.S., Perrott, R.A., Eglinton, G., Barker, P., Ben Khelifa, L., Harkness, D.D., Olago, D.O., 1997. Impact of lower atmospheric carbon dioxide on tropical mountain ecosystems. Science 278 (5342), 1422–1426.

Street-Perrott, F.A., Ficken, K.J., Huang, Y.S., Eglinton, G., 2004. Late quaternary changes in carbon cycling on Mt. Kenya, East Africa: an overview of the delta C-13 record in lacustrine organic matter. Quaternary Science Reviews 23 (7–8), 861–879.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C database and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35, 215–230.

Talbot, M.R., Johannessen, T., 1992. A high resolution paleoclimate record for the last 27,500 years in tropical West Africa from the carbon and nitrogen isotopic composition of organic matter. Earth and Planetary Science Letters 110, 23–37.

Telford, R.J., Heegaard, E., Birks, H.J.B., 2004a. All age-depth models are wrong: but how badly? Quaternary Science Reviews 23 (1–2), 1–5.

Telford, R.J., Heegaard, E., Birks, H.J.B., 2004b. The intercept is a poor estimate of a calibrated radiocarbon age. Holocene 14 (2), 296–298.

Tolentino, L., Peña, M., 1998. Inventario de la vegetación y uso de la tierra en la República Dominicana. Moscosoa 10, 179–203.

Wahl, D., Byrne, R., Schreiner, T., Hansen, R., 2006. Holocene vegetation change in the northern Peten and its implications for Maya prehistory. Quaternary Research 65 (3), 380–389.

Webb, E.A., Schwarcz, H.P., Healy, P.F., 2004. Detection of ancient maize in lowland Maya soils using stable carbon isotopes: evidence from Caracol, Belize. Journal of Archaeological Science 31 (8), 1039–1052.

Webb, E.A., Schwarcz, H.P., Jensen, C.T., Terry, R.E., Moriarty, M.D., Emery, K.F., 2007. Stable carbon isotope signature of ancient maize agriculture in the soils of Motul de San Jose, Guatemala. Geoarchaeology-an International Journal 22 (3), 291–312.

Wilson, S.M., 1997. The Indigenous People of the Caribbean. University Press of Florida, Gainesville.