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Master's thesis

Columbus' footprints on Hispaniola from a coastal perspective

Multi-proxy reconstruction of environmental change in the northern Dominican Republic

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Human impact, paleoenvironmental reconstruction, Hispaniola, charcoal, pre-colonial period, post-colonial period

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Abstract

Columbus founded the very first permanent settlement in the New World, *La Isabela,* on the northwestern coast of the Dominican Republic on the island of Hispaniola during his second voyage in AD 1493. Assessment of the character and scale of human disturbance of the natural environment in one of the earliest colonized regions in the New World is hampered by a lack of independent paleoenvironmental evidence.

We present a reconstruction of environmental change from pre-Columbian to post-Colonial times based on sediment cores from a near-coastal lake (Laguna Grande) and a mangrove swamp (Estero Hondo), reflecting land use changes over the past 3200 years. The environmental history was reconstructed from changing grain size distributions, organic carbon content, fossil pollen, coprophilous fungal spores and charcoal particle concentrations.

During the early Ceramic (ca. 250 cal yr AD), the Saladoid people had only minor impact on the environment and cultivated squashes near the mangroves that provided them with shells and fish. Most likely, cultivation of maize commenced on the shores of Laguna Grande during the late Ceramic (ca. 1150 cal yr AD). Absence of evidence for cattle introduction, Old World crop cultivation or deforestation, suggests early colonial disturbance was mostly restricted to the Cibao valley, where the gold rush lead the colonists to the inlands. Fire frequency increased from ca. 1700 cal yr AD onwards, potentially as a result of large numbers of European immigrants and enslaved Africans that enlarged demographic pressure on the environment. Anthropogenic disturbance had not significantly affected the mangroves until ca. 1770 cal yr AD, when frequent fires and deforestation degraded the forest.

Our results demonstrate that colonization more extensively and more instantly impacted the natural environment in the Cibao valley compared to only minor disturbances on the Atlantic coastal plain. Intensification of anthropogenic disturbance on the Atlantic coast is particularly evident after three centuries of colonization.

This study underlines the importance of reliable age constraints for interpretations regarding cause and effect in terms of natural and human disturbances. Considering a higher level of detail desirable, the suite of proxies could be supplemented by phytholith analysis so as to identify crop plants that are included in the records of higher taxonomic ranks such as potato and tomato (both Solanaceae).

Resúmen

El primer asentamiento permanente en el Nuevo Mundo, llamado La Isabela, fue fundado por Colón en la costa noereste de República Dominicana en la Isla Española, durante su segundo viaje en el año AD 1493. La evaluación del carácter y la extensión del impacto ambiental humano en una de las primeras regiones colonizadas en el Nuevo Mundo, se ve entorpecido por la ausencia de evidencia paleoambiental independiente.

Se presenta aquí una reconstrucción del cambio paleoambiental desde la época Precolombina hasta la época post-Colonial, basada en dos núcleos de sedimentos obtenidos en Laguna Grande, una laguna cercana al mar, y en Estero Hondo, un pantano con manglares, que reflejan el cambio del uso del suelo durante los últimos 3200 años. La historia ambiental se reconstruyó gracias a cambios en las distribuciones del tamaño de grano, carbono orgánico total, polen, esporas de hongos coprófilos y el contenido de carbones.

Durante el período Cerámico Temprano (aprox. 250 cal AD), los indígenas Saladoides generaron un impacto ambiental limitado, solían cultivar calabazas alrededor de los manglares, de los cuales adquirieron conchas y pescado. Probablemente, el cultivo de maíz comenzó en las orillas de Laguna Grande durante el período Cerámico Tardío (aprox. 1150 cal AD); mientras que la falta de evidencia de la introducción de ganado, de los cultivos del Viejo Mundo o de la deforestación, sugiere que la perturbación humana se limitó al Valle de Cibao, donde “la fiebre del oro” llevó a los colonizadores hacia el interior del país. Por otra parte, la frecuencia de fuegos aumentó hace aprox. 1700 cal AD, posiblemente debido al gran número de inmigrantes europeos y africanos esclavizados, lo cual aumentó la presión demográfica y su impacto ambiental. Desde aprox. 1770 cal AD, los fuegos frecuentes y la deforestación causaron el deterioro del bosque, en comparación con periodos anteriores cuando la perturbación humana no afectó significativamente los manglares.

Los resultados demuestran que la colonización tuvo un impacto ambiental más extenso e inmediato en el valle de Cibao que en la costa Atlántica. La intensificación de la perturbación humana en la costa Atlántica, particularmente, es evidente después de tres siglos de colonización.

Finalmente, se señala que los resultados de este estudio demuestran la importancia de dataciones radiométricas fiables para la interpretación de la causa y el efecto en cuanto a perturbaciones naturales y antropogénicas. Además, considerando que se requiere un nivel más detallado de reconstrucción ambiental, se podría añadir a estudios futuros el análisis de fitolitos como una aproximación para identificar cultivos como la papa o el tomate (Solanaceae).

1. Introduction

First encounters between the New World and the Old World, after the Vikings centuries earlier, took place in AD 1492 on the islands of El Salvador, Cuba, the Bahamas and Hispaniola. The Caribbean islands have been inhabited since 6000 years before present (BP) (by definition before 1950) by indigenous people belonging to the Taíno, Caquetió and Carib societies and their ancestors that originate from Mesoamerica (Wilson et al., 1998; Fitzpatrick and Keegan, 2007; Hofman et al., 2018). The 'Columbian Exchange' that followed upon Spanish Colonization still affects our day to day live, since potatoes, tomatoes and maize were introduced to Europe for the first time (Crosby, 1972; Fitzpatrick and Keegan, 2007). On the other hand, European introduction of livestock, cultivars, settlers leading to relatively dense populations, the Spanish *Economienda* system, as well as the diseases that the colonists brought with them, drastically altered the New World. The *Economienda* system was a social-economical system in which indigenous inhabitants, and later African slaves, were forced to carry out work related to the gold rush and need for sugar (Crosby, 1972; Fitzatrick and Keegan, 2007; McCook, 2011; Hofman et al., 2018).

Reconstructions of the natural environment, independent of the historical and archeological record are crucial in the interpretation of (new) archeological findings, providing an environmental context. Aspects of the changes in land-use that the transition from pre-Columbian to post-Columbian times imposed on the Dominican landscape are potentially preserved in sedimentary records. Paleoenvironmental reconstructions based on multiple proxies (e.g. pollen) from sediment archives can answer research questions related to past climate and vegetation change (e.g. Groot et al., 2011; González-Carranza et al., 2012; Flantua et al., 2016) as well human-landscape interactions. Occasionally, archeological findings have successfully been complemented by such independent reconstructions providing a natural context for socio-cultural interpretations (e.g. Clark, 1983; De Boer et al., 2013; Nooren et al., 2018; Avnery et al., 2011; Cooper, 2013, and references therein).

However, this type of research from the Antilles is rare. Examples include reconstructions from Puerto Rico (Siegel et al., 2005, 2015) and Guadeloupe (Beets et al., 2006). Climate, vegetation and fire history reconstructions from Hispaniola include examples based on stable isotopes and pollen in Lake Miragoane, Haïti (Hodell et al., 1991; Higuera-Gundy et al., 1999) and stable isotopes, pollen and charcoal particles from several lakes and a peatbog in the Dominican Cordillera Central (Lane et al., 2009, 2011, 2014; Kennedy et al., 2006).

The northwest coast of the Dominican Republic was the locus of first encounters between the New and Old World. During his second voyage in AD 1493, Columbus founded the city of La Isabela, the first permanent European settlement in the New World . It was in its vicinity that Columbus' men found gold, which led to the 'gold rush'. Despite the historical importance of this area, the only published paleoenvironmental reconstruction from the Atlantic coast of Hispaniola comes from Laguna Saladilla, where a 8000 ^{14}C year long record of natural environmental change, presumably mainly naturally driven, was studied (Caffrey et al., 2015). However, the resolution of that reconstruction does not allow for interpretations of interactions between humans and the environment in the context of the pre- to post-Columbian transition. Recently, records derived from cut-off meanders in the interior Cibao valley of the northwestern Dominican Republic were published reflecting amongst other things past fluvial dynamics (Castilla-Beltran et al., 2018; Hooghiemstra et al., 2018). The limited preservation of pollen in semi-arid to arid environments (Horowitz, 1992), such as those in the northwestern Dominican Republic, requires a multi-proxy approach so as to avoid overinterpreting low pollen concentrations. In the absence of statiscally reliable pollen data, other proxies such as charcoal and grain size distributions (GSDs) can add to the environmental reconstruction. Moreover, cores collected from multiple sites potentially cover spatial dynamics of environmental change.

The lack of paleoenvironmental reconstructions from the northwestern Dominican Republic, where the very first encounters between the New and the Old World took place, impedes assesment of the extent of anthropogene disturbance of the natural environment during pre- and post-Columbian times. Here, we present a new paleoenvironmental study based on a near-coastal lacustrine record and a mangrove swamp record from the northwestern Dominican Republic (Fig. 1) with the aim to elaborate on (1) the timing and character of first (pre-Columbian) human disturbances such as crop cultivation, forest clearings and burning practices, (2) evidence for the potential impact of the 'encounter' preserved in the sediments such as the introduction of New World species as livestock or Cerealia-type crop plants, (3) the rate of development of land-use practices such as fire activity, forest clearings and agricultural activity during the centuries following colonization, for instance in response to increased demographic pressure, (4) differences regarding scale and intensity of human disturbances during pre- and post-Columbian times, (5) differences with respect to timing and character of human disturbances between the Atlantic Coast and the interior *Cibao* valley.

We reconstruct vegetation dynamics from pollen and spore records, total organic carbon (TOC) by loss on ignition (LOI), changes in sediment transport regime and deposition from grain size distributions (GSDs) and carbonate ($CaCO_3$) contents, local fire history from macroscopic charcoal particle analyses, regional fire history from microscopic particle analyses and grazing intensity from spores of coprophilous fungi. We compare our results with recently published inland pollen and charcoal records from the Cibao valley (Castilla-Beltrán et al., 2018; Hooghiemstra et al., 2018) so as to distinguish local from regional signals, for a hitherto lacking integrated perspective on late Holocene anthropogenic disturbance on Hispaniola. All in all, the results presented in this paper could prove a valuable case-study asessing changes in Caribbean environmental dynamics upon European colonization.

2. Setting

2.1 Geology and geography

The island of Hispaniola, divided between the countries Haïti and the Dominican Republic, is part of the Greater Antilles. This group of islands in the Caribbean Sea further comprises Cuba, Puerto Rico, Jamaica and the Caiman Islands. The Greater Antilles are situated on the northernmost plate boundary that separates the North American and Caribbean plates.

Geologically, Hispaniola is divided into two tectonic domains separated by the Enriquillo-Plantain Garden fault. The northern two thirds comprise a segment of the Great Arc of the Carribbean, a volcanic arc that was active from 116 million years ago (Ma) until the Middle-Late Eocene of which remnants can be found around the perimeter of the Caribbean plate (Boschman et al., 2014; Mann et al. 1991). The southern one third consists of Caribbean oceanic plate overlain by Caribbean Large Igneous Province lavas. The Septentrional fault in the north and the Enriquillo-

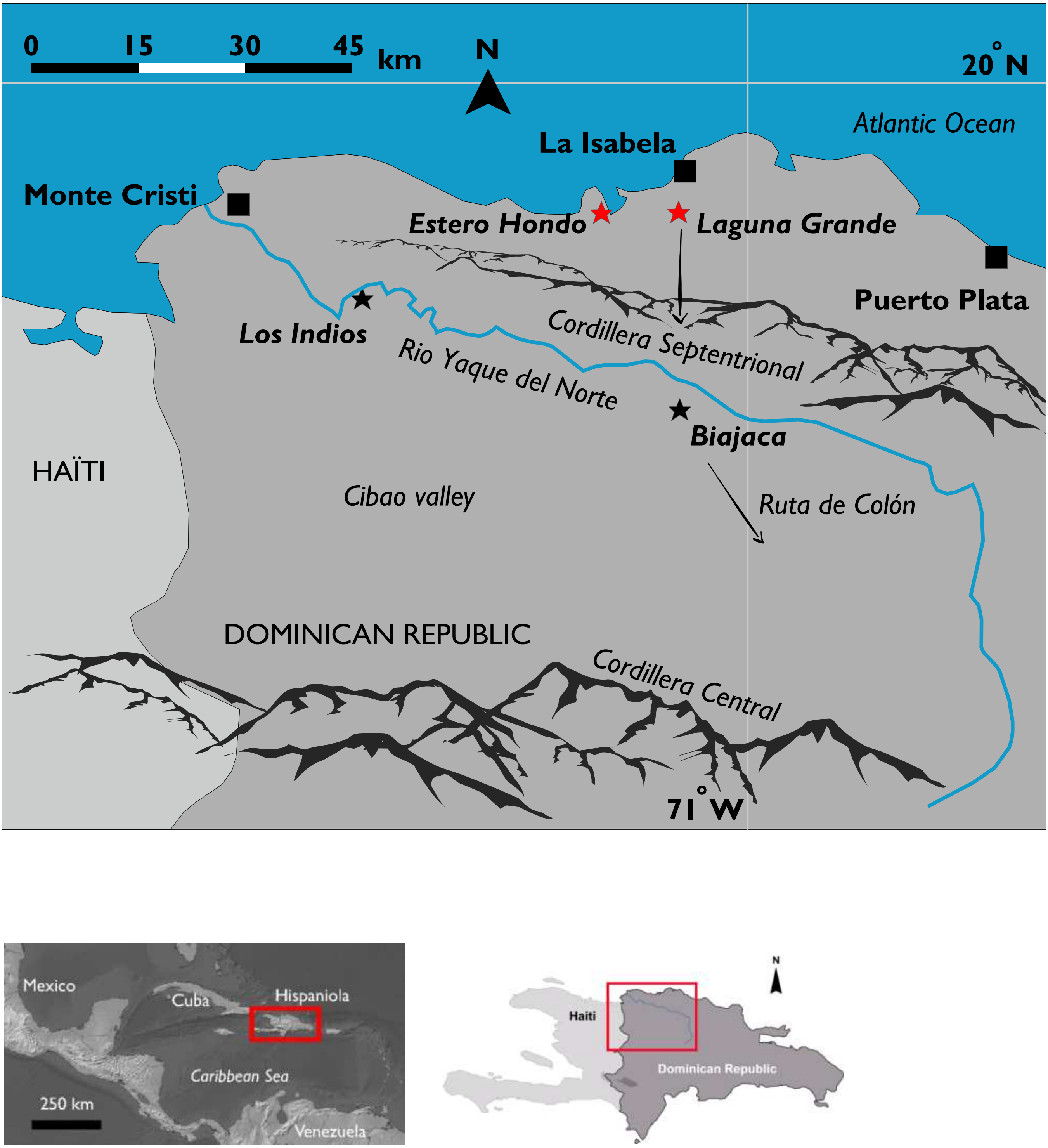

Figure 1 **(lower left)** Map showing the location of the Hispaniola island (red rectangle) in the Caribbean. **(lower right)** Location of the area of interest (red rectangle) on Hispaniola. **(upper panel)** Schematized map of the northwestern Dominican Republic showing the coastal Estero Hondo and Laguna Grande core locations presented in this paper (red stars) as well as the previously published inland Los Indios and Biajaca records (black stars). Note that the mountain ranges are not drawn to scale. Maps were created using the online tool SimpleMappr.

Plantain Garden and Los Pozos faults in the south are NW-SE to W-E striking seismically active faults that accommodate strike-slip motion moving Hispaniola eastward relative to Cuba (Mann et al. 1984; Boschman et al., 2014). Both fault systems have caused mayor earthquakes and related tsunamis such as the one that struck Haïti in 2010. For the Septentrional fault system historical earthquakes have been recorded for AD 1564, 1783, 1842, 1887 and 1897. The earthquake of AD 1842, most likely caused by movement along the fault in the Cibao valley and its seaward extension, caused a tsunami (Mann et al., 1998).

Five roughly WNW-ESE striking mountain ranges characterize the topography of Hispaniola. In the northern Dominican Republic the coast-parallel Cordillera Septentrional, with its highest peak of 1250 m, separates the Atlantic coastal plane from the interior Cibao valley, extending for over 200 km (Hofman et al., 2018). The valley is bordered in the south by the Cordillera Central where Pico Duarte is situated, with its 3098 m the highest peak in the Caribbean (Garcia et al., 1978). The Atlantic coastal plain, also called the Atlantic corridor, where Estero Hondo and Laguna Grande are situated is approximately 10 to 20 km wide, measured perpendicularly from the coast to the Cordillera Septentrional. On its northwestern end a barrier island separates the coastal parallel back-barrier lagoon Estero Hondo from the sea. One tidal inlet is present that connects the back-barrier sedimentary system with the open sea. The tidal cycle is semi-diurnal with a maximum (spring) tidal range of approximately 1 m (Geraldes, 2003). Small tributaries mound into the lagoon, but a large river is absent. Laguna Grande is a near-coastal shallow lake situated 10 km to the east, where it lies at 3 km land inwards. A small outlet drains the lake, where the water level usually varies between 0 and 100 cm. We estimate a surface area of ca. 125 000 m^2.

2.2 Climate and vegetation

Average monthly temperatures in the lowlands of the Dominican Republic vary between 22 and 28 °C (Izzo et al., 2010). Temperatures vary stronger diurnally than seasonally. The interplay between relief and tropical Atlantic moisture bearing northeasterly trade winds largely determine precipitation variability (Lane et al., 2011; Horst, 1992). Southward movement of the North Atlantic Subtropical High (NAH) associated with southward migration of the intertropical convergence zone (ITCZ) during boreal winter strengthens trade winds. Furthermore, subsiding air masses cause a trade wind inversion that limits precipitation. Consequently, lowest monthly precipitation would be expected during boreal winter (January to March). However, the northern coastal stretch experiences wetter conditions with peak precipitation of 230 mm occurring during November and December, with minima of ≤100 mm during February, June, July and September (Garcia et al., 1978). A mechanism for higher winter precipitation in the northern Dominican Republic could be the intrusion of northwesterly polar fronts that meet the orographic barrier of the Cordillera Septentrional (Garcia et al., 1978; Hastenrath, 1991). Izzo et al. (2010) compiled a new climatological map of the Dominican Republic. Mean annual precipitation (MAP) around Estero Hondo and Laguna Grande ranges between 490 and 1500 mm and the climate can be classified as semi-arid (Estero Hondo) to dry subhumid (Laguna Grande) (Izzo et al., 2010). The range of MAP reflects the local annual variability within the semi-arid and dry subhumid climatic zones.

Natural vegetation on the coastal plain, where Estero Hondo and Laguna Grande are situated, is characterized by mangrove forests that also surround the Estero Hondo Lagoon, with *Rhizophora mangle*, *Avicennia nitida* and *Conocarpus erecta* and dry to semi-arid forest with partly evergeen forest on the transition between the coastal lowlands and the Cordillera Septentrional (Durland, 1922; Holdridge, 1945; Izzo et al., 2010).

3. Material and methods

3.1 Coring and sampling

Two cores were retrieved during a fieldwork campaign in 2015. At 5.5 km from the town La Isabela a 100 cm long sediment core was collected from the shallow (ca. 50 cm deep) near-coastal lake Laguna Grande (19º50'27.2"N, 71º05'21.9"W; Fig. 1). The interval 0-50 cm was collected with a Russian corer and sediments from 50 to 100 cm were collected with a gauge and directly subsampled. About 10 km to the northwest at 2 km from the town Estero Hondo a second core of 167 cm was collected in 50-cm long sections from a mangrove swamp (19º50'22.2"N, 71º11'04.4"W; Fig. 1). using a Rusian corer. Both cores were photographed and labelled LG and EH, respectively, prior to wrapping them into plastic foil protected by half PVC-tubes. Upon transport to Amsterdam, the cores were stored under dark and cold (4°C) conditions.

3.2 Age-depth model, pollen and spore analysis

To establish an age model for both records we aimed at collecting plant macrofossils suitable for radiocarbon dating. Unfortunately, we found no such remains in core LG and therefore we dated 5 bulk sediment samples. At 66 cm shell fragments were found that were dated separate from the bulk sediment matrix, making a total of 6 radiocarbon dates. In core EH we dated a sample with plant remains and furthermore dated 3 bulk sediment samples (Table 1). Samples were dated using accelerator mass spectrometry (AMS) by Beta Analytics laboratory, Florida, USA. Radiocarbon ages were calibrated using the Clam package (version 2.2; Blaauw, 2010) in R (version 3.4.4) using the IntCal13 calibration curve (Reimer et al., 2013) and the postbombing NHZ-2 calibration curve for any negative dates (i.e. post-1950). An age-depth model was constructed using the Bacon package (version 2.3.3) in R (version 3.4.4) using the same calibration curves. The Bacon model reconstructed sediment accumulation in both Laguna Grande and Estero Hondo using Bayesian statistics (Blaauw and Christen, 2011) and provided ages with steps of 1 cm.

For pollen and spore analysis samples of 1 cm^3 were collected at 2 cm increments along the core. Samples were prepared following Faegri et al. (1989) including treatment with sodium pyrophosphate, acetolysis and heavy liquid separation using a bromoform-ethanol mixture with a specific gravity of 2.0. A *Lycopodium* tablet (18 583 spores) was added as spike to each sample (1 cm^3) to calculate pollen and spore concentration values. Identification took place using 400X magnification and pollen morphological literature of Erdtman (1952), Hooghiemstra (1984), Roubik and Moreno (1991), Palacios et al. (1991), Willard et al. (2004) as well as the pollen and spore reference collection of the Institute for Biodiversity and Ecosystem Dynamics (IBED).

For the Laguna Grande core, pollen and spore taxa from the aquatic and wet shore vegetation ecological group (e.g. *Typha* and Cyperaceae) were excluded from the pollen sum as well as algae, fern spores and fungal spores, so as to avoid highly local signals to distract from more regional signals reflected by the pollen spectra. Poaceae were included in the pollen sum. For the Estero Hondo core, aquatic and littoral taxa such as Cyperaceae and *Typha* were included in the pollen sum as part of the mangrove and wet shore vegetation ecological group, reflecting (sub)regional mangrove dynamics (Willard et al., 2004). Unidentified pollen grains, either too much corroded for identification or well preserved but unidentified, were counted as 'indeterminable'. Since unidentified well preserved pollen grains were rare, distinguishing from well-preserved from corroded unidentified grains is irrelevant. We followed Lane et al. (2009) in including unidentified pollen grains in the pollen sum, considering them an unspecified part of the regional vegetation. However, we assess the impact of unidentified pollen grains on the overall trends observed in the pollen diagrams and on the zonation, by comparing the pollen diagrams with and without unidentified grains in the pollen sum. We maintained a bare minimal pollen sum of 30, excluding unidentified pollen grains.

Pollen diagrams were plotted with TILIA 2.0.41 (Grimm, 2015). The diagrams were subdivided into zones based on the results of CONISS stratigraphically constrained cluster analysis (Grimm, 1987), a tool included in the TILIA 2.0.41 software, and visual inspection of the records.

3.3 Charcoal particles

For charcoal analysis 1.3 cm^3 sediment samples were collected at 1 cm increments for the upper 30 cm and at 2 cm increments for the lower 70 cm of Laguna Grande. At 93 and 67 cm unsufficient sediment was available for charcoal analysis. For Estero Hondo samples were collected at 2 cm increments. Samples were treated with 10% HCl at 150 ºC for an hour. Subsequently, samples were washed and sieved into a microscopic fraction (75 µm - 160µm) that represents fires in the landscape (in the order of 10s of km from the coring site) and a macroscopic fraction (>160 µm) that represents fires at the study site (Gosling et al., 2017). Both fractions were placed into petridishes and studied using an Olympus stereoscope using both light from above and beneath. We preferred stereoscopic analysis from petridishes for both fractions over countings on (pollen) slides, since charcoal particles counts are easily overestimated. Tropical soils generally contain several mineral components that resemble charcoal (McMichael et al., 2012). Analyses from petridishes allows for poking with a small needle with light from all directions thereby reducing the risk of misidentification. Pictures of identified charcoal particles from the macrofraction were taken for surface area calculation using ImageJ software (available from https://imagej.nih.gov/ij/) to standardize particle size relative to abundance (Gosling et al., 2017). Upon charcoal quantification we determined a local threshold for the intervals with relatively high (i.e. above background signal) fire frequency as 20% of the maximum charcoal concentration (for both microscopic and macroscopic charcoal particles). A lower threshold of 5% of the maximum charcoal concentration was determined as indicative for the absence of fire (Gosling et al., 2017). Both thresholds are by no means absolute and only serve as a first-order guidance in distinguishing signal from noise.

3.4 Grain size distributions

We measured a set of 84 samples of 1 cm^3 collected from the Estero Hondo core at 2 cm increments along the core. Samples were treated with H_2O_2, HCl and $Na_4P_2O_7$.10 H_2O to oxidize organics, dissolve carbonates and disperse the samples respectively (Konert and Vandenberghe, 1997). GSDs were measured between 0.1 and 2000 µm and classified into 56 classes using a Helium-Neon Laser Optical system (Helos KR)-Laser Particle Sizer, Sympatec Inc. at Vrije Universiteit Amsterdam.

Unmixing sediments into components can provide useful information on depositional processes and regimes as well as provenance of sediments (Paterson and Heslop, 2015; van Hateren et al., 2018). End-member modelling (EMM) is a way of unmixing grain-size data that determines subpopulations in the GSDs of sediments not directly visible from the sample GSDs. EMM was carried out on the GSDs using the AnalySize algorithm (Paterson and Heslop, 2015). This algorithm uses non-negative matrix factorization to unmix the GSDs and least squares as a measure of goodness of fit (Paterson and Heslop, 2015; van Hateren et al., 2018).

3.5 Total organic carbon and carbonate contents

TOC and $CaCO_3$ contents were determined as weight percentages by LOI at Utrecht University. Samples collected at 2 cm increments along the core were dried overnight at 105 ºC, subsequently weighted and heated for 5 hours at 550ºC (Heiri et al., 2001). After weighting once more, the TOC as determined by LOI. Carbonate content was determined similarly by further heating the samples for 2 hours at 950 ºC (Heiri et al., 2001).

4. Results

4.1 Chronology and sedimentation rate

We obtained for Laguna Grande 5 AMS ^{14}C dates and for Estero Hondo 6 AMS ^{14}C dates (Table 1). Simple scatter plots of depth against age show a first order approximation of sedimentation rates for both sites as well as outliers (Fig. 2).

For Laguna Grande the Bacon age-depth model is based on 4 out of the 6 radiocarbon dates (Table 1; Fig 3) and shows steady sedimentation with an average of 0.1 cm yr^{-1}. Modern dates found for a bulk sediment sample and a shell, both from 66-68 cm (but measured seperately), were rejected based on their respective percentages modern (post-1950) carbon (pMc) of 104.19 ± 0.39 and 103.93 +/- 0.39, considered a potential coring artefact (Table 1). According to the model sedimentation starts at 1520 cal yr BP (430 cal yr AD) and furthermore provides an age of 510 cal yr BP (1440 cal yr AD) for the surface sample.

The age model for Estero Hondo is based on all 5 obtained radiocarbon dates, including the outlier at 44 cm (Table 1; Fig. 2a; Fig.3). We added a calendar age of AD 2015 for the uppermost sediment, since the cores was collected in that year. The model shows sedimentation of 0.05 cm yr^{-1} on average starting at 3146 cal yr BP (1196 cal yr BC). Sedimentation rates in the interval 60-25 cm are variable.

Table 1 Radiocarbon ages and sample specific information.

Depth (cm)	Lab #	Material	Uncalibrated ^{14}C (^{14}C yr BP)[a]	IRMS $\delta^{13}C$ (‰)[b]	Calibrated age range (cal yr AD)[c]
Laguna Grande					
10-11	506920	bulk organic sediment	620 ± 30	-22.4	1293-1398 (95)
26-27	506921	bulk organic sediment	980 ± 30	-22.2	1057-1153 (49.2) 994-1055 (45.7)
38-39	420883	bulk organic sediment	830 ± 30	-22.5	1162-1261 (95)
66-68 (rejected)	506922	bulk organic sediment	104.19 ± 0.39 pMC[d]	-23.8	2008-2010 (39.9) 1956-1957 (55.1)
66-68 (rejected)	507270	shell	103.93 ± 0.39 pMC[d]	-8.3	2008-2010 (23.4) 1956-1957 (71.5)
92-94	420884	bulk organic sediment	1550 ± 30	-19.3	424-571 (95)
Estero Hondo					
15-16	506923	bulk organic sediment	105.24 ± 0.39 pMC[d]	-28.6	2006-2010 (77.6) 2007 (17.3)
25-26	506924	woody material	140 ± 30	-24.6	1909-1944 (15.4) 1798-1890 (36.5) 1717-1780 (26.6) 1669-1712 (16.5)
44	506925	woody material	50 ± 30	-24.0	1867-1919 (50.2) 1812-1839 (16) 1695-1727 (21.2)
57-58	420878	plant material	1390 ± 30	-24.9	605-671 (95)
104-105	420879	bulk organic sediment	1740 ± 30	-25.4	238-383 (95)
140-141	420885	plant material	2560 ± 30	-25.3	640-586 BC (15.8) 803-746 (66.7)

[a] Corrected for isotopic fractionation.

[b] IRMS $\delta^{13}C$ on the sample material itself, not the AMS $\delta^{13}C$. Values relative to VPDB-1 standard.

[c] Minimum and maximum calibrated ages with the probability in parentheses. Ages rounded to whole numbers. Only one age is given when the minimum and maximum after rounding coincide. For brevity, only ranges with probabilities >10% are given. For calibration the IntCal13 curve was used (Reimer et al., 2013).

[d] Measured radiocarbon larger than modern reference. Result is expressed as percentage modern carbon (pMC). For calibration the postbombing NHZ-2 curve was used (Hua et al. 2013).

Time axes were added to the figures as a guidance for intercomparison of the cores presented here with one another and with the inland Los Indios (Hooghiemstra et al., 2018) and Biajaca (Castilla-Beltrán et al., 2018) records. Ages for every centimeter are provided as a supplement (Supplementary Information; Tables SI1 and SI2). In interpretations of the results, we report ages rounded-off to the nearest multiple of ten.

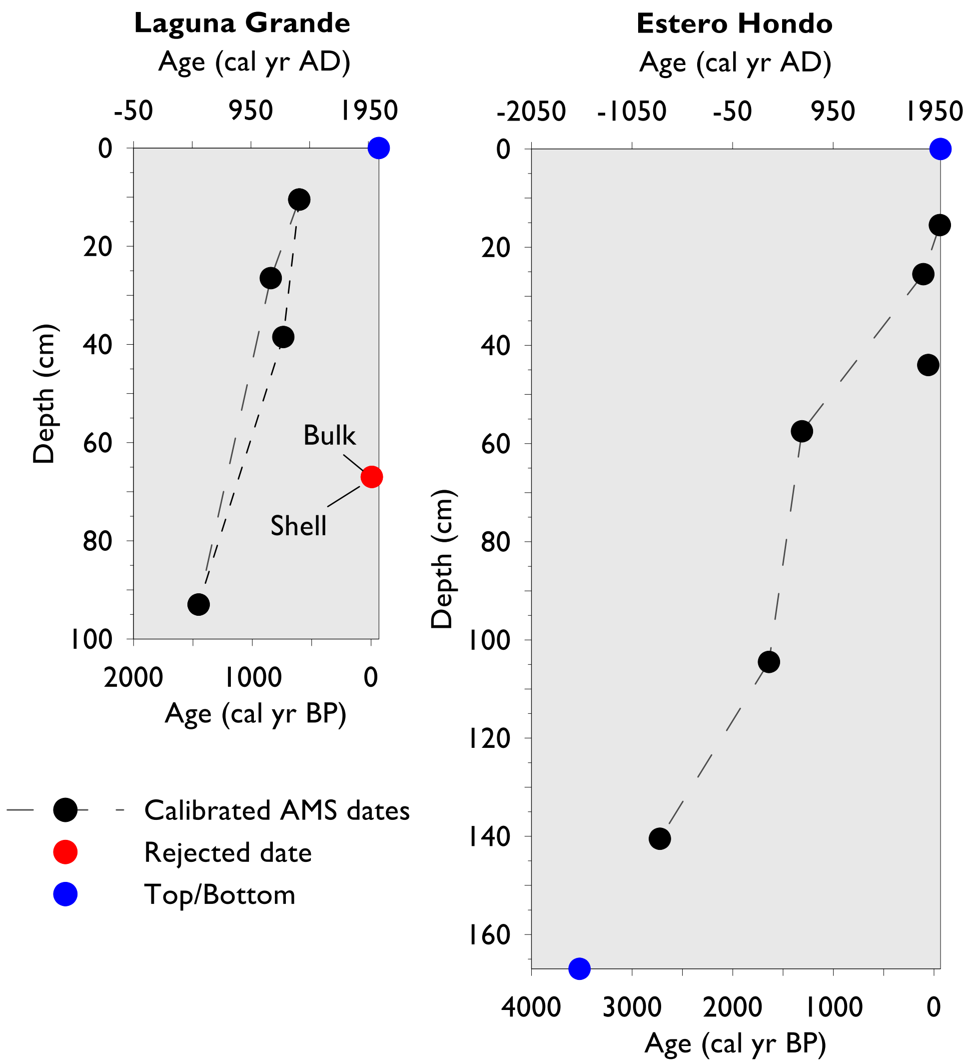

Figure 2 Scatter plots of calibrated AMS ^{14}C dates. Dates are plotted as the mean of the calibrated age range with the highest probability (Table 1). For calibration the IntCal13 and post-bombing NHZ-2 curves were used (Reimer et al., 2013; Hua et al., 2013). **(left)** Laguna Grande. Dashed line segments indicate two possible sedimentation rate trajectories. Blue dot indicates top age assuming the surface sample is modern. **(right)** Estero Hondo. Blue dots indicate the linearly extrapolated bottom and top age assuming the surface sample is modern (AD 2015). Dashed line segments point out apparent changes in sedimentation rates.

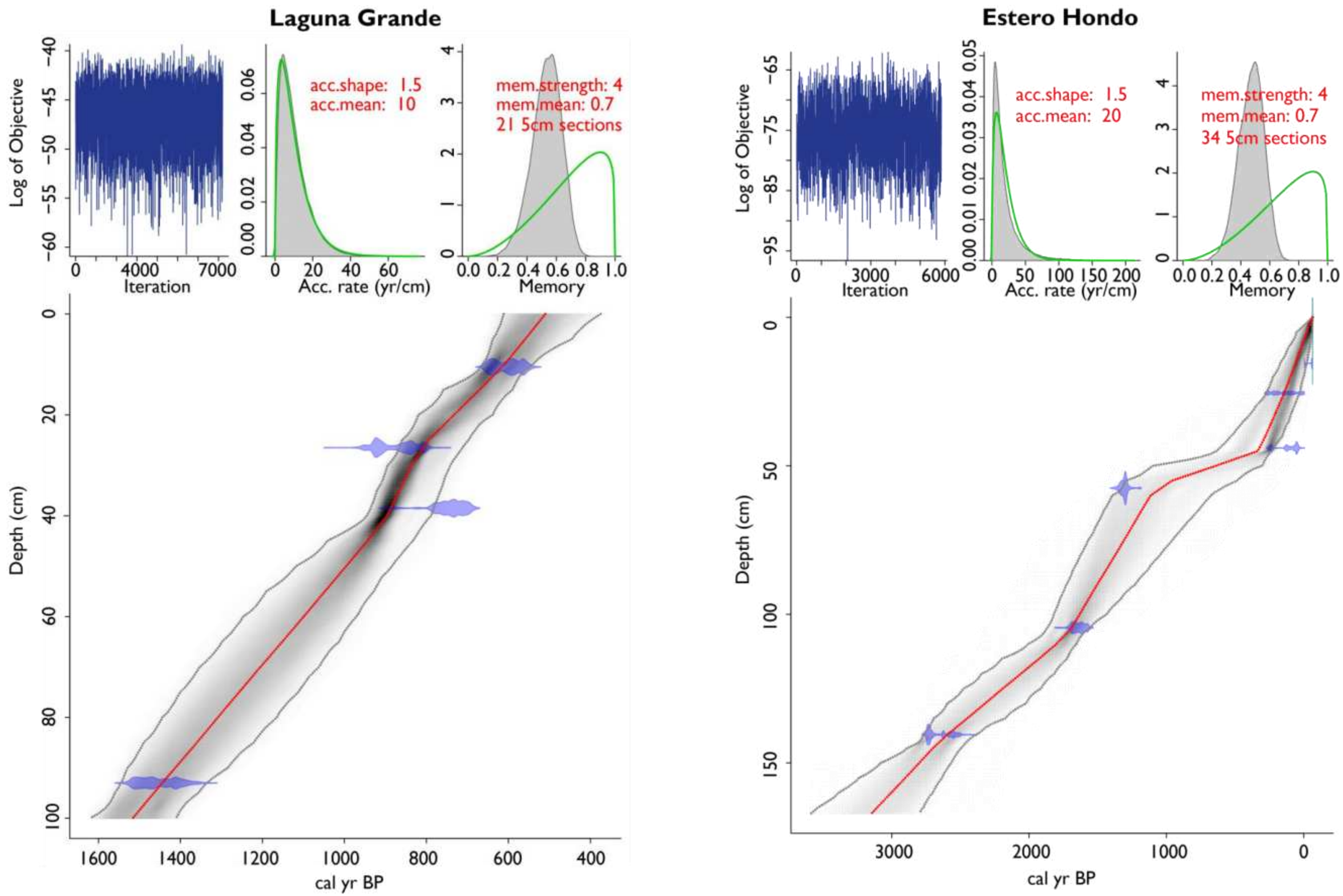

Figure 3 Age-depth models produced with Bacon (default settings; Blauw and Christen, 2011). In the upper left panel Markov Chain Monte Carlo iterations are plotted representing prior accumulation rate distributions. The middle panel histograms represent the posterior ones. The memory of rate distributions are plotted in the right panel. The lower panel shows the age-depth model with the mean (red line) within the 95% confidence interval. **(left)** Laguna Grande. **(right)** Estero Hondo.

4.2 Palynological results

Variations in the pollen spectra are shown in the pollen percentage diagrams as individual records (Laguna Grande, Fig. 4; Estero Hondo, Fig. 8) and summarized by total percentages of ecological groups (LG, Fig. 5; EH, Fig., 9). Both summary percentage plots based on the pollen sum including indeterminable and excluding indeterminable pollen grains are shown. Fern spores, coprophilous fungal spores and non-pollen palynomorphs (NPPs) are plotted as percentages of the pollen sum, allowing for percentages >100% (LG, Fig. 6; EH, Fig. 10). Pollen, spore and NPP concentrations are summarized by totals of ecological groups (LG, Fig 7; EH, Fig. 11), but individual concentration plots are provided as supplementary figures (LG, Suppl. Info. Figs. S1 to S3; EH, Supp. Info. Figs. S4 to S6).

4.21 Laguna Grande

The pollen concentration for Laguna Grande was found to be low throughout the sediment core and varies between <700 and ~27,000 grains cm^{-3} (Fig. 7). The pollen sum includes (1) arboreal pollen (AP), (2) herbaceous pollen also defined as non arboreal pollen (NAP), (3) pollen grains from crop plants and (4) unidentified pollen grains. *Alternanthera* was excluded from the pollen sum given its sudden high abundance and the posibility that it forms floating mats, being a highly local signal and obscuring the dynamics in the taxa reflecting the regional variation. A standard pollen sum of 300 (Moore et al., 1991) was never reached. The pollen sum varied between 9 and 199 (11 to 254 if indeterminable grains are included). Seven samples with a pollen sum <30 were rejected and not included in the diagrams (Table 2).

Zone LG 1 (100 – 85 cm; 2 samples).

The pollen sum is low with 55 grains at the start and 68 by the end. The percentage of AP (AP%) starts at around 16% and decreases to 3%. AP consist *Pinus* (max. 2%), Fabaceae (13% by the start, 1.5% by the end) and Euphorbiaceae (max. 2%). The percentage of NAP (NAP%) is ca. 40% with predominantly Asteraceae tubuliflorae ranging between ca. 18 and 30 %. *Alternanthera* varies between 15 and 20% (note that *Alternanthera* is not included in the pollen sum). Minor abundances of Poaceae (ca. 5%) and *Artemisia* (ca. 2%) complement the suite of herbaceous taxa. No potential crop plants were found. The percentage of aquatic taxa decreases from ca. 35 to 22%. Cyperaceae increase from 11 to 16%, whereas *Typha* decreases from 24 to 2%. The percentage unidentified grains increases from 40 to 56%. Fern abundance increases from ca. 26 to 107%, predominantly caused by an increase of monolete fern spores (absent at the start) and *Cyathea*. We identified 1 spore of the coprophilous fungus *Sporomiella* sp. and 9 chlamydospores of *Glomus* cf..

Zone LG 2 (85 - 48 cm; 7 samples).

The pollen preservation is medium to good with a pollen sum varying between 102 and 254 (160 on average). The AP% ranges from ca. 19 to 32%. Fabaceous taxa are dominant with percentages between 11 and 23%, with a fairly constant abundance of *Pinus* (ca. 4%) and occasionally Myrthaceae (max. 3%), Rubiaceae (max. 1.5%), *Gunnera* (max. 1.5%), Euphorbiaceae (max. 0.6%), Bignoniaceae (max. 0.4%) and Rosaceae (max. 0.4%). The NAP% varies from 49 to 59% and predominantly consists of Asteraceae tubuliflorae (20% on average), *Alternanthera* (20% on average),Poaceae (14% on average) and *Artemisia* (14% on average). We identified a single grain of *Zea mays* (>80 μm) at

79 cm and 2 grains at 51 cm. The percentage of aquatic plants varies between 142 and 235% with a maximum at 59 cm and a subsequent decrease. *Typha* dominates with percentages of 167% on average, followed by Cyperaceae with 18% on average and minor occurences of *Polygonum* (max. 1%). The percentage of unidentified grains is 19% on average. *Azolla* varies between 1 and 10%, whereas *Spirogyra* sp. ranges from 0 to 3%. Ferns are less abundant than in zone LG 1, varying between 27 and 71%, mostly monolete spores. Type HH-313 or cf. *Phaeoceros* (hornworts) is relatively abundant with a maximum of 24% at 57 cm. We identified maximally 9 spores of coprophilous *Sporomiella* sp. The abundance of *Glomus* cf. varies between 1 and 12% with a maximum at 69 cm. Unidentified 2-porate fungus spore type SR-1 shows a maximum of ca. 140% at 59 cm.

Zone LG 3 (48 – 30.5 cm; 2 samples).

Pollen preservation in this core interval is poor. Consequently, 5 out of 7 samples were discarded. The AP% increases to 33% at the start of this interval compared to zone LG 2 and subsequently decreases to 20%. *Pinus* varies from 11 to 6% and is more abundant than in zone LG 2. Fabaceae are less abundant than in zone LG 2 and remain constant at ca. 11%. Myrthaceae show a maximum of 6% at 44 cm. Other minor contributions (max. 1%) of arboreal taxa include occurences of Bombacaceae-type, Proteaceae, Melastomataceae *Ilex, Alnus*, Solanaceae and Urticaceae-Moraceae. The NAP% ranges between 28% by the start of the zone and 39 % at 34.5 cm. Most dominant are Asteraceae tubuliflorae (14-19%), *Alternanthera* (ca. 16%) and Poaceae (4-14%). *Artemisia* is less abundant than in zone LG 2 (ca. 5%). Campanulacae-type (max. 4%) and Bromeliaceae (max. 1%) complement the suite of herbaceous taxa. Amaranthaceae are less abundant than in zone LG 2 (max. 1%). No other potential crop plants were found. The aquatic percentage increases to 216 % by the start of the zone and decreases to 133% at 34.5 cm. *Typha* decreases from 98 to 81% whereas Cyperaceae decrease from 70 to 30%. *Polygonum* is more abundant than in zone LG 2 (ca. 5%). The percentage of unidentified grains is ca. 19%. *Spirogyra* sp. increases from 1 to 6 % and the percentage *Azolla* is ca. 3%. Ferns decrease from 100 to 67%, mostly caused by a decrease in al fern spore types except for monolete psilate spores that increases from 10 to 39%. We found no spores of hornworts (e.g. *Anthoceros seliganella* or type HH-313). We identified a single coprophilous fungal spore of *Sporomiella* sp. at 34.5 cm. Fungal spore type SR-1 is fairly absent (max. 1%). *Glomus* cf. increases from 1 to 11%.

Zone LG 4 (30.5 – 5.5 cm; 10 samples).

Pollen preservation varies from poor to good with the pollen sum varying between 56 and 232 (112 on average). Two slides with a pollen sum (excluding unidentified grains) <30 were discarded. The AP% is variable throughout the zone. It starts with 39% at 26.5 cm and decreases to 20% at 22.5 cm and remains ca. 20% untill it increases from 10.5 cm onwards. The AP% reaches a maximum of 42% at 8.5 cm and decreases to 16% at 7.5 cm. *Pinus* and Fabaceae remain the dominant arboreal taxa. *Pinus* starts at a maximum of 30% and subsequently decreases to values not exceeding 10% until the percentage increases from 10.5 cm onwards to a maximum of 14% at 8.5 cm. The Fabaceae percentage commences with 2% and subsequently increases to a regime of higher abundance (ca. 6 – 30%) with an overall increasing trend. Several arboreal taxa present in LG 3 disappear from the pollen assemblage including Bombacaceae-type, *Ilex*, and *Alnus*. First occurrences include Areaceae (max. 1%), *Warczewiczia* (max. 1%), Euphorbiaceae (max. 1%) *Borreria* (maximum of 5% at 26.5 cm; subsequently max. 2%),), *Alchornea* (max. 1%), Sapindaceae (max. 1%), Malvaceae (max. 2%) and

Urticaceae-Moraceae (max. 1%). The NAP% shows an overall increasing trend starting at ca. 9% and reaching a maximum of 62% at 11.5 cm. *Alternanthera* starts at a maximum of 163% and further varies between 99 and 34%. Occurrences of Amaranthaceae are more abundant than in zone LG 3, ranging between ca. 2 and 13%. We found minor occurences of Caryophyllacae (1% at 22.5 cm) and Polygalaceae (1% at 17.5 cm), whereas no Campanulaceae-type or Bromeliaceae were found. We identified 2 grains of *Zea mays* at 9.5 cm. The percentage of aquatic taxa varies from 26 to 163%. *Typha* dominates with a maximum of ca. 130% between 17.5 and 11.5 cm. A distinct peak of *Polygonum* (14%) is present at 26.5 cm. Subsequently, *Polygonum* does not exceed 4%. Furthermore, we recognized occurences of Apiaceae (max. 2%) and *Sparganium* (max. 1%). The percentage unidentified grains ranges between 14 and 45%. Occurences of *Spirogyra* sp. do not exceed counts of 2 chlamydospores. *Azolla* percentages vary from 0 to 10%. Fern spores start at a maximum of 136% with predominantly *Cyathea* at 26.5 cm and decrease to 49% at 22.5 cm. Subsequently, abundances of ferns vary between ca. 20 and 50%. Hornworts of type HH-313 are more abundant than in zone LG 3 with a maximum of 17% at 11.5 cm. Spores of *Sporomiella* sp. are present throughout the zone (max. 2 spores). The abundance of *Glomus* cf. peaks at 22.5 cm (29%) and 8.5 cm (45%). More spores of type SR-1 are present than in zone LG 3, varying between 0 and 44%.

Zone LG 5 (7 – 0 cm; 4 samples)

Pollen preservation varies from poor to good with the pollen sum ranging from 56 to 207 (Table 2). The AP% varies from 17 to 57%. Fabaceae are dominant with abundances from 23 to 36% with a distinct minimum of 4% at 4.5 cm. *Pinus* abundance varies from 6 to 18%. As opposed to LG 4, we found no Proteaceae, *Warczewiczia*, *Alchornea*, Sapindaceae, Malvaceae nor Urticaceae-Moraceae. We identified Meliaceae (<1%) and noted the reappearance of Rubiaceae (max. 2%). The NAP% ranges from 30 to 68% with predominantly Asteraceae tubuliflorae (21 to 43%), Poaceae (2 to 15%) and *Artemisia* (ca. 8%). Furthermore, Amaranthaceae ranges from 0 to 15 %. We identified 2 grains of *Zea mays* at 4.5 cm and 1 grain at 3 cm. Aquatics peak at 3 cm (323%), mostly by high abundance of *Typha* (296%). We identified 1 grain of *Polygonum* at 1 cm. We found no Apiaceae, *Sparganium* nor *Spirogyra* sp., as opposed to minor occurences in LG 4. *Azolla* ranges from 3 to 7%. The percentage unidentified grains is relatively stable around 10%. Ferns vary from 20 to 73%, with mostly monolete and *Cyathea* spores. The hornworts of type HH-313 peak at 3 cm (43%). We identified 1 fungus spore as *Cercophora*-type (4.5 cm) and found minor occurences of *Sporomiella* sp. (max. 1 spore). *Glomus* cf. peaks at 3 cm (21%) along with unidentified fungus spores of type SR-1 (170%).

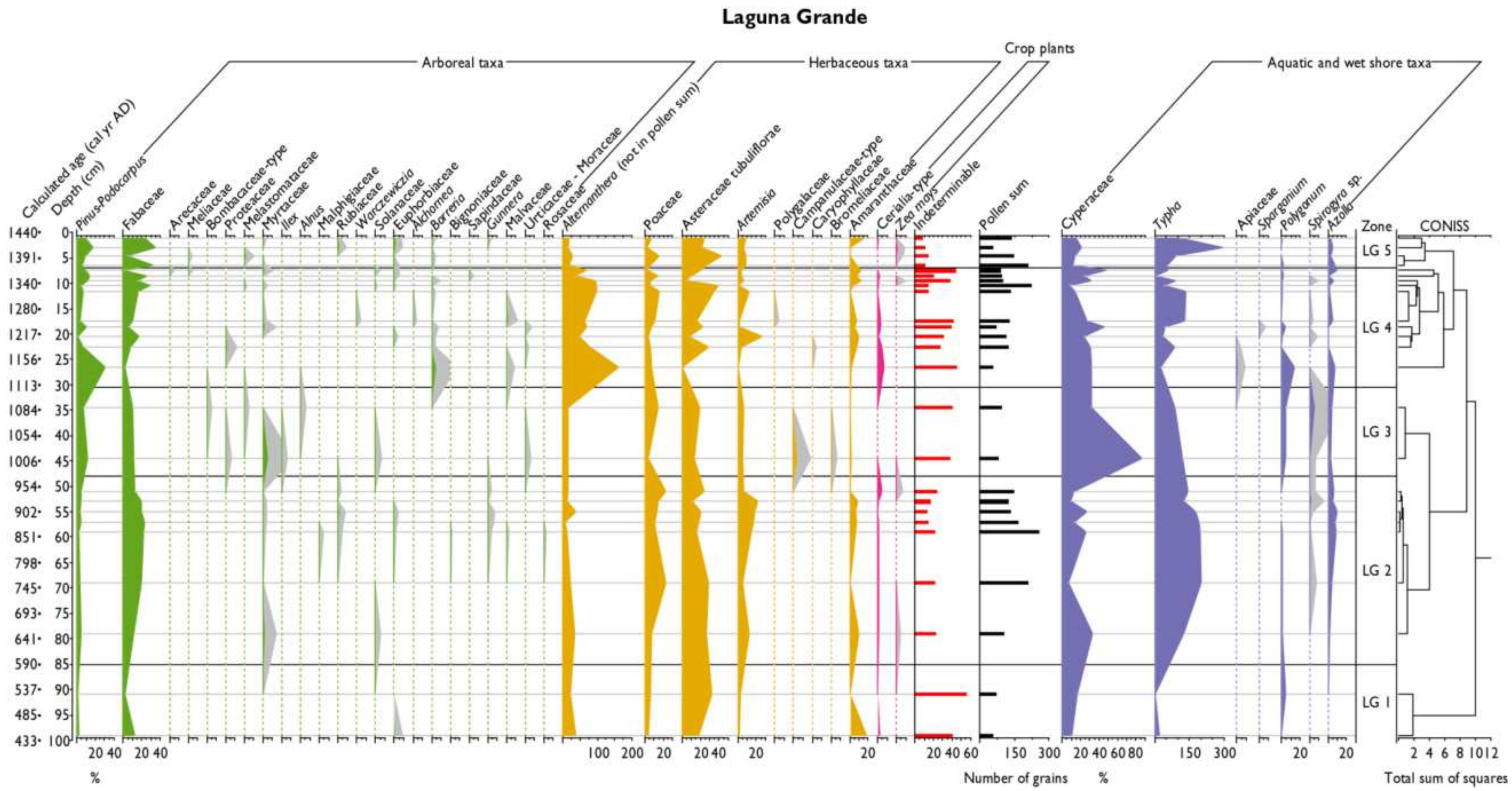

Figure 4 Pollen percentage diagram of core Laguna Grande based on a pollen sum that excludes *Alternanthera* and includes indeterminable grains. Data are plotted on a linear depth scale. From left to right are shown: calculated age (cal yr AD), depth (cm), individual abundances of taxa included in the pollen sum (except for *Alternanthera*) arranged into ecological groups, percentage of indeterminable grains (included in the pollen sum), pollen sum, individual abundances of taxa excluded from the pollen sum (aquatic and wet shore taxa), pollen zones and the CONISS dendrogram. Exaggeration x5.

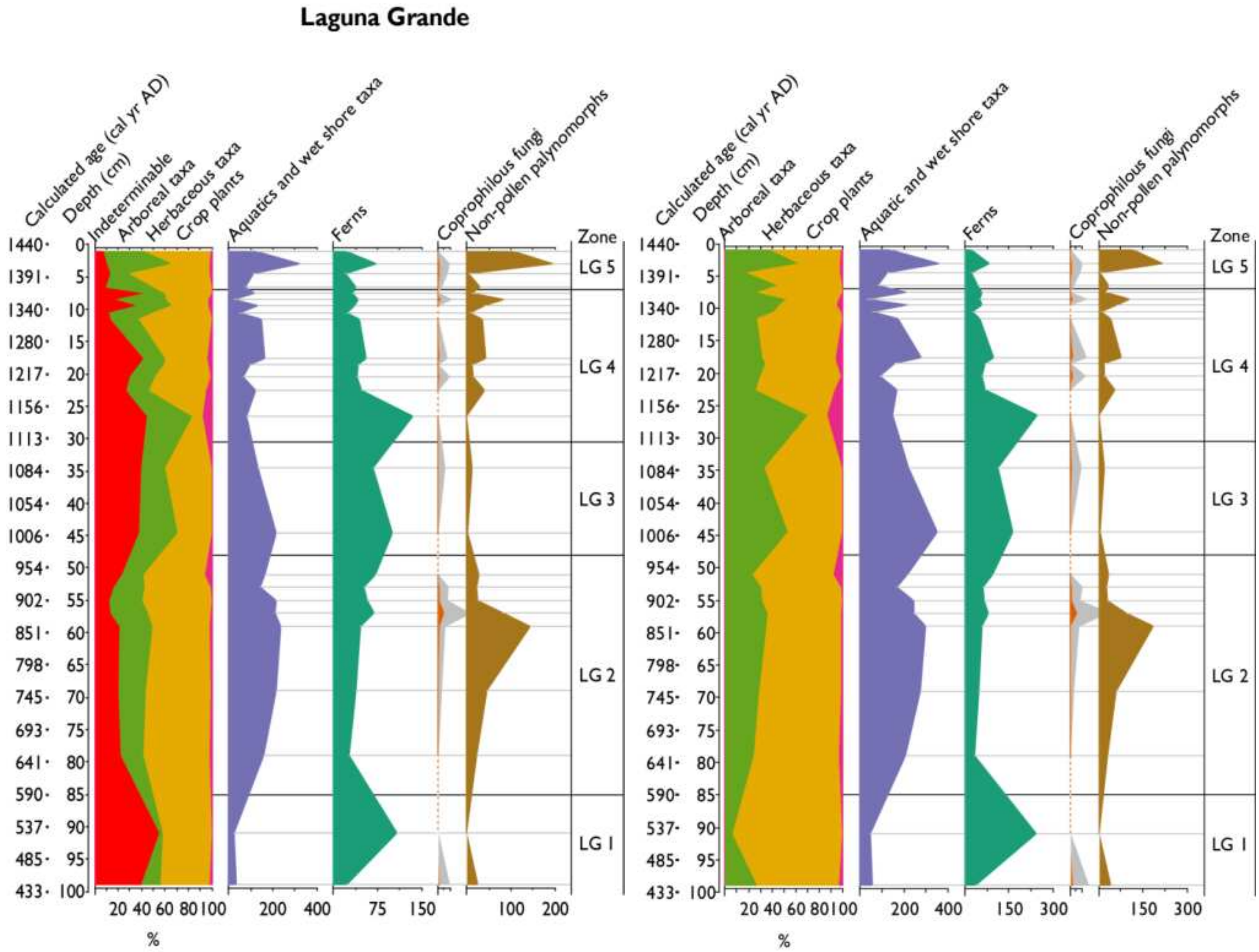

Figure 5 Summary pollen percentage diagram of core Laguna Grande. Data are plotted on a linear depth scale. From left to right are shown: calculated age (cal yr AD), depth (cm), general pollen diagram showing proportions of ecological groups, records of aquatic and wet shore taxa, fern spores, coprophilous fungal spores, non-pollen palynomorphs and pollen zones. Exaggeration x5. **(left)** Including indeterminable pollen grains in the pollen sum. **(right)** Excluding indeterminable grains.

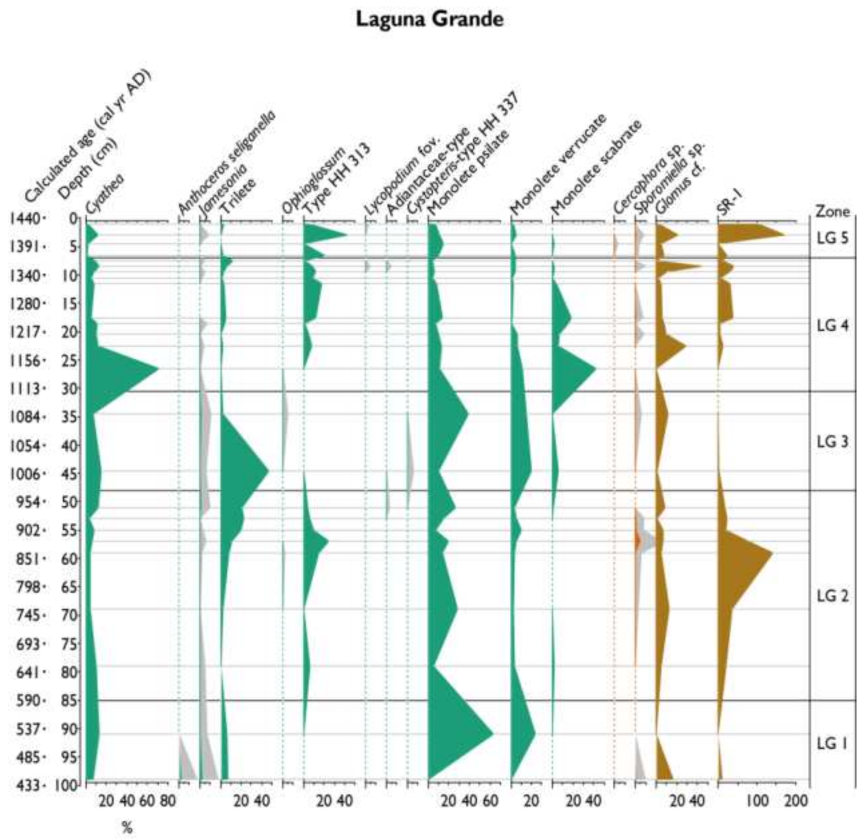

Figure 6 Relative abundances of fern spores, coprophilous fungal spores and non-pollen palnynomorphs from Laguna Grande. Data are plotted on a linear depth scale. From left to right are shown: calculated age (cal yr AD), depth (cm), individual abundances and pollen zones. Exaggeration x5.

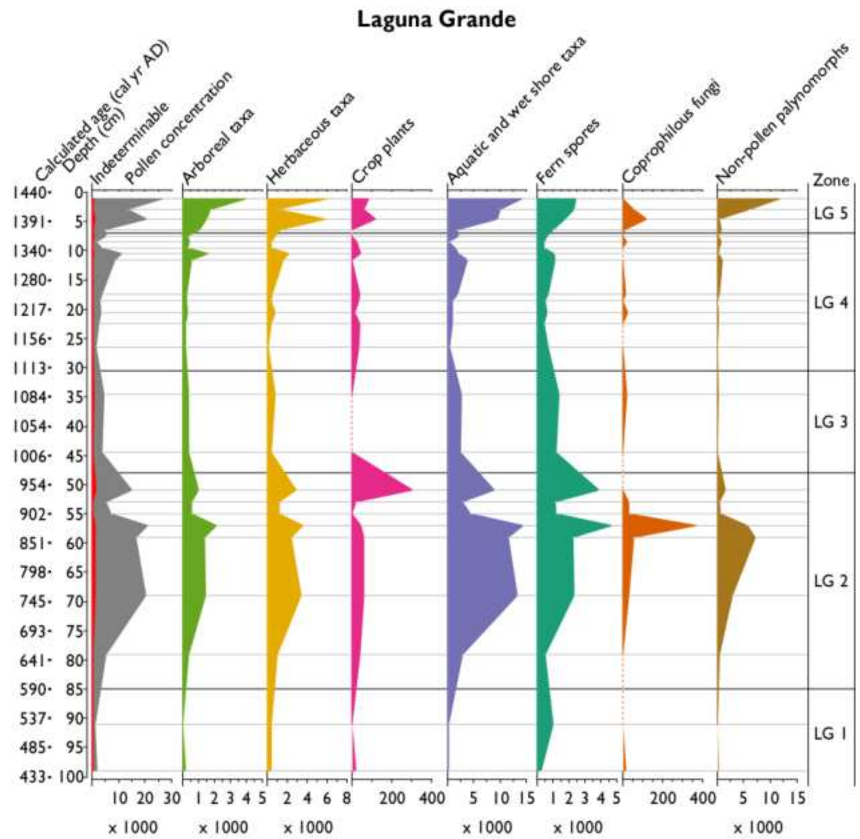

Figure 7 Pollen concentrations of core Laguna Grande (grains cm^{-3} of sediment). Data are plotted on a linear depth scale. From left to right are shown: calculated age (cal yr AD), depth (cm), pollen concentration with indeterminable grains as overlay, concentrations of all ecological groups and pollen zones.

Table 2 A pollen sum including indeterminable grains and a pollen sum excluding indeterminable grains for the Laguna Grande core. Samples in bold were rejected based on a pollen sum (excluding indeterminable grain) <30.

Depth (cm)	Pollen sum (including indeterminable)	Pollen sum (excluding indeterminable)	Indeterminable
0-2	137	126	11
2-4	56	50	6
4-5	146	126	20
6-7	207	185	22
7-8	88	49	39
8-9	92	74	18
9-10	99	62	37
10-11	223	193	30
11-12	132	113	19
14-15	**25**	**20**	**5**
17-18	129	75	54
18-19	70	43	27
20-21	112	78	34
22-23	123	89	34
24-25	**62**	**27**	**35**
26-27	56	31	25
28-29	**41**	**17**	**24**
29-30	**11**	**9**	**2**
30-32	**41**	**23**	**18**
34-35	94	56	38
38-40	**32**	**20**	**12**
40-42	**35**	**23**	**12**
44-45	81	50	31
50-52	145	111	34
52-54	124	103	21
54-56	134	117	17
56-58	164	141	23
58-60	254	199	55
68-70	208	165	43
78-80	102	79	23
90-92	68	30	38
98-100	55	33	22

4.2.2 Estero Hondo

The pollen concentration for Estero Hondo was found to be higher throughout the sediment core as compared to Laguna Grande, though still low varying between <1250 and ~20,000 grains cm^{-3} (Fig. 11). The pollen sum includes (1) AP, (2) NAP, (3) pollen grains of crop plants, (4) mangrove pollen and (5) unidentified pollen. The pollen sum varied between 73 and 474 (79 and 510 if indeterminable grains are included; Table 3).

Zone EH 1 (167-155.5 cm; 1 sample).

Pollen preservation is medium with the pollen sum being 110 (Table 3). The AP% is ca 18%, with predominantly Myrthaceae (12%) and minor occurences of Euphorbiaceae (4%), *Pinus* (2%) and

Ilex (1%) (Fig. 8). The NAP% is ca. 3%, with rare (1%) occurences of *Artemisia*, Bromeliaceae and Onagraceae. Mangrove vegetation dominates with 60%, with mostly *Conocarpus erecta* (40%) and *Rhizophora mangle* (13%). Minor occurences of *Avicennia germinans* (3%) and *Acrostichum* (1%) complement the suite of mangrove taxa. The percentage unidentified grains is 19%. Ferns account for 19% with mostly *Cyathea* (7%) and hornwort *Anthoceros seliganella* (6%).

Zone EH 2 (155.5 – 98; 3 samples).

Pollen preservation is good with the pollen sum varying between 143 and 377 (Table 3). The AP% ranges from 17 to 20 % with predominantly euphorbiaceous (ca. 5%) and dodonaceous (ca 4%) taxa (Fig. 12). Myrtaceae peaks at 125.5 cm (4%). Minor occurences include *Pinus* (ca. 1.5%), Fabaceae (ca. 2 %), Melastomataceae (max. 1.5%) as well as single/rare occurences of *Ilex*, *Borreria*, Boraginaceae, Bignoniaceae, Sapotaceae, Sapindaceae, Malvaceae and Urticaceae – Moraceae. The NAP% varies between 3 and 4% and includes presence of Bromeliaceae (max. 2%), Asteraceae tubuliflorae (<1%), *Ambrosia*-type (max. 3%), Campanulaceae-type (<0.5%) and Poaceae (<0.5%). Cucurbitaceae show abundances of 4% with a peak of 25% at 105.5 cm coeval with the first occurrence of *Ambrosia*-type. Mangrove remains the dominant vegetation with abundances from 44 to 70%. *Conocarpus erecta* starts at 11% (lower than in EH 1) and decreases to 1%. *Avicennia germinans* increases from 1 to 6%. *Rhizophora mangle* is more abundant than in EH 1, with percentages ranging from 34 to 61%. Cyperaceae peak at 105.5 cm (3.5%). The percentage of unidentified grains decreases from 17% at the start to 7% by the end of the zone. Ferns are less abundant than in EH 1, varing from 5 – 15%. Monolete and trilete spores peak at 105.5 cm accounting for 14%. We found 2 fungal spores of both *Cercophora*-type and *Sporomiella* sp. as well as 1 chlamydospore of *Glomus* cf. at 145.5 cm.

Zone EH 3 (98 – 25.5 cm; 7 samples).

Pollen preservation is generally good with the pollen sum being 309 on average with a low pollen sum at 80-81 cm (79 grains). The AP% increases from 23% at the start to 33% by the end of zone EH 3, with two minima at 80.5 cm (14%) and 49.5 cm (21%). In total 23 arboreal taxa were recognized, an increase of ca. 64% compared with zone EH 2 that counts 14 taxa. Both *Pinus* and Fabaceae generally show abundances of 1 to 3%. Between 40.5 and 30.5 cm peak with ca. 5% (*Pinus*) and 4% (Fabaceae). First appearances, either rare or single, include Arecaceae, Meliaceae, Proteaceae, *Datura-Brugmansia*-type, Solanaceae, Sapotaceae, Sapindaceae (max. 3%), *Spondias*-type, *Cordia lanata*-type, *Cordia gerascanthus*-type, Anarcadiaceae, *Juglans* and Rosaceae (ca. 2%). Bignoniaceae, present in zone EH 2, is absent. The NAP% varies between 4 and 8%, except for a maximum of 19% at 80.5 cm. *Ambrosia*-type are dominant, varying between 2 to 4%, except for a maximum of 14% at 80.5 cm. Asteraceae tubuliflorae vary about a mean of ca. 1%. Poaceae account for maximally 1% (max. 3 grains). Bromeliaceae have abundances <0.5%, except for a maximum of 2% at 60.5 cm. Amaranthaceae presence accounts for ca. 1% throughout the zone. Single to rare occurences of herbaceous taxa include Polygalaceae and Onagraceae. Cucurbitaceous taxa start with abundances of 4% and subsequently decrease to ca. 1% from 70.5 cm onwards. Mangrove abundances vary around 55%, with a maximum of 63% at 70.5 cm. *Rhizophora mangle* remains dominant starting with abundances of ca. 47% that decrease to 40% from 60.5 cm onwards. *Avicennia germinas* ranges from 8 to 12% with a maximum of 16% at 70.5 cm. *Conocarpus erecta* shows abundances of ca. 1%. Minor occurences include *Acrostichum* (max. 2 spores), Cyperaceae (max. 1%) and *Typha* (max. 1%) The percentage of unidentified grains varies from 6 to 8% with a maximum of 12% at 49.5 cm. Fern abundances range between 3 and 9% with maxima at 80.5 cm (17%), 49.5 cm (20%) and 40.5 cm (14%). Maxima are primarily caused by higher abundances of trilete fern spores including *Cyathea* and *Jamesonia*. We found 2 fungal spores of *Cercophora*-type and minor occurences of *Sporomiella* sp. (max. 2 spores). Moreover, we identified 2 chlamydospores of *Glomus* cf. at 60.5 cm.

Zone EH 4 (25.5 – 0 cm; 3 samples).

Pollen preservation is good with the pollen sum varying from 235 to 510. The AP% starts at 36%, increases to 42% and decreases to 24% by the end of the zone. The number of arboreal taxa decreased compared to zone EH 3 from 24 to 19. Both *Pinus* and Fabaceae show abundances from 2 to 4%. Abundances of Urticaceae decrease from 7% at the start of zone EH 4 to 3% by the end. Euphorbiaceous taxa decrease in abundance from 8 to 3%. Furthermore, a distinct peak in Rubiaceae abundance of 20% is present at 10.5 cm. *Croton* and Meliaceae appear for the first time. (only single occurences). Other taxa including Arecaceae, Proteaceae, *Brugmansia-Datura*-type, Solanaceae, *Cordia lanata*-type, *Cordia gerascanthus*-type, Anarcadiaceae and *Juglans* are absent as opposed to minor occurences in EH 3. The NAP% ranges from 16 to 24%, and predominantly consists of Asteraceae tubuliflorae that increases from 10 to 16%. Poaceous taxa increase from 2 to 7%. Minor occurences of Polygalaceae (2 grains), Bromeliaceae (max. 2 grains), *Ambrosia*-type (max. 4 grains), *Geranium* (1 grain) and Onagraceae (max. 1 grain). Cerialia-type palynomorphs are more abundant than in other zones, with abundances of ca. 4%. We found 1 grain of *Zea may*distat 10.5 cm. Cucurbitaceae are nearly absent (max. 2 grains). Percentages of mangroves are lower than in the preceding zones, varying from 31 to 40%. Both *Avicennia germinans* (ca. 6%) and *Rhizophora mangle* (20 – 26%) are less abundant than in zone EH 3, whereas *Conocarpus erecta* becomes more abundant (ca. 2%). *Acrostichum* increases from 0 to 3%. Cyperaceae (1 to 2%) is more abundant compared to zone EH 3.The percentage unidentified grains varies from 7 to 11%. Ferns become more abundant throughout the zone varing from 8 to 36% with predominantly monolete spores. We identified fungal spores of *Sporomiella* sp. (max. 1 spore), *Cercophora*-type (max. 2 spores), *Chaetonium*-type (1 spore), type UG1122 (max. 4 spores) and chlamydospores of *Glomus* cf. (max. 3 spores).

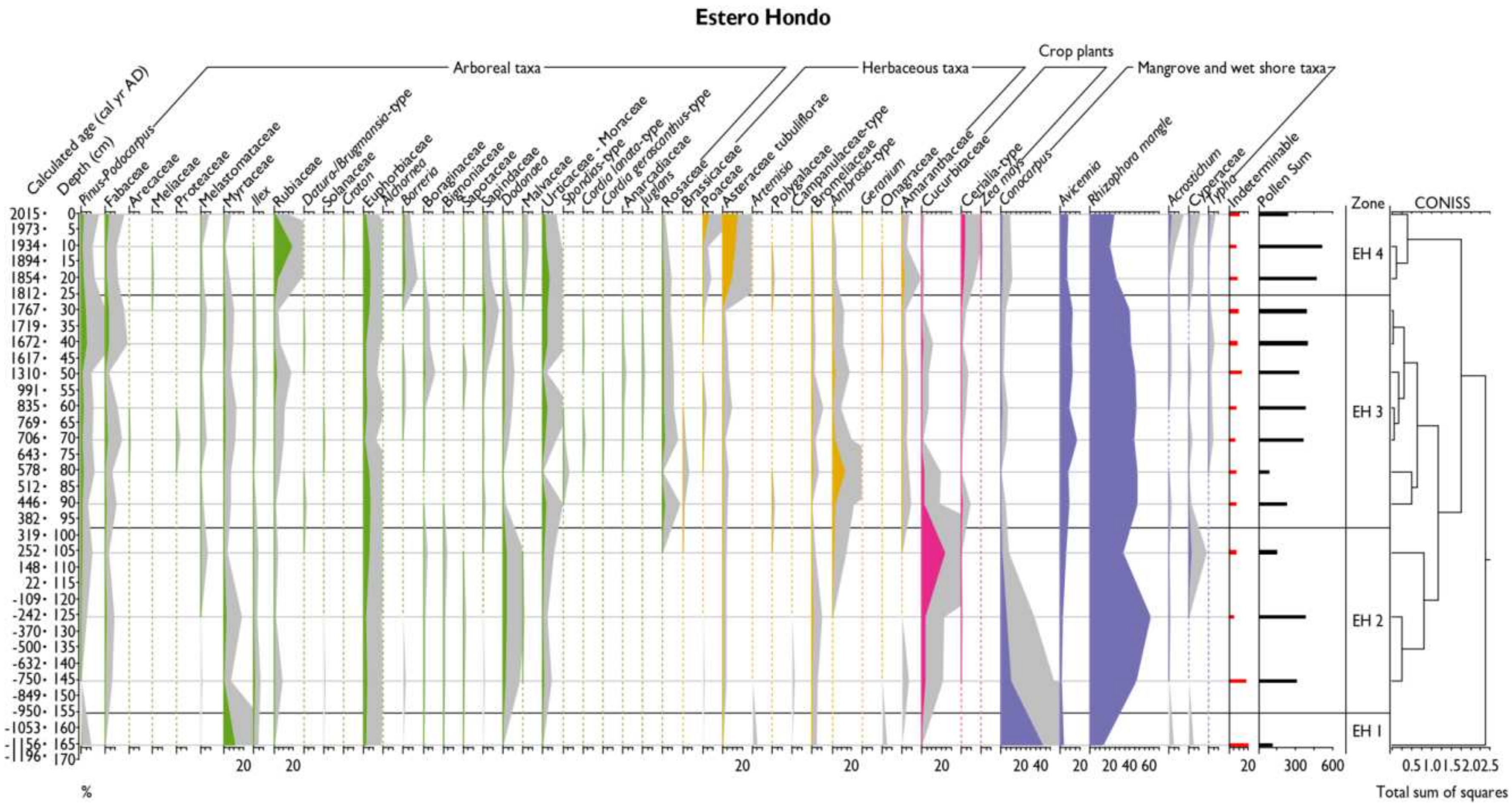

Figure 8 Pollen percentage diagram of core Estero Hondo based on a pollen sum that includes indeterminable grains. Data are plotted on a linear depth scale. From left to right are shown: calculated age (cal yr AD), depth (cm), individual abundances of taxa arranged into ecological groups, percentage of indeterminable grains (included in the pollen sum), pollen sum, pollen zones and the CONISS dendrogram. Exaggeration x5.

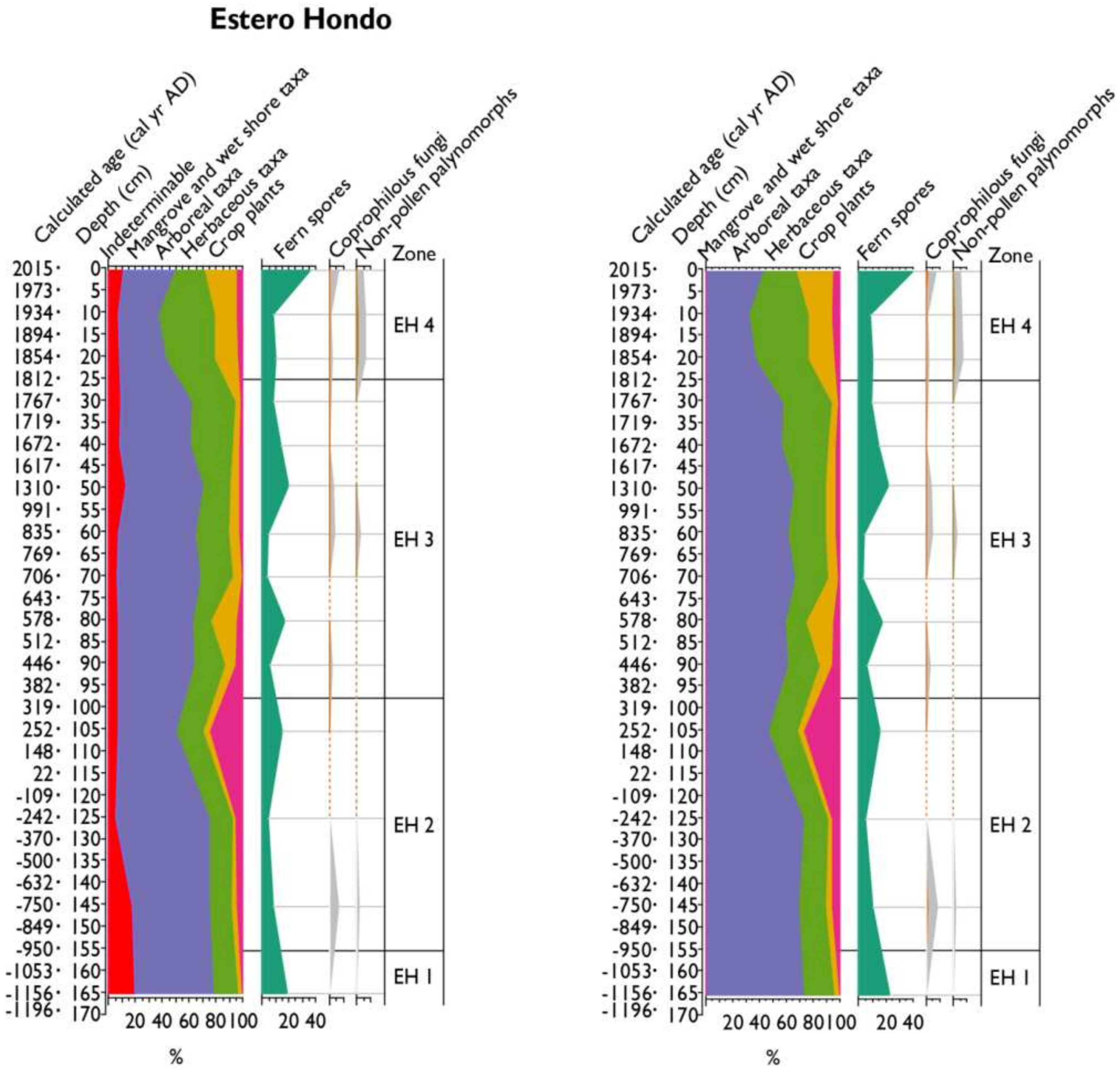

Figure 9 Summary pollen percentage diagram of core Estero Hondo. Data are plotted on a linear depth scale. From left to right are shown: calculated age (cal yr AD), depth (cm), general pollen diagram showing proportions of ecological groups, records of aquatic and wet shore taxa, fern spores, coprophilous fungal spores, non-pollen palynomorphs and pollen zones. Exaggeration x5. **(left)** Including indeterminable pollen grains in the pollen sum. **(right)** Excluding indeterminable grains.

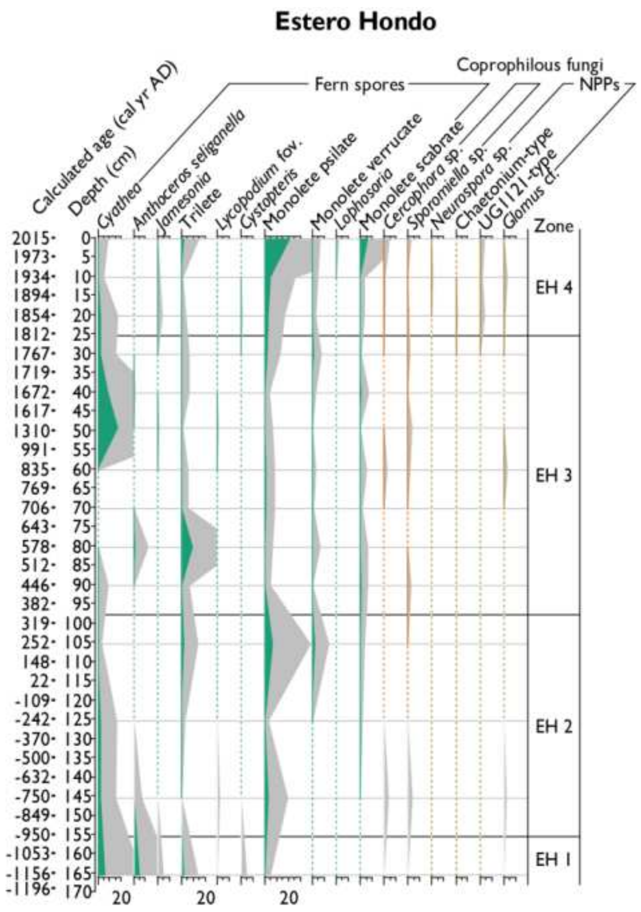

Figure 10 Relative abundances of fern spores, coprophilous fungal spores and non-pollen palynomorphs from Estero Hondo. Data are plotted on a linear depth scale. From left to right are shown: calculated age (cal yr AD), depth (cm), individual abundances and pollen zones. Exaggeration x5.

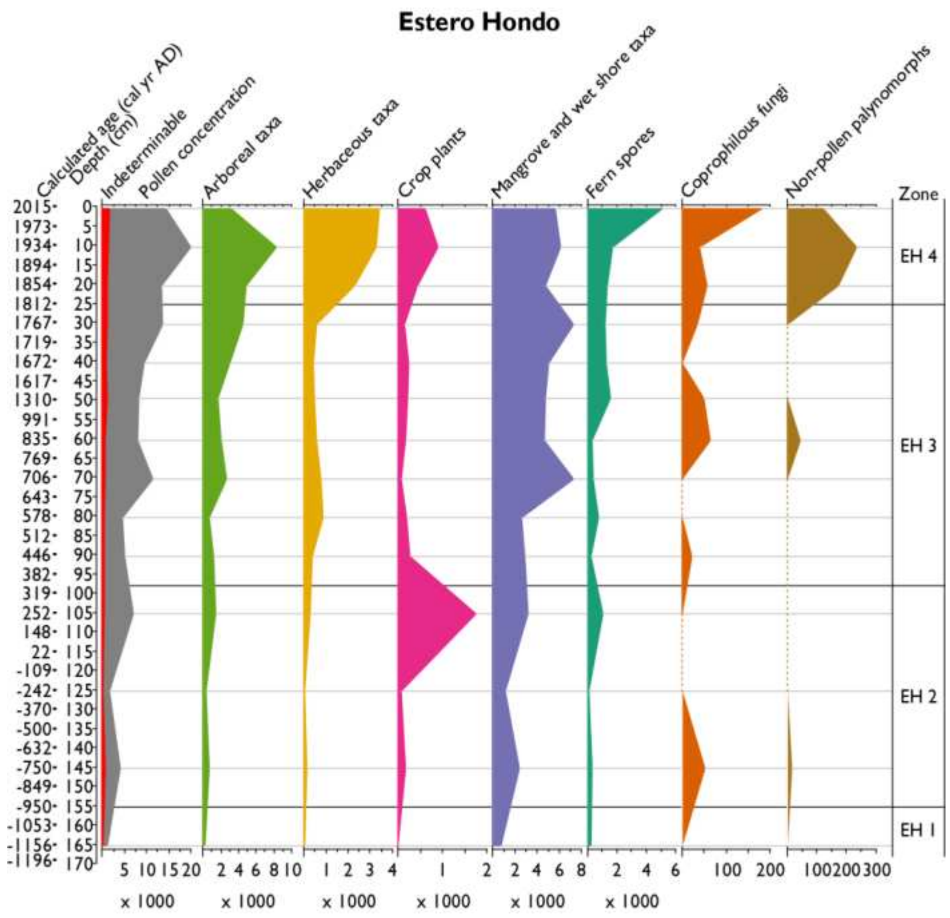

Figure 11 Pollen concentrations of core Estero Hondo (grains cm^{-3} of sediment). Data are plotted on a linear depth scale. From left to right are shown: calculated age (cal yr AD), depth (cm), pollen concentration with indeterminable grains as overlay, concentrations of all ecological groups and pollen zones.

Table 3 A pollen sum including indeterminable grains and a pollen sum excluding indeterminable grains for the Estero Hondo core.

Depth (cm)	Pollen sum (including indeterminable)	Pollen sum (excluding indeterminable)	Indeterminable
0-1	235	210	25
10-11	510	474	36
20-21	472	434	38
30-31	392	357	35
40-41	395	362	33
49-50	327	286	41
60-61	381	353	28
70-71	357	335	22
80-81	79	73	6
90-91	231	214	17
105-106	143	133	10
125-126	377	355	22
145-146	308	254	54
165-166	110	89	21

4.3 Charcoal

We visualized charcoal concentrations on a linear depth scale together with the pollen zones (Fig. 12).

4.3.1 Laguna Grande

A local threshold for frequent regional fire occurrence was determined as ~14 particles per cm^3 of sediment (20 % of the maximum count of 72). We found a threshold of ~4 particles per cm^3 of sediment (5 % of 94) below which we infer near absence of regional fire. Accordingly we determined thresholds of 0.45 mm^2 cm^{-3} for frequent local fire occurences and 0.11 mm^2 cm^{-3} for near absence of local fires (maximum 2.27 mm^2 cm^{-3}). Both fractions show an increase with decreasing depth (Fig. 12).

In zone LG 1 (100 – 85 cm) we found no concentrations above the lower threshold. Note that at 93 cm no sample was available.

In zone LG 2 (85 – 48 cm) microscopic charcoal concentrations in all samples from 73 cm onward surpass the lower threshold. Except for peaks at 69 and 63 cm, concentrations do not surpass the upper threshold. Macroscopic charcoal concentrations do not surpass either of thresholds. Note that at 67 cm no sample was available.

In zone LG 3 (48 – 30.5 cm) microscopic concentrations at 37 and 31 cm surpass the lower threshold. No samples surpass the upper threshold. The macroscopic charcoal concentrations at 31 cm overcomes the lower threshold. No samples overcome the upper threshold.

In zone LG 4 (30.5 – 7 cm) all microscopic concentrations are larger than the lower threshold and upper threshold, except for the intervals 24.5 to 23.5 cm and 17.5 to 14.5 cm where concentrations do not overcome the upper threshold value. Macroscopic concentrations from 26.5

to 21.5 cm and at 19.5 and 16.5 cm do not surpass the lower threshold value, all other concentrations do. Concentrations at 13.5, 10.5, 9.5 and 7.5 cm overcome the upper threshold value.

In zone LG 5 (7 – 0 cm) all microscopic concentrations are larger than the upper threshold value exceptly at 3.5 cm. Macroscopic concentrations at 6.5 and 3.5 cm do not surpass the lower threshold; all others do. Macroscopic concentrations at 5.5 and 4.5 cm overcome the upper threshold value.

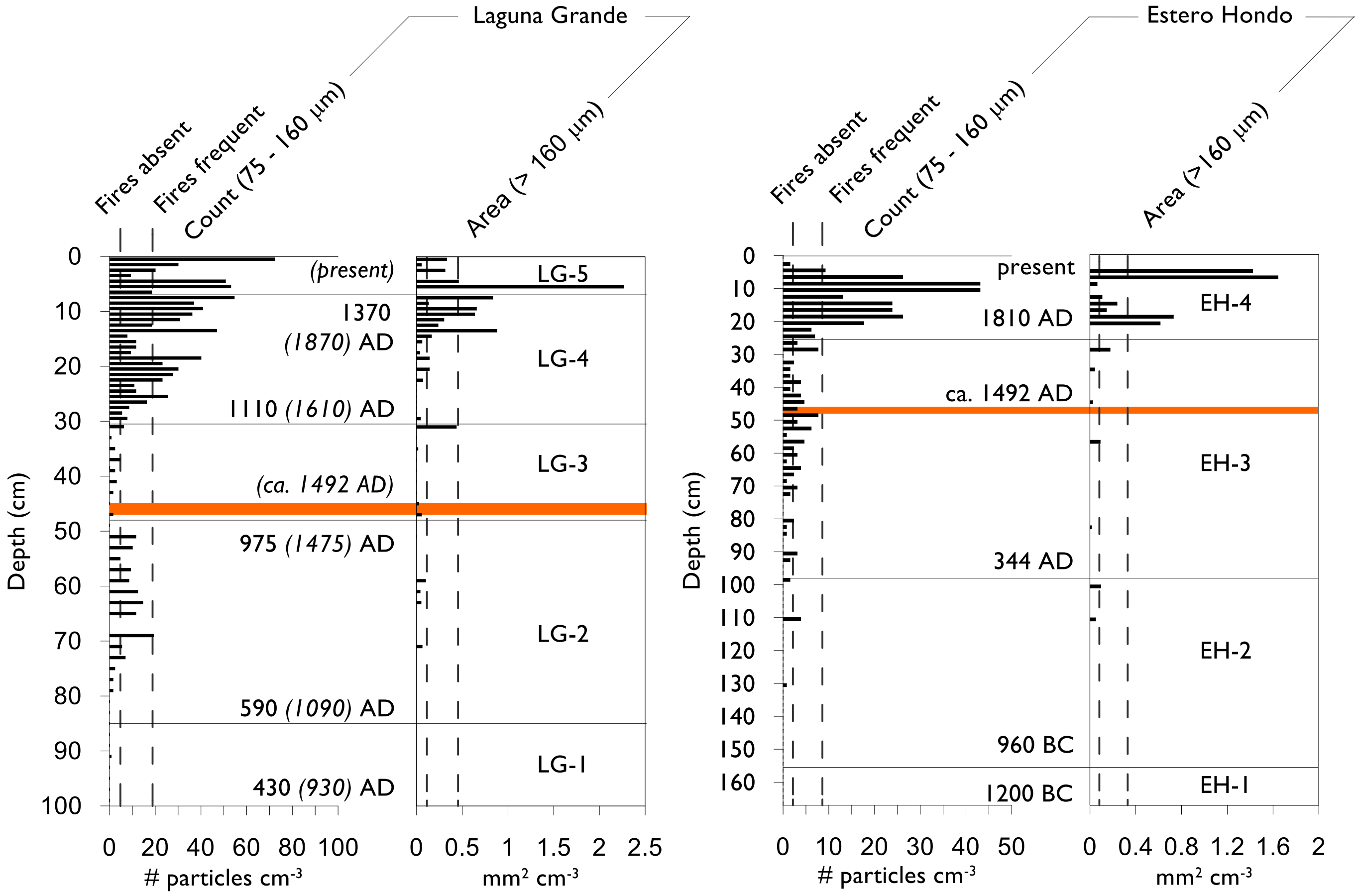

Figure 12 Microscopic (75-160 µm) and macroscopic (>160 µm) charcoal contents as counts (particles cm^{-3}) and surface area (mm^2 cm^{-3}), respectively. Pollen zones are provided as a reference with calculated ages in cal yr AD. For Laguna Grande ages in parentheses refer to a reservoir age correction of 500 years. Dashed grey lines indicate lower (near absence of fire) and upper (frequent fires) thresholds. Orange horizontal lines indicate ~AD 1492. **(left)** Laguna Grande. **(right)** Estero Hondo.

4.3.2 Estero Hondo

A local threshold for frequent regional fire occurrence was determined as ~9 particles per cm^3 of sediment (20 % of the maximum count of 43). We found a threshold of ~2 particles per cm^3 of sediment (5 % of 43) below which we infer near absence of regional fire. Both fractions show an increase with decreasing depth (Fig. 12).

In zone EH 1 (167 – 155.5 cm) charcoal is absent.

In zone EH 2 (155.5 – 98 cm) the microscopic concentration at 110.5 surpasses the lower threshold value. The macroscopic concentration at 100.5 cm surpasses the lower threshold value.

In zone EH 3 (98 – 25.5 cm) 18 out of 38 microscopic charcoal concentrations surpass the lower threshold value. The upper threshold value is not surpassed. Macroscopic concentrations at 56.5 and 28.5 cm surpass the lower threshold.

In zone EH 4 (25.5 – 0 cm) all microscopic concentrations surpass the uper threshold, except for 2.5 and 0.5 cm that do not surpass the lower threshold. All macroscopic concentrations surpass the lower threshold except for 10.5, 8.5, 2.5 and 0.5 cm. Macroscopic concentrations at 20.5, 18.5, 6.5 and 4.5 cm overcome the upper threshold.

4.4 Grain size distributions and loss on ignition

Based on visual inspection of Estero Hondo variations in median grain size and relative abundances of clay, silt, coarse silt and sand and supported by TOC and carbonate percentages, 5 main zones are recognized (Fig. 13).

Zone 1 (167-90 cm; 39 samples) is characterized by low median grain sizes, generally <10 µm, clay percentages steadily averaging around 60% and silt contributions with about 35%. Both coarse silt and sand contributions vary between 5 and 10%. TOC steadily increases from 10% to 20%, whereas carbonate contents vary between 5 and 13%.

Zone 2 (90-78 cm; 7 samples) is characterized by the smallest median grain size found along the record. The representation of clay reaches its maximum of approximately 85%, whereas contributions of silt, coarse silt and sand reach their absolute respective minima. TOC first increases to 25% and then decreases to 10%, whereas carbonate varies between 8 and 13%.

Zone 3 (78 – 35 cm; 21 samples) shows largest variability in median grain size observed along the core with three distinct peaks of 25, 40 and 40 µm, respectively. Variations in median grain size coincide with alternating relative contributions of clay and sand, whereas percentages silt and coarse silt demonstrate less variability. A general increase of TOC is observed, so that a maximum by the end of the zone around 35 cm is observed. A minimum in carbonate content mirrors maximum contributions of sand.

Zone 4 (35 – 10 cm; 13 samples) commences with an increase in median grain size to 20 µm at 28 cm, coinciding with clay and sand contributions that decrease and increase, respectively. Subsequently, median grain sizes decrease steadily, with clay percentages up to 50% and decreasing percentages sand. TOC shows an overall decrease from initial values of 35% to 20% at 35 cm depth. Carbonate contents peak around 20 cm depth.

Zone 5 (10 – 0 cm; 5 samples;) is characterized by decreasing median grain sizes flattening of toward 3 µm. Simultaneously, percentages of clay increase, whereas contributions of silt, coarse silt and sand decrease. TOC is slightly lower than in the preceding zone.

Estero Hondo

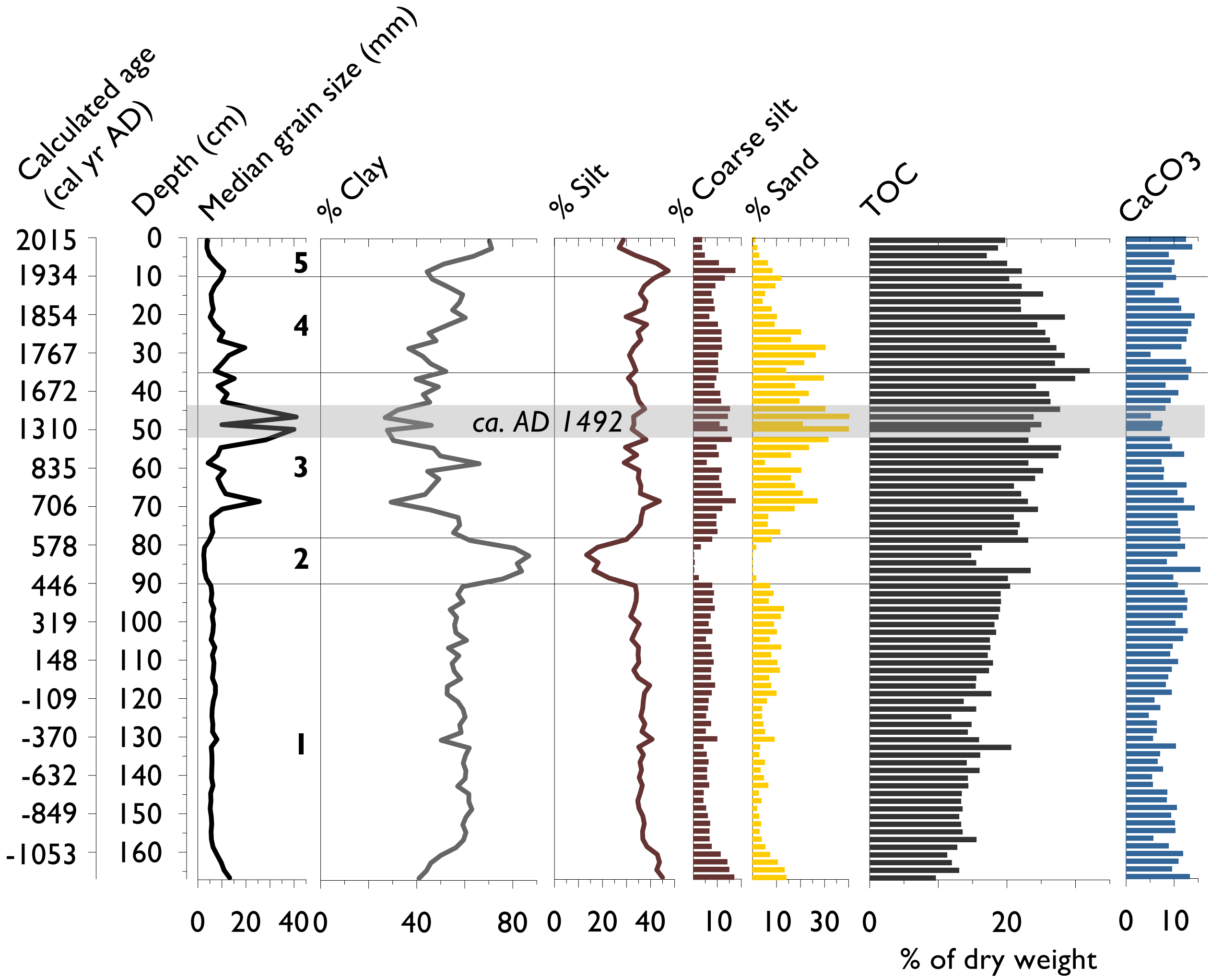

Figure 13 Estero Hondo records of grain size distributions (μm, %), total organic carbon (TOC) and carbonate ($CaCO_3$) contents by loss on ignition (%). Grey shading indicates ca. AD 1492. Refer to the main text for zone descriptions.

EMM of the GSDs demonstrates that the lithology can best be described by 4 to 5 end-members (EMs) as shown by relatively large R^2 for both class size and sample wise EM approximations, except for a small interval centered around 30 cm depth (Fig. 14 c/d). Frequency distributions of the respective 4 and 5 EM scenarios show relatively fine-grained EM along the record with the coarsest EM frequencies centered around 200 μm. (Fig. 14 a/b). All EMs show a secondary mode between 2 and 15 μm, though not as distinct in each EM. Such non-unimodal distributions (either bimodal or nearly bimodal) could indicate that the AnalySize algorithm has not fully unmixed the dataset (van Hateren et al., 2018). Changes in the relative contributions of the EM are described using the 5 EM scenario, given its higher detail in the coarser tail of the GSD.

EM 1 with a mode of 2 μm represents 'clay', EM 2 with a mode of 9 μm represents 'fine silt', EM 3 with a primary mode of 31 μm and a subordinal mode of 2 μm represents 'fine silt with a clayey component', EM 4 with a mode of 100 μm represents 'very fine sand' and EM 5 with a primary mode of 215 µm and a subordinal mode of 2 µm represents 'very fine sand with a clayey component' (Fig. 14b).

Temporal variations in relative EM contributions closely resemble trends observed in the GSD (Fig. 14 e/f), with EM 1 and EM 2 dominance and in zone 1 (167-90 cm) and, particularly, zone 2 (90 – 78 cm). Zone 3 (78 – 35 cm) is characterized by high relative contributions of EM 4 and 5. Relative contributions of the latter subsequently decrease in zone 4 (35 – 10 cm), where EM 1, 2 and 3 increase. Zone 5 demonstrates increases of EM1, 2 and 3, at the cost of EM 4 and 5, that are nearly absent.

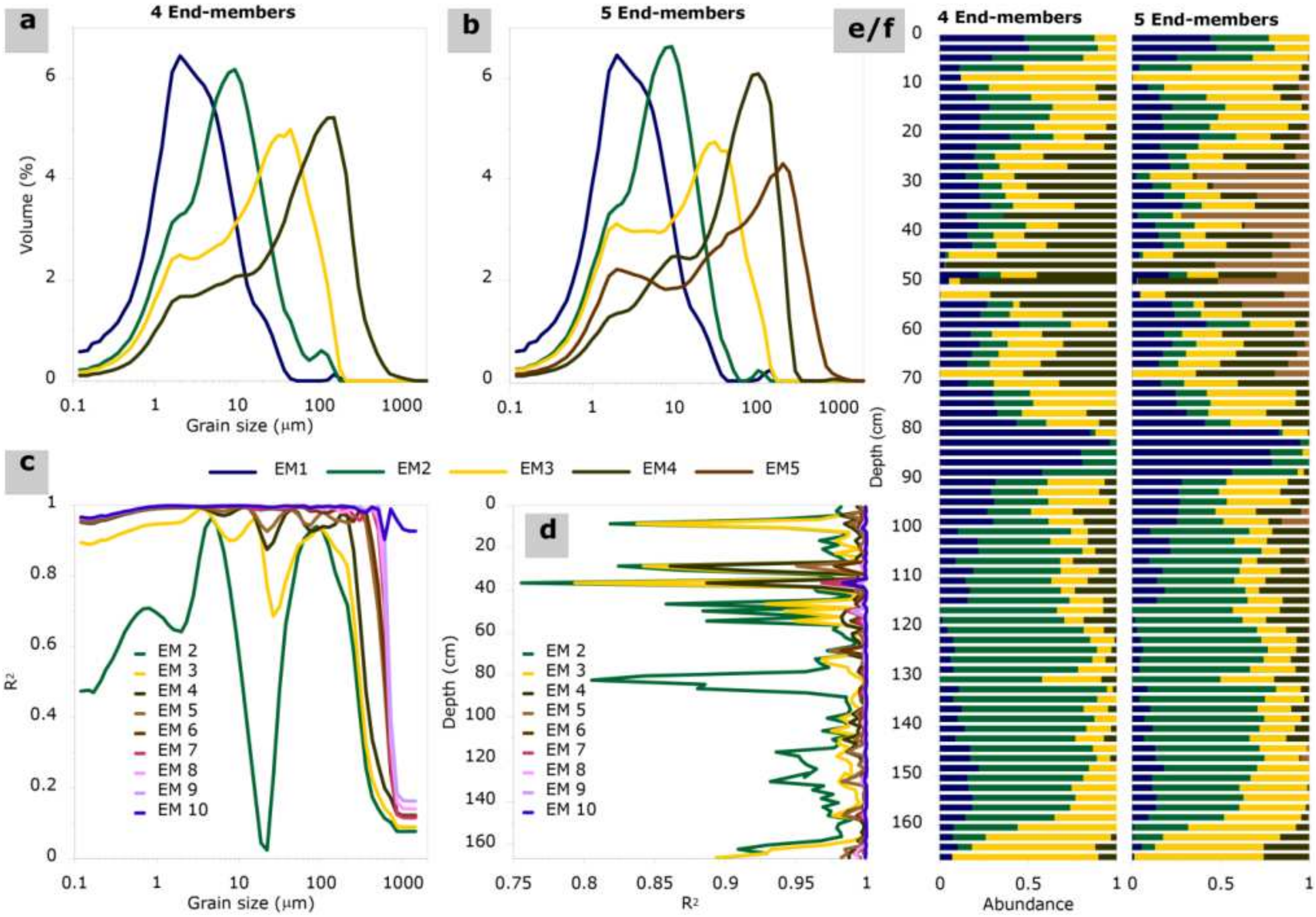

Figure 14 Estero Hondo end-member modelling results. **(a)** 4 End-member grain size distributions. **(b)** 5 End-member grain size distributions. **(c)** Grain size-wise R^2 for2 to 10 end-member models. **(d)** Sample-wise R^2 for 2 to 10 end-member models. **(e/f)** Down-core relative end-member contributions for a 4 and 5 end-member model, respectively.

Given the limited amount of sediment available for Laguna Grande, no GSD measurements were caried out. LOI results are presented as weight percentages TOC, carbonate and clastics (Fig. 15). TOC varies between 6 and 13% along the record, with a more dynamic character between 80 and 55 cm. Carbonate content varies between 8% and 12%. Clastic material dominates along the record.

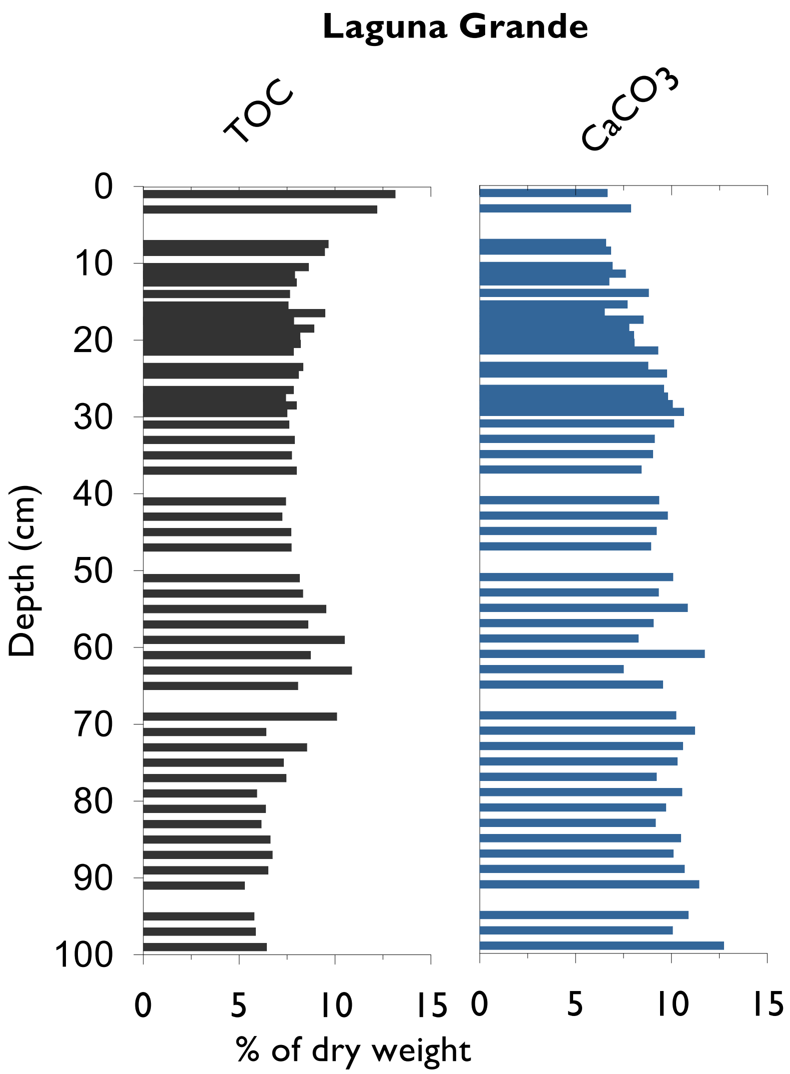

Figure 15 Laguna Grande total organic carbon (TOC) and carbonate ($CaCO_3$) contents by loss on ignition

5. Environmental reconstruction and discussion

5.1 Reliability of the age-depth models

The age-depth model of Laguna Grande provides a top age of ca. 1440 cal yr AD. This age is older than expected, for one assumes a modern age of at least 1950 cal yr AD (0 cal yr BP) for the uppermost sediment. Sources of error in radiocarbon dating that could explain this apparently erroneously old top age include contamination by incorporation of older carbon residues. For instance, influx of older carbon, both organic and inorganic, through erosion from the catchment slopes could introduce age-offsets of 400 years with a contamination of 5% and 850 years with a contamination of 10% (Walker, 2005; Lowe and Walker, 2015). Moreover, seepage of groundwater containing dissolved carbonates could reduce the $^{14}C/^{12}C$ ratio, thereby introducing a so-called reservoir-effect aging factor (Lowe and Walker, 2015). For Laguna Grande we could not overcome these problems by dating inwashed terrestrial materials such as seeds, since the only seeds present were of the aquatic Alismataceae-type. All radiocarbon dates were obtained by dating bulk sediments. Relatively low TOC indicates the susceptibility of our material to small contaminations of older carbon. Moreover, the presence of carbonates could point to a reservoir-effect. Extrapolation of the available age constraints to the top of the core reveals an apparent age of ca. 500 years. The downcore age-depth model is approximately linear. We therefore hypothesize that our age-depth model provided ages that are in the order of 500 years too old. This hypothesis requires falsification by dating the uppermost sediment. However, radiocarbon dating of of sediments in the age of 1650 to 1950 AD is problematic because of a plateau in de calibration curve (Kemp et al., 2012). Use of the decay of short-lived radioactive isotopes such as naturally dervived ^{210}Pb for dating recent sediments and artificially (by nuclear weapon testing) generated ^{137}Cs as independent validation could help to overcome this limitation of radiocarbon dating (Oldfield et al., 2003; Appleby, 2008; Abril, 2004; Maezumi et al., 2018). Based on the age constraints and sedimentation rates inferred from short-lived radioactive isotopes, the reservoir-age could independently be determined. Application of such a reservoir-age correction is only valid assuming contamination by influx of older carbon and carbonates is constant over time.

We have considerable doubts regarding the reliability of our age-depth model for Laguna Grande. Therefore, interpretations of the individual records in the time domain should be treated accordingly. In our interpretations of the data we applied a reservoir correction of 500 years (RAC 500 yrs).

For Estero Hondo a bulk date at 15-16 cm gave a modern age. Woody, probably root, material at 44 cm gave a age of 1870 – 1920 cal yr AD. Possibly, this results from contamination with modern carbon incorporated into the sediment by downward penetrating mangrove roots (at 44 cm) and/or humic acids (Walker, 2005; Lowe and Walker, 2015). Another cause for disturbance of the sediment sequence comes from bioturbation. Benthic fauna such as crabs and a diverse molluscan fauna contribute significantly to mangrove bioturbation (Lee, 2008; Osborne, 2012). Furthermore, uncompacted mangrove sediments from the relatively thick active layer consisting of roots and plant remains could result in apparent sedimentation rates up to 1 cm yr^{-1}. Consequently, decreasing compaction with shallower depths could as well explain younger than expected radiocarbon ages. Lastly, following the reasoning for sources of older carbon incorporation into the Laguna Grande sediments, presence of carbonates could as well point to some reservoir-effect. However, we tentatively consider the younging effect of bioturbation and root penetration dominant. As stressed earlier, dating of recent sediments based on radiocarbon is problematic. Preferentially, short-lived radioactive isotopic dating should be applied to the uppermost sediments. It is reasonable to assume that bioturbation and root penetration processes have affected sediment sequences throughout the record. Therefore, interpretation of the individual records for Estero Hondo in the time domain should be carried out with caution.

5.2 Environmental reconstruction: a coastal perspective

Pollen preservation for Estero Hondo is generally better than for Laguna Grande. Low pollen sums obtained from Laguna Grande, barely above 30 grains, complicate statistically reliable interpretations of vegetation dynamics. T

The pollen records of Laguna Grande and Estero Hondo contain pollen and spores indicative of open, potentially disturbed, vegetation as well as more mature hardwood forest. Higher percentages of Asteraceae, Poaceae and Amaranthaceae could point to increased (anthropogenic) disturbance (Clement and Horn, 2001; Siegel et al., 2015). Interpreting amaranthaceous taxa as indicative of human disturbance follows from the fact that *Amaranthus cruentus* (inca wheat) was domesticated 6000 years BP (Greenwood et al., 2003) but pollen morphological identification is unsure. Sparse occurences of *Zea mays* (max. 3 grains) indicate crop cultivation in the vicinity of the lake. Given the relatively heavy pollen grains of *Zea mays*, presence is likely to result from cultivation on the immediate lake shore, to allow for deposition in the lake sediments (Raynoz et al., 1972; Islebe et al., 1996). However, extrapolation of evidence for crop cultivation to a regional scale is problematic, given the particular interest of humans to lakes, both in pre- and post-Columbian times (Bush et al., 2015). Another complication in interpreting evidence of crop cultivation is the limited availability of pollen morphological studies of crop plants (Hooghiemstra et al, 2018). Pollen grains of several pre- and post-Columbian crop plants are possibly 'hidden' in the records of higher taxonomic ranks. Consequently, natural occurences of herbs and weeds cannot be distinguished from occurences of cultivars such as tomato, potato or tobacco, nor from oneanother (all Solanaceae).

Mangrove dynamics inferred from Estero Hondo together with GSD and EMM possibly reflect regional scale variability in precipitation, wave and tidal dynamics as well as sea-level changes. Accordingly, continuous presence of (semi-)aquatic typhaceous and cypraceous taxa inferred from Laguna Grande point to presence of water in the lake, though variability in their respective abundances could reflect varying water levels related to regional precipitation patterns. Macroscopic charcoal concentrations reflect local fire occurences, whereas microscopic charcoal concentrations reflect regional scale fire occurences. Concentrations of charcoal above our defined upper threshold indicative of frequent fire occurences together with evidence for crop cultivation could indicate slash-and-burn practices. However, such evidence is likely to be diluted in the sediments of particularly Estero Hondo, since wet or submerged areas not subjected to slash-and-burn cultivation als contribute to the record (McMichael et al., 2012).

Considering the vegetation history leading in the reconstruction of crop cultivation, fire history, grazing and sedimentary dynamics, we integrate the evidence from the various proxies using the pollen assemblage zone boundaries. We use the calculated ages (Suppl. Info. Tables SI1 and SI2) to discuss the environmental dynamics in the time domain.For discussions of the results from Laguna Grande we will use the age-depth model corrected by 500 years for an inferred reservoir effect.

5.2.1 Reconstruction of past environmental change as inferred from Laguna Grande

Period LG 1 (100 – 85 cm): ca. 930 – 1090 cal yr AD (after RAC 500 yrs).

Poor pollen preservation is evident from very low pollen sums (<70) and high percentages of unidentified grains (40 – 56 %) (Fig. 4; Table 2). Herbaceous vegetation with *Alternanthera*, Poaceae, Asteraceae tubiliflorae and *Artemisia* dominates, indicating open vegetation was present in the immediate surroundings of the lake. Relatively high abundances of fern spores (22 – 107 %), possibly indicate moist conditions, supported by rare occurences of *Polygonum* (max. 3 grains) that is known from humid soils and as wet shore vegetation along lake and river margins (Marchant et al., 2002). Evidence for the presence of at least some water in the lake comes from occurences of cyperaceous taxa. From the near absence of deep water indicating *Typha,* we infer relatively low water levels. We speculate that relatively low water levels might have resulted in temporal drying of the lake during the dry season, explaining relatively high percentages of corroded unidentied pollen grains and a low pollen sum. Furthermore, low water levels reduce the catchment area reflected in the pollen spectra, in agreement with nearly absence of taxa from the hardwood forest (Peros et al., 2007). We thus interpret this period as reflecting a very local signal. Occurences of fires cannot be deduced from the charcoal record, nor can we infer pre-Columbian crop cultivation from the pollen record.

Relatively dry conditions at ca. 1030 cal yr AD (sample 90 – 92 cm) are in agreement with paleo-ecological and paleoclimatological records from Hispaniola (Higuera-Gundy et al., 1999; Lane et al., 2009, Lane et al., 2011).

Period LG 2 (85 – 48 cm): ca. 1090 – 1480 cal yr AD (after RAC 500 yrs).

Local vegetation is dominated by cyperaceous and typhaceous aquatic and wet shore taxa. Based on higher relative abundances of deeper water indicating *Typha* compared to LG 1, we infer higher water levels. This is supported by rare occurences of *Polygonum* and relatively high abundances (1 – 10 %) of typical anchor-shaped glochidia and spores of the aquatic fern *Azolla.* Moreover, algal zygospores of *Spirogyra* sp. belonging to the Zygnemataceae point to the presence of oxygen-rich, stagnant and shallow fresh water (van Geel, 1976). Regular presence of Characeae oospores, several seeds of the aquatic herb Alismataceae and two ostracodes in the charcoal samples as well indicate shallow fresh and nutrient-poor water conditions. Characeae is often abundant under oligotrophic pioneering conditions characterized by input of clastic material (Mauquoy and van Geel, 2007). Higher water levels imply a larger catchment area of pollen, since the lake size is expected to increase, given its shallow bathymetry, thus allowing for a more regional signal. This is in agreement with generally higher AP% (ca. 25%; Fig. 4).

Arboreal taxa are dominated by Fabaceae and *Pinus-Podocarpus* that on average show abundances of 20 and 4%, respectively. Minor appearances of Myrthaceae, Malphigiaceae, Rubiaceae, Solanaceae, Euphorbiaceae, Bignoniaceae, Malvaceae, Rosaceae and disturbance indicating *Gunnera* (Marchant et al., 2002), could all point to diversification of the mixed hard wood forest. However, increased lake size could allow for more wind dispersed arboreal pollen to be trapped into the sediment. Therefore, we cannot conclude whether the apparent diversification results from a more regional signal or a ‘true’ diversification of the hard wood forest.

Herbaceous taxa remain dominant in the pollen sum indicating open vegetation in the vicinity of the lake, without considerable changes compared to the preceding period.

Presence of *Glomus* cf. chlamydospores, both on pollen slides and as complete 'clouds' in the charcoal samples indicate that soil erosion occurred, probably originating from the hills surrounding the lake. Minor occurences of *Zea mays* (1 grain at ca. 1150 cal yr AD; 2 grains at ca. 1440 cal yr AD) form the first reliable evidence for crop cultivation in the vicinity of the lake. Moreover, abundances of amaranthaceous taxa up to 10 % could be interpreted as indicative for crop cultivation. Regional fires occur, but we can only infer high frequency at 69 and 63 cm. Local fire is evidence by macroscopic charcoal at 31 cm. However, we found no evidence for frequent local fires. We therefore surmise that the charcoal record points to naturally ocurring regional fire events, with only minor and localized anthropogenic contributions.

First evidence for settlements that we find are in agreement with archeological data of increased settlement density reflecting higher population densities in the two centuries prior to colonization (Hofman et al., 2018). Moreover, first evidence for *Zea mays* cultivation from Laguna Grande is in agreement with first evidence for *Zea mays* from coastal northern Hispaniola dating from 1250 AD (Newsom and Deagon, 1994) and some of the earliest evidence of maize agriculture from the interior of Hispaniola dated at ca. 1060 AD (Lane et al., 2008). Lastly, relatively moist conditions have been reported for Hispaniola during this interval (Higuera-Gundy et al., 1999; Lane et al., 2009), in agreement with higher water levels inferred from Laguna Grande.

Period LG 3 (48 – 30.5 cm): ca. 1480 – 1610 cal yr AD (after RAC 500 yrs).

Pollen concentrations are lower than in period 2, with values around 4000 grains per cm^3 of sediment, whereas the number of unidentified pollen grains increases (Figs 4, 7). In this core interval 5 out of 8 samples were rejected based on very low pollen sums (Table 2) pointing to poor pollen preservation. Percentages of *Typha* decrease and Characeae oospores and Alistmataceae-type seeds were absent from the charcoal samples, possibly reflecting lower water levels, though occurences of *Polygonum*, *Spirogyra* sp. and *Azolla* indicate that significant water remained. Moreover, maximum abundance of Cyperaceae suggests that water level lowering was limited.

Pinaceous and fabaceous taxa remain dominant, but minor contributions of Myrthaceae, Bombacaceae-type, Proteaceae, Melastomataceae, *Ilex, Alnus,* Solanaceae and Urticaceae-Moraceae complement the suite of arboreal taxa. Given the generally low pollen concentrations and rare counts of individual arboreal taxa, we do not interpret absence of a taxon as a loss of diversity. Moreover, the taxa that first appear during zone LG 3 do not unequivocally point to either drier or more humid conditions. No *Zea mays* nor hardly any amaranthaceous representatives were found, possibly indicating reduced or absence of agricultural activy around the lake. Concentrations of microscopic charcoal are lower than in LG 2 indicating either absence or low frequency of regional fire occurrence. Local fire occurrence is evident at 31 cm but does not indicate frequent fire occurrence. Reduced agricultural activity could point to site abandonment following first contact in 1492, possibly as a result of the collapse of the indigenous population (Deagan, 1985; Live-Bacci, 2006). The relatively moist conditions (i.e. at Laguna Grande, as inferred from aquatic taxa and fern abundances with regional moist conditions between 1250 – 1600 AD.

Period LG 4 (30.5 – 7 cm): ca. 1640 – 1870 cal yr AD (after RAC 500 yrs).

Most prominent is the apparent initial increase in the abundance of both *Pinus*-*Podocarpus* and *Alternanthera* and a subsequent decrease of both relative abundances (Fig. 4). This trend is also reflected by a peak in AP% (Fig. 5). However, low pollen concentration (ca. 1500 grains per cm^3 of sediment) might indicate that these peaks are statistical artefacts (Fig. 7; Suppl. Info. Figs. SI 1, SI 2). *Pinus-Podocarpus* concentrations remain low until ca. 1230 cal yr AD and subsequently increase.

Alternanthera philoxeroides (alligator weed) is known for its invasive nature around the globe (Basett et al., 2012). *Alternanthera* in general and particularly alligator weed are known from disturbed areas (Marchant et al. 2002) under hypertrophic conditions (Basett et al., 2012). Possibly, the distinct maximum in its abundance points to elevated nutrient influx.

Fresh water is present at the coring site, evidenced not only by cyperaceous and typhaceous taxa, but also by presence of *Azolla*, *Polygonum*, and *Spirogyra* sp. as well as regular occurences of oospores of Characeae, Alismatacea-type seeds and ostracods found in the charchoal samples. Higher relative abundances and concentrations of amaranthaceous taxa and rare occurences of *Zea mays* (only at ca. 1850 cal yr AD) point to crop cultivation near the coring site. Microscopic charcoal concentrations indicate generally high frequence of regional fires. From the macroscopic charcoal concentrations we infer frequent local fires that combined with increased crop plant abundances indicate increased human disturbance around the lake. Higher percentages of *Glomus* cf. chlamydospores indicate increased soil erosion, possibly resulting from the postulated increase of anthropogenic disturbance. Decreasing abundance of *Pinus*, combined with maxima in fern spore abundances pointing to forest clearance as well as higher fire frequence and evidence for crop cultivation point to intensified human interference from AD 1640 onward. We postulate that such human disturbance could have altered the nutrient budget in and around the lake, promoting *Alternanthera* to form a floating mat (Basett et al., 2012). Furthermore, indications for drier conditions from Laguna Grande (e.g. *Borreria,* Euphorbiaceae and Fabaceae) line up with paleoclimatological records from Hispaniola that indicata a trend toward increasing aridity from 1600 AD onwards (Higuera-Gundy et al., 1999; Lane et al., 2009), though we assess this evidence as rather limited given the evidence for the presence of a standing water body.

Period LG 5 (7 – 0 cm): ca. 1870 – present (after RAC 500 yrs).

The pollen concentration is relatively high during this time interval ranging between 4000 and 26 000 pollen grains per cm^3 of sediment (Fig. 7). Apart from higher relative abundance of *Typha* and reduced abundance of *Alternanthera*, no significant changes in vegetation were observed as compared to period 4. Evidence for fresh water at the coring site comes from presence of *Azolla*, *Polygonum* and oospores of Characeae and Alismataceae-type seeds found in the charcoal samples, with some occurences of ostracods. A single specimen of rotaloid-type foraminifera was identified from a organic lining at ca. 1920 cal yr AD. Given the proximity of the present shoreline (only 3 km), storm events (Horst, 1991; Geerts et al., 2000) may cause that marine waters are blown inland and forams may be wind-blown more inland. However, we refrain from drawing any conclusions regarding marine influences based on a single foraminifera specimen, that could as well be deposited by a bird. Diatom analysis is a useful tool in paleo-salinity reconstructions, but all samples were found to be sterile for diatoms (M.I. Vélez, personal communication, October 2018). Sediments retrieved did not have sufficient volume to allow for adding grain size analysis to the suite of proxies studied from Laguna Grande. Sparse evidence for agricultural activity comes from the identification of *Zea mays* in two out of four samples. Microscopic charcoal indicate regular to frequent regional fire occurence. A maximum in macroscopic charcoal surface area of 2.3 mm^2 cm^{-3} was present at ca. 1880 cal yr pointing to a large fire event in the vicinity of the lake, since this concentration is unprecedented in earlier zones. Presence of *Glomus* cf. on pollen slides as well as in charcoal samples shows that soil erosion continued to be part of the sedimentary dynamics. Evidence for maize cultivation, increased burning activity and erosion could point to intensified land-use in agreement with an increased demand for tropical products such as tobacco, cacao and sugar by the end of the nineteenth century in industrializing countries of the Old World (Baud, 1987).

5.2.2 Reconstruction of past environmental change as inferred from Estero Hondo

Period EH 1 (167 -155.5 cm): ca. 1200– 960 cal yr BC.

Vegetation is dominated by mangroves (60 %) with predominantly *Conocarpus erectus* (43 %) and *Rhizophora mangle* (13 %). *Rhizophora mangle* is the only anemophilous mangrove species and consequently easily (re)distributed around a large area. *Concocarpus erectus* and *Avicennia germinans* are entomophilous mangroves and therefore generally underrepresented in the pollen rain. Consequently, percentages of over 60 % *Rhizophora mangle* are interpreted as evidence for the presence of the *Rhizophora* mangrove forest at the coring site. Percentages <40% are considered redistributed from a more distant location (Behling et al., 2001; Urrego et al., 2010). Given the ecological preference of *Conocarpus erectus* for the zone just above the high tide (Peros et al., 2007) we infer the presence of the back-mangrove at the coring site. Minor contributions come from myrthaceous (wet to dry) and euphorbiaceous (dry) trees that form the matrix of the hardwood forest (Marchant et al., 2002) with abundances of ca. 15% (Figs. 8 and 9). Herbs are nearly absent as are potential crop plants such as *Zea mays* or Amaranthaceae. GSDs show increasing contributions of clay and decreasing contributions of silt and sand, thereby decreasing median grain sizes (Fig. 13). This is also illustrated by a transition from EM3 dominance at the onset of Period 1 and EM2 dominance by the end of Period 1 (Fig. 14). Simultaneously, TOC percentages increase (Fig. 13), suggesting that energy levels at Estero Hondo decreased, possibly as a result of the tempering effect of mangrove vegetation or increased terrestrial influx, reflecting increased run-off. No evidence for fire occurences nor crop cultivation has been found.

Period EH 2 (155.5 – 98 cm): 960 cal yr BC – 344 cal yr AD.

The most prominent change in terms of vegetation for this zone compared to EH 1 is the increase in relative abundance of *Rhizophora mangle* reaching values up to 60% reflecting presence of the *Rhizophora* forest at or its proximity to the coring site (Behling et al., 2001; Urrego et al., 2010). Coeval decreases in the abundance of *Conocarpus* from 41 % in period 1 to 11% at the start of zone 2 and further to 1% by the end indicate expansion of the intertidal zone (Fig. 8). Abundance of *Avicennia* increases throughout zone 2, an observation that indicates increased salinity (Urrego et al., 2010, 2013; Donders et al., 2008). The compositional changes of the mangrove and wet shore ecological group as observed from the relative abundances are confirmed by the individual concentration diagrams (Suppl. Inf. Fig. SI 6). The AP show a peak in both the relative abundance and concentration of *Dodonaea*, considered a disturbance indicator, present in patches of open forest and on eroded soils (Islebe and Hooghiemstra, 1995; Marchant et al, 2002; Gómez et al., 2007). Herbaceous vegetation is sparse throughout zone 2, with apparent increases of Bromeliaceae and *Ambrosia*-type (Asteraceae) in the percentage as well as the concentration diagrams (Fig. 8; Figs. SI 5 and SI 6). Both increases of Bromeliaceae and *Ambrosia*-type could point to agricultural activity, since pine-apple, a member of the Bromeliaceae family has been cultivated throughout the

Americas and the Caribbean in pre-Columbian times (Collins, 1951) and *Ambrosia* is occasionally associated with maize cultivation and disturbance (Islebe and Sanchez, 2002). However, we did not find any *Zea mays* in this interval. Nevertheless, a distinct maximum of 25 % in Cucurbitaceae abundance is observed at ca. 250 cal yr AD. Several potential crop plants belong to the Cucurbitaceae family such as squash, pumpkin and chayote, cultivated by the indigenous peoples of the Americas (Zaldivar et al., 2002; Dillehay et al., 2007). Increased abundances and concentrations of monolete psilate fern spores could point to moist conditions, since ferns are known to be part of the ground layer in humid forests (Rodgers and Horn, 1996) or general disturbance, possibly related to burning and forest clearance. This evidence for human disturbance related to agricultural practices is in agreement with a maximum in *Dodonaea*.

Evidence for either regional or local fire occurrence is nearly asent. Relative contributions of the coarser EM 4 and EM 5 increase (Fig. 14), pointing to periodically higher energetic levels, possibly as a result of increased wave action over fluvial and tidal powers (Reading and Collinson, 1996). Furthermore, wash-over events induced by storms, hurricanes (Horst, 1991; Geerts et al., 2000) and tsunamis can cause rapid deposition of sand in back-barrier systems such as lagoons and tidal flats, preserved in the sediment as intercalations of sand (Donelly et al., 2001; Leeder, 2011). During such short-lived events, the back-barrier system can temporarily be (re)connected to the open ocean. In (partially) isolated back-barrier systems in arid environments, salinities can significantly increase with occasionally formation of salt pans. Particularly when soil salinities overcome values of 65‰, mangroves such as *Rhizophora mangle* might be limited, whereas higher salinity tolerant *Avicennia germinans* expands its territory. Therefore, increases in both the relative abundance and concentration of the more salt-tolerant black mangrove *Avicennia germinans* from ca. 240 BC onward could point to increased isolation of the lagoon, possibly by closure of the tidal inlet. Alternatively, the increased contribution of coarser EM 4 and 5 could result from overall vegetation cover increase as observed from higher TOC% and higher pollen concentrations, thereby more easily trapping coarser sediments (Vriend et al., 2012).

The first potential evidence for agricultural practices coming from Cucurbitaceae at ca. 250 cal yr AD could confirm that early Ceramic Saladoid people already managed or cultivated crop plants, complementing their diet that further consisted of marine foods such as fish, turtles and molluscs (Fitzpatrick and Keegan, 2007).

Period EH 3 (98- 25.5 cm): 344 – 1810 cal yr AD.

Vegetation during zone 3 significantly diversifies with, albeit mostly based on few counts per sample, first appearances of Arecaceae, Meliaceae, Proteaceae, Solanaceae, *Brugmansia*-type, Sapotaceae, *Spondias*-type, *Cordia*, Anarcadiaceae, *Juglans*, Rosaceae and disturbance indicating *Borreria* (Fig. 8), the latter an open savana element (Marchant et al., 2002). Taxa of *Pinus-Podocarpus*, Fabaceae, Euphorbiaceae and Urticaceae-Moraceae dominate in the arboreal ecological group and reflect mixed forest. Herbaceous vegetation reaches a maximum abundance at ca. 580 cal yr AD, with predominantly disturbance indicating *Ambrosia*-type. Mangrove vegetation is dominated by *Rhizophora mangle*, but abundances of *Avicennia germinans* significantly contribute to the mangrove composition. Palynological evidence for agricultural activity in the vicinity of the coring site is sparse and consists a small peak of Cucurbitaceae taxa at ca 1670 cal yr AD. We found evidence for regular occurrence of regional fires and sparse evidence for local fires (2 concentrations out of 35 samples surpassed the lower threshold value). Given the lack of evidence for frequent regional fires and sparse evidence for local fires as well as rare occurences crop plant palynomorphs, we postulate that human impact near the coring site was either low or absent during this time interval. More regular regional fire occurences could result from increased droughts reflected by near absence of ferns between at ca. 710 and 840 cal yr AD. Indeed, paleo-records from Hispaniola point to drought events and increasing regional aridity (Lane et al., 2009; Higuera-Gundy et al., 1999) as well as Circum-Caribbean droughts reported from the Cariaco Basin (Venezuela; Haug et al., 2001) and the Yucatan Peninsula (Hodell et al., 2005) in agreement with evidence for increased salinities from Estero Hondo, reflected by increased in *Avicennia*.

Peaks of fern spores centered at ca. 580 and 1310 cal yr AD could indicate more humid conditions (Fig. 10). Alternatively, coeval maxima in Cucurbitaceae and/or *Ambrosia*-type could link increased fern abundance to human disturbance, possibly as a result of small-scale opening of the forest.

Two counts of *Cercophora*-type. fungal spores at ca. 1420 cal yr AD potentially indicate either presence of dung or decaying wood (van Geel et al., 2011). Two counts of *Glomus* cf. chlamydospores at ca. 840 cal yr AD (Fig. 10) could indicate soil erosion given the formation of its spores below the soil surface (Anderson et al., 1984; van Geel et al., 1989). Dominance of EM 1, with a relative contribution larger than 75%, during the time interval ca. 450 - 580 cal yr AD (Fig. 14), reflecting deposition of fine clays, coincides with increased abundance of ferns and *Ambrosia*-type herbs. Therefore, we postulate that run-off increased, accounting for more clastic influx as reflected by lower TOC% (Fig. 13) and and a richer asteraceous vegetation. Subsequently, TOC% steadily increases from ca. 580 cal yr AD onward. Three distinct peaks in median grain size contrast with the lower median grain sizes generally observed during zone 3. From ca. 710 to 810 cal yr AD EM4 abundances over 40% reflect deposition of fine sands possibly originating from overwash events caused by storm surges. From ca. 960 to 1670 cal yr AD EM 4 contributes for over 40% with somewhat coarser fine sands deposited at ca. 1055, 1310 and 1650 cal yr AD, as reflected by distinct peaks in EM5 contributions. This interval of coarser material coincides with decreased sedimentation rates of approximately 0.017 cm yr^{-1} as calculated between the radiocarbon ages (Fig. 2), reflecting a more dynamic sedimentary system. Two even larger relative contributions of EM5 are centered at ca. 1710 and 1800 cal yr AD, reaching values of 60 to 70% that are not observed elswhere along the record. We postulate that particularly the peaks in EM5 contributions could indicate storm surges causing overwash events or could be the result of earthquakes possibly causing a tsunami.

Decreasing TOC% from ca. 1720 cal yr AD onward are not reflected by lower pollen concentrations. Potentially, this reflects an increase in the relative contribution of wind pollinating arboreal taxa as well as herbaceous taxa (Poaceae, Asteraceae tubuliflorae), whereas lower mangrove concentrations point to a decrease of TOC production by mangroves from 1770 cal yr AD onward. Therefore, we infer a potential deforestation signal starting from ca. 1770 cal yr AD.

Period EH 4 (25.5 – 0 cm): 1810 cal yr AD - present

The three uppermost pollen assemblages reflect somewhat lower abundance of the mangrove forest taxa with relatively higher contributions of *Conocarpus erecta* potentially indicating lowering of the tidal range and/or a prograding shoreline. As compared to period 3, the hardwood forest is shows lower relative abundances of *Pinus-Podocarpus* and Fabaceae (Fig. 8), though this is not confirmed by the individual concentrations (Suppl. Info Fig. SI 4). The forest is predominantly composed of rubiaceous, euphorbiaceous and urticaceous taxa, with minor contributions of

Borreria and Rosaceae taxa. *Borreria* is a savanna element and can therefore be indicative of open and potentially degraded forest (Hooghiemstra, 1984; González et al., 2010). The herbaceous elements of the vegetation are dominated by poaceous, asteraceous and amaranthaceous taxa, indicative of open vegetation from the transition zone to a swamp with more fresh water influences supported by higher abundances of Cyperaceae, *Typha* and *Acrostichum* (Peros et al., 2007). Evidence for opening of the landscape complemented by disturbance indicators and a decrease in mangrove abundance point to deforestation and mangrove degradation. In such disturbed settings *Acrostichum* generally increases (Urrego et al., 2013) in agreement with our data. More humid conditions could be deduced from increases in the relative abundance of (monolete) fern spores supported by minor counts of *Glomus* cf. chlamyodspores indicative of soil erosion. However, in the context of human disturbance, increased fern abundance supports deforestation.

Evidence for fire events comes from large increases in both microscopic and macroscopic charcoal concentrations (Fig. 12), not observed in pre-modern times. Supplementary evidence for fire occurrence comes from the identification of a single *Neurospora* ascospore, a fungus that grows on burnt plant remains (van Geel and Aptroot, 2006). Further evidence for anthropogene disturbance around the coring site comes from increased abundance of Cerealia-type, supported by its concentrations (Suppl. Info. Fig SI 6) and the identification of a single *Zea mays* pollen grain. From the the aforementioned evidence, we deduce significantly intensified human impact near the coring site from 1810 onward, characterized by burning, forest clearance and crop cultivation, possibly resulting in reduced mangrove forest cover.

5.3 Synthesis of human disturbance on the northern Dominican Atlantic coastal plain during the past ~3200 years.

The earliest palynological evidence for anthropogenic disturbance during pre-Columbian times consists of a peak in Cucurbitaceae abundance from Estero Hondo at ca. 250 AD. The first evidence from Laguna Grande comes from a single grain of *Zea mays* at ca. 1150 cal yr in agreement with published estimates for the onset of maize cultivation (Newsom and Deagan, 1994; Lane et al., 2008).

Evidence for pre-Columbian forest clearings is sparse. From Estero Hondo we infer proximity of the mangrove forest to the coring site throughout the record. A minimum in *Rhizophora mangle* is coincident with a peak in Cucurbitaceae at ca. 250 cal yr AD. However, *Rhizophora mangle* concentrations do not confirm this minimum. The AP% is generally larger than the NAP% during pre-Columbian times for Estero Hondo except for a minimum at 80.5 cm (ca. 570 cal yr AD) when disturbance indicating *Ambrosia*-type peaks. Possibly, indigenous people opened-up the forest on a small-scale allowing for crop cultivation. Noteworthy is the overall increase of AP% as well as an increase in the number of arboreal taxa, whereas NAP generally does not exceed 8%, suggesting forest clearings, if present at, all had no persistent effect on the composition of the vegetation.

Pre-Columbian vegetation around Laguna Grande is predominantly herbaceous. Increases of AP% generally coincide with increases in the fern abundances. If we infer more humid conditions from increasing fern abundance, we could postulate that moisture availability drove AP abundances. In that light, the decrease in *Pinus* and AP from a peak at ca. 1640 cal yr AD point to naturally driven turn-over rather than clearance practices.

From 1200 cal yr BC – 1000 cal yr AD the charcoal records show only but minor evidence for frequent regional or local fire occurences or 'fire zones'as Gosling et al. (2017) defined them. Based on the Estero Hondo data we find no evidence for landscape scale slash and burn practices during pre-Colonial times. Episodes of somewhat higher peaks in microscopic charcoal in period EH 3 are likely to reflect natural variability, since the upper threshold is not surpassed (Fig. 12). Absence of frequent fires untill Columbus'arrival in 1492 is supported by Laguna Grande (Fig. 12).

Evidence for the potential impact of the 'encounter' preserved in the sediments from Estero Hondo is absent. No evidence for the introduction of New World species such as Cerealia-type cultivars can be deduced. A complicating factor in interpreting the potential impact of the encounter is the lack of temporal resolution in this interval as a result of a relatively sedimentation rate in the order of 0.026 cm yr^{-1}. However, Cerialia-type only increases in the upper most (modern) samples. Apparently, the surroundings of Estero Hondo were not suitable for cereal crop cultivation, confirmed by absence of pre-Columbian *Zea mays*. Rare (in the order of a single count per sample) counts of spores of coprophilous *Sporomiella* sp. or *Cercophora*-type do not unequivocally point to introduction of cattle to the surroundings of Esterho Hondo. Between 1310 and 1670 cal yr AD, the percentage of *Pinus* increased and we find no evidence for forest clearance nor increased fire occurences that can be related to the 'encounter'.

From the Laguna Grande sediments we could deduce evidence for New World crop introduction. From ca. 1640 cal yr AD onward, Cerialia-type abundance tend to increase. However, during pre-Columbian times we interpreted Cerealia-type grains (i.e. >40μm) as naturally occuring grasses or reeds, since no Cerealia-types were introduced prior to European colonization. The post-1640 cal yr AD cereal abundances are not larger than the pre-Columbian abundances.. We therefore cannot unequivocally determine post-Columbian Cerealia-type cultivation. *Sporomiella* sp. is present throughout the record without a clear increase that can be related to the 'encounter'. Decreases in the *Pinus* abundances from ca. 1640 cal yr AD onwards could point to forest clearance. However, the sample with an apparent maximum in *Pinus* abundances has a very low pollen sum and a high percentage of indeterminable grains (Fig. 4). Consequently, we refrain from drawing conclusions regarding deforestation based on this particular sample. Furthermore, Laguna Grande shows no evidence for increased fire activity directly following the 'encounter' (Fig. 12).

The two centuries following colonization (1492 – 1700 AD) are represented by a single pollen sample from Estero Hondo. Consequently, we cannot draw conclusions on the development of potential human disturbance during the early colonial period. Landscape scale fires seem to have occurred regularly, based on three microscopic charcoal samples. Concentrations do not surpass the upper threshold indicating that no above-background such as anthropogenic fires contributed to the occurrence of fires. Local fires were nearly absent.

Human distburance around Laguna Grande during the early colonial period is most evident from ca. 1640 cal yr AD onwards. The AP% decreases to ca. 20% and *Pinus* abundance to <10%. Simultaneously, abundances of the savana element and disturbance indicating *Borreria* increase. Multiple peaks in microscopic charcoal concentrations above the upper threshold suggest that fires occurred with high frequency on the Atlantic coastal plain. The rate of erosion as evidenced by a peak in *Glomus* cf. probably increased as well.

The late colonial period (between ca. 1670 and 1770 cal yr AD) seen from Estero Hondo is characterized by elevated AP % (max. 33%). Does this trend indicate an interval of lower human interference in the landscape surrounding Estero Hondo? Charcoal concentrations remain below the upper threshold, indicating fires were not frequent. Alternatively, increased AP% could result from larger fresh water fluxes carrying with it AP from the hinterland (Martin et al., 2007; Caffrey et al., 2015) entering the back-barrier lagoon. However, the coeval mangrove abundance decrease is in our opinion the most plausible explanation for the increase in relative abundance of AP. From ca. 1770 onwards, human disturbance such as deforestation increases as evidenced by asteraceous and poaceous vegetation that reaches abundance not seen in preceding samples. Evidence for crop cultivation other than Cucurbitaceae is nearly absent.

Laguna Grande shows an overall decrease in AP% from ca. 1700 to 1890 cal yr AD most likely pointing to deforestation. An exception is the maximum in AP% centered at ca. 1830 cal yr AD. A coeval peak in the abundance of chlamydospores of *Glomus* cf. suggests deposition of eroded material might be responsible for this increase. Occurences of *Zea mays* indicate maize cultivation in the surroundings of the lake. Fires were frequent possibly pointing to a human contribution to fire occurrence. We found no evidence for increased grazing by cattle.

In summary, changes in the degree of possible anthropogenic disturbance is most evident from the microscopic charcoal concentrations of Laguna Grande from the first halve of the 17th century onwards. Accordingly, decreases in the AP% could tentatively be related to deforestation, but evidence is equivocal. Estero Hondo seems to reflect less human disturbance prior, during and after colonization than Laguna Grande. Only from ca. 1770 cal yr AD onwards could human disturbance be deduced from decreasing AP and mangrove percentages as well as frequent local and regional fire occurrences indicating deforestation and pointing to mangrove degradation, supported by coeval increases in Poaceae and Asteraceae tubuliflorae. Given the poor pollen preservation from Laguna Grande, we assess the Estero Hondo pollen record as most reliable.

5.4 A regional perspective on environmental change and human disturbance in the northern Dominican Republic from pre-Colonial to modern times.

As a result of the rather poor age constraints of all, but particularly the Laguna Grande and Estero Hondo records, integration of the results for a regional reconstruction is not straightforward. Fully aware of the limitations of our age-models, we assess the similarities and differences between Biajaca, Los Indios, Estero Hondo and Laguna Grande. First, we compared all individual pollen zone descriptions and subsequently redefined and generalized period boundaries (Fig. 16). Of all proxy records available, the charcoal records have the highest resolution and they possess the most regional signal allowing for region-wide comparisons. Additionally, we visualized the evidence for crop cultivation in the same figures (Fig. 16). For completeness, we provide the same comparison using the uncorrected age-depth model for Laguna Grande (Suppl. Inf. Fig SI 7).

Given the differences in methodologies (e.g. pollen slide versus stereoscope counting or differences in size fractions) we refrain from quantitative comparisons. We redefine the Los Indios charcoal concentrations as sub-regional rather than strictly local (Hooghiemstra et al., 2018), since the fraction studied (>100 μm) partially overlaps with our microscopic charcoal fraction that we considered reflecting regional fire occurrence.

During pre- to early Ceramic times (before 1000 AD), regional fires occurred frequently in the Cibao valley, though concentrations from Los Indios are more convincing than from Biajaca. Possibly, (part of) the microscopic charcoal found in Estero Hondo and Laguna Grande originates from the Cibao valley rather than from the Atlantic coastal plain, supported by only sparse evidence for local fire occurences.

The Biajaca records shows first evidence for maize cultivation at ca. 950 cal yr AD preceding first evidence from the Atlantic coastal plain (Laguna Grande; ca. 650 cal yr AD). Possibly, the Cerealia-type record from Los Indios indicates maize cultivation as early as ca. 300 cal yr AD, more or less coeval with possible squash and pumpkin cultivation evidenced by a Cucurbitaceae peak at ca. 250 cal yr AD from Estero Hondo. However, Cerialia-type grains were not seperated from *Zea mays* in the published data (Hooghiemstra et al., 2018). Possibly, occurences of Cerialia-type from ca. 300 cal yr AD reflect wild grasses producing large pollen grains rather than maize cultivation. All records indicate only minor effects of any human disturbance on the environment, since the records suggest a more or less forested landscape in both the Cibao valley and the Atlantic coastal plain.

Human disturbance in the Cibao valley during the late Ceramic (ca. 1000 – 1492 yr AD) intensified and was characterized by crop cultivation (maize and squashes or pumpkins; Castilla-Beltrán et al., 2018) and possibly slash and burn practices. Noteworthy is that Castilla-Beltrán et al. (2018) used their Bacon calibrated ages to define the pollen zone boundaries in the time domain, but inconsistently used a lithological change between 140 and 130 cm to define the level of ca. 1492 AD and thus refrained from using the Bacon calibration median for inferring the depth of ca. 1492 AD. Therefore, we visualized this alternative level for 1492 AD (dashed orange vertical line; Fig 16, Suppl. Info. Fig. SI 7). Nevertheless, frequent local fire occurences are evident from Biajaca between ca. 1200 and 1492 cal yr AD, consistent archeological data indicating increased population density (Hofman et al., 2018). Los Indios does not show this increase in fire frequency, but increased potential crop abundances (Amaranthaceae and Cerealia-type) would allow for such an interpretation. Estero Hondo does not show above-background charcoal concentrations, indicating fires at the Atlantic coastal plain were not frequent, consistent with Laguna Grande concentrations..

Evidence for the impact of the ‘encounter’ is most clear from Biajaca, where large peaks in the abundance of fungus spores of coprophilous fungi are present at ca. 1492, absent in the other records. Immediate introduction of livestock to parts of the Cibao valley possibly was favored by the availability of grass on the floodplains of the Yaque river. The relatively restricted Atlantic coastal plain apparently was less appealing to cattle breeders, possibly as a result of dry conditions and the absence of a river supplying nutrients to the ‘pasture’ during flooding. Moreover, considering the ‘gold rush’ an important motivation for colonization of the inlands along ‘la ruta de Colón’ (Columbus’ route), the Cibao valley might immediately have become the center of gravity in terms of the Early Colonial economy.

Biajaca shows absence of local fire occurences during the early colonial period (ca.1492 -1700 cal yr AD) probably reflecting reduced slash and burn practices when indigenous social structures collapsed after colonization and decimation of their numbers (Livi-Bacci, 2006). Moreover, regional fire frequence was lower in all records as well.

Evidence for crop cultivation during the Early Colonial period is sparse, but Estero Hondo points to sustained cultivation of Cucurbitaceae. The pollen records of Los Indios and Biajaca point to deforestation, but apparently without using fire in agreement with a postulated need for timber during early urbanization under Spanish rule. Absence of evidence for Old World style agriculture, except for cattle breeding in part of the Cibao valley could reflect initial colonists’dependence of existing indigenous knowledge and structures in the rush for gold. By the early 17th century, agricultural practices around Biajaca were complemented by introduced crops, possibly reflected by Solanaceae (e.g. tomato and potato) and Cerealia-type. Moreover, cattle breeding was extended to other parts of the Cibao valley (Los Indios) and shortly thereafter (ca. 1750 AD) evidence for banana (Musacaceae) cultivation and the return of frequent local and regional fires point to intensified land use, coeval with accounts of increased population density resulting from European immigration and transport of enslaved Africans (Greenwood et al., 2003). Intensification of human disturbance (i.e. deforestation) on the Atlantic coastal plain is apparent from the Laguna Grande pollen and charcoal records from ca. 1640 cal yr AD onward. Decreasing trends in charcoal concentrations from the Cibao valley marking the transition to modern times are contrasted by increases found on the Atlantic coast evident from Laguna Grande (from 1700 onward). Only by ca. 1770 was the mangrove forest degraded by human disturbance such as deforestation. Apparently, the mangrove forest surrounding Estero Hondo was not of particular interest to the colonists, possibly as a result of its marine (i.e. saline) conditions, not suitable for agriculture like the floodplains of the Yaque river.

Comparisons of the inland Cibao valley records with the records from the Atlantic coastal plain is complicated by poor temporal resolution and unequivocal and circumstantial evidence for human disturbance. Elaboration on research questions related to differences in timing, character and rate of human disturbance, such as deforestation, between the Cibao valley and the Atlantic coastal plain, requires temporal resolutions in the order of decades. Furthermore, identification of potential crop plants currently hidden in their higher taxonomic families requires a proxy such as phytolith analysis. Castilla-Beltrán et al. (2018) showed that such an approach adds a signifcant level of detail to the environmental reconstruction.

6. Conclusions

First evidence for pre-Columbian human disturbance from the northwest coast of the Dominican Republic comes from possible Cucurbitaceae cultivation by early Ceramic Saladoid people around 250 cal yr AD. Pre-Columbian disturbance as inferred from Estero Hondo was limited in its extent, given near absence of both (above background) regional and local fires and no indications for deforestation. First evidence for crop cultivation (*Zea mays*) from Laguna Grande dates from ca. 1150 cal yr AD. Human induced fires and deforestation were nearly absent around Laguna Grande during pre-Columbian times.

Unequivocal evidence for the potential impact of the ‘encounter’ from the Atlantic coastal plain is absent, contrasting with evidence for cattle introduction and deforestation from the Cibao valley, suggesting the center of gravity in terms of population and disturbance was located in the Cibao valley, where the gold rush might have lead the colonists to the Cordillera Central, along *la Ruta de Colón* (Columbus’ route).

Laguna Grande shows intensified human disturbance from ca 1640 cal yr AD onward, reflected by increased occurrences of local and regional fires as well as indicators for a more open and disturbed landscape. Possibly, population numbers increased due to demographic pressure in the Cibao valley, resulting from large numbers of European immigrants and enslaved Africans. Only after ca. 1770 cal yr AD are frequent fires and deforestation apparent from the Estero Hondo record, suggesting that by the end of the 18^{th} century demographic pressure and economic demands caused degradation of the mangrove forest.

Human impact on the natural environment was of a limited and mostly local extent during Pre-Columbian times, whereas regional scale deforestation and introduction of cattle in the Cibao valley followed in the first century after the ‘encounter’. On the Atlantic coastal plain late and post-colonial human disturbance altered the landscape by increasing fire frequence and deforestation. Evidence for Old World style agriculture such as cattle breeding following colonization is absent.

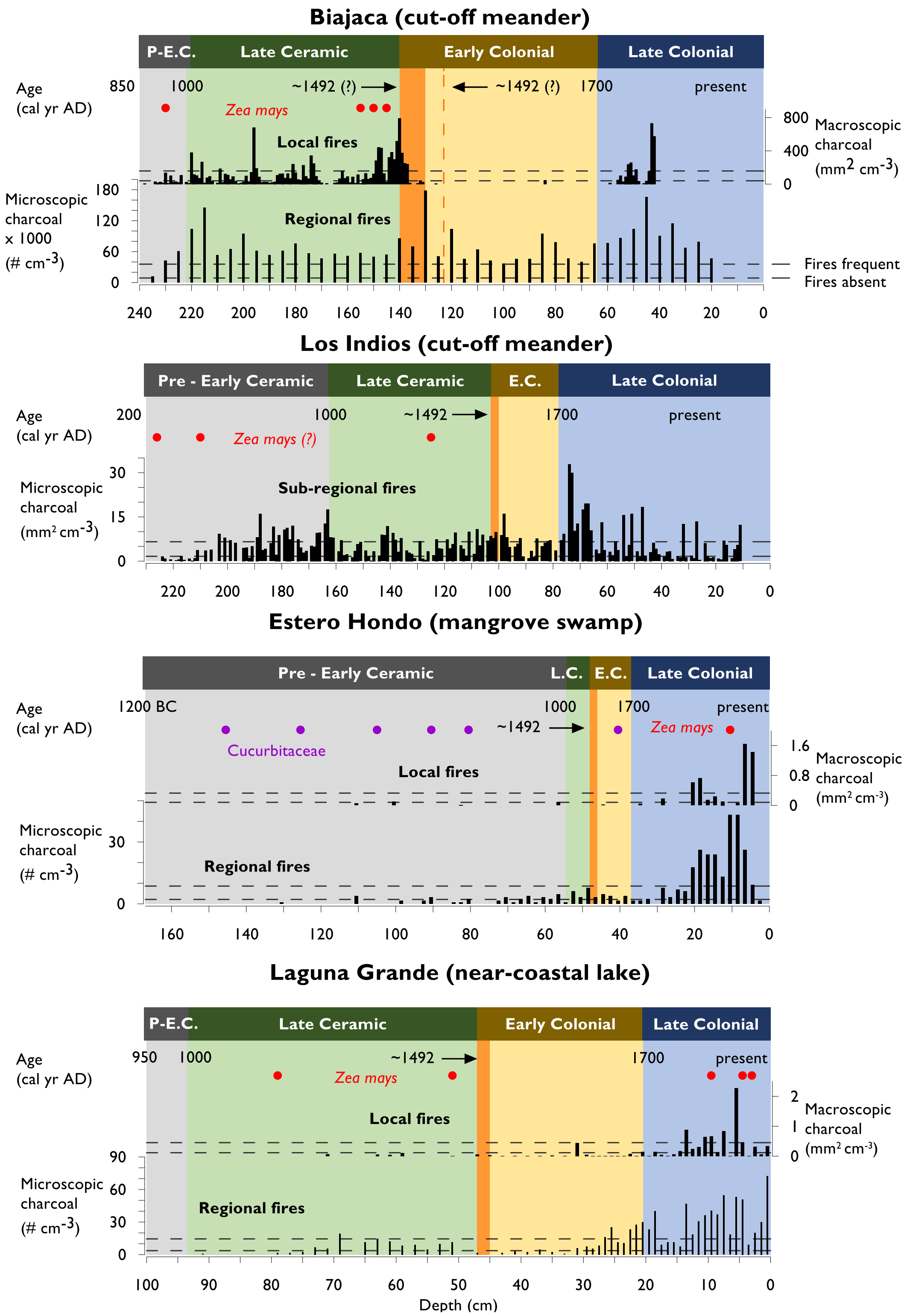

Figure 16 Regional comparison of charcoal records and evidence for crop cultivation. All records are plotted on a linear depth scale. Upper histograms show macro-charcoal concentrations indicative for local fire occurrences, lower histograms show micro-charcoal indicative for regional fire occurrences. Threshold values (dashed lines) are provided as a guidance for distinguishing signal from noise. Lower thresholds indicate absence of fires, upper thresholds indicate frequent occurrence of fires.

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References

Abril, J.M., 2004. Constraints on the use of ^{137}Cs as a time-marker to support CRS and SIT chronologies. Environmental Pollution, 129(1), 31-37.

Anderson, R.S., Homola, R.L., Davis, R.B., Jacobson Jr., G.L., 1984. Fossil remains of the mycorrhizal fungal *Glomus fasciculatum* complex in postglacial lake sediments from Maine. Canadian Journal of Botany 62, 2325-2328.

Avnery, S., Dull, R.A. and Keitt, T.H., 2011. Human versus climatic influences on late-Holocene fire regimes in southwestern Nicaragua. The Holocene 21, 699-706.

Bassett, I., Paynter, Q., Hankin, R., & Beggs, J. R. (2012). Characterising alligator weed (*Alternanthera philoxeroides*; Amaranthaceae) invasion at a northern New Zealand lake. New Zealand Journal of Ecology 36, 216-222.

Baud, M., 1987. The origins of capitalist agriculture in the Dominican Republic. Latin American Research Review 22, 135-153.

Beets, C.J., Troelstra, S.R., Grootes, P.M., Nadeau, M.J., Borg, K.V.D., Jong, A.D., Hofman, C.L. and Hoogland, M.L., 2006. Climate and pre-Columbian settlement at Anse à la Gourde, Guadeloupe, Northeastern Caribbean. Geoarchaeology: An International Journal 21, 271-280.

Behling, H., Cohen, M.C.L. and Lara, R.J., 2001. Studies on Holocene mangrove ecosystem dynamics of the Bragança Peninsula in north-eastern Pará, Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology 167, 225-242.

Blaauw, M. and, Christen, J.A., 2011. Felixible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Analysis 6, 457-474.

Blaauw, M., 2010. Methods and code for 'classical'age-modelling of radiocarbon sequences. Quaternary Geochronology 5, 512-518.

Boschman, L.M., van Hinsbergen, D.J.J., Torsvik, T.H., Spakman, W. and Pindell, J.L., 2014. Kinematic reconstruction of the Caribbean region since the Early Jurassic. Earth-Science Review 138, 102-136.

Bush, M.,B., McMichael, C.H., Piperno, D.R., Silman, M.R., Barlow, J., Peres, C.A., Power, M. and Palace, M.W., 2015. Anthropogenic influence on Amazonian forests in pre-history: An ecological perspective. Journal of Biogeography 42, 2277-2288.

Caffrey, M.A., Horn, S.P., Orvis, K.H. and Haberyan, K.A., 2015. Holocene environmental change ate Laguna Saladilla, coastal north Hispaniola. Palaeogeography, Palaeoclimatology, Palaeoecology 436, 9-22.

Castilla-Beltrán, Á., Hooghiemstra, H., Hoogland, M.L.P., Pagán-Jiménez, J., van Geel, B., Field, M.H., Prins, M., Donders, T.H., Herrera Malatesta, E, Ulloa Hung, J. McMichael, C.H., Gosling, W.D. and Hofman, C.L., 2018. Columbus' footprint in Hispaniola: A paleoenvironmental record of indigenous and colonial impacts on the landscape of the central Cibao Valley, northern Dominican Republic. Anthropocene 22, 66-80.

Cintron, G., Lugo, A.E., Pool, D.J. and Morris, G., 1978. Mangroves of arid environments in Puerto Rico and adjacent islands. Biotropica 10, 110-121.

Clement, R.M. and 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. The Holocene 11, 419-426.

Collins, J.L., 1951. Antiquity of the pineapple in America. Southwestern Journal of Anthropology 7, 145-155.

Cooper, J. 2013. The Climatic Context for Pre-Columbian Archaeology in the Caribbean. In W.F. Keegan, C.L. Hofman and R. Rodríguez-Ramos (eds.) The Oxford Handbook of Caribbean Archaeology, Oxford: Oxford University Press, 47–58.

Crosby, A.W. Jr., 1972. The Columbian Exchange: Biological and Cultural Consequences of 1492. Westport, Connecticut: Greenwood Press, pp. 268.

de Boer, E.J., Slaikovska, M., Hooghiemstra, H., Rijsdijk, K.F., Vélez, M.I., Prins, M., Baider, C. and Florens, V. Multi-proxy reconstruction of environmental dynamics and colonization impacts in the Mauritian uplands. Palaeogeography, Palaeoclimatology, Palaeoecology 383-384, 42-51.

Dillehay, T.D., Rossen, J., Andres, T.C. and Williams, D.E., 2007. Preceramic adoption of peanut, squash and cotton in northern Peru. Science 316, 1890-1893.

Donders, T.H., Gorissen, P.M., Sangiorgi, F., Cremer, H., Wagner-Cremer, F. and McGee, V., 2008. Three-hundred-year hydrological changes in a subtropical estuary, Rookery Bay (Florida): Human impact versus natural variability. Geochemistry, Geophysics, Geosystems 9, Q07V06.

Donelly, J.P., Bryant, S.S., Butler, J., Dowling, J., Fan, L., Hausmann, N., Newby, P., Shuman, B., Stern, J., Westover, K., Webb, T., 2001. 700 yr sedimentary record of intense hurricane landfalls in southern New England. GSA Bulletin 113, 714-727.

Durland, W.D., 1922. The forests of the Dominican Republic. Geographical Review 12, 206-22.

Erdtman, G., 1952. Pollen Morphology and Plant Taxonomy: Angiosperms. Almqvist & Wiksell, Stockholm, Sweden, pp. 539

Faegri, K., Kaland ,P.E. and Krzywinski, K., 1989. Textbook of Pollen Analysis. 4th Edition. Wiley, Chichester, U.K., pp. 328.

Fitzpatrick, S.M. and Keegan, W.F., 2007. Human impacts and adaptations in the Caribbean islands: an historical ecological approach. Earth and Environmental Science, Transactions of the Royal Society of Edinburgh 98, 29-45.

Flantua, S.G.A., Blaauw, M., Hooghiemstra, H., 2016. Geochronological database and classification system for age uncertainties in Neotropical pollen records. Climate of the Past 12, 387-414. doi: 10.5194/cp-12-387-2016.

Flantua, S.G.A., Hooghiemstra, H., Vuille, M., Behling, H., Carson, J.F., Gosling, W.D., Hoyos, I., Ledru, M.P., Montoya, E., Mayle, F., Maldonado, A., Rull, V., Tonello, M.S., Whitney, B.S., Gonzalez-Arango, C., 2016. Climate variability and human impact in South America during the last 2000 years: synthesis and perspectives from pollen records. Climate of the Past 12, 483-523. doi: 10.5194/cp-12-483-2016.

Garcia, O., Bosart, L. and DiMego, G., 1978. On the nature of the winter season rainfall in the Dominican Republic. Monthly Weather Review 107, 961-982.

Geerts, B., Heymsfield, G.M., Tian, L., Halverson, J.B., Guillory, A. and Mejia, M.I., 2000. Hurricane Georges's landfall in the Dominican Republic: Detailed airborne Doppler radar imagery. Bulletin of the American Meteorological Society 81, 999-1018.

Geraldes, F. X., 2003. The coral reefs of the Dominican Republic. In Cortés (ed.) Latin American coral reefs, Elsevier, Amsterdam, Netherlands, pp. 77-110.

Gómez, A., Berrio, J.C., Hooghiemstra, H., Becerra, M. and Marchant, R., 2007. A Holocene pollen record of vegetation change and human impact from Pantano de Vargas, an intra-Andean basin of Duitama, Colombia. Review of Palaeobotany and Palynology 145, 143-157.

González, C., Urrego, L.E., Martínez, J.I., Polanía, J. and Yokoyama, Y., 2010. Mangrove dynamics in the southwestern Caribbean since the 'Little Ice Age': A history of human and natural disturbances. The Holocene 20, 849-861.

González-Carranza, Z., Hooghiemstra, H. and Vélez, M.I., 2012. Major altitudinal shifts in Andean vegetation on the Amazonian flank show temporary loss of biota in the Holocene. The Holocene 22, 1227-1241.

Gosling, W.D., de Kruif, J., Norder, S.J., de Boer, E.J., Hooghiemstra, J., Rijsdijk, K.F. and McMichael, C.N.H., 2017. Mauritius on fire: Tracking historical human impacts on biodiversity loss. Biotropica 49, 778-783.

Greenwood, R., Hamber, S., and Dyde, B., 2003. Amerindians to Africans (Caribbean Certificat History) 1, 2nd edition. Macmillan Education, Oxford, UK.

Grimm, E.C., 1987. CONISS: A FORTRAN 77 Program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers & Geosciences 13, 13-35.

Grimm, E.C., 2015. Tilia version 2.0.41. Illinois State Museum, Springfield, Illinois, USA.

Grindrod, J., 1985. The Palynology of Mangroves on a Prograded Shore, Princess Charlotte Bay, North Queensland, Australia. Journal of Biogeography 12, 323-348.

Groot, M.H.M., Bogotá-Angel, R.G., Lourens, L.J., Hooghiemstra, H., Vriend, M., Berrio, J.C., Tuenter, E., van der Plicht, J., van Geel., B., Ziegler, M., Weber, S.L., Betancourt, A., Contreras, L., Gaviria, C., Giraldo, C., González, N., Jansen, J.H.F., Konert, M., Ortega, D., Rangel, O., Sarmiento, G., Vandenberghe, J., van der Hammen, T., van der Linden, M. and Westerhoff, W., 2011. Ultra-high resolution pollen record from the Northern Andes reveals rapid shifts in montane climates within the last two glacial cycles. Climate of the Past 7, 299-316.

Hastenrath, S., 1991. Climate Dynamics of the Tropics. Atmospheric Sciences Library, Kluwer Academic Publishers, Netherlands, pp. 488.

Haug, G.H., Günther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A. and Aeschlimann, B., 2003. Climate and the collapse of Maya civilization. Science 299, 1731-1735.

Heiri, O., Lotter, A.F. and Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology 25, 101-110.

Higuera-Gundy, A., Brenner, M., Hodell, D.A., Curtis, J.H., Leyden, B.W. and Binford, M.W., 1999. A 10,300 ^{14}C yr record of climate and vegetation change from Haïti. Quaternary Research 52, 159-170.
Hodell, D.A., Brenner, M., Curtis, J.H., Medina-Gonzalez, R., Can, E.I.C., Albornaz-Pat, A. and Guilderson, T.P., 2005. Climate change on the Yucatan Peninsula during the Little Ice Age. Quaternary Research 63, 109-121.
Hodell, D.A., Curtis, J.H., Jones, G.A., Higuera-Gundy, A., Brenner, M., Binford, M.W. and Dorsey, K.T., 1991. Reconstruction of Caribbean Climate Change over the Past 10,500 years. Nature 352, 790-793.
Hofman, C.L, Mol, A., Hoogland, M.L.P. and Valcárcel Rojas, R., 2014. Stage of encounters: migration, mobility and interaction in the pre-colonial and early colonial Caribbean. World Archaeology 46, 590-609.
Hofman, C.L., Ulloa Hung, J., Herrera Malatesta, E., Jean, J., Sonneman, T. and Hoogland, M.L.P., 2018. Indigenous Caribbean perspectives: archaeologies and legacies of the first colonized region in the New World. Antiquity 92, 200-216.
Holdrige, L.R., 1945. A brief sketch of the flora of Hispaniola. In Verdoorn, F. (ed.) Plants and Plant Science in Latin America. Chronica Botanica Co, Waltham, MA, USA, pp. 76-81.
Hooghiemstra, H., 1984. Vegetational and climatic history of the high plain of Bogotá, Colombia. Dissertaciones Botanicae 79. J. Cramer Verlag, Vaduz.
Hooghiemstra, H., Olijhoek, T., Hoogland, M.L.P., Prins, M., van Geel, B., Donders, T.H., Gosling, W.D. and Hoffman, C.L., 2018. Columbus' environmental impact in the New World: Land use change in the Yaque valley, Dominican Republic.The Holocene 28, 1818-1835.
Horowitz, A., 1992. Palynology of Arid Lands. Elsevier, Amsterdam, The Netherlands, pp. 546.
Horst, O.H., 1992. Climate and the 'encounter' in the Dominican Republic. Journal of Geography 91, 205-210.
Hua, Q., Barbetti, M. and Rakowski, A. Z., 2013. Atmospheric radiocarbon for the period 1950–2010. Radiocarbon 55, 2059-2072.
Islebe, G.A. and Hooghiemstra, H., 1995. Recent pollen spectra of highland Guatemala. Journal of Biogeography 22, 1091-1099.
Islebe, G.A. and Sánchez, O., 2002. History of Late Holocene vegetation at Quintana Roo, Caribbean coast of Mexico. Plant Ecology 160, 187-192.
Islebe, G.A., Hooghiemstra, H., Brenner, M., Curtis, J.H. and Hodell, D. A., 1996. A Holocene vegetation history from lowland Guatemala. The Holocene 6, 265-271.
Izzo, M., Rosskopf, C.M., Aucelli, P.P., Maratea, A., Méndez, R., Pérez, C. and Segura, H., 2010. A new climatic map of the Dominican Republic based on the Thornthwaite classification. Physical Geography, 31, 455-472.
Kelly,R.F., Higuera, P.E., Barrett, C.M. and Hu, F.S., 2011. Short Paper: A signal-to-noise index to quantify the potential for peak detection in sediment–charcoal records. Quaternary Research 75, 11-17.
Kemp, A.C., Sommerfield, C.K., Vane, C. H., Horton, B.P., Chenery, S., Anisfeld, S. and Nikitina, D., 2012. Use of lead isotopes for developing chronologies in recent salt-marsh sediments. Quaternary Geochronology 12, 40-49.
Kennedy, L.M., Horn, S.P. and Orvis, K.H., 2006. A 4000-year record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic. Palaeogeography, Palaeoclimatology, Palaeoecology 231, 279-290.

Konert, M. and Vandenberghe, J., 1997. Comparison of laser grain size analysis with pipette and sieve analysis: a solution for the underestimation of the clay fraction. Sedimentology 44, 523-535.
Lane, C.S., Horn, S.P. and Orvis, K.H., 2008. The earliest evidence of Ostionoid maize agriculture from the interior of Hispaniola. Caribbean Journal of Science 44, 43-52.
Lane, C.S., Horn, S.P., Mora, C.I. and Orvis, K.H., 2009. Late-Holocene paleoenvironmental change at mid-elevation on the Caribbean slope of the Cordillera Central, Dominican Republic: a multi-site, multi-proxy analysis. Quaternary Science Reviews 28, 2239-2260.
Lane, C.S., Horn, S.P., Orvis, K.H. and Thomason, J. M., 2011. Oxygen isotope evidence of Little Ice Age aridity on the Caribbean slope of the Cordillera Central, Dominican Republic. Quaternary Research 75, 461-470.
Lee, S.Y., 2008. Mangrove macrobenthos: Assemblages, services and linkages. Journal of Sea Research 59, 16-29.
Leeder, M., 2011. ‘Chapter 18 Linear siliciclastic shorelines’, Sedimentology and Sedimentary Basins, from Turbulence to Tectonics, second edition, Wiley-Blackwell, Chichester, West Sussex, UK, pp. 417-438.
Livi-Bacci, M., 2006. The depopulation of Hispanic America after the conquest. Population and Development Review 32, 199-232.
Lowe, J. and Walker, M., 2015. Reconstructing Quaternary Environments, third edition. Routledge, New York, US, pp. 538.
Maezumi, S.Y., Alves, D., Robinson, M., de Souza, J.G., Levis, C., Barnett, R.L., Almeida de Oliveira, E., Urrego, D., Schaan, D. and Iriate, J., 2018. The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon. Nature Plants 4, 540.
Mann, P, Prentice, C.S., Burr, G., Peña, L.R. and Taylor, F.W., 1998. Tectonic geomorphology and paleoseismology of the Septentrional fault system, Dominican Republic. Geological Society of America, Special Paper 326, 63-123.
Mann, P., Draper, G. and Lewis, J.F., 1991. An overview of the geologic and tectonic development of Hispaniola. Geological Society of America, Special Papers 262, 1-28.
Marchant, R., Almeida, L., Behling, H. et al., 2002. Distribution and ecology of parent taxa of pollen lodged within the Latin American Pollen database. Review of Palaeobotany and Palynology 121, 1-75.
Martin, P.H., Sherman, R.E. and Fahey, T.J., 2007. Tropical montane forest ecotones: climate gradients natural disturbance, and vegetation zonation in the Cordillera Central, Dominican Republic. Journal of Biogeography 34, 1792-1806.
Mauquoy, D. and van Geel, B., 2007. Plant macrofossil methods and studies: mire and peat macros. In Encyclopedia of Quaternary Science. Elsevier Science, pp. 3575.
McCook, S., 2011. The Neo-Columbian Exchange: The Second Conquest of the Greater Caribbean, 1720-1930. Latin American Research Review, 11-31.
McMichael, C.H., Piperno, D.R., Bush, M.B., Silman, M.R., Zimmerman, A.R., Raczka, M.F., Lobato, L.C., 2012. Sparse Pre-Columbian Human Habitation in Western Amazonia. Science 336, 1492-1431.
Moore, P.D., Webb, J.A. and Collinson, M.E., 1991. Pollen Analysis. 2nd edition. Blackwell, Oxford and London, UK.
Newsom, L.A. and Deagan, K.A., 1994. *Zea mays* in the West Indies: the archaeological and early historic record. Corn and culture in the prehistoric New World, 203-217.

Osborne, P.L., 2012. Tropical Ecosystems and Ecological Concepts, 2nd edition. Cambridge University Press, Cambridge, UK, pp. 522.

Palacios-Chávez, R., Ludlow-Wiechers B. and Villanueva, G.R., 1991. Flora palinológica de la reserva de la biosfera de Sian Ka'an, Quintana Roo, México. Chetumal; Quintana Roo; México City, Mexico: Centro de Investigaciones de Quintana Roo, pp. 321.

Paterson, G.A. and Heslop, D., 2015. New methods for unmixing sediment grain size data. Geochemistry, Geophysics, Geosystems 16, 4494-4506.

Peros, M.C., Reinhardt, E.G., Davis, A.M., 2007. A 6000-yr record of ecological and hydrological changes from Laguna de la Leche, north coastal Cuba. Quaternary Research 67, 69-82.

Power, M.J., Mayle, F.E., Bartlein, P.J., Marlon, J. R., Anderson, R.S., Behling, H., Carcaillet, C., Colombaroli, D., Gavin, D.G., Hallett, D.J., Horn, S.P., Kennedy, L.M., Lane, C.S., Long, C.J., Moreno, P.I., Paitre, C.,Robinson, G.,Taylor, Z., Walsh, M.K. and Hallett, D.J., 2013. Climatic control of the biomass-burning decline in the Americas after AD 1500. The Holocene, 23, 3-13.

Reading, H.G. and Collinson, J.D., 1996. In H.G. Reading (ed.) Sedimentary Environments, processes, facies and stratigraphy, Blackwell Publishing, Malden, MA, USA, pp. 688.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, M.E., Southon, J.R., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 yr cal BP. Radiocarbon 55, 1869-1887.

Rodgers, J.C. and Horn, S.P., 1991. Modern pollen spectra from Costa Rica. Palaeogeography, Palaeoclimatolgy, Palaeoecology 124, 53-71.

Roubik, D.W. and Moreno, P., 1991. Pollen and Spores of Barro Colorado Island (Panama). Monographs in Systematic Botany 36. Botanical Garden, St. Louis, MO, U.S.

Siegel, P.E., Jones, J.G., Pearsall, D.M. and Wagner, D.P., 2005. Environmental and cultural correlates in the West Indies: A view from Puerto Rico. Ancient borinquen: archaeology and ethnohistory of native Puerto Rico, 1-54.

Siegel, P.E., Jones, J.G., Pearsall, D.M., Dunning, N.P., Farrell, P., Duncan, N.A., Curtis, J.H. and Singh, S.K., 2015. Paleoenvironmental evidence for first human colonization of the eastern Caribbean. Quaternary Science Reviews 129, 275-295.

Sonnemann, T.F., Ulloa Hung, J., Hofman, C.L., 2016. Mapping indigenous settlement topography in the Caribean using drones. Remote Sensing 8, 791.

Stuiver, M. and Reimer, P.J., 1993. Extended 14 C data base and revised CALIB 3.0 14 C age calibration program. Radiocarbon 35, 215-230.

Ulloa Hung, J., 2014. Arqueología en la Línea Noroeste de La Española. Paisajes, cerámicas e interacciones. Dissertación, Leiden University, The Netherlands, pp. 352.

Urrego, L.E., Correa-Metrio, A., González, C., Castaño, A.R. and Yokoyama, Y., 2013. Contrasting responses of two Caribbean mangroves to sea-level rise in the Guajira Peninsula (Colombian Caribbean). Palaeogeography, Palaeoclimatology, Palaeoecology 370, 92-102.

Urrego, L.E., González, C., Urán, G. and Polanía, J., 2010. Modern pollen rain in mangroves from San Andres Island, Colombian Caribbean. Review of Palaeobotany and Palynology 162, 168-182.

van Geel, B. and Aptroot, A., 2006. Fossil ascomycetes in Quaternary deposits. Nova Hedwigia, 82, 313-329.

van Geel, B., 1976. Fossil spores of Zygnemataceae in ditches of a pre-historic settlement in Hoogkarspel (The Netherlands). Review of Palaeobotany and Palynology 22, 337-344.

van Geel, B., Gelorini, V., Kyaruu, A. et al., 2011. Diversity and ecology of tropical African fungal spores from a 25,000-year paleoenvironmental record in southeastern Kenya. Review of Palaeobotany and Palynology 164, 174-190.

van Geel., B., Coope, G.R., van der Hammen, T., 1989. Paleoecology and stratigraphy of the Lateglacial type section at Usselo (The Netherlands). Review of Palaeobotany and Palynology 60, 25-129.

van Hateren, J.A., Prins, M.A. and van Balen, R.T., 2018. On the genetically meaningful decomposition of grain-sisze distributions: A comparison of different end-member modelling algorithms. Sedimentary Geology 375, 49-71.

Vriend, M., Groot, M.H.M., Hooghiemstra, Bogotá-Angel, R.G., Berrio, J.C., 2012. Changing depositional environments in the Colombian Fúquene Basin at submillennial time-scales during 284-27 ka from unmixed grain size distributions and aquatic pollen. Netherlands Journal of Geosciences 91, 199-214.

Walker, M., 2005. Quaternary Dating Methods. John Wiley, Chichester and New York, pp. 286.

Willard, D.A., Bernhardt, C.E., Weimer, L., Cooper, S.R., Gamez, D. and Jensen, J., 2004. Atlas of pollen and spores of the Florida Everglades. Palynology 28, 175-227.

Zaldivar, M.E., Rocha, O.J., Castro, E. and Barrantes, R., 2002. Species diversity of edible plants grown in homegardens of Chibchan Amerindians from Costa Rica. Human Ecology 30, 301-316.

Supplementary information

Table 1 Bacon age model Laguna Grande.

depth (cm)	min (cal yr BP)	max (cal yr BP)	median (cal yr BP)	mean (cal yr BP)	mean (cal yr AD)
0	375	611	516	510	1440
1	394	615	525	520	1430
2	411	619	535	530	1420
3	424	625	544	539	1411
4	436	630	554	549	1401
5	445	639	564	559	1391
6	472	642	573	569	1381
7	494	645	583	579	1371
8	513	649	593	589	1361
9	529	655	604	600	1350
10	541	663	616	610	1340
11	558	672	629	622	1328
12	570	686	640	634	1316
13	578	706	651	646	1304
14	584	730	661	658	1292
15	590	758	671	670	1280
16	605	764	684	683	1267
17	616	774	697	695	1255
18	625	785	710	708	1242
19	632	801	722	720	1230
20	638	820	734	733	1217
21	658	824	746	745	1205
22	672	830	760	757	1193
23	681	837	773	770	1180
24	690	846	787	782	1168
25	697	860	800	794	1156
26	708	864	807	803	1147
27	716	868	815	811	1139
28	725	874	823	820	1130
29	734	883	833	829	1121
30	741	895	842	837	1113
31	747	898	848	843	1107
32	753	903	854	849	1101
33	757	907	860	855	1095
34	761	913	866	860	1090
35	765	921	872	866	1084
36	770	925	878	872	1078
37	775	928	883	878	1072
38	780	933	889	884	1066
39	784	938	895	890	1060
40	789	945	901	896	1054
41	800	956	911	906	1044

42	809	974	919	915	1035
43	817	995	927	925	1025
44	825	1017	935	934	1016
45	833	1042	943	944	1006
46	845	1051	953	954	996
47	855	1063	963	965	985
48	865	1077	973	975	975
49	875	1097	982	985	965
50	884	1118	991	996	954
51	894	1129	1002	1006	944
52	907	1140	1012	1016	934
53	915	1154	1023	1027	923
54	921	1172	1034	1037	913
55	928	1191	1044	1048	902
56	939	1198	1054	1058	892
57	948	1207	1064	1068	882
58	956	1216	1075	1079	871
59	963	1229	1086	1089	861
60	971	1247	1096	1099	851
61	981	1254	1106	1110	840
62	991	1265	1118	1120	830
63	1000	1274	1128	1131	819
64	1007	1285	1139	1141	809
65	1013	1299	1149	1152	798
66	1027	1306	1160	1162	788
67	1038	1316	1171	1173	777
68	1047	1327	1181	1184	766
69	1055	1339	1192	1194	756
70	1062	1353	1203	1205	745
71	1075	1361	1214	1215	735
72	1087	1369	1225	1226	724
73	1095	1378	1236	1236	714
74	1104	1388	1247	1246	704
75	1113	1400	1257	1257	693
76	1126	1408	1267	1267	683
77	1138	1414	1278	1278	672
78	1148	1423	1289	1288	662
79	1158	1431	1299	1298	652
80	1165	1444	1310	1309	641
81	1179	1451	1320	1319	631
82	1192	1458	1330	1329	621
83	1203	1466	1341	1340	610
84	1213	1477	1351	1350	600
85	1221	1490	1362	1360	590
86	1238	1496	1372	1371	579
87	1253	1503	1382	1381	569
88	1264	1510	1392	1392	558
89	1275	1518	1403	1402	548

90	1285	1529	1413	1413	537
91	1303	1534	1423	1423	527
92	1321	1539	1433	1434	516
93	1336	1545	1444	1444	506
94	1347	1552	1454	1455	495
95	1357	1560	1465	1465	485
96	1373	1565	1475	1475	475
97	1386	1572	1487	1486	464
98	1396	1583	1497	1496	454
99	1404	1599	1508	1506	444
100	1411	1620	1518	1517	433

Table 2 Bacon age model Estero Hondo.

depth (cm)	**min (cal yr BP)**	**max (cal yr BP)**	**median (cal yr BP)**	**mean (cal yr BP)**	**mean (cal yr AD)**
0	-68	-62	-65	-65	2015
1	-65	-42	-58	-57	2007
2	-64	-19	-51	-48	1998
3	-63	5	-44	-40	1990
4	-62	28	-37	-31	1981
5	-61	51	-30	-23	1973
6	-56	58	-22	-15	1965
7	-53	67	-13	-7	1957
8	-50	79	-4	0	1950
9	-48	93	4	8	1942
10	-46	108	12	16	1934
11	-40	118	20	24	1926
12	-36	127	28	32	1918
13	-31	137	36	40	1910
14	-29	150	43	48	1902
15	-26	166	51	56	1894
16	-19	173	58	64	1886
17	-14	182	65	72	1878
18	-10	193	73	80	1870
19	-5	207	80	88	1862
20	-1	223	86	96	1854
21	7	230	94	104	1846
22	13	238	102	113	1837
23	18	247	110	121	1829
24	22	256	119	130	1820
25	26	268	127	138	1812
26	35	277	135	147	1803
27	44	290	142	156	1794
28	53	310	149	165	1785
29	61	329	156	174	1776
30	69	351	164	183	1767
31	78	361	171	193	1757

32	87	379	179	202	1748
33	96	395	186	212	1738
34	102	416	194	221	1729
35	107	440	202	231	1719
36	122	455	207	240	1710
37	132	475	213	250	1700
38	141	492	219	259	1691
39	149	507	225	269	1681
40	155	530	232	278	1672
41	172	549	238	289	1661
42	189	567	244	300	1650
43	205	590	250	311	1639
44	219	611	257	322	1628
45	228	634	265	333	1617
46	254	677	351	395	1555
47	268	748	438	456	1494
48	281	845	505	517	1433
49	292	971	563	578	1372
50	302	1100	618	640	1310
51	364	1127	688	704	1246
52	402	1157	765	767	1183
53	435	1186	844	831	1119
54	461	1235	915	895	1055
55	487	1298	983	959	991
56	531	1307	1010	990	960
57	577	1316	1043	1021	929
58	613	1329	1077	1052	898
59	651	1355	1108	1083	867
60	676	1396	1137	1115	835
61	694	1404	1150	1128	822
62	716	1416	1163	1141	809
63	732	1427	1176	1154	796
64	750	1440	1188	1167	783
65	767	1456	1201	1181	769
66	788	1463	1212	1193	757
67	806	1474	1225	1206	744
68	826	1484	1239	1218	732
69	848	1497	1250	1231	719
70	864	1508	1263	1244	706
71	883	1520	1275	1256	694
72	902	1528	1287	1269	681
73	921	1539	1299	1282	668
74	939	1553	1312	1294	656
75	956	1570	1323	1307	643
76	974	1579	1336	1320	630
77	993	1588	1349	1333	617
78	1013	1601	1362	1346	604
79	1029	1611	1373	1359	591

80	1046	1625	1387	1372	578
81	1064	1634	1399	1385	565
82	1087	1645	1411	1399	551
83	1106	1655	1424	1412	538
84	1121	1668	1436	1425	525
85	1133	1679	1450	1438	512
86	1157	1687	1462	1452	498
87	1178	1695	1474	1465	485
88	1196	1705	1487	1478	472
89	1213	1716	1500	1491	459
90	1228	1729	1513	1504	446
91	1258	1737	1525	1517	433
92	1280	1746	1536	1530	420
93	1303	1757	1548	1543	407
94	1319	1766	1560	1555	395
95	1335	1777	1572	1568	382
96	1360	1784	1583	1581	369
97	1381	1791	1594	1593	357
98	1404	1800	1606	1606	344
99	1420	1811	1619	1619	331
100	1435	1820	1631	1631	319
101	1469	1826	1641	1645	305
102	1500	1835	1652	1658	292
103	1526	1845	1664	1671	279
104	1547	1859	1677	1685	265
105	1565	1874	1690	1698	252
106	1596	1888	1708	1719	231
107	1617	1907	1729	1739	211
108	1634	1935	1747	1760	190
109	1646	1968	1767	1781	169
110	1655	2008	1787	1802	148
111	1676	2029	1815	1827	123
112	1691	2059	1842	1852	98
113	1704	2099	1869	1878	72
114	1715	2148	1893	1903	47
115	1724	2201	1916	1928	22
116	1748	2219	1944	1954	-4
117	1769	2238	1972	1981	-31
118	1789	2265	2000	2007	-57
119	1803	2301	2029	2033	-83
120	1816	2348	2054	2059	-109
121	1845	2361	2081	2086	-136
122	1867	2378	2109	2112	-162
123	1885	2402	2137	2139	-189
124	1902	2438	2163	2165	-215
125	1913	2478	2190	2192	-242
126	1950	2493	2218	2218	-268
127	1976	2511	2244	2243	-293

128	1996	2536	2270	2269	-319
129	2010	2563	2298	2295	-345
130	2022	2596	2323	2320	-370
131	2065	2607	2350	2346	-396
132	2099	2620	2375	2372	-422
133	2131	2639	2402	2398	-448
134	2154	2662	2428	2424	-474
135	2171	2695	2454	2450	-500
136	2227	2703	2477	2476	-526
137	2276	2715	2501	2503	-553
138	2314	2728	2525	2529	-579
139	2341	2743	2549	2556	-606
140	2365	2765	2574	2582	-632
141	2406	2773	2592	2606	-656
142	2433	2782	2611	2629	-679
143	2456	2797	2633	2653	-703
144	2475	2839	2660	2676	-726
145	2494	2888	2686	2700	-750
146	2513	2912	2707	2720	-770
147	2528	2947	2729	2740	-790
148	2543	2988	2750	2760	-810
149	2555	3031	2771	2780	-830
150	2567	3079	2792	2799	-849
151	2583	3101	2812	2820	-870
152	2597	3128	2833	2840	-890
153	2612	3158	2853	2860	-910
154	2624	3192	2871	2880	-930
155	2633	3238	2889	2900	-950
156	2649	3256	2910	2921	-971
157	2666	3287	2930	2941	-991
158	2678	3314	2953	2962	-1012
159	2690	3348	2973	2982	-1032
160	2699	3385	2991	3003	-1053
161	2720	3406	3014	3024	-1074
162	2735	3431	3033	3044	-1094
163	2748	3468	3054	3065	-1115
164	2761	3501	3074	3085	-1135
165	2769	3538	3094	3106	-1156
166	2788	3561	3114	3126	-1176
167	2798	3588	3134	3146	-1196

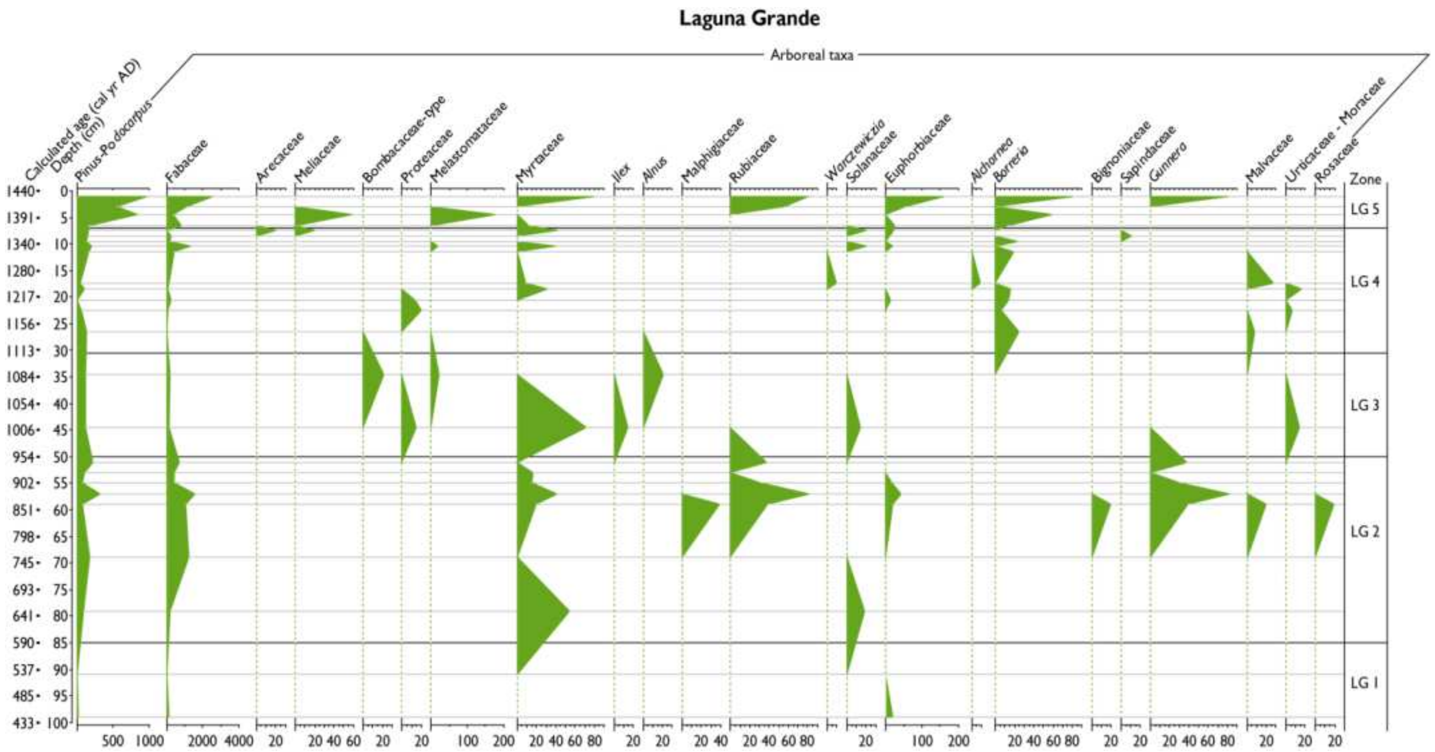

Figure 1 Pollen concentrations Laguna Grande. Data are plotted on a linear depth scale. From left to right are shown: age (cal yr AD), depth (cm), individual concentrations of arboreal taxa (grains cm^{-3} of sediment) and pollen zones.

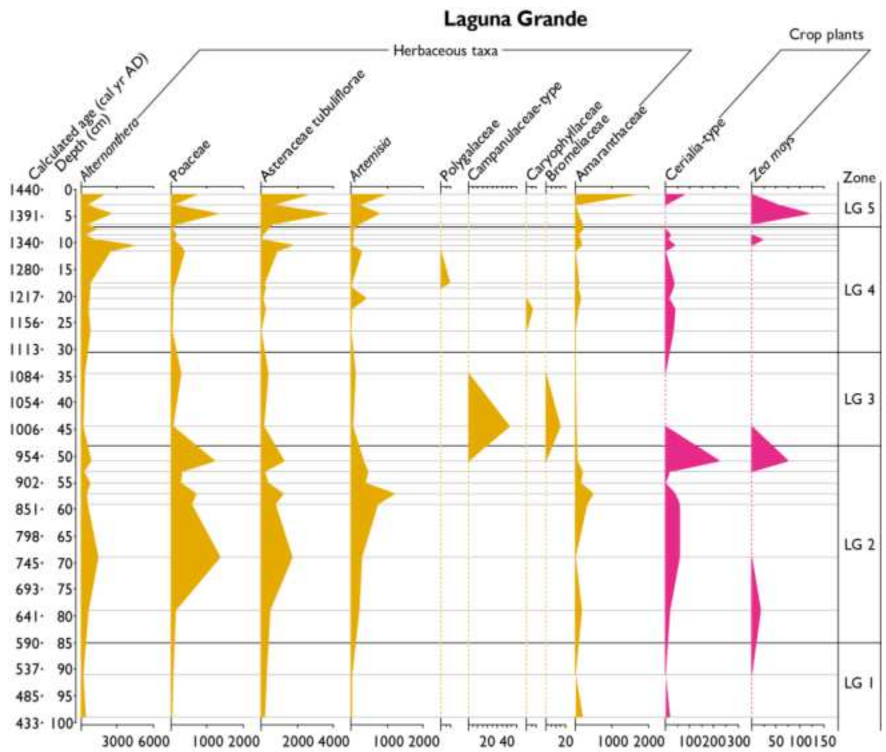

Figure 2 Pollen concentrations Laguna Grande. Data are plotted on a linear depth scale. From left to right are shown: age (cal yr AD), depth (cm), individual concentrations of herbaceous and crop plant taxa (grains cm^{-3} of sediment) and pollen zones.

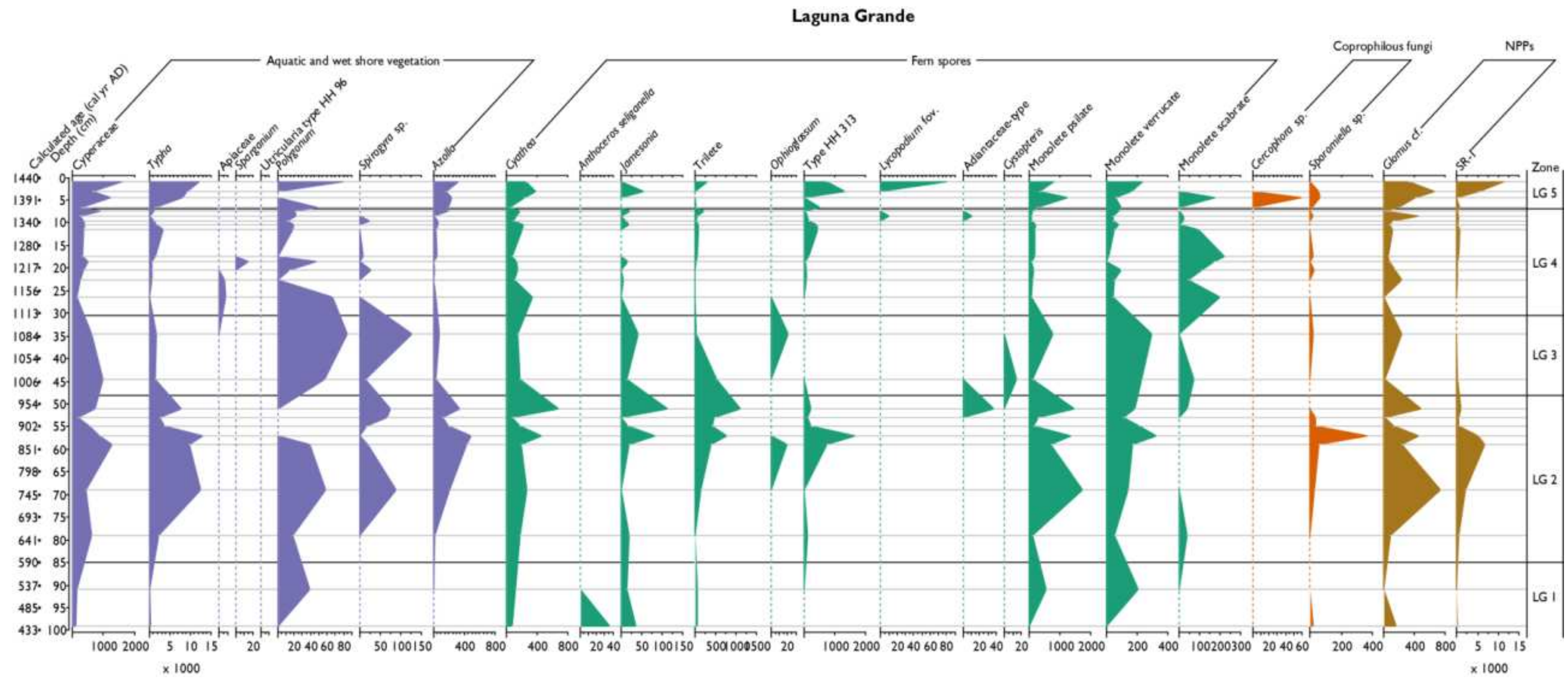

Figure 3 Pollen concentrations Laguna Grande. Data are plotted on a linear depth scale. From left to right are shown: age (cal yr AD), depth (cm), individual concentrations of aquatic and wet shore taxa, fern spores, coprophilous fungal spores and non-pollen palynomorphs (palynomorphs cm^{-3} of sediment) and pollen zones.

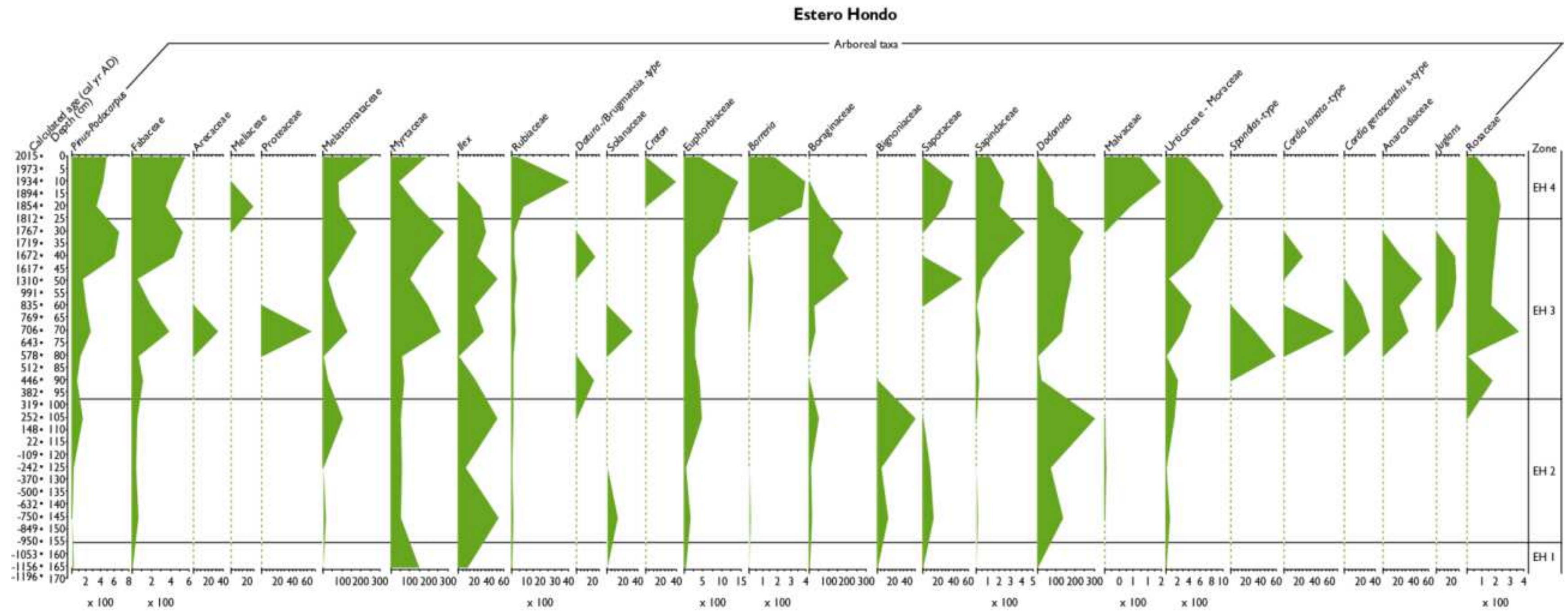

Figure 4 Pollen concentrations Estero Hondo. Data are plotted on a linear depth scale. From left to right are shown: age (cal yr AD), depth (cm), individual concentrations of arboreal taxa (grains cm^{-3} of sediment) and pollen zones.

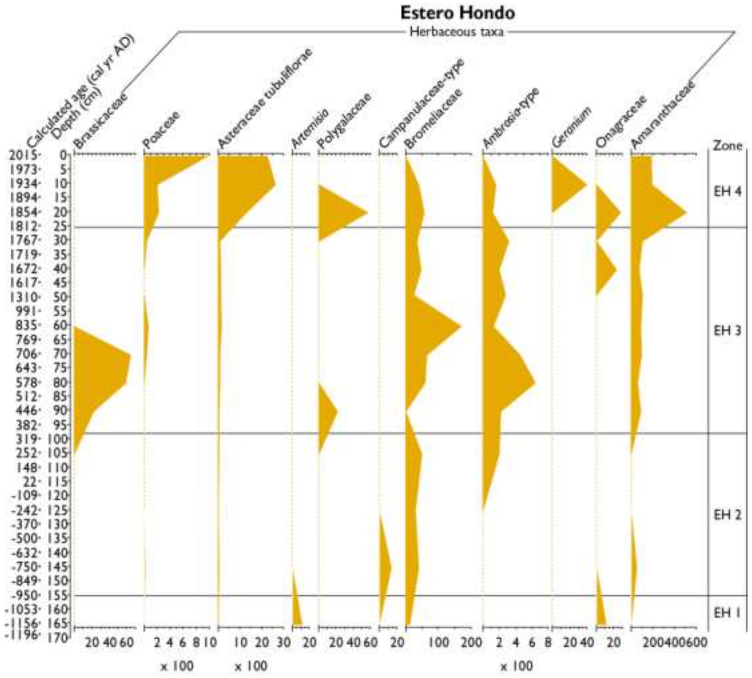

Figure 5 Pollen concentrations Estero Hondo. Data are plotted on a linear depth scale. From left to right are shown: age (cal yr AD), depth (cm), individual concentrations of herbaceous taxa (grains cm^{-3} of sediment) and pollen zones.

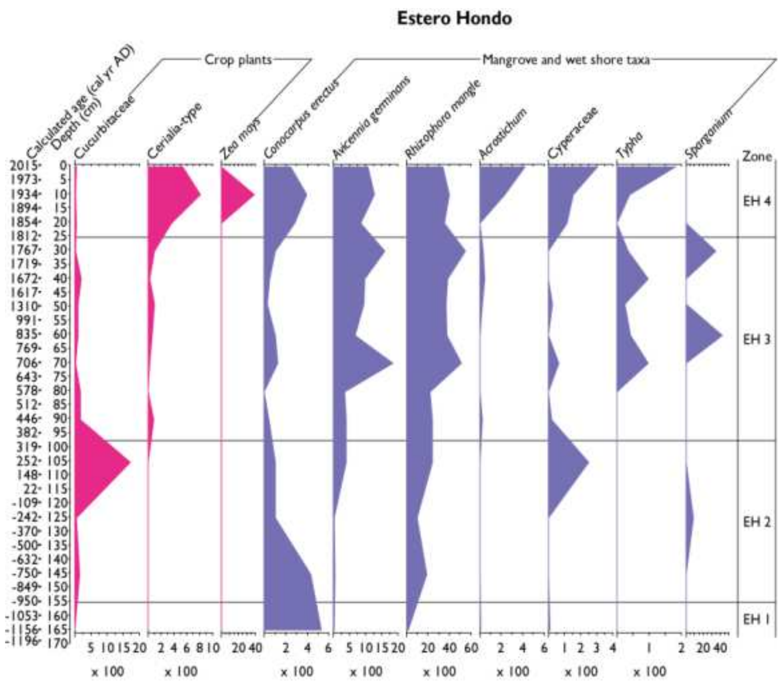

Figure 6 Pollen concentrations Estero Hondo. Data are plotted on a linear depth scale. From left to right are shown: age (cal yr AD), depth (cm), individual concentrations of crop plant, mangrove and wet shore vegetation taxa (grains cm^{-3} of sediment) and pollen zones.

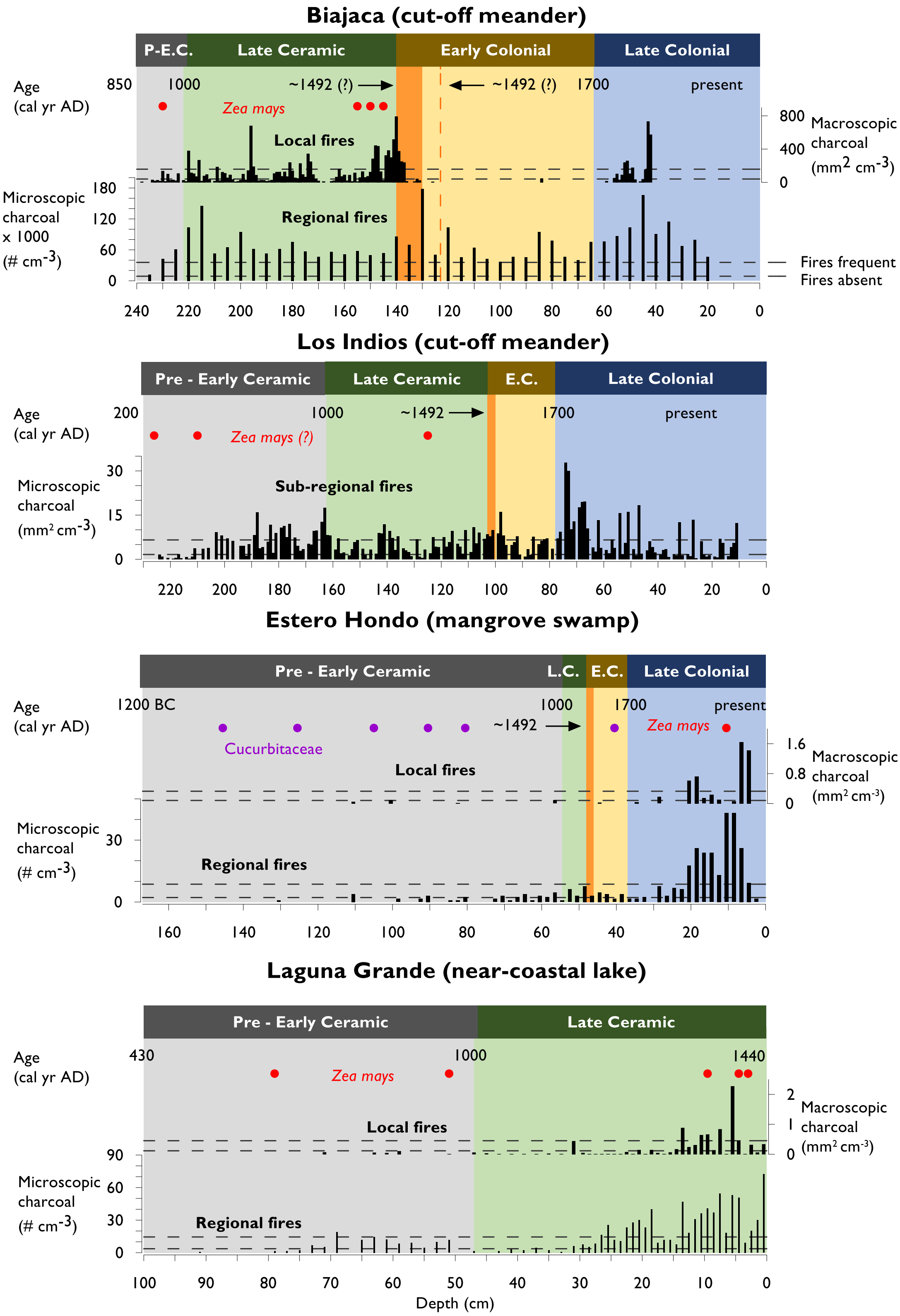

Figure 7 Regional comparison of charcoal records and evidence for crop cultivation. All records are plotted on a linear depth scale. For Laguna Grande (lower most panel) ages without reservoir age correction are shown.