

Columbus' environmental impact in the New World: Land use change in the Yaque River valley, Dominican Republic

The Holocene
2018, Vol. 28(11) 1818–1835
© The Author(s) 2018



Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/0959683618788732
journals.sagepub.com/home/hol



Henry Hooghiemstra,¹ Thomas Olijhoek,^{1,2} Menno Hoogland,³
Maarten Prins,⁴ Bas van Geel,¹ Timme Donders,² William Gosling¹
and Corinne Hofman³

Abstract

Columbus' arrival in the New World in AD 1492 on the northern coast of Hispaniola was followed by a suite of changes in land-use. We reconstruct environmental change from a 225-cm-long sediment core from site Los Indios from an abandoned and sediment-filled meander of the Yaque River, Cibao Valley, northeastern Dominican Republic. The sediment record starts ca. AD 195 (ca. 1755 cal. yr BP) and the history of the meander infill was monitored by changing grain size distributions, organic matter concentration and pollen from wetland plants. From ca. AD 200 to ca. AD 1525, the pollen record indicates a diverse forest assemblage; however, the presence of pollen from potential crop plants suggest nearby small-scale subsistence crop cultivation. More abundant charcoal after ca. AD 1410 shows Amerindians increasingly used fire. The record of grain size distributions shows that the meander was temporarily part of a low energetic drainage system in which bedload and suspended sediments accumulated. After European colonization of Hispaniola increasing spores of coprophilous fungi evidence that Europeans had introduced during the first decades of colonization cattle in the Cibao Valley which gradually resulted in more open forest. The charcoal record around ca. AD 1650 reflects intensive forest clearing, suggesting that small-scale Pre-Colonial practice of crop cultivation became replaced by large-scale agriculture on the moist and nutrient rich soils along the Yaque River. Further deforestation and signals of erosion suggest that the population of colonists and introduced enslaved labour force must have increased rapidly. After ca. AD 1740 charcoal influx decreased suggesting that last deforestation activities used selective cutting to produce fire wood and timber for construction, rather than burning forest in situ. Two centuries after European colonization, by the 18th century, land-use within the Cibao Valley had become a balance between substantial livestock and crop cultivation (pollen grains have evidenced cereals, maize, and potentially also sugar cane, amaranthaceous crops and tobacco). After ca. AD 1950, swamp vegetation of *Typha* and Cyperaceae decreased, pointing to an almost fully terrestrialized meander with only few bodies of standing water, reflecting the present-day setting. This multiproxy reconstruction of anthropogenic environmental change shows a clear differentiation between an immediate introduction of livestock and after some 150 years the development of a European style agriculture, providing a context for archaeological investigations.

Keywords

charcoal, colonial period, Hispaniola, grain size distributions, land-use change, livestock development, pre-colonial period

Received 16 February 2018; revised manuscript accepted 6 June 2018

Introduction

Columbus arrival in the Americas in AD 1492 initiated for the first time a division of the world into a Spanish and Portuguese realm (Vidal-Naquet, 1987). Strengthened by the blessing of the Pope (Inter Caetera Bull, 1493) and the Treaty of Tordesillas (1494) newly discovered territories west of 50°W longitude were assigned to Spain. During Columbus' second voyage, he established the first Spanish town in the New World, which he called 'La Isabella' after Queen Isabella of Castile. At the time of European arrival Hispaniola had already been inhabited for some 7000 years by indigenous peoples, now known as Taino (Lane et al., 2009). When Europeans arrived in AD 1492 some 300,000 Taino are estimated to have been living on Hispaniola (Greenwood et al., 2003). However, following European colonization slaughter, suicide and disease lead to the near eradication of indigenous people by ca. AD 1550; Livi-Bacci, 2006). During the Spanish administration (late 16th and 17th centuries), the demand for tropical agricultural products, sugar in particular, increased significantly in Europe. The change in population and demands placed

¹Department of Ecosystem & Landscape Dynamics, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, The Netherlands

²Department of Physical Geography, Utrecht University, Utrecht, The Netherlands

³Faculty of Archaeology, Leiden University, Leiden, The Netherlands

⁴Faculty of Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

Corresponding authors:

Henry Hooghiemstra, Department of Ecosystem & Landscape Dynamics, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands.
Email: h.hooghiemstra@uva.nl

Corinne Hofman, Faculty of Archaeology, Leiden University, Leiden, The Netherlands.
Email: c.l.hofman@arch.leidenuniv.nl

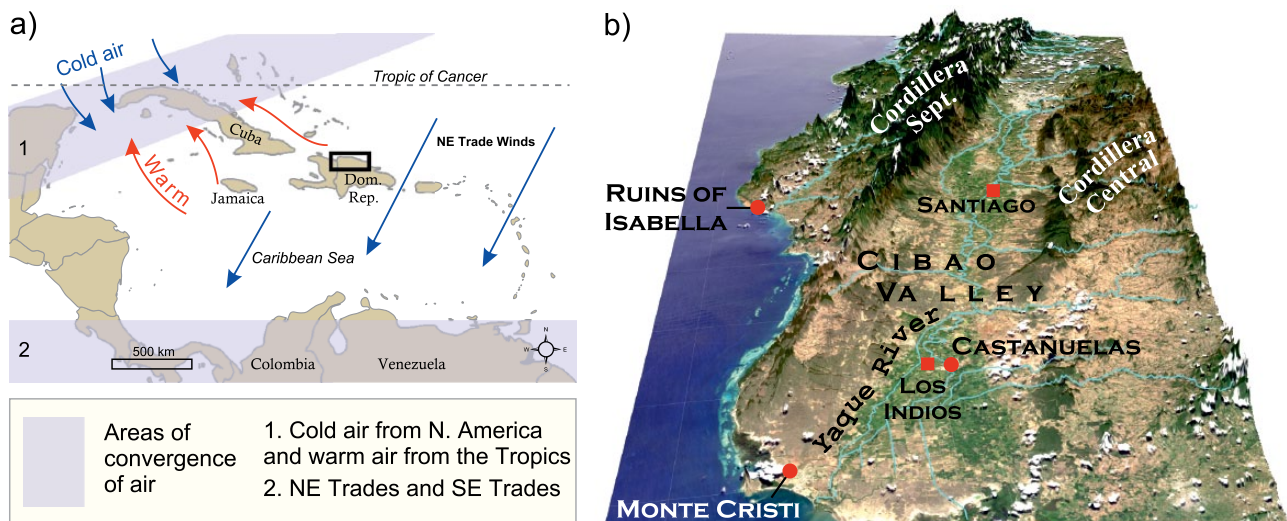


Figure 1. (a) Map showing the location of the island of Hispaniola in the Caribbean area. The northernmost and southernmost positions of the ITCZ are shown. (b) Map of the western Dominican Republic showing the drainage area of the Yaque River and the location of the site Los Indios.

on the islands resources caused land-use changes on Hispaniola which potentially have been archived in sediment records.

The island of Hispaniola is today divided into the territory of two sovereign nations, the Dominican Republic and Haïti. Few paleoecological studies from sediment cores are known from either the Dominican Republic or Haïti. The most notable studies are from the highlands of the Cordillera Central; we mention Cafrey (2011, 2015), Kennedy et al. (2005, 2006) and Lane et al. (2008, 2009, 2011), and from southern Haïti the studies by Higuera-Gundy et al. (1999) and Hodell et al. (1991). These studies suggest Holocene vegetation change on Hispaniola was driven by regional climate change while archaeological evidence indicates multiple sites where humans had an impact on the landscape. On a local scale, paleoecological records may potentially fill a gap between regional reconstructions of environmental and climate change and site-specific archaeological reconstructions.

The study presented here is located in the Cibao Valley at some 40 km from a pre-existing north-south route through Hispaniola, now known as the 'Ruta de Colón' (Hofman et al., 2014), along which the first Europeans travelled to explore for gold and other resources. The Cibao Valley, traversed by the meandering Yaque River, has prosperous conditions for agriculture and a long indigenous settlement history as a consequence. This is a challenging location to reconstruct the degree of Pre-Colonial land use and to document the suite of changes in the landscape during Colonial times. Given the long occupation history of this fertile river valley the history of human occupation may be longer than the sediment record found in the sediment filled abandoned river channel. In addition, human impact on the landscape may be locally substantial and evidence from the various proxy records may reflect local anthropogenic impact rather than regional signals of climate change. However, once a landscape is degraded by human impact, it is difficult to separate anthropogenic evidence from signals of natural change. Therefore, comparing our results with archaeological narratives (e.g. Hofman et al., 2014, 2018) is as challenging as making comparisons with regional reconstructions of environmental and climatic change. The river dynamics and recent expansions of banana and rice cultivation have given the modern valley floor a flat topography enabling large-scale hydrological systems of canals to inundate agricultural fields. In 2015, a part of the Cibao Valley was explored for sediment archives left in between agricultural areas and suitable to paleoecological studies. The aim of the present paper is to show changing levels of land-use in the Cibao Valley during Pre-Colonial and

Post-Colonial times and focus on aspects as how indigenous peoples and European colonists interacted with the landscape.

Setting

Geography and geology

Hispaniola is located on the northern edge of the Caribbean Plate. The island consists essentially of a series of four mountain ranges, roughly parallel and oriented in a WNW to ESE direction, and separated by interior plains. The northernmost of these plains, located between the Cordillera Septentrional and the Cordillera Central (Figure 1) is the Cibao Valley and reflects the most important natural region of the Dominican Republic (McNeill et al., 2008; Van Royen, 1938). The area is underlain by young bedrock, mostly of Miocene to Recent age. Soft marls, shales, sands, and clays predominate in the area with rolling plains, but occasionally limestone, sandstone and conglomerate are forming the relief of the Tertiary hills dissected by the Yaque River (Mann et al., 1991, 1998; Van Royen, 1938). The coring site at Los Indios is at an altitude of ca. 30 m asl. Regular volcanic activity is a.o. related to location of the Septentrional Fault Zone along the northern border of the Cibao Valley (Bolay, 1997). The valley is traversed by the Yaque River which flows from southeast to northwest. The Yaque River winds down from head waters in the Cordillera Central (2580 m asl) over 296 km to its mouth in the Bay of Monte Cristi bordering the Caribbean Sea (Soldner et al., 2004). Four main rivers originating from the Cordillera Central feed into the Yaque River (Hofman et al., 2018).

Climate and vegetation

Hispaniola is located in the relatively dry central Caribbean region (Niles, 2005). The annual migration of the intertropical convergence zone (ITCZ) where northeast and southeast trade winds meet, reaches its northernmost position in the Caribbean area south of Hispaniola (Figure 1). As a consequence a relatively wet season occurs from May to September to the south of Hispaniola (Durland, 1922; Higuera-Gundy et al., 1999). In addition relatively warm air from the central Caribbean (including Hispaniola) meets with relatively cold air masses from North America at the latitudes of Cuba and creates there another zone of increased precipitation leaving Hispaniola located in a relatively dry central Caribbean east to west zone (Niles, 2005). Lowest monthly precipitation values in Hispaniola occur in December and January

when the North Atlantic Subtropical High (NAH) moves south. The NAH leads to stronger trade winds and cooler temperatures from January to March (Giannini et al., 2000, 2001). The Cordillera Septentrional in the north and the Cordillera Central in the south are protecting the Cibao Valley from influence of the northern and southern trade winds (Caffrey, 2011). As a consequence, the Cibao Valley, located in between both mountain ranges, receives less precipitation than other parts of the Hispaniola. In the western Cibao Valley, the mean annual precipitation (MAP) is ca. 700 mm, whereas other regions receive up to ca. 2400 mm yr⁻¹ (Bolay, 1997). The highest temperatures in the Cibao Valley occur in August, with mean monthly maxima reaching ca. 33°C, and the lowest temperatures are measured in January, with a mean of ca. 28°C (Caffrey, 2011; Müller, 1983). Although the Cibao Valley is located in the driest part of Hispaniola, the Yaque River, which meanders through it, floods annually under natural conditions (Morales et al., 2009). The annual flooding enhanced soil fertility (e.g. Windingstad et al., 2008), and therefore, the Cibao Valley was during Pre-Colonial and Post-Colonial times an important area for crop cultivation. Its economy must have been continuously subject to effects of climate change, droughts in particular (Cooper and Peros, 2010).

On Hispaniola, vegetation studies are most abundant for the area of the Dominican Republic (Cano et al., 2014; Cano-Carmona, 2010; Cano-Ortiz et al., 2015; Durland, 1922; Hager and Zanoni, 1993; Harcourt et al., 1996; Liogier, 1981; Marcus, 2008; Martin et al., 2007). The natural vegetation consists of (a) dry forest (Cano-Ortiz et al. (2015) and references therein; Garcia-Fuentes, 2015), (b) mesic forest, (c) wet forest (including high elevation 'cloud forest' at locations where ascending air masses cause local condensation zones (Crausbay et al., 2015), and low elevation 'gallery forest' which is periodically flooded in the study area by the Yaque River), (d) pine forest of *Pinus occidentalis* (endemic to Hispaniola) found from 200 to 3100 m elevation in the Cordillera Central (Darrow and Zanoni, 1990; Farjon and Styles, 1997), (e) shrubland, and (f) herbaceous vegetation types (Holdridge, 1945; Marcus et al., 2008). In the Cibao Valley, only remnants of degraded natural vegetation can be found. The local vegetation also includes wet river bank vegetation, marsh vegetation (a fluctuating watertable permits seasonal aeration of the topsoil), swamp vegetation (perpetually waterlogged soil) and aquatics (Beard, 1955). The broad valley floor is covered by the strongly meandering Yaque River which was originally flanked by gallery forest. Where the course of rivers had changed in the recent past open grassy meadows, cyperaceous swamp, and swamp forest were left to form a vegetation mosaic. Nowadays, a system of dikes, which are part of the irrigation system, protect extensive monocultures of banana, tobacco, rice and sugar cane from flooding. Meanders with potentially sedimentary archives of high interest were developed into canals and water reservoirs and some disappeared through equalising the riverine plains.

Short history

At Columbus' arrival indigenous people, commonly known as Taíno people, lived in the Cibao Valley (Castilla-Beltrán et al., 2018). We hypothesize that early settlements with small-scale crop cultivation left a mosaic of small clearings in the mainly forested valley. We suppose the highlands and steep slopes of the mountains mostly retained their cover with needle forests including *Pinus orientalis* (Caffrey, 2011). When Europeans started to explore the inlands shortly after AD 1493 they discovered the Cibao Valley. In general, the Spanish created a European-style economy based on livestock and plantations. The indigenous people suffered much from introduced European diseases (Livi-Bacci, 2006). Later, enslaved labour force was imported from West Africa and slave trade increased rapidly during the 16th

century (Fitzpatrick and Keegan, 2007; Rawley and Behrendt, 2005). How this development took place in the Cibao Valley in particular is unknown. New settlers and enslaved labour force caused a growth of the human population and provoked more deforestation. Hispaniola became a springboard for Spanish conquest of the Caribbean and the adjacent American mainland. In AD 1697, Spain recognized French dominion over the western third of Hispaniola, which in AD 1804 became the independent nation of Haïti. The remainder of the island, by then known as Santo Domingo, sought to gain its own independence in AD 1821, but was conquered and ruled by the Haïtians for 22 years before it finally attained independence in AD 1844 as the Dominican Republic. The last two centuries has seen population growth in conjunction with the large-scale development of agricultural activities, such as sugar, coffee, tobacco, cacao, and recently also banana and rice, and concomitant population growth (Higuera-Gundy et al., 1999). Only during the second half of the last century have national parks been established. Increased state control over land management and timber resource use through national parks aims to protect the last remnants of the natural mountain forest (Bolay, 1997; Harcourt et al., 1996; Holmes, 2014).

Material and methods

Site selection and coring

We selected an abandoned meander from the Yaque River filled with sediments near a farm known under the name Los Indios (coordinates UTM 19Q0239540 east; 2183400 north) with La Castañuelas as the nearest village. The site is at some 40 km from the road from La Isabella, through the Cordillera Septentrional to the interiors and southern coast of Hispaniola. This route was followed by Christopher Columbus in AD 1493 in his search for resources and is known as the 'Ruta de Colón' (Hofman et al., 2018). The sediment-filled meander is covered by herbaceous grassy vegetation with shrubs (Figure 2). We walked a transect across the former river channel and examined the thickness and quality of the sediments with a hand-operated fibre glass probe of 10 mm diameter. The steel point of the probe allowed us to hear the difference between clayey, silty, and sandy intervals and so get a quick impression of the thickness and nature of the sediment. The sediment core was collected where sediments had a maximal depth and clays dominated. We used a hand operated Russian Corer of 5 cm diameter and 50 cm length to collect a sediment core. At 226-cm depth, we most probably reached the ancient river gravel bed. Following recovery, each core section was transferred into longitudinally cut PVC-tubes and wrapped in plastic foil for protection during transport. After transport to the palynological laboratory at the University of Amsterdam, sediment cores received an additional plastic protection against desiccation and were stored in a cold room at 4°C.

Radiocarbon dating, pollen and spore analysis

To establish the chronology of the sediment core 7 sediment samples were radiocarbon dated: at three depths, we found plant macro-fossil remains suitable for dating, while in four other levels, we found no suitable fossils so dated bulk organic sediment. Samples for radiocarbon dating were preferably taken at important transitions in the record and dated by Beta Analytic using accelerator mass spectrometry (AMS). Age–depth relationships were reconstructed using the R-code CLAM version 2.2 (Blaauw, 2010; R Development Core Team, 2014) and calibrated ages have been rounded off to the nearest multiple of 10 years.

Analysis of the fossil pollen content of sediment samples is the principal technique available for determining vegetation response to past terrestrial environmental change (Moore et al., 1991). For pollen analysis, sediment samples of 1 cm³ were taken at 5 cm

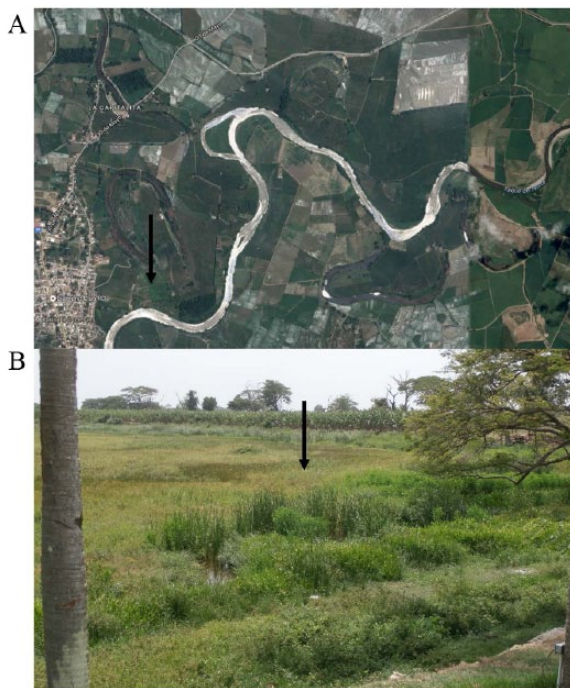


Figure 2. (A) Map showing a part of the Yaque River valley and the location of the meander of Los Indios. The background shows a Landsat 8 satellite imagery; multispectral LC80080462016231LGN00_MTL downloaded from <https://earthexplorer.usgs.gov/>. To emphasize the mountain ranges, we applied a vertical exaggeration of 7.74368e-005 using ArcScene software 10.5.1 (ESRI, Redlands, CA) (courtesy of S.G.A. Flantua); (B) photograph of the coring site. The arrow in A indicates the location of the meander and in B the location of the drilling site.

increments along the core. Sample preparation followed Faegri et al. (1989), including sodium pyrophosphate, acetolysis, and heavy liquid separation by a bromoform–ethanol mixture with a specific gravity of 2.0. A tablet with exotic *Lycopodium* spores was added to each sample to calculate pollen concentration values following Stockmarr (1971). For the identification of pollen and spores, we used the pollen morphological literature of Erdtman (1952), Hooghiemstra (1984), Olivera (1997), Roubik and Moreno (1991), Olivera (1997), Palacios-Chávez et al. (1991) and the pollen reference collection of the University of Amsterdam. We followed Marchant et al. (2002) for ecological ranges of the identified taxa. To identify the potential presence of *Zea mays*, we used the criterium of a diameter greater than 62 μm (Beug, 2004; Lane et al., 2008a; Whitehead and Langham, 1965) and to identify pollen of Cerealia, we followed Beug (2004). Given the poor preservation of pollen grains, we leave the possibility open that the archeologically so important records of Cerealia and maize pollen are incomplete. Therefore, we refrain from identifying ‘first’ records and we present Cerealia and maize as a joint record. The analysis of non-pollen palynomorphs (NPPs), including spores of fungi and remains of algae, cyanobacteria and invertebrates have indicator value for local environmental conditions (Van Geel, 2001). For identification of spores of coprophilous fungi and other NPPs, we used Cugny et al. (2010), van Geel et al. (1981), Van et al. (2003), Van Geel et al. (2011), van Geel and Aptroot (2006) and Hillbrand et al. (2012).

Palynological research in arid lands may encounter restrictive conditions and corroded grains and low pollen concentration may challenge environmental reconstructions based on pollen alone (Horowitz, 1992) (see also section 6.1). For two reasons, we present in the pollen diagrams only a simplified set of vegetation types to illustrate changes in land-use: (1) much of pre-human

disturbance ‘natural’ vegetation types do not exist in the Cibo Valley today and (2) the relatively low pollen sum values detract from the statistical reliability that the suite of forest types are properly reflected. More authors tried to avoid an over-interpretation of the data and are using a simplified set of arboreal habitat preferences (Higuera-Gundy et al., 1999). Thus, the pollen record shows to which degree the inhabited landscape had been opened by settlements, pastures and crop fields, rather than documents changes in the share of the various forest types. The pollen sum includes taxa characteristic of (1) forest, the fraction of arboreal pollen (AP); (2) herbaceous vegetation, the fraction of non-arboreal pollen (NAP); and (3) pollen grains from crop plants. *Cyathea* tree ferns are a substantial part of the cloud forests (Cano et al., 2014) and under such conditions spores of *Cyathea* are included in the pollen sum (e.g. Groot et al., 2013). Pollen taxa characteristic of aquatic and swamp vegetation, algae, fern spores, fungal spores and moss spores were excluded from the pollen sum.

Pollen sum values were reached after counting two microscope slides. The relatively low pollen sum values and the relatively high proportion of unidentified pollen grains need special attention in the methodology to be followed. Unidentified well-preserved pollen types are few (5 types) and occur at low frequency (max. ca. 5% of all unidentified grains) making separation between well-preserved and corroded pollen grains irrelevant. The literature shows different methodological approaches for unidentified pollen grains which may be included in the pollen sum (e.g. Higuera-Gundy et al., 1999), or excluded from the pollen sum (e.g. Lane et al., 2008b, 2009). However, unidentified pollen grains reflect an unspecified part of the regional vegetation, justifying unidentified pollen grains are included in the pollen sum. On the basis of this pollen sum, the pollen record shows changes in the proportion of forested and open herbaceous landscapes and the share of crop cultivation. The development of the aquatic and swamp vegetation in the meander is expressed on the pollen sum. To explore the impact of unidentified pollen grains on the zonation, we compared the main pollen diagrams including and excluding the group of unidentified pollen grains.

Pollen diagrams were plotted using the computer program TILIA 1.7.16 (Grimm, 1993, 2004, 2011). Pollen zones are based on CONISS analysis (Grimm, 1987), an application included in TILIA 1.7.16, in combination with visual inspection of the records.

Grain size distributions, organic matter and charcoal

Changes in grain size distributions (GSDs) are used to reconstruct changes in the energy level of the drainage system. GSDs were measured in samples taken at 5 cm increments along the core. Samples originate from approximately 1 cm core intervals and had a volume of ca. 1 cm^3 . Samples were pre-treated with 10 mL 30% H_2O_2 in order to remove organic matter (OM). Subsequently samples were exposed to 5 mL 10% HCl to remove calcium carbonate, followed by 300 mg of $\text{Na}_4\text{P}_2\text{O}_7 \cdot 10\text{H}_2\text{O}$ to further disperse grains (Konert and Vandenberghe, 1997). GSDs were measured between 0.1 and 2000 μm and classified into 56 classes with a Sympatec HELOS KR laser-diffraction particle sizer available at the Vrije Universiteit, Amsterdam. End-Member Modelling was done using the GSD as input data for the End-Member Modelling Algorithm (EMMA) (Prins and Weltje, 1999; Weltje and Prins, 2003). Summary statistics were calculated through the mean GSD of the dataset.

To estimate how much OM was present in the sediments the OM content (% weight loss) was determined (Meijers and Teranes, 2001). Analysis was carried out at Utrecht University by loss on ignition (LOI) at 550°C and followed Heiri et al., (2001). Samples of 1 cm^3 were collected continuously along the core at

Table 1. Radiocarbon ages and sample specific data of sediment core Los Indios.

Depth (cm)	Lab #	Material	^{14}C	$\delta^{13}\text{C}$	Cal. yr BP (2σ)	Age (AD)
36–37	437560	plant material	Post 0	-15.4 o/oo		
80–81	420880	bulk organic sediment	260 ± 30	-25.0 o/oo	1525–1555	425–395
105–106	437561	bulk organic sediment	1060 ± 30	-23.8 o/oo	900–925	1050–1025
123–124	437562	plant material	920 ± 30	-28.2 o/oo	1650–1690	300–260
165–166	420881	bulk organic sediment	870 ± 30	-24.5 o/oo	1050–1085	900–865
179–180	420882	bulk organic sediment	980 ± 30	-25.0 o/oo	1015–1050	935–900
224–225	437563	plant material	1840 ± 30	-25.9 o/oo	1665–1780	285–170

1-cm-thick intervals. Samples were dried overnight at 105°C. Dried samples were weighted and heated for 5 hours at 550°C. Samples were weighted once more and the percentage weight loss was determined.

Charcoal analysis of lake sediments was used to reconstruct variations in past fire occurrence (Martin and Fahey, 2006; Siegert et al., 2001; Whitlock and Larsen, 2001) taking climate-driven burning in the Caribbean islands and more local anthropogenic burning into consideration (Caffrey and Horn, 2015). The amount of macroscopic charcoal was recorded at 1 cm increments along the core. The samples were deflocculated with 10% H_2O_2 over the course of a night. Afterwards the samples were washed through a 100 μm sieve. The remaining material was collected in Petri dishes and charcoal was then identified using an Olympus stereoscope. The surface area of charcoal particles in the Petri dish was digitally calculated (mm^2 charcoal/ cm^3 of sediment) using Image-J following <http://rsbweb.nih.gov/ij/>.

Results

Lithology and chronology

The 226-cm-long core consists of homogeneous sediment without clear stratigraphical layering. Transition from coarse to fine-grained sediments is gradual. Throughout the core roots are sparse and other plant macro remains almost absent.

Seven sediment samples were AMS radiocarbon dated (Table 1). The depth vs age model (Figure 3) shows that the samples at 105 cm and 123 cm core depth have an unrealistically old age in comparison to the two samples at 165 and 179 cm. River currents may have transported older material from elsewhere and re-deposited at the coring site. Both samples were rejected. The sediments reflect the period from ca. AD 1100 (850 cal. yr BP) to ca. AD 1980 (-30 cal. yr BP). The abandoned meander developed from open water into a swamp and recently into a wet herb rich meadow where no sediment accumulation takes place, explaining the last ca. 35 years are not reflected.

Changes in sediment accumulation follow from the depth vs age graph (Figure 3) and potentially have impact on the pollen concentration records (Figure 4b). In intervals with coarse grained sediments corroded grains are more abundant and pollen concentration records should be used with care.

Palyнологical results and GSDs

The pollen concentration in the sediments was found to be low throughout the sediment core (< 5000 to 50000 grains cm^{-3} ; Figure 4b). A standard pollen sum of 300 identified pollen grains of terrestrial plants (Moore et al., 1991) was never reached. In the intervals with best preserved grains, the pollen sum varied from 100 to 198 (from 154 to 435 if unidentified pollen grains are included); in the intervals with poorly preserved grains, the pollen sum varied from 12 to 48 (12 to 220 if unidentified pollen grains are included) (Table 2). All identified taxa of pollen, spores, algae and other microfossils, and ecological groups are shown in Table 3.

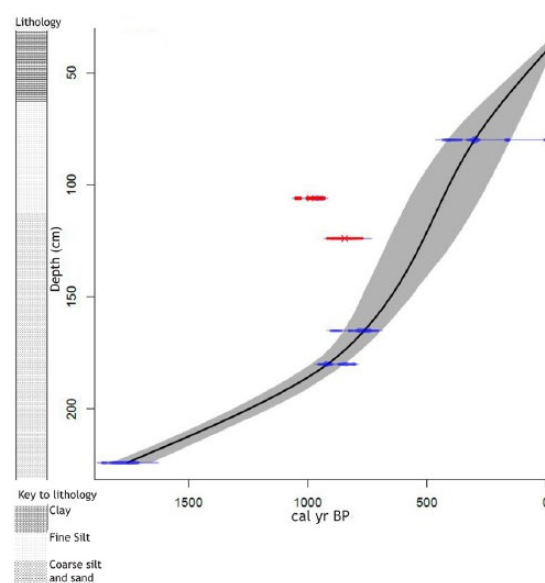


Figure 3. Age model of Los Indios sediment core. The sediment column reflects the period from ca. 1755 cal. yr BP (ca. AD 195) to ca. AD 1980. The lithology of the sediment core is shown at the left.

Changes in the pollen spectra are shown in the pollen percentage diagram as individual records (Figure 4a) and records of ecological groups (Figure 4b). Records of fungal spores are shown in Figure 5. Five pollen assemblage zones have been recognized: pollen zone LI-1: 226–210 cm core interval (4 samples), pollen zone LI-2: 205–135 cm core interval (15 samples), pollen zone LI-3: 130–85 cm core interval (10 samples), pollen zone LI-4: 80–40 cm core interval (9 samples) and pollen zone LI-5: 35–0 cm core interval (7 samples). The pollen diagram is calculated on the basis of a pollen sum including ‘unidentified’ pollen grains, ‘well preserved unidentified’ and ‘poorly preserved unidentified’ grains included. A concise description of the pollen zones is provided in available online Supplementary Information Table S1.

Changes in the median GSDs (Figure 6c) show coarse grained sediments from 226 to 100 cm, grains of intermediate size from 99 to 41 cm, and fine grained sediments from 40 cm to the core top. End-member (EM) modelling of the GSDs shows that the sediments can be best described as a mixture of five end-members (Figure 6b). The end-member GSD (Figure 6b) shows a wide range of grain sizes, from grains that have been transported as bed load to smaller grain sizes that appear as suspended load. The lowermost sediments from 225 to 60 cm are coarse grained, around 100 μm (sand), reflecting EM1 to EM3. Samples between 55 and 40 cm are of intermediate sizes, around 40 μm (silt), reflecting EM4. The upper part of the core (35 to 0 cm) is fine grained, around 5 μm (clay), reflecting EM5. We recognized visually 6 zones with characteristic GSDs (Figure 6a, Supplementary Information Table S2) and the transitions between the zones reflect changes in the energy level in the drainage system.

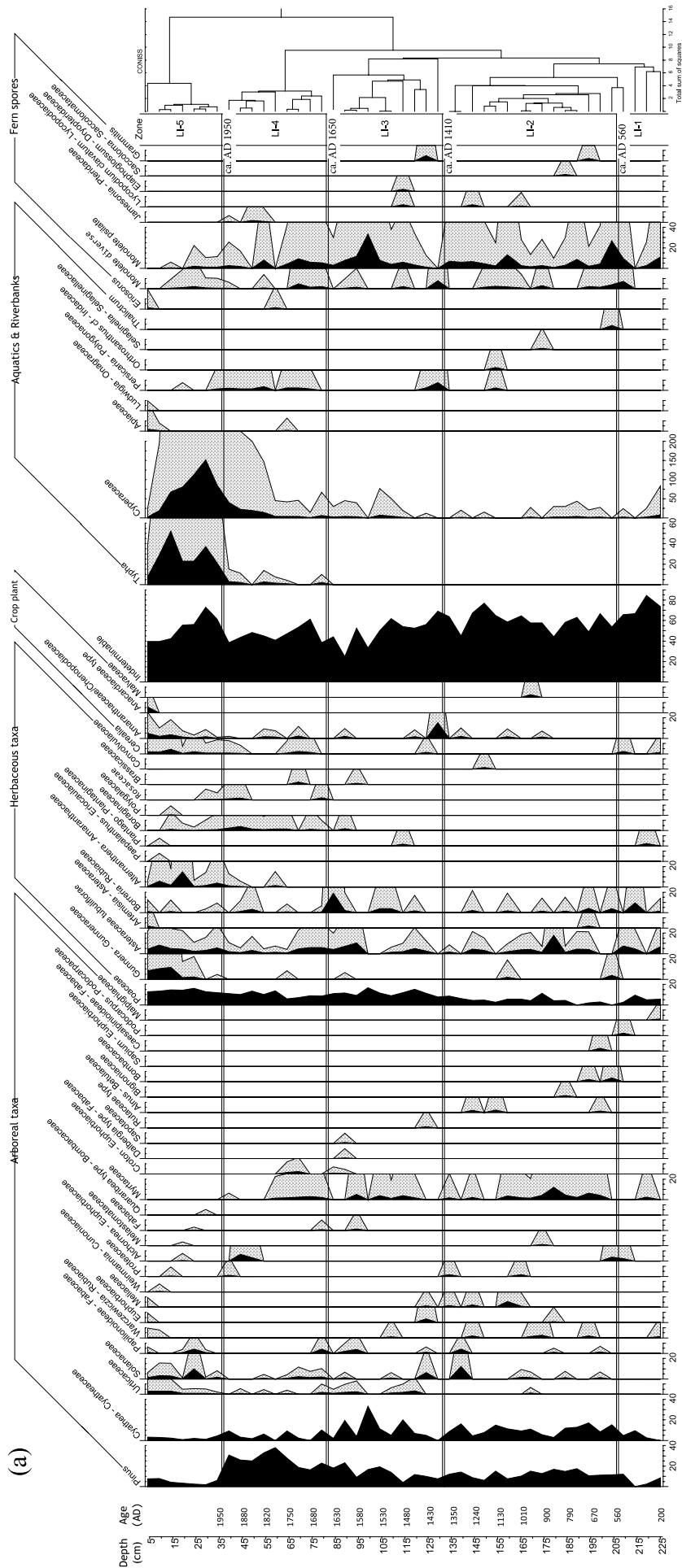


Figure 4. (a) Pollen percentage diagram Los Indios. Data are plotted on a linear depth scale. From left to right are shown: depth scale showing interpolated ages, individual curves of the most important taxa arranged into ecological groups, pollen zones, and the CONISS dendrogram. (b) Summary pollen percentage diagrams plotted on a linear depth scale. From left to right are shown: depth scale, general diagram showing proportions of ecological groups including indeterminate pollen grains, the same excluding indeterminate pollen grains, records of aquatics and swamp vegetation, fern spores, and spores of coprophilous fungi, and pollen concentration records based on pollen taxa in the pollen sum (pollen grains/cm³ of sediment).

(Continued)

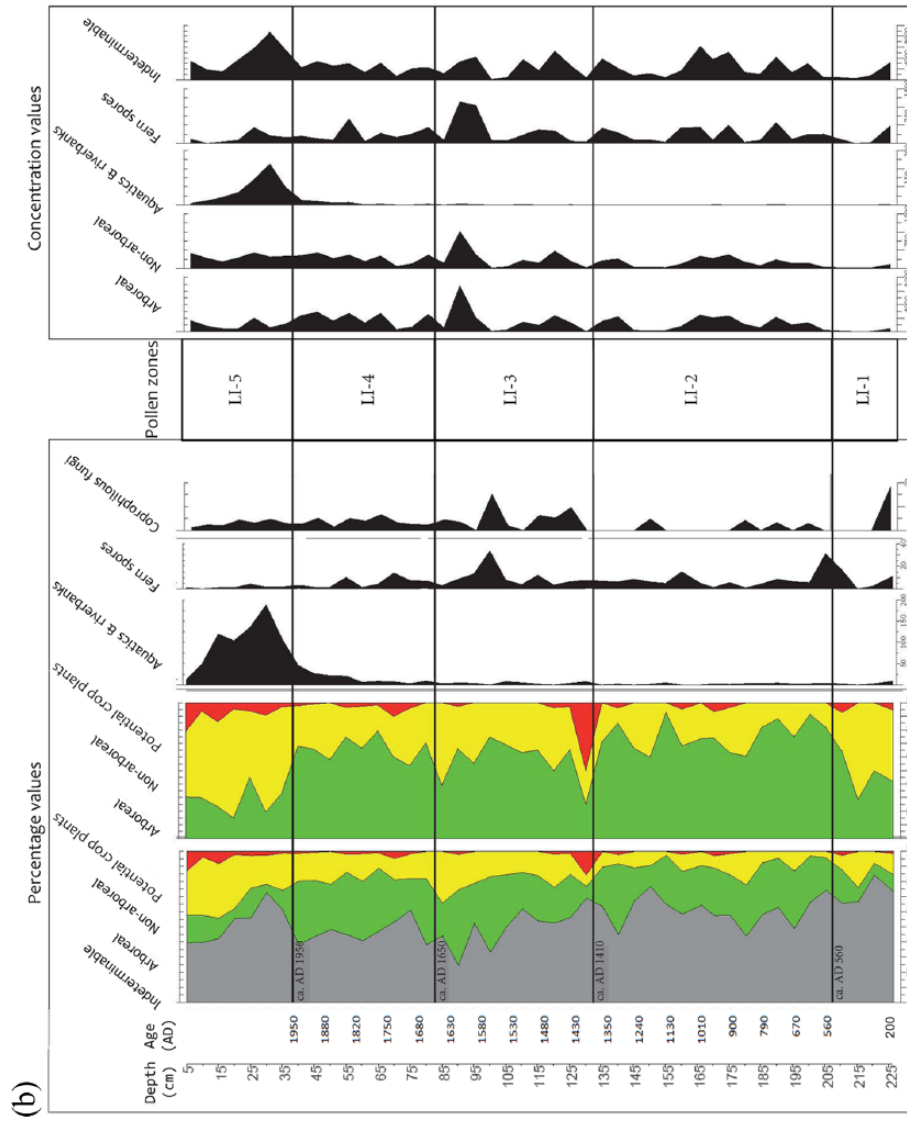


Figure 4. (Continued)

Table 2. Pollen sum values of record Los Indios shown with indeterminate pollen grains included and excluded from the pollen sum.

Depth (cm)	Indeterminable pollen	
	Included	Excluded
5	150	88
10	180	103
15	161	92
20	401	178
25	405	198
30	285	77
35	435	168
40	234	144
45	177	100
50	60	31
55	109	60
60	66	39
65	119	63
70	43	20
75	67	26
80	149	92
85	100	56
90	154	116
95	152	72
100	12	8
105	52	26
110	158	60
115	100	46
120	118	56
125	160	70
130	26	8
135	114	40
140	98	54
145	92	30
150	130	30
155	80	28
160	106	44
165	214	76
170	146	62
175	142	60
180	200	112
185	134	56
190	92	34
195	94	48
200	144	48
205	52	24
210	82	28
215	42	14
220	78	12
225	144	38

In zone-1 (226–202 cm), GSDs reflect a coarse grained bedload deposition, with major flooding events. Zone-2 (201–167 cm) shows a bedload deposition with two events of reduced grain size, suggesting events of temporarily reduced river flow. Zone-3 (166–97 cm) shows a bedload deposition with an event in which coarse sediments peaked. Zone-4 (96–65 cm) reflects conditions that the meander was cut-off from the main drainage system. The energetic level of the water currents had decreased substantially and more quiet water flows allowed deposition of mainly fine grained silts. In zone-5 (64–37 cm), a median grain size of around 15 μm is observed, which is higher than would be expected in a completely cut-off oxbow lake. This suggests that the water body in the meander had developed into stagnant waters in an oxbow

lake that was only occasionally flooded. During zone-6 (36–0 cm), the lake was permanently isolated from the drainage system, with only minor flooding events, and the low energy level allowed the accumulation of clays.

OM content and charcoal

The record of OM content, expressed in weight% (Figure 6a) shows increasing values. We recognized visually 6 zones with characteristic levels of OM. The transitions between the periods may reflect events of increased/decreased production of OM, reflecting changes in vegetation abundance in and around the water body and/or changes in sediment accumulation rate (causing a concentration or dilution of OM in the clastic sediment).

In zone 1 (226–202 cm), OM content is ca. 2%. In zone 2 (201–167 cm), percentages vary from ca. 5% to max 10%. In zone 3 (166–97 cm), OM content decreases from 7% to about 2.5%, than increases and shows maxima between ca. 7% and 10%. Zone 4 (96–65 cm) shows two peaks of ca. 10% with values decreasing to ca. 3% in between. In zone 5 (64–37 cm), OM content increases to a plateau at ca. 13%, at the end of the zone decreasing to ca. 7%. In zone 6, OM content increase from ca. 7% to a maximum of 33%, than lowers to ca. 5% and ends at levels of ca. 25%.

Charcoal concentrations varied between 1 and 20 mm^2/cm^3 with peaks up to 33 mm^2/cm^3 . The record shows gradually increasing values throughout the sediment core (Figure 6a). We recognized 5 zones and transitions are reflecting changes in burning activity; either natural fire or man-induced fires.

In zone 1 (226–207 cm), a low charcoal surface of ca. 1 mm^2/cm^3 is registered, at the end of this period increasing to ca. 4 mm^2/cm^3 . In zone 2 (206–80 cm), charcoal concentration varies between ca. 2 and 10 mm^2/cm^3 with peaks up to 17 mm^2/cm^3 . In zone 3 (79–67 cm), charcoal concentrations increase up to ca. 19 mm^2/cm^3 with a peak value of 33 mm^2/cm^3 . In zone 4 (66–40 cm), charcoal concentrations decrease to levels between 3 and 6 mm^2/cm^3 , with several peaks up to 18 mm^2/cm^3 . In zone 5 (39–12 cm), low charcoal concentrations range between 1 and 6 mm^2/cm^3 with two peaks reaching 13 mm^2/cm^3 .

Reconstruction of past environments and land use change

The zone boundaries of the various proxies are sharp or transitional and vary in core depth, illustrating that the various aspects of landscape dynamics each had their own history in time. Here, we integrate the evidence from the various proxies and we show an integrated reconstruction of environmental change. The five periods of the pollen record are leading the reconstruction and the histories of fire, crop cultivation and meander dynamics are connected to the history of vegetation change.

Period 1: ca. AD 200 to AD 560 (ca. 1750 to c. 1390 cal. yr BP). Vegetation is dominated by herbs, Poaceae and *Borreria*, all plants characteristic of open grasslands and savanna-like vegetation (Kahn and De Granville, 2012; Marchant et al., 2002). Arboreal taxa reflect moist lowland forest and tall gallery forest along the Yaque River with *Warszewiczia*, Myrtaceae and Malpighiaceae. Few pollen grains of Cerealia are present from the start of the record pointing to small scale crop cultivation. During this period, we found peaks in the representation of chlamydo spores of the fungus *Glomus*, associated with soil erosion (Van Geel et al., 2011). Low concentrations of charcoal suggest that local Taino burned forest only occasionally, and we suggest that the landscape still had much of its original forest cover with a mosaic of small-scale clearings for settlements and crop cultivation in the

Table 3. List of identified microfossils arranged by ecological preference including pollen, fern spores, non-pollen palynomorphs and spores of coprophilous fungi.

ARBOREAL POLLEN	
<i>Alnus</i> (Betulaceae)	
Bignoniaceae	
<i>Quararibea</i> type (Bombacaceae)	
Bombacaceae s.l.	
<i>Weinmannia</i> (Cunoniaceae)	
<i>Cyathea</i> (Cyatheaceae)	
<i>Alchornea</i> (Euphorbiaceae)	
<i>Croton</i> (Euphorbiaceae)	
<i>Sapium</i> (Euphorbiaceae)	
Euphorbiaceae others	
Caesalpinioideae (Fabaceae)	
<i>Dalbergia</i> type (Fabaceae)	
Papilionoideae (Fabaceae)	
Fabaceae s.l.	
Malpighiaceae	
Melastomataceae	
Meliaceae	
Myrtaceae	
<i>Pinus</i> (Pinaceae)	
<i>Podocarpus</i> (Podocarpaceae)	
Protaceae	
<i>Warszewiczia</i> (Rubiaceae)	
Rutaceae type	
Sapotaceae	
Solanaceae	
Urticaceae	
NON-ARBOREAL POLLEN	
<i>Alternanthera</i> (Amaranthaceae)	
<i>Artemisia</i> (Asteraceae)	
Asteraceae s.l.	
Boraginaceae	
Brassicaceae	
Convolvulaceae	
<i>Paepalanthus</i> (Eriocaulaceae)	
<i>Gunnera</i> (Gunneraceae)	
<i>Plantago</i> (Plantaginaceae)	
Poaceae s.l.	
Polygalaceae	
<i>Rubus</i> (Rosaceae)	
<i>Borreria</i> (Rubiaceae)	
POTENTIAL CROP PLANTS	
Amaranthaceae	
Anacardiaceae type	
Malvaceae	
Cereale (Poaceae)	
AQUATIC & RIVERBANK VEGETATION	
Apiaceae	
Cyperaceae	
<i>Orthrosanthus</i> cf (Iridaceae)	
<i>Ludwigia</i> (Onagraceae)	
<i>Persicaria</i> (Polygonaceae)	
<i>Thalictrum</i> (Ranunculaceae)	
<i>Selaginella</i> (Selaginellaceae)	
<i>Typha</i> (Typhaceae)	
FERN SPORES	
<i>Elaphoglossum</i> (Dryopteridaceae)	
<i>Lycopodium clavatum</i> (Lycopodiaceae)	
Monolete diverse	
Monolete psilate	
<i>Grammitis</i> (Polypodiaceae)	
<i>Eriosorus</i> (Pteridaceae)	
<i>Jamesonia</i> (Pteridaceae)	
<i>Saccoloma</i> (Saccolomataceae)	
INDETERMINABLE TYPES	
Type 4	
Type 6	
Type 7	
Type 9	
Type 10	

Table 3. (Continued)

NON-POLLEN PALYNOMORPHS	
<i>Apiosordario</i>	
<i>Cercophora</i>	
<i>Coniochaeta</i>	
<i>Diplocladiella</i>	
<i>Diporotheaca</i>	
<i>Gelasinospora</i>	
<i>Glomus</i>	
<i>Lasiodiplodia</i>	
<i>Podospora</i>	
<i>Potamomyces</i>	
<i>Sordario</i>	
<i>Tetraploa</i>	

dooryard gardens. Coarse grained sediments prevail suggesting that the meander still had a temporary drainage function at a low energetic level. The record of *Glomus* suggests that also hill slope erosion may have supplied sediments to the oxbow lake. Sediments show a low OM content suggesting that aquatics were few and restricted to meander shores. The rate of sediment accumulation is low suggesting the meander is still temporarily connected to the active river system, but most of the time an unimportant part of the drainage system. Low sediment accumulation is supported by the age model (Figure 3).

Period 2: ca. AD 560 to AD 1410 (ca. 1390 to 540 cal. yr BP). *Alnus* reflecting swamp forest along the rivers, and Bignoniaceae, Bombacaceae, Malpighiaceae, *Podocarpus* and *Sapium* as elements of gallery forest on the valley floor where inundations are rare or absent. The variety of fern spores is relatively high and point to humid gallery forest with much shady damp and wet habitat (Carabia, 1945; Gentry, 1986, 1993; Rodgers and Horn, 1996). Peaks of *Potamomyces* spores, characteristic of humid subtropical environments with high levels of OM in the soil (Otaño et al., 2016) suggest abundant forest cover. A decreasing abundance of *Glomus* chlamydo spores, indicative of soil erosion (Anderson et al., 1984; Van Geel et al., 1989), and the low diversity of NAP suggest a landscape dominated by forest). Some representatives of Sordariales are specific for faeces as a substrate but according to Lundqvist (1972) *Cercophora* is an exception. *Cercophora* species are coprophilous or occur on decaying wood, on culms and on other herbaceous stems and leaves (see also Van Geel and Aptroot, 2006; Van Geel et al., 2011) potentially supporting a forested landscape, as is the case with *Lasiodiplodia theobromae*, which grows on woody plants in the subtropics (Mbenoun et al., 2008; Mohali et al., 2005). Amaranthaceous species occur as natural herbs in dry vegetation but may also reflect crops of the pseudo-cereal *Amaranthus cruentus* (inca wheat) which was domesticated ca. 6000 years ago in Central America (Greenwood et al., 2003). However, pollen grains within the Amaranthaceae family (the Chenopodiaceae family included) cannot be distinguished morphologically, and consequently, the ecological interpretation of the record is unsure. However, sudden increases in representation and relatively high percentages during periods of time may point to cultivation practice. The record of Malvaceae possibly reflect native wild herbs as we assume that presence of malvaceous crops (Kahn and De Granville, 2012; Smartt and Simmonds, 1995; Van Wyk, 2005) would have produced a higher pollen representation. Cereal pollen is not registered. The variety in GSDs and changing percentages of OM suggest water currents had varying intensities. After ca. AD 1170 (ca. 780 cal. yr BP), the energy of water currents increased again. Charcoal concentrations are periodically peaking up to ca. 15 mm²/cm³ suggesting fires were a regular phenomenon. Presence of fire coincides with evidence of humans in the archaeological record (Sinelli, 2013) suggesting that humans might be the most likely source of ignition.

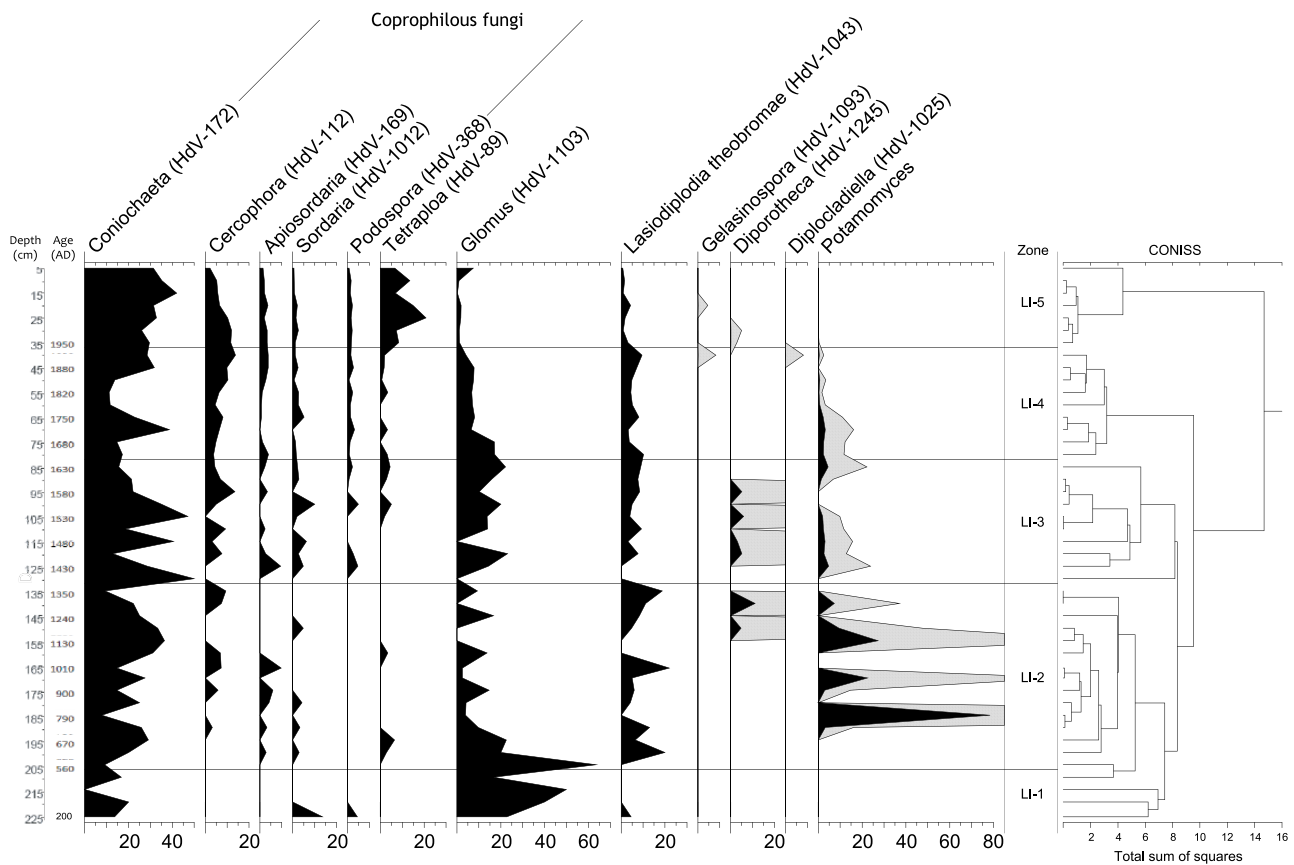


Figure 5. From left to right: depth scale, scale showing interpolated ages, percentage diagram of core Los Indios showing spores of coprophilous fungi and other non-pollen palynomorphs, and the CONISS dendrogram. Zones follow the zonation of the pollen diagram. Data are plotted on a linear depth scale.

Period 3: ca. AD 1410 to ca. AD 1650 (ca. 540 to ca. 300 cal. yr BP). AP% decrease with some 15% compared to the previous zone and with some 10% if indeterminable gains are included (Figure 4b) suggesting the rate of forest clearing increased. The diversity in herbs and shrubs increased, pointing to a more open landscape. Several indicators of environmental disturbance appear in the record for the first time, such as *Plantago*, Boraginaceae, Polygalaceae and Brassicaceae. *Plantago* may grow along sandy roads (Gentry, 1993). Boraginaceae species usually grow in drier areas (Gentry, 1993; Pereira et al., 1985). Representatives of Polygalaceae occur frequently on river banks (Marchant et al., 2002; Salgado-Labouriau, 1986) and representatives of Brassicaceae have been introduced in the Americas and grow in disturbed sites and grasslands (Cabrera, 1976; Kahn and De Granville, 2012). Grass vegetation (Poaceae) increased as well. We infer a transition from tall gallery forest on nutrient rich moist to wet soils to a more open landscape with wet to dry meadows rich in herbs. Cereal pollen are hardly present. Among the coprophilous spores *Sordaria* increased and *Podospira* started its record suggesting a marked increase in cattle breeding in the first half of the 17th century (Bell, 2005; Farr and Rossman, 2013; Krug et al., 2004; Lundqvist, 1972). The European colonists were livestock people, as their ancestors had been for millennia (Crosby, 2004). The first hundred years of this period shows a high median GSD and low amounts of OM pointing to a still regular drainage function. During the second half of this period, when Europeans had already changed land-use effectively; three peaks in OM suggest the meander was temporarily closed, perhaps blocked by sediments fluxes that became available through increasing erosion in the catchment area. The meander became repeatedly filled up with aquatic vegetation. Variable GSDs suggest that only during short intervals the meander was

still an active part of the drainage system. The charcoal record does not show significant changes suggesting that large-scale forest clearings had not started before ca. AD 1650.

Period 4: ca. AD 1650 to ca. 1955 (ca. 300 to ca. -3 cal. yr BP). The diversity in arboreal taxa further diminished. In particular, the arboreal taxa *Dalbergia* and Sapotaceae, characteristic of moist lowland forests (De Boer et al., 2014; Gentry, 1993; Thomas, 1999; Webb and Peralta, 1998), but here in the Cíboa Valley growing on frequently inundated wet soils, disappeared. While the diversity in forest trees lowered, the percentage of *Pinus* increased. Although we are aware pine may be over-represented in the pollen spectra (Wu et al., 2013), we believe this is not the case here as the meander gradually terrestrialized. Pine is an important tree in the natural regional vegetation (Darrow and Zaroni, 1990; Farjon and Styles, 1997) and potentially important to provide timber for constructions. We hypothesize that the increased pine percentages reflect plantations at close distance to the expanding settlements to produce timber for constructions. In the 17th century evidence of agroforestry in the Iberian Peninsula is unclear but actions to develop new pine forests have been known since AD 1748 from ordinances and cadastral archives (Valbuena-Carabaña et al., 2010; see also González-Gómez, 1977; Gordo, 1995; Pino, 1990; Pardo and Gil, 2005; Wing, 2015) allowing to hypothesize that the practice of agroforestry was known and could have been potentially introduced in Hispaniola. We need evidence from more sites to further support this hypothesis. With the first appearance of *Alternanthera*, typical for lake margins, the variety of herbs increased. Rosaceae type pollen grains are observed for the first time and possibly reflect introduced blackberry (*Rubus* sp.) (Crosby, 2004: 97). The decrease in variety of ferns, *Potamomyces* and *Coniochaeta* is in support of a more open landscape. In the 19th century, a marked

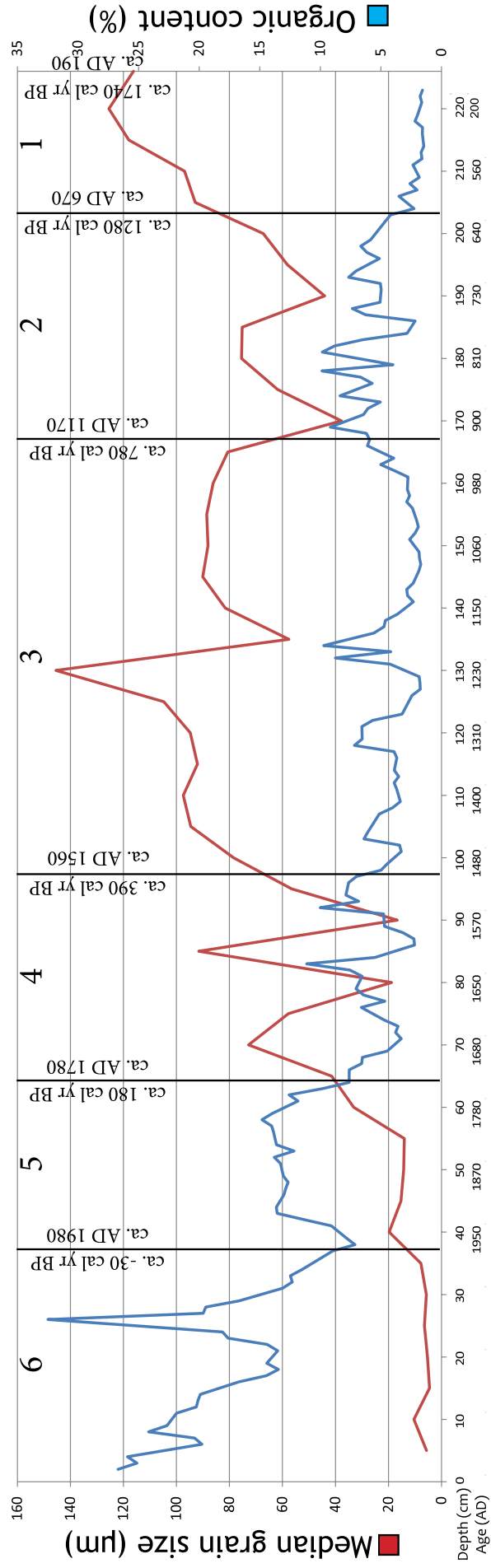
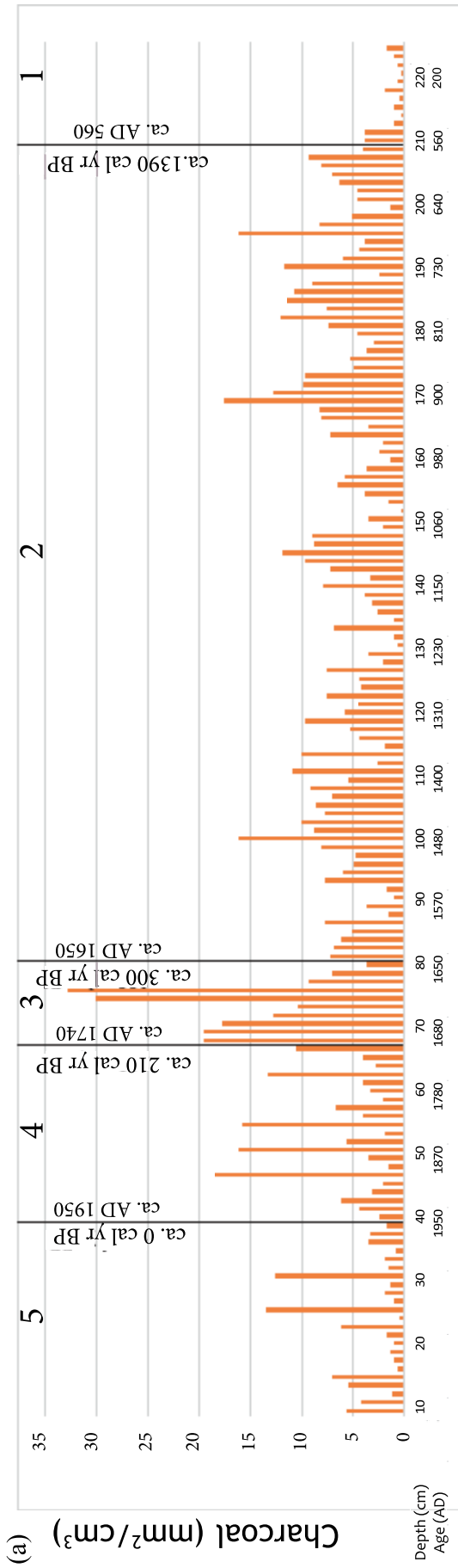
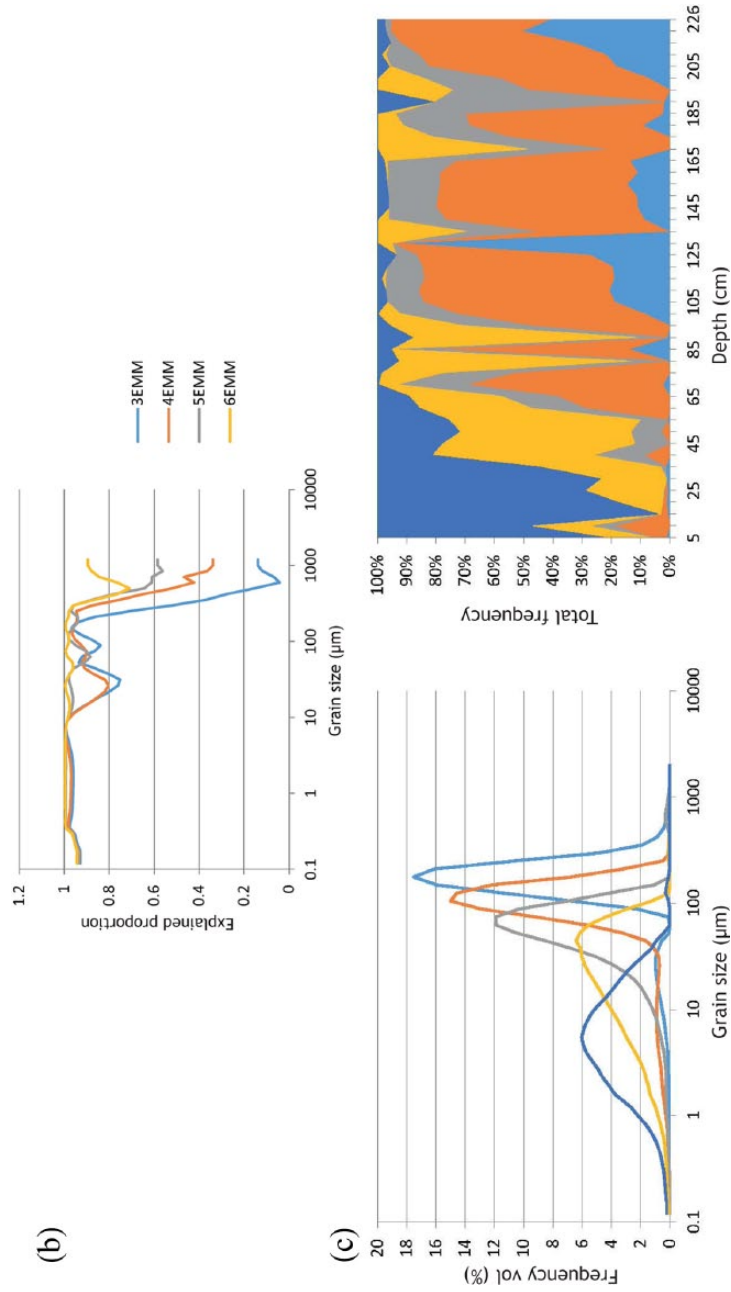


Figure 6. (a: top) Record of charcoal content; (a: bottom) median grain size values (red curve) showing a trend from coarse grained sediments at the bottom to fine grained sediments at the top of the core; organic matter content (blue curve) showing a trend from low proportions at the bottom to high proportions at the top of the core. All data are plotted on a linear depth scale and a scale with interpolated ages is added; (b) End-member modelling of the grain size distributions showing that sediments are best described by a mixture of five end-members; (c) End-member grain size distributions showing a wide range of grain sizes from grains that have been transported as bed load to smaller grain sizes that appear as suspended load (left); downcore changes in end-member proportions (right). Colours are explained in the left figure. (Continued)

Figure 6. (Continued)



decrease in mean GSDs to below 20 μm , and a contemporaneous increase of OM rising above 60% suggest that aquatic and swamp vegetation expanded in the isolated oxbow lake which became now rarely flooded. Higher values of NAP concentrations (Figure 4b) under a more or less constant sediment accumulation regime (Figure 3) points to a more open landscape. The concentration of indeterminate pollen grains is relatively stable in pollen zones LI-1 to LI-4 (Figure 4b) supporting the conclusion that corrosion of pollen grains was a non-selective process that affected all pollen grains in a similar way. The increase of Cyperaceae, *Typha*, *Persicaria* and *Glomus* is in support of a process of terrestrialization in the oxbow lake. A peak (up to ca. 30 mm^2/cm^3) in the charcoal record around 270 cal. yr BP (AD 1680) suggests that forest clearance progressed rapidly reaching a status that most of the landscape in the Cibao Valley was cleared in the second half of the 17th century. By that time the Cibao Valley must have been a major production area for sugar (potentially reflected in the pollen record of Poaceae), cerealia (in this period few pollen grains of maize have been observed), tobacco (potentially included in the pollen record of Solanaceae), and amarantaceous crop plants.

Period 5: ca. AD 1950 – Present (ca. 0 cal. yr BP to Present). Pollen from local wetlands and wet shore vegetation are mainly of local origin. As the meander was disconnected from the river system presence, or changes in the contribution of water transported pollen is unlikely; most AP in the meander sediments have been transported by wind, the bisaccate pollen grains of *Pinus* in particular. The decreasing AP% point to a decreasing load of airborne AP, thus reflecting further deforestation, a conclusion supported by the low concentration values of AP (Figure 4b). *Croton*, a common tree in floodplains and swamps, as well as lower montane forests (Kahn and De Granville, 2012; Marchant et al., 2002) disappeared from the record together with Myrtaceae. Also the decrease of *Lasiodiplodia theobromae* suggests a decrease in forest cover. Aquatic and riverbank vegetation is reflected by peaks in the records of *Typha* and Cyperaceae. In the most recent part of the last century, the presence of *Typha* and Cyperaceae decreased (Figure 4a) pointing to an almost fully terrestrialised meander with only few standing water bodies and closely reflecting the present-day situation. The increase in *Tetraploa*, growing on leaves and stems close to the ground (Ellis, 1971; Farr and Rossman, 2013) is in support of this interpretation. Cultivated plants, including cerealia, maize (a few grains included in the record of cerealia), and potentially Amaranthaceae and Anacardiaceae, reach a maximum representation suggesting intensive crop cultivation. Compared to the 18th and 19th centuries (the previous period 4), the amount of charcoal had decreased again. We hypothesize that woodlands were not burned any more to expand crop fields, rather the last forest patches provided the increasing population with construction timber and fire wood. The appearance in the record of *Gelasinospora*, growing on charred material (Van Geel and Aptroot, 2006), is related to burning of crop fields after harvest. The low mean GSD and the high content of OM is proof that the meander had completely lost its function in the drainage system.

Discussion

Preservation

We found a high proportion of corroded pollen grains in intervals where the lithology and GSDs showed coarse-grained sediments in particular, and a significant part of the pollen spectrum could not be identified. Pollen sum values in most of the samples range between 50 and 198 (Table 2). Poor pollen preservation, and low pollen counts as a consequence, is a well-known limitation in the dry Caribbean (e.g. Peros et al., 2015). Changes in the pollen

spectra could be reasonably well interpreted in terms of forest cover, crop cultivation, and changing land-use. In addition, the pollen-based reconstruction is embedded in a suite of other proxies together building the environmental story. We explored the impact of the proportion of unidentified pollen grains on the zonation by plotting the main pollen diagram including and excluding this category (Figure 4b). The identical zonation of the pollen record suggests unidentified pollen grains are not driving the zonation. Coarse-grained sediments reflect periods with higher energy levels and an active phase of the meander in the drainage function. In such conditions, pollen and spores may be partly water-transported, reflecting in particular swamp and wet shore vegetation and gallery forest at distance, but also re-deposited pollen from eroded river banks and slopes. Better preserved pollen grains are found in core intervals with fine-grained sediments reflecting quiet sedimentary environments. The studied sediment core potentially may include small gaps when too high energy levels prevented sediment accumulation, or even caused erosion of previously accumulated sediments. We have not encountered evidence of relevant sedimentary gaps, and therefore, we interpreted the record into a paleoenvironmental narrative without assuming major hiatuses in the record.

Taxonomy

Although regional pollen morphological literature is increasing (Hooghiemstra and Van Geel, 1998; Hooghiemstra, unpublished manuscript), pollen morphological studies of crop plants are limited. Within the Poaceae family pollen grains of cereals and maize can be identified with certainty (Andersen and Bertelsen, 1972; Beug, 2004; Joly et al., 2007; Köhler and Lange, 1979; Whitehead and Langham, 1965) but poor pollen preservation let us decide not to specify both in separate records. However, pollen grains from a wide variety of (tropical) crop plants are mostly included in the records of higher taxonomic ranks, such as potato, tomato and tobacco in the record of Solanaceae, and amarantaceous grains in the record of Amaranthaceae. However, these families include also wild herbs and weeds of natural origin, and for Post-Colonial times also introduced plants. Therefore, identification with certainty is still beyond our possibilities and we are using circumstantial evidence to suggest where peaks in these records may hint to agricultural activities.

Climate change

Haug et al. (2003, 2001) showed that the first European encounters and first steps in the colonization process coincided with changes in Caribbean climate (see also Horst, 1992). Studies from several Caribbean sites show climate turned to more arid conditions during the last 2500 years (Caffrey et al., 2015), or during the last 1000 years (Lane et al., 2015; Peros et al., 2015; coinciding with our pollen zones 2 (last part), 3, 4 and 5), in other sites during the period from ca. 1450 to 1800 AD (Lane et al., 2011; Peros et al., 2015; coinciding with our pollen zones 3 and the first part of zone 4). Charcoal records reflecting the last 7000 years suggest that changes in winter insolation might be a driver of climate change (Caffrey and Horn, 2015). However, results mainly pre-date our 1800 yr record and peaks of charcoal that may be interpreted as anthropogenic occur during the last 500 years which coincides with increased human activities in the Cibao Valley. Although our reconstruction from Los Indios, and also from site Bijajaca at c. 40 km distance (Castilla-Beltrán et al., 2018), includes different inter-related stories, including the regional vegetation, local aquatic and wetland vegetation, crop cultivation, animal husbandry (based on coprophilous fungi), fire history (based on charcoal), and OM production and GSDs both reflecting the evolution of the meander, we have no information about climate change.

From Pre-Colonial to Post-Colonial environments: Columbus' footprint

The record starts with showing from ca. AD 195 to ca. AD 560 (ca. 1755 to ca. 1390 cal. yr BP) a forested but inhabited river valley suggesting that small settlements and small-scale subsistence agriculture formed a mosaic pattern of clearings. Site Los Indios shows an early but modest start of forest disturbance which may contrast with other sites (Binford et al., 1987; Lane et al., 2009). Forest clearings, crop cultivation and archaeological findings of early human settlements in the Cibao Valley (Ulloa Hung, 2014; Ulloa Hung et al., 2015) may find support in the records of Poaceae, Amaranthaceae and Solanaceae that potentially may include a suite of crop plants.

A second period is recognized from ca. AD 560 to ca. AD 1410 (ca. 1390 to ca. 540 cal. yr BP) in which the pollen record shows an expansion of mesic forest. In the setting of Los Indios such evidence may point to more frequent floodings. The increasing presence of charcoal reflects a more frequent use of fire in support of an increasing population. Indeed, Ulloa Hung (2014) evidenced during this time an increase of human presence in the Cibao Valley. Our record shows no pollen-based evidence of forest clearings and expanding crop cultivation. Forest clearing was evidenced on the southern side of the Cordillera Central (Lane et al., 2009) based on decreasing AP values and an increase in charcoal influx. Riverine gallery forest in the Cibao Valley might be less attractive to clear for crop cultivation as these grounds are flooded frequently (Morales et al., 2009). From the forest and crop pollen, a picture is emerging of a forested river valley with small-scale clearings to accommodate villages and crop cultivation for local use. AP-based evidence pointing to changing areas of dry and wet forest (Martin et al., 2004), most possibly relates to changes in the drainage pattern such as flooding frequency and water depth (Martin et al., 2004) rather than changes in regional climate.

The third period recognized as homogeneous interval of time lasted from ca. AD 1410 to ca. AD 1650 (ca. 540 to ca. 300 cal. yr BP). As Columbus arrived in the Cibao valley around AD 1494, almost halfway this period, the record suggests that during the first century of European colonization the impact on the natural environment was relatively small. The Cibao Valley was described by the European chroniclers as a region in which conflicts took place between the colonizers and the indigenous population (Taviani et al., 1994) probably driven by the economic and strategic value of the valley in terms of plant species, animals, water courses and gold in particular. Colonization had rapidly disrupted the indigenous socio-political structure (Livi-Bacci, 2006) and later on the area came under the Spanish rule of 'poblamiento' (settlements) and colonization. Lands were seized and redistributed, and indigenous peoples were dispersed across different towns and regions in so-called 'repartimientos' and 'encomiendas' (forced labour systems). This process is reflecting the beginning of urbanization (Hofman et al., 2018).

The pollen record suggests that the landscape became gradually more open, and the charcoal record also shows a gradual increase of the use of fire for forest clearings. In contrast to human density, the record of coprophilous fungi indicates that in the Cibao Valley cattle breeding was rapidly implemented after colonization, possibly supported by absence of cattle diseases. Foraging cattle, horses, sheep and pigs may have significantly contributed to the gradual, but steady degradation of forest (Baker et al., 2016). The opening up of the landscape probably gradually accelerated as juvenile trees were grazed out over a period of decades and so did not replace the older generation of trees, not sensitive to grazing, that gradually died out over the course of their natural lifecycle (Bakker et al., 2016; Vera, 2000). The 16th century was characterized by European exploitation for gold in the Cibao Valley. During this period, Hispaniola became an important hub in the Spanish network of Caribbean contacts (Hofman et al., 2018). After a period of predominantly

livestock-based agriculture, larger-scale agriculture was needed to reply to the increasing demands of the Spanish fleet and its homeland.

The period from ca. AD 1650 to ca. AD 1950 (ca. 300 to ca. 0 cal. yr BP) is also a characteristic interval within the record. Peaks in the charcoal record hint at ongoing deforestation. In the pollen record, deforestation of the diverse vegetation of the Cibao Valley is partly hidden by the increase in pine (*Pinus*) pollen. The rapidly expanding settlements with Spanish rulers and enslaved working force must have driven the need for construction timber that occurred naturally on the slopes of the Cordillera Central. We hypothesize that the increasing representation of *Pinus* in the pollen record reflects pine plantations in the Cibao Valley at much closer distance to Los Indios (Valbuena-Carabaña et al., 2010; see also González-Gómez, 1977; Gordo, 1995; Pardo and Gil, 2005; Pino, 1990; Wing, 2015). After ca. AD 1650, the human population of Hispaniola was bolstered by immigrants from Europe and renewed transports of African slaves (Greenwood et al., 2003). According to Knight et al. (1997) the production of tobacco (*Nicotiana tabacum*, included in the pollen record of Solanaceae) and sugar cane (*Saccharum officinarum*, included in the pollen record of Poaceae) plantations expanded rapidly in the Cibao Valley and the pollen records of both taxa allow this interpretation. Cultivation of cerealia and maize became common practice during this period.

Increasing proportions of clay in the record of GSDs and an increasing proportion of aquatic and marsh plants in the pollen spectra show that around ca. AD 1780 (ca. 170 cal. yr BP) the river channel became definitively cut off from the main drainage system. The process of terrestrialization, from open water through a phase with swamps to the present-day status of a wet meadow, progressed rapidly under influence of eutrophication of the water by humans and domesticated animals.

During the period from ca. AD 1950 to the present (ca. 0 cal. yr BP to Present), the last forest remnants were cleared. Most vegetation change shown in the pollen record relates to vegetation succession in the oxbow lake where shallow water vegetation, dominated by *Typha* and Cyperaceae, was abundant. The water body and swamp vegetation disappeared in the 1970s and 1980s. We assume this was a human driven process to obtain meadows for cattle grazing, a practice that continues along the Yaque River up to today. In forest clearing fire was not functional anymore and charcoal almost disappeared from the record. Today, the burning of stubble fields after crop plants have been harvested is a common practice.

Conclusion

The study of the sediments of Los Indios is a first attempt to shed light how the landscape in the Cibao Valley changed from Pre-Colonial to Post-Colonial times and how the present-day open landscape came into existence. Currently, infrastructure for irrigation is rapidly expanding; meander infills are disappearing and there is some urgency to continue paleoecological investigations to prevent archives of past environmental change are being lost.

A relatively stable and low-impact on the environment was shown during Pre-Colonial times and crop cultivation followed the local needs. After Columbus' arrival in Hispaniola, the indigenous socio-political structure was disrupted. Spores of coprophilous fungi show a rapid introduction of livestock, but most of the proxy records show some hundred years delay in response: around AD 1650 European interest for Caribbean colonies increased and the Cibao Valley became rapidly deforested. Agriculture was levelled up to European practice and continued so for two centuries. Shortly after ca. AD 1950, the Cibao Valley followed the global pattern of agricultural expansion shown in the records by an almost complete deforestation. Trees were not burned in situ any more but more probably used as fire wood, livestock intensified, and crop cultivation reached scales that go

beyond regional needs. The record is ending around AD 1980 when sediment accumulation did not continue anymore and cultivation of banana and rice had been introduced.

An archive from riverine sediments located in a climatologically dry area is a challenging setting for pollen analysis. Notwithstanding the limitations, we encountered poor pollen preservation, low pollen sum values and rejected radiocarbon dates, the multiproxy approach produced a fascinating reconstruction of changing demography and land-use after Columbus's arrival in the New World.

Acknowledgements

This research is part of the European Union's Seventh Framework Programme (FP7/2007-2013)/ERC grant 'New World Encounters in a Globalizing World' (www.Nexus1492.eu), agreement no. 319209 of the European Research Council directed by prof. Corinne Hofman, Faculty of Archaeology of Leiden University in collaboration with the Free University Amsterdam and Konstanz University. The NEXUS1492 project aims to provide a new perspective of encounters between the Old and the New World and the impact of these encounters on the natural environment, with focus on the perspective of the indigenous Caribbean people. This paper is based on results obtained in the context of a master thesis (Olijhoek, 2016). The NEXUS1492 project covered costs for field work, radiocarbon dating, and grain size analysis. The University of Amsterdam provided coring equipment and provided the pollen and charcoal samples. We thank Menno Hoogland, Peter Siegel, Pat Farrell, Mike Field and Jorge Ulloa Hung for support and expertise in the field. Data were developed at the universities of Leiden (archaeology), Utrecht (LOI), Amsterdam (pollen, spores, NPPs, coprophilous fungal spores, charcoal), and Vrije Universiteit Amsterdam (GSDs). Suzette Flantua supported the age model and prepared Figure 1. We thank the owner of Finca Sanchez, Quilito Sanchez, and Silverio Mendoza for permission to collect the sediment core. Luis Gil (Madrid) and José Carrion are thanked for information about agroforestry in Spain. We thank three anonymous reviewers for constructive comments on an earlier draft of this paper. Project and paper development: C.H. is Corresponding Principal Investigator of the NEXUS1492 project and provided the archaeological context for this paper. M.H. co-directs the fieldwork in the Dominican Republic. H.H. supported one palynological field campaign in the Cibao Valley and organized the multiproxy analysis. Pollen analysis was supervised by H.H., non-pollen palynomorphs and human impact indicators by BvG, charcoal analysis by W.G., LOI measurements by T.D., and grain size analysis by M.P. T.O. carried out the analysis of all proxies. M.P. carried out the end-member modelling. Suzette Flantua constructed the age vs depth model and the map based on a digital elevation model, and M.P. carried out the end-member modelling. H.H. and T.D. supervised the writing of the master thesis and H.H. prepared the present paper. All authors contributed to the final text.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Supplementary material

The online supplementary material is available at <http://journals.sagepub.com/doi/suppl/10.1177/0959683618788732>.

References

- Andersen ST and Bertelsen F (1972) Scanning electron microscope studies of pollen of cereals and other grasses. *Grana* 12: 79–86.
- Anderson RS, Homola RL, Davis RB et al. (1984) Fossil remains of the mycorrhizal fungal *Glomus fasciculatum* complex in postglacial lake sediments from Maine. *Canadian Journal of Botany* 62: 2325–2328.
- Baker AG, Cornelissen P, Bhagwat SA et al. (2016) Quantification of population sizes of large herbivores and their long-term functional role in ecosystems using dung fungal spores. *Methods in Ecology and Evolution* 7: 1273–1281.
- Bakker ES, Gill JL, Johnson CN et al. (2016) Combining paleodata and modern enclosure experiments to assess the impact of megafauna extinctions on woody vegetation. *Proceedings of the National Academy of Sciences of the United States of America* 113: 847–855.
- Beard JS (1955) The classification of tropical American vegetation-types. *Ecology* 36: 89–100.
- Bell A (2005) *An Illustrated Guide to the Coprophilous Ascomycetes of Australia*. Utrecht: Centraalbureau voor Schimmelcultures.
- Beug HJ (2004) *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*. München: F. Pfeil, p. 542.
- Binford MW, Brenner M, Whitmore TJ et al. (1987) Ecosystems, paleoecology and human disturbance in subtropical and tropical America. *Quaternary Science Reviews* 6: 115–128.
- Blaauw M (2010) Methods and code for 'classical' age-modelling of radiocarbon sequences. *Quaternary Geochronology* 5: 512–518.
- Bolay E (1997) *The Dominican Republic: A country between rain forest and desert: Contributions to the Ecology of a Caribbean Island*. Weikersheim: Markgraf, p. 456.
- Cabrera L (1976) Regiones fitogeográficas argentinas. In: Parodi LR (ed.) *Enciclopedia Argentina de Agricultura y Jardenería*, vol. 2. Buenos Aires: ACME, pp. 81–85.
- Caffrey MA (2011) *Holocene climate and environmental history of Laguna Saladilla, Dominican Republic*. PhD Thesis, University of Tennessee.
- Caffrey MA and Horn SP (2015) Long-term fire trends in Hispaniola and Puerto Rico from sedimentary charcoal: A comparison of three records. *The Professional Geographer* 67(2): 229–241.
- Caffrey MA, Horn SP, Orvis KH et al. (2015) Holocene environmental change at Laguna Saladilla, coastal north Hispaniola. *Palaeogeography Palaeoclimatology Palaeoecology* 436: 9–22.
- Cano E, Veloz A and Cano-Ortiz A (2014) Rain forests in subtropical mountains of Dominican Republic. *American Journal of Plant Sciences* 4: 1459–1466.
- Cano-Carmona E (2010) Contribution to the biogeography of the Hispaniola (Dominican Republic, Haiti). *Acta Botanica Gallica* 157: 581–598.
- Cano-Ortiz A, Musarella CM, Piñar JC et al. (2015) Vegetation of the dry bioclimatic areas in the Dominican Republic. *Plant Biosystems* 149: 451–472.
- Carabia JP (1945) The vegetation of Sierra de Nipe, Cuba. *Ecological Monographs* 15: 321–341.
- Castilla-Beltrán A, Hooghiemstra H, Hoogland MLP, Pagan-Jiménez J et al. (2018) Columbus' footprint in Hispaniola: A paleoenvironmental record of indigenous and colonial impacts on the landscape of the central Cibao Valley, northern Dominican Republic. *The Anthropocene* 22: 66–80.
- Cooper J and Peros M (2010) The archaeology of climate change in the Caribbean. *Journal of Archaeological Science* 37: 1226–1232.
- Crausbay SD, Martin PH and Kelly EF (2015) Tropical montane vegetation dynamics near the upper cloud belt strongly associated with a shifting ITCZ and fire. *Journal of Ecology* 103: 891–903.
- Crosby AW (2004) *Ecological Imperialism; the Biological Expansion of Europe, 900–1900*. 2nd Edition. Cambridge: Cambridge University Press, p. 368.
- Cugny C, Mazier F and Galop D (2010) Modern and fossil non-pollen palynomorphs from the Basque mountains (western Pyrenees, France): The use of coprophilous fungi to reconstruct

- pastoral activity. *Vegetation History and Archaeobotany* 19: 391–408.
- Darrow WK and Zanoni T (1990) Hispaniolan pine (*Pinus occidentalis* Schwartz): A little known sub-tropical pine of economic potential. *Commonwealth Forestry Review* 69: 133–146.
- De Boer EJ, Tjallingii R, Vélez MI et al. (2014) Climate variability in the SW Indian Ocean from an 8000-yr long multiproxy record in the Mauritian lowlands shows a middle to late-Holocene shift from negative IOD-state to ENSO-state. *Quaternary Science Reviews* 86: 175–189.
- Durland WD (1922) The forests of the Dominican Republic. *Geographical Review* 12: 206–222.
- Ellis MB (1971) *Dematiaceous Hypomycetes*. Kew: Commonwealth Mycological Institute Publication.
- Erdtman G (1952) *Pollen Morphology and Plant Taxonomy: Angiosperms*. Stockholm: Almqvist & Wiksell, p. 539.
- Faegri K, Kaland PE and Krzywinski K (1989) *Textbook of Pollen Analysis*. 4th Edition. Chichester: Wiley, p. 328.
- Farjon A and Styles BT (1997) *Pinus (Pinaceae): Flora Neotropica*, vol. 75. New York: Botanical Garden Press.
- Farr DF and Rossman AY (2013) *Fungal Databases, Systematic Mycology and Microbiology Laboratory*. ARS, USDA. Available at: <https://nt.ars-grin.gov/fungaldatabases/> (accessed 17 September 2013).
- Fitzpatrick SM and Keegan WF (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.
- Gentry AH (1986) Species richness and floristic composition of Chocó region plant communities. *Caldasia* 15(71–75): 71–91.
- Gentry AH (1993) *A Field Guide to the Families and Genera of Woody Plants of Northwest South America*. Washington DC: Conservation International, p. 895.
- Giannini A, Kushnir Y and Cane MA (2000) Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *Journal of Climate* 13: 297–311.
- Giannini A, Kushnir Y and Cane MA (2001) Seasonality in the impact of ENSO and the North Atlantic High on Caribbean rainfall. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* 26: 143–147.
- González-Gómez A (1977) *Moguer en la baja edad media (1248–1538)*. Huelva: Instituto de Estudios Onubenses ‘Padre Marchena’, Diputación Provincial de Huelva.
- Gordo AJ (1995) *Reseña geográfico-histórica de los bosques de Castilla y León: Provincia de Valladolid*. In: *IFN 2 Valladolid*. Madrid: Icona, pp. 34–71.
- Greenwood R, Hamber S and Dyde B (2003) *Amerindians to Africans (Caribbean Certificate History)*, vol. 1. 2nd Edition. Oxford: Macmillan Education.
- Grimm EC (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 EC (1993) *TILIA: A Pollen Program for Analysis and Display*. Springfield, IL: Illinois State Museum.
- Grimm EC (2004) *TG View 2.0. 2 (Software)*. Springfield, IL: Illinois State Museum.
- Grimm EC (2011) *TILIA 1.7. 16*. Springfield, IL: Illinois State Museum, Research and Collection Center.
- Groot MHM, Hooghiemstra H, Berrío JC et al. (2013) North Andean environmental and climatic change at orbital to sub-millennial time-scales: Vegetation, water-levels, and sedimentary regimes from Lake Fúquene during 130–27 ka. *Review of Palaeobotany and Palynology* 197: 186–204.
- Hager J and Zanoni TA (1993) La vegetación natural de la República Dominicana: una nueva clasificación. *Moscovia* 7: 39–81.
- Harcourt CS, Ottenwalder J, Schubert A et al. (1996) Hispaniola. In: Harcourt CS and Sayer JA (eds) *The Conservation Atlas of Tropical Forests: The Americas*. New York: Simon & Schuster, pp. 102–111.
- Haug GH, Günther D, Peterson LC et al. (2003) Climate and the collapse of Maya civilization. *Science* 299: 1731–1735.
- Haug GH, Hughen KA, Sigman DM et al. (2001) Southward migration of the intertropical convergence zone through the Holocene. *Science* 293: 1304–1308.
- Heiri O, Lotter AF 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 DA et al. (1999) A 10,300 14 C yr record of climate and vegetation change from Haiti. *Quaternary Research* 52: 159–170.
- Hillbrand M, Hadorn P, Cugny C et al. (2012) The palaeoecological value of *Diporothea rhizophila* ascospores (Diporotheaceae, Ascomycota) found in Holocene sediments from Lake Nussbaumersee, Switzerland. *Review of Palaeobotany and Palynology* 186: 62–68.
- Hodell DA, Curtis JH, Jones GA et al. (1991) Reconstruction of Caribbean climate change over the past 10 500 years. *Nature* 352: 790–793.
- Hofman C, Mol A, Hoogland M et al. (2014) Stage of encounters: Migration, mobility and interaction in the pre-colonial early colonial Caribbean. *World Archaeology* 46: 590–609.
- Hofman CL, Ulloa Hung J, Herrera Malatesta E et al. (2018) Indigenous Caribbean perspectives: Archaeologies and legacies of the first colonized region in the New World. *Antiquity* 92(361): 200–216.
- Holdridge LR (1945) A brief sketch of the flora of Hispaniola. In: Verdoorn F (ed.) *Plants and Plant Science in Latin America*. Waltham, MA: Chronica Botanica Co, pp. 76–81.
- Holmes G (2014) Defining the forest, defending the forest: Political ecology, territoriality, and resistance to a protected area in the Dominican Republic. *Geoforum* 53: 1–10.
- Hooghiemstra H (1984) *Vegetational and Climatic History of the High Plain of Bogotá (Colombia)*. *Dissertationes Botanicae*. Vaduz: J. Cramer.
- Hooghiemstra H and Van Geel B (1998) World list of quaternary pollen and spore atlases. *Review of Palaeobotany and Palynology* 104: 157–182.
- Horowitz A (1992) *Palynology of Arid Lands*. Amsterdam: Elsevier, p. 546.
- Horst OH (1992) Climate and the ‘encounter’ in the Dominican Republic. *Journal of Geography* 91: 205–210.
- Joly C, Barillé L, Barreau M et al. (2007) Grain and annulus diameter as criteria for distinguishing pollen grains of cereals from wild grasses. *Review of Palaeobotany and Palynology* 146: 221–233.
- Kahn F and De Granville JJ (2012) *Palms in Forest Ecosystems of Amazonia*. New York: Springer Science & Business Media, p. 172.
- Kennedy LM, Horn SP and Orvis KH (2005) Modern pollen spectra from the highlands of the Cordillera Central, Dominican Republic. *Review of Palaeobotany and Palynology* 137: 51–68.
- Kennedy LM, Horn SP and Orvis KH (2006) A 4000-year record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic. *Palaeogeography Palaeoclimatology Palaeoecology* 231: 279–290.
- Knight FW, Emmer PC and Higman BW (1997) *General History of the Caribbean: The Slave Societies of the Caribbean*. London: UNESCO, p. 379.
- Köhler E and Lange E (1979) A contribution to distinguishing cereal from wild grass pollen grains by LM and SEM. *Grana* 18: 133–140.
- Konert M and Vandenbergh JEF (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.
- Krug JC, Benny GL and Keller HW (2004) *Coprophilous Fungi: Biodiversity of Fungi*. Amsterdam: Elsevier.
- Lane CS, Horn SP and Kerr MT (2014) Beyond the Mayan Lowlands: Impacts of the terminal classic drought in the Caribbean Antilles. *Quaternary Science Reviews* 86: 89–98.
- Lane CS, Horn SP, Mora CI et al. (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 CS, Horn SP, Orvis KH et al. (2008a) The earliest evidence of Ostonoid maize agriculture from the interior of hispaniola. *Caribbean Journal of Science* 44: 43–52.
- Lane CS, Horn SP, Orvis KH et al. (2011) Oxygen isotope evidence of Little Ice Age aridity on the Caribbean slope of the Cordillera Central, Dominican Republic. *Quaternary Research* 75: 461–470.
- Lane CS, Mora CI, Horn SP et al. (2008b) Sebsitivity of bulk sedimentry stable carbon isotopes to prehistoric forest clearance and maize agriculture. *Journal of Archaeological Science* 35: 2119–2132.
- Liogier AH (1981) Ecosistemas de montañas en la República Dominicana. *Anuario* 5: 87–102.
- Livi-Bacci M (2006) The depopulation of Hispanic America after the conquest. *Population and Development Review* 32: 199–232.
- Lundqvist N (1972) Nordic Sordariaceae s. lat. *Symb. Bot. Upsal* 20(1): 1–374
- McNeill DF, Klaus JS, Evans CC et al. (2008) *An Overview of the Regional Geology and Stratigraphy of the Neogene Deposits of the Cibao Valley, Dominican Republic. Evolutionary Stasis and Change in the Dominican Republic Neogene*. New York: Springer Science, pp. 21–45.
- Mann P, Draper G and Lewis JF (1991) An overview of the geologic and tectonic development of Hispaniola. *Geological Society of America, Special Papers* 262: 1–28.
- Mann P, Prentice CS, Burr G et al. (1998) Tectonic geomorphology and paleoseismology of the Septentrional fault system, Dominican Republic. *The Geological Society of America, Special Paper* 326: 63–123.
- 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 Paleobotany and Palynology* 121: 1–75.
- Marcus A, Robbins J, Eckelmann C-M et al. (2008) Forest fires in the insular Caribbean. *Ambio* 37: 528–534.
- Martin PH and Fahey TL (2006) Fire history along environmental gradients in the subtropical pine forests of the Cordillera Central, Dominican Republic. *Journal of Tropical Ecology* 22: 289–302.
- Martin PH, Sherman RE and Fahey TJ (2004) Forty years of tropical forest recovery from agriculture: structure and floristics of secondary and old-growth riparian forests in the Dominican Republic. *Biotropica* 36: 297–317.
- Martin PH, Sherman RE and Fahey TJ (2007) Tropical montane forest ecotones: Climate gradients, natural disturbance, and vegetation zonation in the Cordillera Central, Dominican Republic. *Journal of Biogeography* 34: 1792–1806.
- Mbenoun M, Mono-Zeutsa EH, Samuels G et al. (2008) Dieback due to *Lasiodiplodia theobromae*, a new constraint to cocoa production in Cameroon. *Plant Pathology* 57: 381.
- Meijers PA and Teranes JL (2001) Sediment organic matter. In: Last WM and Smol JP (eds) *Tracking Environmental Change Using Lake Sediments: Physical and Geochemical Methods*, vol. 2. Dordrecht: Kluwer, pp. 239–269.
- Mohali S, Burgess TI and Wingfield MJ (2005) Diversity and host association of the tropical tree endophyte *Lasiodiplodia theobromae* revealed using simple sequence repeat markers. *Forest Pathology* 35: 385–396.
- Moore PD, Webb JA and Collinson ME (1991) *Pollen Analysis*. 2nd Edition. Oxford and London: Blackwell
- Morales C, Ortega T, González C et al. (2009) *Mapa de exposición ante inundaciones en la cuenca de Río Yaque del Norte*. Proyecto 00050116. Unidad de Coordinación Técnica del Programa de Prevención y Preparación ante desastres. Available at: [http://www.onu.org.do/Licitaci.NSF/5b4908be027078f0042570a5005ea141/8bdeac2bd36cc77904257409004d4e23/\\$FILE/Pliego%20SDP%2004%202008%20Mapa%20de%20Riesgo%20Hidro%20C3%B3gico.pdf](http://www.onu.org.do/Licitaci.NSF/5b4908be027078f0042570a5005ea141/8bdeac2bd36cc77904257409004d4e23/$FILE/Pliego%20SDP%2004%202008%20Mapa%20de%20Riesgo%20Hidro%20C3%B3gico.pdf).
- Müller MJ (1983) *Handbuch ausgewählter Klimastationen der Erde*. 3rd Edition. Trier: Universität Trier and Forschungsstelle Bodenerosion.
- NEXUS 1492 (2016). Objectives. Available at: http://www.nexus1492.eu/?page_id=21 (accessed 27 September 2016).
- Niles J (2005) *Modern Caribbean Geography*. 3rd Edition. Oxford: Macmillan Caribbean, p. 240.
- Olijhoek T (2016) *Environmental change in the Yaque River Area, North Western Dominican Republic: Human impact before and after Columbus' arrival in the new world*. Unpublished master's Thesis, University of Utrecht, p. 36.
- Olivera GM (1997) *Flora palinologica de Guerrero: 5 Menyanthaceae, Nymphaeaceae, Pontederiaceae y Typhaceae*. Mexico City, Mexico: Universidad Nacional Autonoma De México, pp. 28.
- Otaño NN, di Pasquo M and Bianchinotti MV (2016) The occurrence of *Potamomyces palmarensis* sp. nov. in the late-Holocene at the El Palmar National Park (Colón, Entre Ríos, Argentina) and transfer of fossil species of *Mediaverrinites* to *Potamomyces*. *Palynology* 40: 1–34. Available at: <http://www.tandfonline.com/doi/full/10.1080/01916122.2016.1146174>.
- Palacios-Chávez R, Ludlow-Wiechers B and Villanueva-G R (1991) *Flora palinológica de la reserva de la biosfera de Sian Ka'an, Quintana Ro, México*. Chetumal; Quintana Roo; México City, Mexico: Centro de Investigaciones de Quintana Roo, p. 321.
- Pardo F and Gil L (2005) The impact of traditional land use on woodlands: A case study in the Spanish Central System. *Journal of Historical Geograpy* 31: 390–408.
- Pereira BAS, Mendonca RC, Filgueiras YS et al. (1985) Levantamento florístico da área de proteção ambiental (APA) da bacia do Rio São Bartolomeu. In: *Proceedings of the Anais Do XXXVI Congresso Brasileiro De Botânica*, Federal, 20 May, pp. 419–492. Curitiba, Brazil: Sociedade Botanica do Brasil.
- Peros M, gregory B, Matos F et al. (2015) Late-Holocene record of lagoon evolution, climate change, and hurricane activity from southeastern Cuba. *The Holocene*. Epub ahead of print 26 May. DOI: 10.1177/0959683615585844.
- Pino RF (1990) *El primer libro de Actas del Ayuntamiento de Valladolid Año 1947*. Valladolid: Publicaciones del Archivo Municipal de Valladolid, p. 192.
- Prins MA and Weltje GJ (1999) End-member modeling of siliciclastic grain-size distributions: The late Quaternary record of eolian and fluvial sediment supply to the Arabian Sea and its paleoclimatic significance. In: Harbaugh L (ed.) *Numerical Experiments in Stratigraphy: Recent Advances in Stratigraphic and Sedimentologic Computer Simulations*. Broken Arrow, OK: Society for Sedimentary Geology, pp. 91–111 (Special Publication 62).
- R Development Core Team (2014.) R: A language and environment for statistical computing. *R Foundation for Statistical Computing*. Available at: <http://www.R-project.org/> (accessed January 2015).
- Rawley JA and Behrendt SD (2005) *The Transatlantic Slave Trade: A History*. Lincoln, NE: University of Nebraska Press.

- Rodgers JC and Horn SP (1996) Modern pollen spectra from Costa Rica. *Palaeogeography Palaeoclimatology Palaeoecology* 124: 53–71.
- Roubik DW and Moreno P (1991) *Pollen and Spores of Barro Colorado Island (Panama)*. (Monographs in Systematic Botany), vol. 36. St. Louis, MO: Botanical Garden.
- Salgado-Labouriau ML (1986) Estudios paleoecológicos de la región de Rancho Grande, Venezuela. In: Huber O (ed.) *La Selva Nublada de Rancho Grande, Parque Nacional 'Henri Pittier'*. Caracas, Venezuela: Fondo Editorial Acta Científica Venezolana, pp. 109–110.
- Siegert F, Rueker G, Hinrichs A et al. (2001) Increased damage from fires in logged forests during droughts caused by El Niño. *Nature* 414: 437–440.
- Sinelli PT (2013) Meillacoid and the origins of classic Taino society. In: Keegan WF, Hofman CL and Rodríguez-Ramos R (eds) *The Oxford Handbook of Caribbean Archaeology*. New York and Oxford University Press, pp. 221–231.
- Smartt J and Simmonds NW (1995) *Evolution of Crop Plants*. 2nd Edition. Harlow: Longman, p. 531.
- Soldner M, Stephen I, Ramos L et al. (2004) Relationship between macroinvertebrate fauna and environmental variables in small streams of the Dominican Republic. *Water Research* 38: 863–874.
- Stockmarr J (1971) Tablets with spores used in absolute pollen analysis. *Pollen et Spores* 13: 614–621.
- Taviani PE, Varela C, Gil J et al. (eds) (1994) *Christopher Columbus. Accounts and Letters of the Second, Third and Fourth Voyages*. Roma: Instituto Poligrafico e Zecca dello Stato, Libreria dello Stato.
- Thomas WW (1999) Conservation and monographic research on the flora of tropical America. *Biodiversity & Conservation* 8: 1007–1015.
- Ulloa Hung J (2014) *Arqueología En La Línea Noroeste De La Española. Paisajes, Cerámicas E Interacciones*. Santo Domingo, Dominican Republic: Instituto Tecnológico de Santo Domingo, República Dominicana.
- Ulloa Hung J and Herrera Malatesta E (2015) Investigaciones arqueológicas en el norte de la Española. Entre viejos esquemas y nuevos datos. *Boletín Del Museo Del Hombre Dominicano* 42: 75–107.
- Valbuena-Carabaña M, López de Heredia U, Fuentes-Utrilla P et al. (2010) Historical and recent changes in the Spanish forests: A socio-economic process. *Review of Palaeobotany and Palynology* 162: 492–506.
- Van Geel B (2001) Non-pollen palynomorphs. In: Smol JP, Birks HJB and Last WM (eds) *Tracking Environmental Change Using Lake Sediments, Vol. 3 Terrestrial, Algal and Siliceous Indicators*. Dordrecht: Kluwer, pp. 99–119.
- Van Geel B and Aptroot A (2006) Fossil ascomycetes in quaternary deposits. *Nova Hedwigia* 82: 313–329.
- Van Geel B, Bohncke SJ and Dee H (1981) A palaeoecological study of an upper Late Glacial and Holocene sequence from 'De Borchert', The Netherlands. *Review of Palaeobotany and Palynology* 31: 367–448.
- Van Geel B, Coope GR and Van der Hammen T (1989) Paleocology and stratigraphy of the Lateglacial type section at Usselo (The Netherlands). *Review of Palaeobotany and Palynology* 60: 25–129.
- Van Geel B, Buurman J, Brinkkemper O et al. (2003) Environmental reconstruction of a Roman Period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. *Journal of Archaeological Science* 30: 873–883.
- Van Geel B, Gelorini V, Kyaruu A et al. (2011) Diversity and ecology of tropical African fungal spores from a 25,000-year palaeoenvironmental record in southeastern Kenya. *Review of Palaeobotany and Palynology* 164: 174–190.
- Van Royen W (1938) A geographical reconnaissance of the Cibao of Santo Domingo. *Geographical Review* 28: 556–572.
- Van Wyk BE (2005) *Food Plants of the World: An Illustrated Guide*. Portland, OR: Timber Press, p. 480.
- Vera FWM (2000) *Grazing Ecology and Forest History*. Wallingford: CABI Publishing.
- Vidal-Naquet P (ed.) (1987) *The Harper Atlas of World History*. New York: Harper & Row, p. 340.
- Webb EL and Peralta R (1998) Tree community diversity of lowland swamp forest in northeast Costa Rica, and changes associated with controlled selective logging. *Biodiversity & Conservation* 7: 565–583.
- Weltje GJ and Prins MA (2003) Muddled or mixed? Inferring palaeoclimate from size distributions of deep-sea clastics. *Sedimentary Geology* 162: 39–62.
- Whitehead DR and Langham EJ (1965) Measurement as a means of identifying fossil maize pollen. *Bulletin Torrey Botanical Club* 92: 7–20.
- Whitlock C and Larsen V (2001) Charcoal as a fire proxy. In: Smol JP, Birks HJB and Last WM (eds) *Tracking Environmental Change Using Lake Sediments: Terrestrial, Algal and Siliceous Indicators*, vol. 3. Dordrecht: Kluwer, pp. 75–97.
- Windingstad JD, Sherwood SC, Gremillon KJ et al. (2008) Soil fertility and slope processes in the Western Cumberland Escarpment of Kentucky: Influences on the development of horticulture in the Eastern Woodlands. *Journal of Archaeological Science* 35: 1717–1731.
- Wing JT (2015) *Roots of Empire. Forest and State Power in Early Modern Spain, C. 1500–1750*. Leiden: Brill.
- Wu F, Fang X, An C et al. (2013) Over-representation of *Picea* pollen induced by water transport in arid regions. *Quaternary International* 298: 134–140.