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A 4000-year record of fire and forest history from Valle de Bao, Cordillera Central, Dominican Republic

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Abstract

We examined evidence of past vegetation, climate, and disturbance history in a sediment core from a bog on the windward slope of the Cordillera Central in the Dominican Republic. The sediments revealed a continuous 4000 cal yr history of pine (*Pinus occidentalis*) dominance and fire. Bog formation may have been linked with a regional shift toward wetter conditions seen at other highland sites around 4000 cal yr BP. Low pollen influx, low organic content, and poor pollen preservation suggested periodic drying of the bog surface between ~3700 and 1200 cal yr BP and the loss of sediments to either deflation or erosion. Spikes in pollen of broadleaf trees and shrubs, mainly before 2500 cal yr BP, may indicate warmer or wetter intervals. Remobilized old charcoal, along with peaks in Poaceae, *Cyathea*, and *Lophosoria*, indicate a possible large tropical storm event around 2900 cal yr BP. Transported clasts of peat and soil in the core signal other high precipitation events. We found no clear evidence of prehistoric human activity.

Keywords: Dominican Republic; Pollen analysis; Tropical; Holocene; Charcoal; Prehistory

1. Introduction

Despite growing interest in tropical climate and environmental history, paleoenvironmental records from lakes and swamps in the Caribbean and neighboring subtropical Atlantic region remain sparse. Published sediment records are available from Lake Miragoâne, Haiti (18° N, 73° W; Brenner and Binford, 1988; Hodell et al., 1991; Curtis and Hodell, 1993; Higuera-Gundy et al., 1999); Wallywash Great Pond, Jamaica (18° N, 78° W; Street-Perrott et al., 1993; Holmes, 1998); Laguna Tortuguero, Puerto Rico (18° N, 68° W; Burney et al., 1994); and Church's Blue Hole, Bahamas (25° N, 78° W; Kjellmark, 1996). All of these are from lakes located near sea level (1–20 m elevation). This paper presents a 4000–year sediment record from a montane bog (~1800 m) at the ecotone between humid montane broadleaf forest and higher-elevation pine forests in the Cordillera Central, Dominican Republic.

Some prior research in the region has focused on sedimentary evidence of prehistoric human activity. Burney et al. (1994) studied sedimentary charcoal from Laguna Tortuguero in part to refine the date of initial colonization of Puerto Rico. Kjellmark (1996) interpreted a peak in charcoal concentrations concurrent with a shift from pollen of hardwoods to pine in sediments from Church's Blue Hole to signal either human arrival, or an increase in human-set fires. In both the

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Puerto Rico and Bahamas studies, climatic interpretations for at least parts of the records are complicated by the likely influence of human activity.

Other sediment studies have focused primarily on evidence of climatic change. At Wallywash Great Pond, Jamaica, physical and geochemical properties of sediments (Street-Perrott et al., 1993; Holmes et al., 1995) and changes in ostracod assemblages (Holmes, 1998) yielded a continuous record of climate covering the late Quaternary. Stable isotopes, geochemistry, and pollen and charcoal assemblages in a sediment profile from Lake Miragoâne, Haiti, documented environmental history over the past ~12,000 cal year (Binford et al., 1987; Brenner and Binford, 1988; Hodell et al., 1991; Curtis and Hodell, 1993; Higuera-Gundy et al., 1999).

This study provides information on the climate, vegetation, and fire history of a portion of the windward slope of the Cordillera Central, Dominican Republic. It is part of an ongoing study of modern and ancient environments of the larger highland region (Orvis et al., 1997; Horn et al., 2000, 2001; Clark et al., 2002; Speer et al., 2004; Kennedy et al., in press).

2. Study area

2.1. Physical setting

Hispaniola is the second largest island in the Greater Antilles. The northwest-southeast trending Cordillera Central includes the highest peaks in the Caribbean, Pico Duarte and La Pelona (3098 and 3094 m, respectively; Orvis, 2003), and extends from northwest Haiti to the southeastern coast of the Dominican Republic. The trade winds dominate highland climate for most of the year, but weaken with Intertropical Convergence Zone (ITCZ) proximity in summer, while midlatitude cyclonic storms sometimes reach Hispaniola in winter (Horst, 1992). In winter (January–March), subtropical high pressure defines dry, stable conditions. With more than 20 peaks over 2000-m elevation, the Cordillera Central provides an effective barrier to the northeasterly trade winds. Leeward slopes receive less than half the rainfall of windward slopes (Horst, 1992). The trade wind inversion creates a rainfall maximum near its 2150-m elevation (Schubert et al., 1995). Elevations above 2500 m are relatively arid and fog becomes an important moisture source for plants (Liogier, 1981).

Long-term climate data are entirely lacking for high elevations, but general trends can be derived from stations at lower elevations, such as Jarabacoa at 529 m on the lower windward slope. Records for Jarabacoa indicate an annual average rainfall of ~1500 mm (Horst, 1992). Horst (1992) estimated that high-elevation windward slopes in the Cordillera Central receive 1750–2500 mm of rain annually, while leeward slopes receive 625–825 mm. Bolay (1997) estimated as much as 4000 mm in certain high relief areas. Tropical storms and hurricanes can produce very large rainfall totals and may skew long-term averages. During the 1871–1991 period, hurricanes struck the Dominican Republic every 3.6 years on average (Horst, 1992).

Temperatures in the highlands are strongly influenced by topography; annual variation is small, but diurnally temperatures oscillate from below 0 to over 30 °C (Bolay, 1997). Temperatures as low as -8 °C have been recorded (Bolay, 1997). Subzero temperatures occur everywhere in the highlands at elevations above 2100 m (Hudson, 1991), especially under clear skies in winter, producing katabatic cold-air drainage, and frequent frosts in cold air traps such as Valle de Bao (~1800 m, Fig. 1).

Highland vegetation consists of a mosaic of dense pine forests, open woodlands, and grasslands (locally referred to as "sabanas") with physiognomy and composition reflecting interrelationships between disturbances, such as fire, windthrow, and landslides; land use history; and environmental variables, such as topography, local climate, and soil conditions. At higher elevations (>1800 m), forests are dominated by the single endemic pine species, *Pinus occidentalis*. Below that, and in some higher sites that are protected from cold and frost, tropical montane trees such as *Alchornea*, *Bocconia*, *Brunellia*, *Cecropia*, *Didymopanax*, *Garrya*, *Hedyosmum*, *Ilex*, *Juglans*, *Myrica*, *Myrsine*, *Trema*, and *Weinmannia* join pines in the canopy. Some of these trees, such as *Garrya*, *Myrica*, *Myrsine*, and *Ilex*, shrink in stature to form a shrub understory at high elevations. The upper limit of most broadleaved species in the Cordillera Central is 2500–2600 m (Bolay, 1997). Members of the Ericaceae family (especially *Lyonia* spp.) are also common in the pine forest shrub layer, along with ferns and an herb layer that is dominated by tussock grasses, especially the endemic *Danthonia domingensis*. The Poaceae, Cyperaceae, and Asteraceae families are well represented in the open grasslands.

Two roadless parks (Fig. 1) protect much of the remaining pine forests and humid montane broadleaf forests in the Dominican Republic. The Armando Bermúdez National Park (ABNP) encompasses 766 km^2 on the windward (northern) flank of the Cordillera Central. Along the crest of the range, ABNP adjoins José del Carmen Ramírez National Park (JCRNP), which protects a nearly equal area on the leeward (southern) slopes.

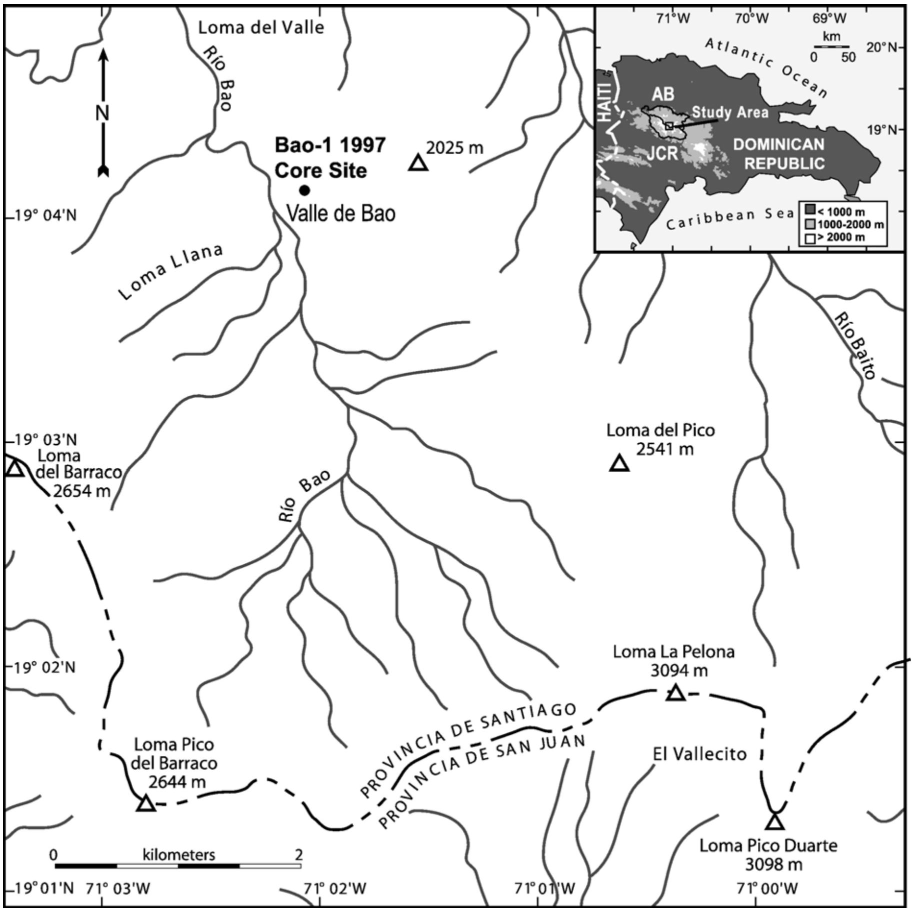

Fig. 1. Map of study area and Bao-1 1997 core site. Inset shows position of study area in the Cordillera Central, Dominican Republic, and the two national parks, AB (Armando Bermúdez) and JCR (José del Carmen Ramírez). The core site is in AB. The spine of the Cordillera Central divides the parks and is shown on the larger map as a dashed line. The elevations of the peaks of La Pelona and Pico Duarte are based on Orvis (2003).

2.2. Human history

The earliest colonists are believed to have arrived in Hispaniola by about 6000 year BP, and to have come from the Yucatan Peninsula by way of Cuba (Wilson et al., 1998). This first colonization appears to have been followed by several migrations from the South American mainland and Puerto Rico (Keegan, 2000). The movements of prehistoric people around the island of Hispaniola are still largely unknown. Prehistoric peoples from all periods appear to have depended on some combination of marine resources and on wild (and later cultivated) tropical plants (Petersen, 1997). Broad-scale landscape alteration of the highlands by prehistoric people is unlikely, due to the lack of game and temperatures too cold to support cultivation of the early staple, manioc. Prehistoric petroglyphs in ABNP (Hoppe, 1989), however, attest to at least some human activity in the highlands, possibly for ceremonial purposes. There is some indication that Tainos fled to mountainous areas under the repressive conditions associated with the later Spanish occupation (Bolay, 1997).

European settlers arrived in Hispaniola in A.D. 1492, but the Cordillera Central apparently remained largely uninhabited between A.D. 1650 and 1850 (Kustudia, 1998). Historical accounts and photos indicate that clearing of mountain pine forest by slash and burn agriculturalists was occurring in areas around Jarabacoa and Constanza at least by the late 19th and early 20th centuries (Darrow and Zanoni, 1990). Commercial logging began on small scales in the early 1900s, but increased dramatically under the dictatorship of Rafael L. Trujillo Molina in the 1940s (Darrow and Zanoni, 1990; Bolay, 1997). Uncontrolled logging continued until it was banned by the Dominican government in 1962 (Kustudia, 1998). ABNP and JCRNP were established in 1956 and 1958, respectively (Ottenwalder, 1989), as pine forest reserves became depleted.

Table 1
Radiocarbon determinations for Bao-1 1997 core samples

Core section depth (cm)	Lab no.	$\delta^{13}C$	Uncalibrated ^{14}C age (^{14}C yr BP)	Calibrated age(s) (cal yr BP)	Calibrated age range (cal yr BP)	
					± 1σ	± 2σ
PVC 16–18	AA40257	−25.5	191 ± 34	280, 170, 153	290–3	301–1
PVC 16–18	AA40258	−26.1	167 ± 43	273, 188, 147, 12, 4	285–1	299–0
PVC 38–40	AA43339	−24.2	2126 ± 59[a]	2118	2300–2000	2310–1950
PVC 40–42	AA40256	−26.4	553 ± 66	545	640–520	660–500
PVC 58–60	AA43340	−23.9	1816 ± 57[b]	1723	1820–1630	1880–1570
Section I 47.5–48.5	AA39458	−25.5	3016 ± 49[a]	3236, 3232, 3211	3081–3322	3064–3356
Section I 75.5–76.5	β-155839	−25.2	1300 ± 40	1261	1285–1170	1293–1155
Section I 86.5–87.5	β-155840	−25.9	2260 ± 50	2312, 2218, 2211	2340–2160	2350– 2120
Section I 99–100	β-13524	−24.9	5210 ± 50[a]	5933	5990–5920	6170–5900
Section II 105.5–106.5	AA40253	−26.6	3083 ± 38	3334, 3282, 3270	3357–3258	3379–3170
Section II 112.5–113.5	AA40254	−24.8	3348 ± 38	3628, 3620, 3605, 3602, 3576	3636–3481	3688–3470
Section II 125.5–126.5	AA40255	−24.5	3690 ± 86	4070, 4046, 3988	4150–3890	4280–3730

AA samples were dated by the NSF Arizona AMS Facility; β samples were dated by Beta Analytic, Inc. All of the dated samples were charcoal except AA40257, which was seeds, and β-155839, which was seeds and charcoal. Dates were calibrated using the CALIB 4.3 calibration program (Stuiver and Reimer, 1993) and the datasets of Stuiver et al. (1998). Errors estimate 68% (1σ) and 95% (2σ) probability. [a] Samples interpreted as redeposited charcoal (see text). [b] The radiocarbon date for sample AA43340 does not appear in the pollen diagrams (Figs. 3–5) or age–depth graph (Fig. 2) because pollen samples were only taken from the PVC core section between 0 and 40 cm; all lower pollen samples are from Core Sections I and II.

2.3. Core site

Our core site (Fig. 1) is in Valle de Bao (19°04′ N, 71°02′ W, ~1800 m elevation) in ABNP on the windward (northern) flank of the Cordillera Central. Valle de Bao is a 2.5 × 0.3 km trough located ~6 km northwest of Pico Duarte. The valley floor is treeless, dominated by *D. domingensis* and other grasses and sedges, and punctuated by several bog-filled depressions. Cold air drained from higher slopes and trapped in the valley likely inhibits invasion by pine (Clark et al., 2002). Scattered colonies of *Rubus* spp. (blackberry) are the only woody plants occupying the valley floor. The lower slopes above the valley floor support pure pine stands, but certain middle slopes of Loma del Pico and La Pelona (~1900–2500 m) are effec-

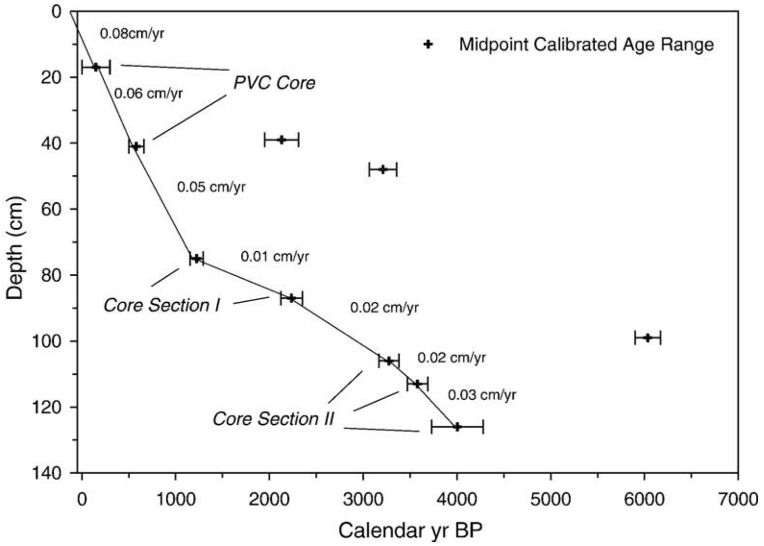

Fig. 2. Radiocarbon ages plotted against depth for the Bao-1 1997 core. Bars indicate 2σ calibrated age ranges, and crosshair symbols indicate the midpoint of the range. Approximate sedimentation rates (labeled and represented by the lines between dates) are estimated by linear interpolation between the midpoints. The three bars on the right side of the graph (not connected by lines) represent calibrated age ranges on samples that are interpreted to be redeposited charcoal. The core sections that the dated material was taken from are shown in italics. There are two overlapping samples at 17 cm with nearly identical age ranges.

tively drained of cold air and presently support a diverse assemblage of tropical broadleaf trees. The core site was a small peat bog (Bao Bog 1) with a water depth of ~15–20 cm in a topographically low area (~1775 m) of the valley.

3. Methods

We retrieved the bog sediments in February 1997 in a 340 cm core that penetrated deep into an underlying mineral soil developed on alluvial fan deposits. We recovered the core in successive one-meter drives using a Colinvaux–Vohnout (C-V) locking-piston corer (Colinvaux et al., 1999), and returned the core sections to the laboratory in the original sampling tubes (5 cm diameter, aluminum). We obtained near-surface sediments using a PVC tube (5 cm in diameter) that had a serrated edge for twisting the tube into the sediment. We extruded and sliced these sediments in 2-cm increments in the field, storing them in plastic bags. The C-V core sections and material from the PVC tube together constitute the Bao-1 1997 sediment core.

Here we report pollen and charcoal analysis of the organic-rich, pollen bearing bog sediments in the uppermost 126.5 cm of the core. These organic sediments overlie a truncated paleo-surface of mottled clay soil that exhibited desiccation cracks and contained little pollen. The underlying mineral sediment in which the paleosol developed was also poor in pollen and reflects deposition in a different context than the modern bog. Samples from 0 to 40 cm in the analyzed section are from the PVC tube; those from 40 to 103 cm are from C-V Core Section I, and those from 103 to 126.5 cm are from C-V Core Section II. The C-V core sections and the PVC tube section were collected from separate holes a short distance (<2 m) apart.

In the laboratory, we opened the C-V core sections with a table-mounted router, photographed them, and described their texture and color. We sampled for pollen and charcoal analysis at 4-cm intervals, avoiding clasts of redeposited peat and soil. We dried duplicate samples at 100 °C for 8 h minimum to determine water content, and performed loss on ignition (LOI) for one hour at 550 and 1000 °C to estimate organic and carbonate

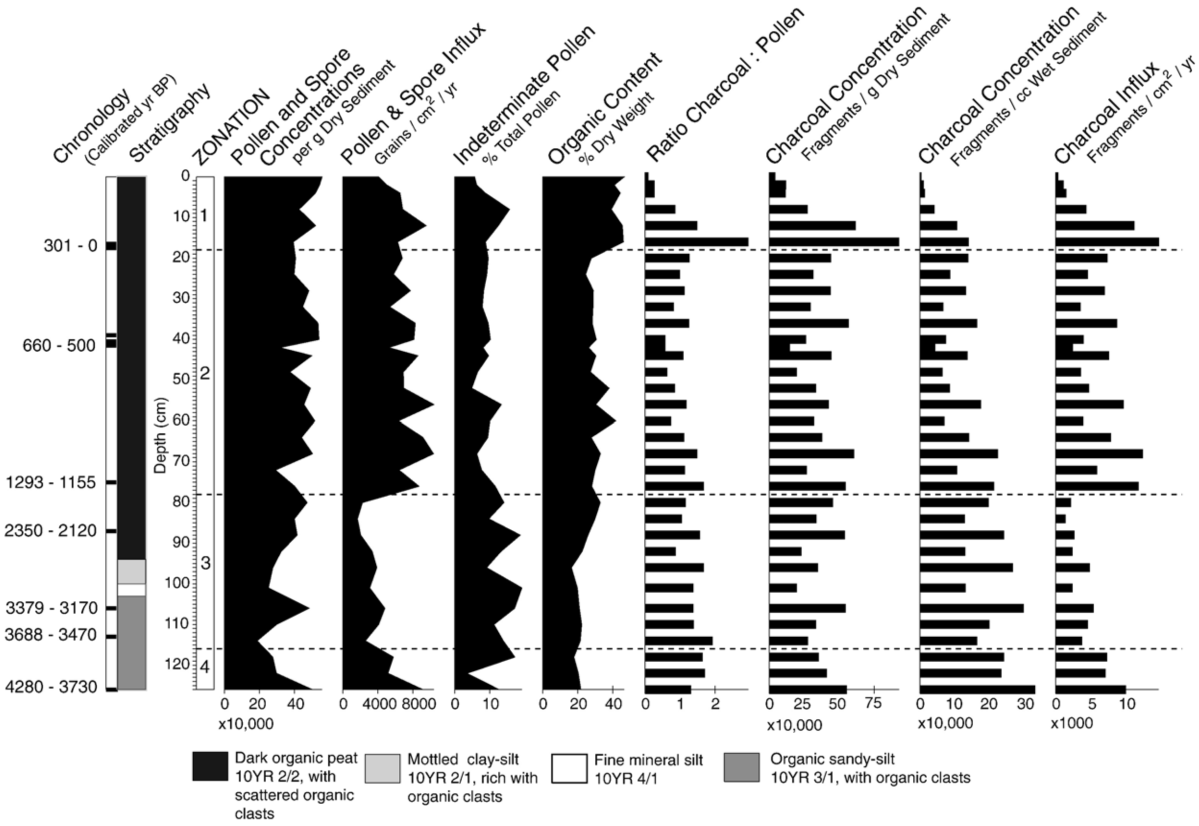

Fig. 3. Diagram showing chronology and stratigraphy, pollen and spore concentrations and influx, indeterminate pollen percentages, organic content (%), and charcoal fragments (>50 mm) expressed as charcoal : pollen ratios, fragments per g dry sediment, fragments per cc wet sediment, and influx (per cm^2 per year) of the Bao-1 1997 core. Dates shown are the 2σ calibrated age ranges.

content (Dean, 1974). We used sample volumes for pollen and LOI analysis of 1.2 cm^3 for the two uppermost levels (0 and 2 cm depth), 0.6 cm^3 for the next two deeper samples (4 and 6 cm depth), and 0.5 cm^3 for the remaining levels.

We processed the samples using standard pollen preparation techniques (HF, HCl, KOH, acetolysis, safranin stain; Faegri and Iverson, 1989) and added *Lycopodium* tablets as controls (Stockmarr, 1971). We mounted the pollen residues on microscope slides in silicone oil, and counted a minimum of 400 pollen grains per sample exclusive of indeterminate pollen and spores. Pollen and spores were identified at 400x magnification using pollen reference material from the Dominican highlands and elsewhere, and published keys and photographs (Heusser, 1971; McAndrews et al., 1973; Markgraf and D'Antoni, 1978; Moore and Webb, 1978; Hoogheimstra, 1984; Moore et al., 1991). Pollen grains of the Urticales were classified by pore number, except for *Cecropia* and *Trema*.

We sketched unknown pollen grains and recorded them as morphological types. Unknown fern spores were classified by morphology. Although the same *Lycopodium* species used for the control tablets, *L. clavatum*, grows in the Cordillera Central, the vast majority of *Lycopodium* spores in our samples appear to be the controls we added. Our control spores had a slightly shrunken and darker appearance; native spores were brighter, retained truer size and shape compared to modern reference samples from the highlands, and exhibited a broader reticulate pattern. We identified fewer than 20 native *Lycopodium* spores in all samples.

We counted charcoal fragments >50 μm in maximum dimension during the standard pollen counts. We tallied only completely black, opaque, angular fragments. Pollen and spore percentages and charcoal values were plotted using a modified version of CalPalyn (Bauer et al., 1991). For the purpose of discussion, we divided the diagrams into four zones based on stratigraphic changes and shifts in influx rates of pollen, spores, and charcoal. To construct the chronology of the core, we submitted 12 samples from the upper organic section of the Bao-1 1997 core for AMS radiocarbon dating.

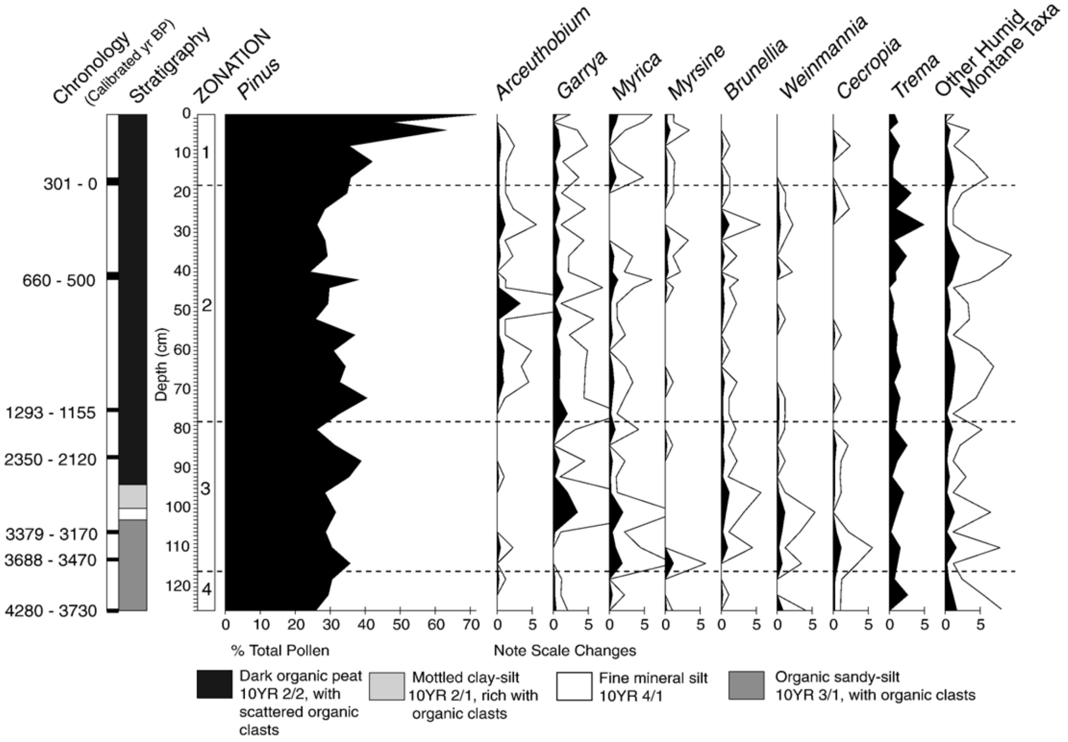

Fig. 4. Pollen percentage diagram of tree and shrub taxa for the Bao-1 1997 core. The "Other Humid Montane Taxa" group includes *Ilex*, *Hedyosmum*, *Didymopanax*, *Alchornea*, *Juglans*, Melastomataceae, *Bocconia*, *Piper*, *Zanthoxylum*, and Solanaceae (which may include herbaceous taxa). Black lines represent a 5× exaggeration.

4. Results

4.1. Radiocarbon dates and core description

Radiocarbon dates (Table 1 and Fig. 2) obtained on charcoal fragments and seeds were in order except for three dates on apparently redeposited charcoal. From 103 to 126.5 cm the sediment is composed of organic-rich sandy silt (10YR 3/1) with occasional clasts of redeposited organic sediment and coarse sand. A thin layer of lighter-colored (10YR 4/1) fine-grained mineral silt extends from 100 to 103 cm. From 94 to 100 cm the sediment resembles the 103 to 126.5 cm sediment, but is mottled by light-colored material (10YR 4/6), is more clay-rich, and contains abundant redeposited peat and mineral soil clasts. From 0 to 94 cm is dark (10YR 2/1), fine-textured silty peat, grading upward to material with a lower silt content (10YR 2/2), with some sand and scattered organic clasts, mainly below 40 cm in Core Section I. The uppermost 20 cm of sediment is especially rich in plant roots and undecayed plant material.

4.2. Pollen and charcoal

We identified 50 pollen types, many of them rare; unknown pollen grains accounted for less than 1% of the pollen in all levels (Figs. 3–5). Pollen preservation varied with indeterminate grains accounting for 3–16% of the total pollen. Indeterminate percentages were highest in the lower, less organic sediments (below ~85 cm, Fig. 3). Pollen and spore influx (Fig. 3) is high in the basal pollen zone (Zone 4), lower in Zone 3, then remains generally higher in Zones 2 and 1, except in the uppermost samples of Zone 1. Pine (*Pinus*), grass (Poaceae), and sedge (Cyperaceae) pollen dominate the record, together accounting for ~50–90% of the pollen in most samples (Fig. 3). Fern (pteridophyte) spore percentages show little change over time, except for prominent peaks in *Cyathea* and *Lophosoria* (Fig. 5).

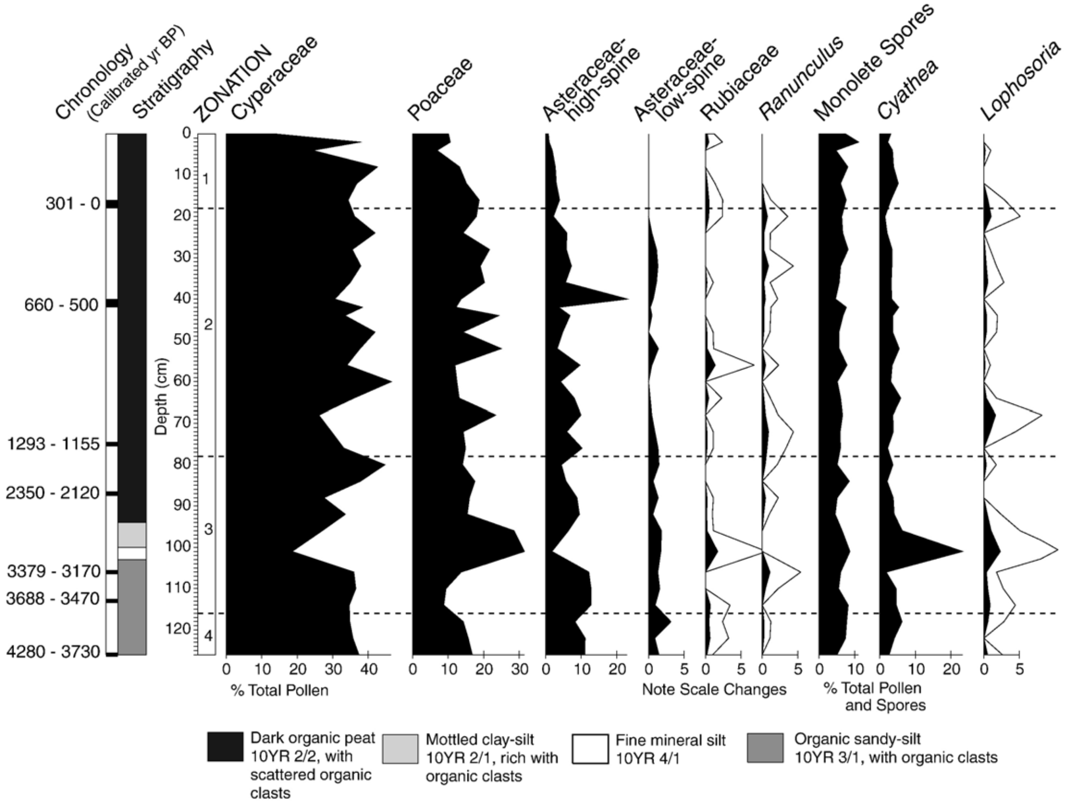

Fig. 5. Percentage diagram showing selected mainly herbaceous pollen taxa and pteridophyte spores from the Bao-1 1997 core. The Rubiaceae pollen was mainly *Galium*, but also included pollen of *Mitracarpus* and *Spermacoce*. Herbs in the Asteraceae family are common in the highlands and we expect that most pollen in that group represents herbaceous plants, but some may represent woody genera such as *Baccharis* and some *Senecio* species. Black lines represent a 5× exaggeration.

Charcoal fragments smaller than 50 μm were not counted but were ubiquitous. Charcoal >50 μm is abundant throughout the record with the only dramatic change a decline in the uppermost section representing about the past 50–100 years. Charcoal : pollen ratios and concentrations in dry sediment (Fig. 3) show generally similar patterns. Charcoal concentrations in wet sediment are higher in Zones 4 and 3 and gradually decline toward the surface, a pattern that reflects in part the water content of the sediments. The charcoal influx curve generally mirrors the pollen and spore influx curve, with a dramatic increase in Zone 2. Both charcoal influx and charcoal to pollen ratios display a period of slightly lower values between ~300 and 1000 cal yr BP.

5. Discussion

5.1. Fire and climate history

The most prominent signal in the record is the continuous history of pine dominance and fire (Fig. 3). This is not surprising given Agee's (1998) "inextricable link" between pines and fire through space and time. The Bao record indicates that fire has been an important element of high elevation landscapes in the Cordillera Central, including the windward slope, for at least the past 4000 years. This is consistent with our previous findings of ubiquitous charcoal of ages between ~1200 and 13,000 cal yr BP (and some older) in soils and sediments from other highland sites in ABNP and elsewhere in the Cordillera Central (Horn et al., 2000). Our detailed fire history for the last 4000 years in Valle de Bao demonstrates that fire was a constant component of the highland environment during the late Holocene.

Our sediment record provides no clear signal of prehistoric human activity in Valle de Bao. This supports the idea (Wilson, 1990) that preHispanic people spent little time in mountainous areas where food sources would have been scarce. Dominicans only began to exploit the highlands as a source of timber and for cattle grazing during the last century (Bolay, 1997). It is likely that most of the charcoal in the Bao record was generated in fires ignited by lightning.

A dramatic decrease in charcoal in the uppermost levels of Zone 1 (probably representing the last ~50 years) follows a steep spike in charcoal at the base of the zone that marks a major fire, or a period of high fire frequency, that probably occurred over a century ago. The recent decrease is coupled with a marked increase in pine pollen, which reaches percentages unprecedented in the earlier record, where it generally remains between 25 and 35% of the pollen sum. The earlier percentages are consistent with percentages of pine pollen in modern surface sediments of several bogs of the Cordillera Central (Kennedy et al., in press).

The increase in pine pollen in the uppermost sediments probably reflects a local increase in pine in and around Valle de Bao. It may just signal regeneration after the large fire that generated the charcoal peak, or after other disturbance. Alternatively, the pine pollen peaks may point to higher temperature minima during recent times, which would have allowed pine to encroach down onto the upper floor of the basin.

The initiation of organic sedimentation at the Bao-1 site around 4000 cal yr BP is consistent with evidence from other highland sites of a shift to wetter climate at about that time (Orvis et al., 2005). Geomorphic evidence and evidence from other valley-floor profiles suggest that a smooth late-Pleistocene valley floor of coalesced fans was later overlain by fine, nearly pure mineral lacustrine silts deposited during a temporary ponding event, and then became dendritically incised. The Bao-1 bog is located in a bowl-shaped erosion head of this incision, from which both the lacustrine facies and the uppermost portion of the solum developed in fan deposits are missing. The bowl shape suggests that spring sapping may have contributed to its formation, and this is consistent with its modern spring-fed bog dynamics and with its distal fan position. It seems most likely that a shift to wetter climate fostered initiation of bog conditions in the formerly eroding spring-head depression.

Both the pollen-and-spore and charcoal influx curves show relatively high influx levels in the basal portion of the bog sediments (Zone 4), but values decline abruptly upcore and remain low until ~1200 cal yr BP (Fig. 3). This decline could reflect a major change in vegetation, but no other stratigraphic evidence supports such a change. Instead, reduced pollen and spore concentrations and reduced organic content, and peaks in indeterminate pollen (Fig. 3) suggest poor conditions for pollen preservation and sediment accumulation prior to ~1500 cal yr BP. We infer that periods of aridity, or else enhanced seasonal drying, desiccated the site at least occasionally between ~3700 and 1200 cal yr BP, allowing pollen degradation. The lower influx levels and sedimentation rates (Fig. 2) during that period may be due to missing sediments removed by deflation, erosion, or both. Interestingly, even in the uppermost part of Zone 3 (~2500 cal yr BP) when organic content is increasing, influx of pollen, spores, and charcoal are at their lowest levels. This may indicate a semi-permanent high water table in the bog, but still with occasional losses of material. Near the boundary between Zones 3 and 2 (~1500–1200 cal yr BP), concentrations and influxes rise and largely stabilize throughout Zone 2 at levels similar to Zone 4.

The isotopic data from Lake Miragoâne, near sea level far in the lee of the central mountain ranges of Hispaniola, indicate a climate in the region that remained moist from the early Holocene until about 6100 cal yr BP, when lake levels began to drop gradually through the middle Holocene, accelerating after 3400 cal yr BP (Hodell et al., 1991; Curtis and Hodell, 1993; Higuera-Gundy et al., 1999). The pollen data contrast with this picture, revealing that moist-forest taxa expanded during the middle Holocene, possibly because of reductions in seasonal moisture stress despite overall increasing E/P. After 3400 cal yr BP, moist-forest taxa diminished and lake levels remained low, continuing through the present with only brief returns to moister conditions (e.g., ~1600–900 cal yr BP) (Hodell et al., 1991; Curtis and Hodell, 1993; Higuera-Gundy et al., 1999). This Late Holocene drying trend has also been noted in sediment records from Church's Blue Hole, Bahamas (timing uncertain due to problems with chronology) (Kjellmark, 1996); Lake Valencia, Venezuela (Bradbury et al., 1981; Curtis et al., 1999); Lake Chichancanab, Mexico (Hodell et al., 1995); and in geomorphic investigations of Lago Enriquillo, Dominican Republic (Mann et al., 1984; Taylor et al., 1985). Orbitally-driven changes in seasonality have been invoked to explain Holocene climatic trends at Lake Miragoâne (Hodell et al., 1991) and Lake Valencia (Curtis et al., 1999). Moist conditions in the early to middle Holocene at these sites are attributed to enhanced seasonality, and the recent drying trend to decreased seasonality, as perihelion shifted into Northern Hemisphere winters resulting in reduced N–S movement of the ITCZ and decreased summer precipitation in the circum-Caribbean region (Hodell et al., 1991; Curtis et al., 1999).

The basal date of ~4000 cal yr BP on the Bao-1 1997 organic sediments indicates that the bog originated during the period of regional lowland drying discussed above. That the site did not support a bog earlier in the Holocene, when Lake Miragoâne was at its fullest and lowland E/P ratios were lowest, may reflect local or elevational climate gradients different from modern ones.

Peaks in pollen percentages of several broadleaf tree taxa (Fig. 4) in the older (>~2500 years BP, Zone 3) Bao sediments suggest that broadleaf forest may have expanded on the slopes above or below Valle de Bao. Modern surface pollen samples (Kennedy et al., in press) suggest that *Weinmannia* and *Brunellia* may be good indicators of broadleaf forest cover. An increase in temperature minima, possibly associated with cloudy skies (and higher precipitation), might allow expansion of broadleaf species, which are currently limited by frost and cold. Upslope transport of pollen is likely in mountainous areas (Markgraf, 1980; Fall, 1992), and the broadleaf pollen may have been transported from forests downslope that are presently dominated by pine in their upper elevations.

Although there is no associated change in pine pollen percentages, the consistent presence of *Arceuthobium* (mistletoe) pollen beginning around 1000 cal yr BP may indicate a local increase in pine around Valle de Bao. The pollen represents the endemic *Arceuthobium bicarinatum* (Viscaceae), the only known species in Hispaniola, which is parasitic on *P. occidentalis* (Hawksworth and Wiens, 1996). Alternatively the *Arceuthobium* increase could signal a change in the local fire regime. Widespread crown fires may limit *Arceuthobium* populations because trees can regenerate much faster than the mistletoe (Hawksworth and Wiens, 1996). But spotty fires (not affecting all crowns) may actually increase dwarf mistletoe populations by leaving behind live mistletoes that can re-infest forests (Hawksworth and Wiens, 1996). Thus the increase in *Arceuthobium* pollen would suggest a shift in fire regime toward few fires overall, or fewer crown fires. The lower charcoal in Zone 2 may also suggest such a shift.

5.2. Redeposited charcoal as evidence of tropical storm events

Though down-mixing of younger carbon is possible, we believe that the most likely explanation for the out-of-sequence dates in the Bao-1 chronology is the redeposition of old charcoal remobilized during storm events. Numerous slope scars that expose bare rock or show regenerating vegetation of various ages testify to the frequency of landslides in the Cordillera Central. Rugged topography combined with orographically enhanced rainfall induces widespread slope failures, especially when high intensity precipitation occurs during tropical storm events (Hartshorn et al., 1981). During fieldwork in January–February 1999, about 4 months after Hurricane Georges (September 22–23, 1998) crossed the Cordillera Central as a Saffir-Simpson Category IV storm, we found that a debris flow from Loma del Pico (Fig. 1) had spilled onto the valley floor, reaching to within a few meters of our 1997 core site. Such events can easily expose older subsurface charcoal, and transport it in streams or debris flows. Distinct clasts up to a centimeter in diameter composed of peat or soil are visible in the core sections and also likely indicate deposition of eroded material.

In the 99–100 cm interval (~2900 cal yr BP interpolated age) redeposited charcoal (Table 1) along with synchronous peaks (Fig. 5) in Poaceae (grass) pollen, and *Cyathea* (tree fern) and *Lophosoria* spores, may be evidence of a particularly large tropical storm event. *Cyathea arborea*, a tree fern species primarily of humid montane forests in the Dominican highlands (Bolay, 1997), is often a pioneer in landslide areas and slippage sites along streams (Tryon and Tryon, 1982; and personal observation). *Lophosoria* is a terrestrial fern also associated with disturbed sites (Tryon and Tryon, 1982).

6. Conclusion

This sediment record from a high elevation bog on the windward slope of the Cordillera Central provides the first stratigraphic evidence of past climate change and disturbance history in the Caribbean highlands. Continuous pine dominance and fire are the central themes in the 4000-year environmental history. The sediment record also indicates that tropical storms and climatic fluctuations have been integral to the Late Holocene highland ecosystem.

The Bao-1 1997 sediment record provides no clear evidence of prehistoric human activity (although changes in the uppermost sediment may partly reflect historical impacts). The timing of bog formation and some of the inferred hydrological shifts are inconsistent with Holocene moisture trends inferred from the consensus of lowland records, although certain features parallel some aspects of the Miragoâne record. Further paleoecological studies are needed in the Caribbean to refine knowledge of the timing and directions of past climatic change at different elevations, and of other aspects of environmental and human history.

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