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A 10,300 ^{14}C yr Record of Climate and Vegetation Change from Haiti

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Pleistocene and Holocene vegetation dynamics in the American tropics are inferred largely from pollen in continental lake sediments. Maritime influences may have moderated climate and vegetation changes on Caribbean islands. Stable isotope (δ^{18}O) study of a 7.6-m core from Lake Miragoane, Haiti, provided a high-resolution record of changing evaporation/precipitation (E/P) since ~10,300 ^{14}C yr B.P. The Miragoane pollen record documents climate influences and human impacts on vegetation in Hispaniola. The δ^{18}O and pollen data near the base of the core indicate cool, dry conditions before ~10,000 ^{14}C yr B.P. Lake Miragoane filled with water in the early Holocene as E/P declined and the freshwater aquifer rose. Despite increasing early Holocene moisture, shrubby, xeric vegetation persisted. Forest expanded ~7000 ^{14}C yr B.P. in response to greater effective moisture and warming. The middle Holocene (~7000–3200 ^{14}C yr B.P.) was characterized by high lake levels and greatest relative abundance of pollen from moist forest taxa. Climatic drying that began ~3200 ^{14}C yr B.P. may have driven some mesophilic animal species to extinction. The pollen record of the last millennium reflects pre-Columbian (Taino) and European deforestation. Long-term, Holocene vegetation trends in southern Haiti are comparable to trends from continental, lowland circum-Caribbean sites, suggesting a common response to regional climate change. © 1999 University of Washington.

INTRODUCTION

Paleoenvironmental investigations have shed light on Pleistocene and Holocene changes in the circum-Caribbean tropics and subtropics. Paleoclimate inferences are based on marine cores from the Caribbean Sea and lake sediment sequences from continental sites in Florida, the Yucatan Peninsula (Mexico, Guatemala), Panama, and northern South America (Fig. 1). In Florida, only deep sinkholes held water during the arid late glacial interval and earliest Holocene (Watts and Hansen, 1994). Shallow Florida lakes first filled with water ~8000 ^{14}C yr B.P., in response to increased rainfall and rising aquifers (Watts and Hansen, 1994).

Lakes on the Yucatan Peninsula, Mexico, filled with water ~8000 ^{14}C yr B.P. (Hodell *et al.,* 1995; Whitmore *et al.,* 1996), when sea levels rose to near-present levels (Fairbanks, 1989) and rainfall increased. During the dry late Pleistocene, deep basins in Peten, Guatemala, had water levels >40 m below present stands (Leyden *et al.,* 1994). Shallow Peten lakes and presently shallow areas of deep lakes began accumulating sediment ~8400 yr ago (Leyden *et al.,* 1994). Peten lakes lie ~150 km from the
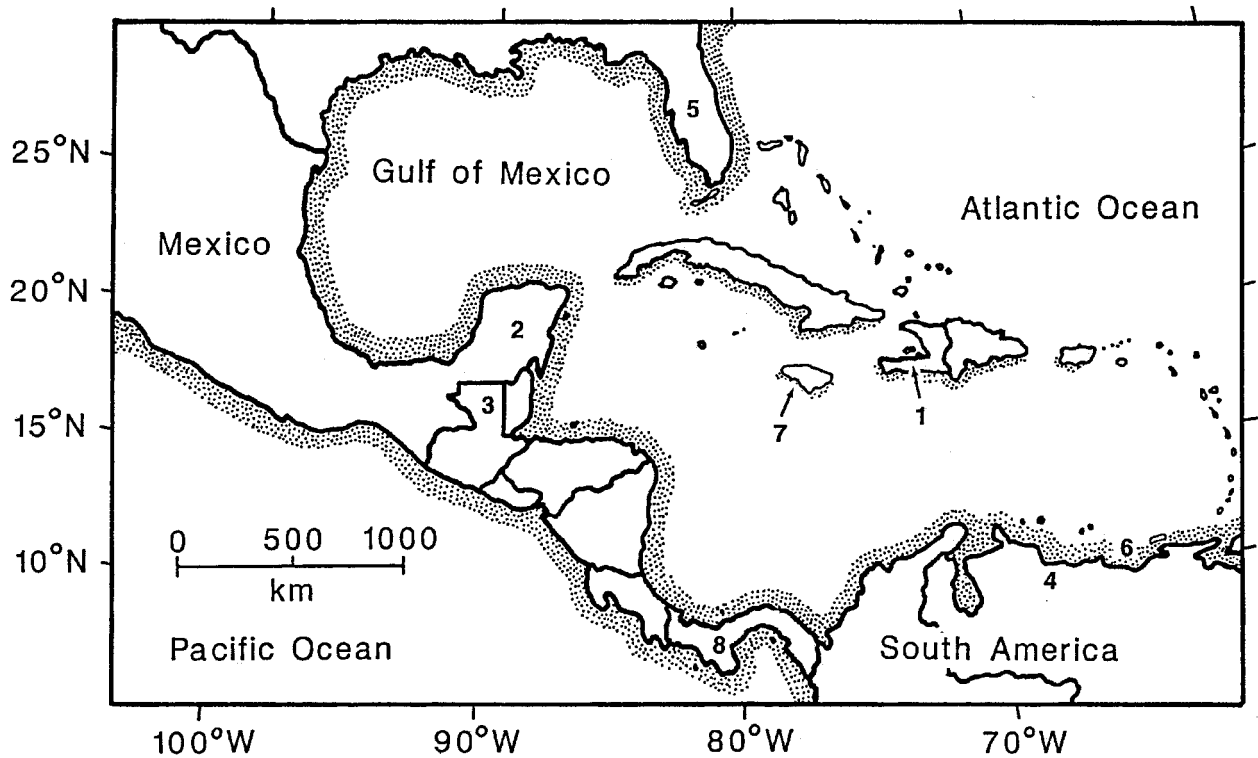
FIG. 1. Map of the Caribbean region. Study areas mentioned in the text are Lake Miragoane, Haiti (1), Yucatan, Mexico (2), Peten, Guatemala (3), Lake Valencia, Venezuela (4), Florida, USA (5), Cariaco Basin (6), Jamaica (7), and Panama (8).

Caribbean Sea, and >100 m above present sea level, so early Holocene filling was a response to increased rainfall. Major vegetation changes accompanied the Pleistocene/Holocene climate shift in Peten. Late glacial pollen spectra from northern Guatemala lack moist forest components and are dominated by savanna taxa, indicating cool, arid conditions. Moist forest taxa first appeared in the Peten pollen record ca. 10,500 ^{14}C yr B.P. (Leyden, 1984) and persisted until Maya deforestation began ca. 3000 ^{14}C yr B.P. (Leyden, 1987).

Sediment cores from Lake Valencia, Venezuela, indicate an ephemeral waterbody existed from ~13,000 to ~10,500 ^{14}C yr B.P., with grassland vegetation and saline marsh taxa dominating the pollen spectrum (Leyden, 1985). A shallow, saline lake prevailed from ~10,500 to ~10,000 ^{14}C yr B.P. and was surrounded by savanna-chaparral vegetation. Lake Valencia deepened and freshened after 10,000 ^{14}C yr B.P. Semi-evergreen and deciduous tropical forest was established by 9500 ^{14}C yr B.P. Essentially modern vegetation associations have existed for the past 8300 yr.

Marine cores from the Cariaco Basin suggest that upwelling diminished after ~10,000 ^{14}C yr B.P., when the trade winds weakened as a consequence of northward movement of the ITCZ (Peterson et al., 1991). Early Holocene northward migration of the ITCZ would have generated greater circum-Caribbean precipitation (Hastenrath, 1984), consistent with wetter conditions inferred from continental lake records.

There are few paleoenvironmental records from Caribbean island sites. Studies of Jamaican land snails (Goodfriend and Mitterer, 1988) and investigations of high-elevation sites in the Dominican Republic (Orvis et al., 1997) indicate Pleistocene temperature depression and aridity. Early Holocene sea-level rise promoted development of Jamaica's coastal wetlands and offshore shelf (Hendry and Digerfeldt, 1989), as well as coral reef formation in the Enriquillo Valley, Dominican Republic (Taylor et al., 1985).

Sites for paleolimnological investigations on Caribbean islands are scarce, but a few records exist. A core from Wallywash Great Pond, Jamaica, shows that cool, dry climate prevailed from ~93,000 yr ago to ~9500 ^{14}C yr B.P. (Street-Perrott et al., 1993). A 7.6-m core from Lake Miragoane, Haiti, yielded a high-resolution paleoclimate record for the past ~10,300 ^{14}C yr, based on $\delta^{18}O$ and trace metals in ostracod shells (Hodell et al., 1991; Curtis and Hodell, 1993). Climate was dry and lake level was low before ca. 10,000 ^{14}C yr B.P. From ~10,000 to 7000 ^{14}C yr B.P., relative evaporation/precipitation (E/P) decreased and lake level rose. Wetter conditions persisted until about 3200 ^{14}C yr B.P., after which there was general drying. The stable isotope/trace metal record from Lake Miragoane describes relative E/P shifts in southwestern Haiti. Here we report palynological and geochemical results from the Miragoane core, and present them in light of climate inferences based on $\delta^{18}O$ data. Holocene vegetation trends are

compared with records from continental sites surrounding the Caribbean Sea, and the impact of climate and habitat change on local fauna is considered.

STUDY AREA

The climate of southern Haiti is warm and equable. Mean annual temperatures in coastal lowlands range from 25 to 27°C; highland sites are considerably cooler. Seasonal rainfall begins in April, with maximum precipitation typically in May. Following a brief mid-summer dry spell, rains start again and reach a maximum in October and November. Rainfall in the lowlands near Lake Miragoane averages about 1000–2000 mm yr^{-1}. The highland Massif de La Selle receives ~2000 mm yr^{-1}, and the wetter Massif de La Hotte (Fig. 2) receives 3000–5000 mm yr^{-1} (Woods, 1987).

Holdridge (1945) described Hispaniola's major plant associations as tropical lowland dry forests, highland mesic and pine forests, and coastal mangrove swamps (Fig. 2). Xeric vegetation is found in warm, dry, coastal lowlands. Diverse mesic forests inhabit low- and high-elevation slopes and descend to lowest elevations on wetter, windward-facing mountainsides in northeastern Hispaniola. The only pine species on Hispaniola, *Pinus occidentalis,* is predominantly a high-elevation tree, but it is also found in ravines and on poor soils at low elevation. It often dominates areas with frequent fires. On Haiti's southern peninsula, tropical dry forest occupies coastal lowlands and the area between the Massifs de La Selle and La Hotte. The Massifs support mesic plant communities and pine forests.

Lake (Etang) Miragoane (area, 7.06 km^2; maximum depth, 41 m) is a cryptodepression located in a tectonic rift system at 18°24′ N, 73°05′ W (Fig. 2). Perhaps the largest freshwater lake in the Caribbean, Miragoane's surface is presently ~20 m above msl. A marsh separates Lake Miragoane from a smaller lake to the east, Petit Etang Miragoane. The lakes lie in a pull-apart basin that developed in the Enriquillo-Plantain Garden Fault Zone (Mann *et al.,* 1983).

Vegetation in the Miragoane watershed is dominated by shrubs, herbs, and fruit trees such as *Mangifera indica* (mango), *Persea americana* (avocado), and *Cocos nucifera* (coconut). Remnants of secondary forest include *Cecropia, Trema, Bursera, Catalpa, Prosopis,* and *Acacia.* Aquatic plants include *Cladium jamaicense, Typha domingensis, Potamogeton, Vallisneria, Paspalidium, Eleocharis, Najas, Sagittaria, Nelumbo lutea,* and the macroalga *Chara.*

METHODS

We collected a 7.67-m core from the deep, central area of Lake Miragoane (Fig. 2) using a plastic-barrel piston corer (0.00–0.72 m) and a square-rod piston corer (1.10–7.67 m) (Wright *et al.,* 1984). The section has a 0.38-m gap (0.72–1.10

m). Core chronology is based on ^{210}Pb and AMS ^{14}C dating (Table 1). Organic matter content was determined by weight loss on ignition (LOI) at 550°C. Carbonate content was estimated by LOI between 550 and 990°C (Dean, 1974). Cations (Ca, Mg, Fe, K, and Mn) and total P were measured on a Jarrell–Ash^{TM} Model 9000 Inductively Coupled Plasma (ICP), after ashing and digestion of samples in 1 N HCl (Andersen, 1976). Total S was measured turbidimetrically by BaSO$_4$ precipitation (APHA, 1992).

Ostracod shells (*Candona* sp.) were isolated from 515 stratigraphic levels for δ^{18}O analysis. Each sample contained ~20 adult valves, and isotopic ratios were measured with a VG Prism I mass spectrometer. Details of the method are presented in Curtis and Hodell (1993), and results are reported in standard delta notation relative to the VPDB standard.

Pollen slides were prepared from 1 cm^3 wet sediment samples using a sequence of KOH, HCl, HF, and acetolysis. Residue was dehydrated with absolute ethanol and brought to volume in tertiary butyl alcohol. Volumetric aliquots were placed in warm silicone oil on a slide and sealed with a coverslip. Pollen and charcoal fragments were counted at 200× and 300× magnification, using oil immersion when necessary. All carbonized plant fragments were enumerated, regardless of size. Remains of monocotyledons and dicotyledons were not tabulated separately. Pollen grains were identified using reference slides, herbarium specimens, and relevant publications. At least 300 pollen grains were counted in each sample, including arboreal, non-arboreal, and unidentified grains. Aquatic pollen were included in the total pollen sum, but fern, moss, and fungal spores were excluded. Fifteen unidentified grain types and poorly represented taxa were included in the pollen sum, but excluded from diagrams.

RESULTS

Chronology

Paired AMS dates on ostracod shells and wood from 2.33 m suggest a hardwater lake error (HWLE) (Hodell *et al.,* 1991) of ~1025 yr (Table 1). HWLE is also suggested by the ~950-yr difference between the ^{210}Pb date at 0.08 m (~1850 A.D.) and the AMS ^{14}C date of 1085 ± 60 yr B.P. on ostracod shells at 0.22 m. The ^{14}C date on calcite at 7.18 m is older than the date on bulk organic matter at 7.53 m, also indicating HWLE. We generated a "HWLE-corrected" chronology by subtracting 1000 yr from ^{14}C dates on ostracods (Table 1). We assumed the ^{14}C date on bulk organic matter at 7.53 m was unaffected by HWLE and applied no correction. Excluding AMS dates on ostracods from 2.16 and 2.33 m, corrected ^{14}C dates are in stratigraphic order. The age–depth relationship is described by the polynomial: age (^{14}C yr B.P.) = 47.2 + 394.8 (depth) + 127.2 (depth)^2, where age is the HWLE-corrected ^{14}C age, and depth is in meters (Hodell *et al.,* 1991). We considered the chronology provisional and did not calibrate dates.
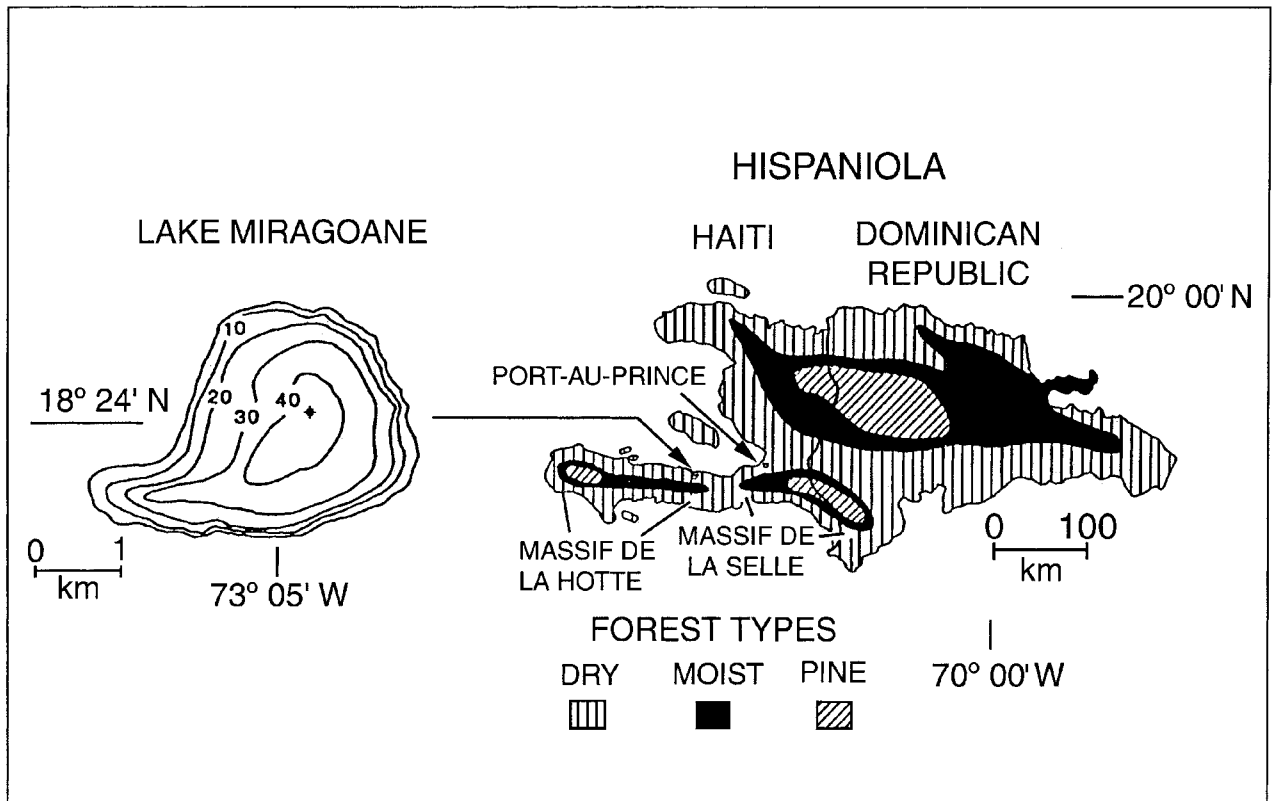
FIG. 2. Bathymetric map of Lake Miragoane, Haiti, showing 10-m contour intervals and the sediment coring site (●) (modified from Brenner and Binford, 1988), and vegetation map of Hispaniola showing the general distribution of dry, moist, and pine forests (modified from Holdridge, 1945).

Geochemistry and Stable Isotopes

Sediments from 7.67 to 1.10 m are dominated by $CaCO_3$ (52–85%), whereas organic matter (OM) content is <13%

TABLE 1
Sediment Depth–Age Relations for the Lake Miragoane Core
(Modified from Hodell *et al.,* 1991)

Depth (m)	Sample (material)	Accession number	Age (^{14}C yr B.P.)[a]	HWLE-corrected age (^{14}C yr B.P.)[b]
0.22	Ostracods	AA6703	1085 ± 60	85
2.16	Ostracods	AA5814	2780 ± 55	1780
2.33	Ostracods	AA6704	2680 ± 60	1680
2.33	Wood	AA6705	1655 ± 60	1655
3.21	Ostracods	AA5815	4110 ± 60	3110
4.18	Ostracods	AA5816	4780 ± 60	3780
5.20	Ostracods	AA5817	6945 ± 65	5945
6.22	Ostracods	AA5818	9005 ± 75	8005
6.71	Ostracods	AA5369	9700 ± 90	8700
7.18	Ostracods	AA5952	10,300 ± 85	9300
7.53	Bulk organic	GX13055	10,230 ± 160	10,230

[a] AMS ^{14}C ages are for ostracod shells (*Candona* sp.) and terrestrial wood.
[b] Carbonate ^{14}C ages were corrected by 1000 yr for hardwater lake error (HWLE).

(Fig. 3). Sediments in the short core (0.00–0.72 m) are richer in OM than are deeper deposits. OM is 27–37% of the matrix from 0.72 to 0.30 m and 11–22% above 0.30 m. $CaCO_3$ in the bottom half of the short core is 29–40% of dry mass, whereas above 0.30 m it ranges as high as 75%. Potassium, iron, and magnesium are positively correlated over the length of the section. Their negative correlation with calcium content suggests K, Fe, and Mg are associated with non-carbonate clastics. Phosphorus and sulfur concentrations are correlated stratigraphically with OM. Although P and S may be bound in OM, stratigraphic correlation among the constituents may simply reflect shifts in the concentration of dominant $CaCO_3$.

Highest $\delta^{18}O$ values were measured in ostracod shells deposited before 10,000 ^{14}C yr B.P. (Fig. 4). In the earliest Holocene, $\delta^{18}O$ values decreased. Low $\delta^{18}O$ values were measured in ostracods deposited from ~7000 to 3200 ^{14}C yr B.P. At ~3200 ^{14}C yr B.P., $\delta^{18}O$ values increased, but lower values were measured in samples deposited between ~1700 and 1000 ^{14}C yr B.P. Ostracod shells deposited during the last few centuries displayed some of the highest $\delta^{18}O$ values of the last 8000 yr.

Pollen

Arboreal pollen dominates the record. Combined percentages of *Cecropia,* Moraceae, *Trema,* and *Celtis* account for
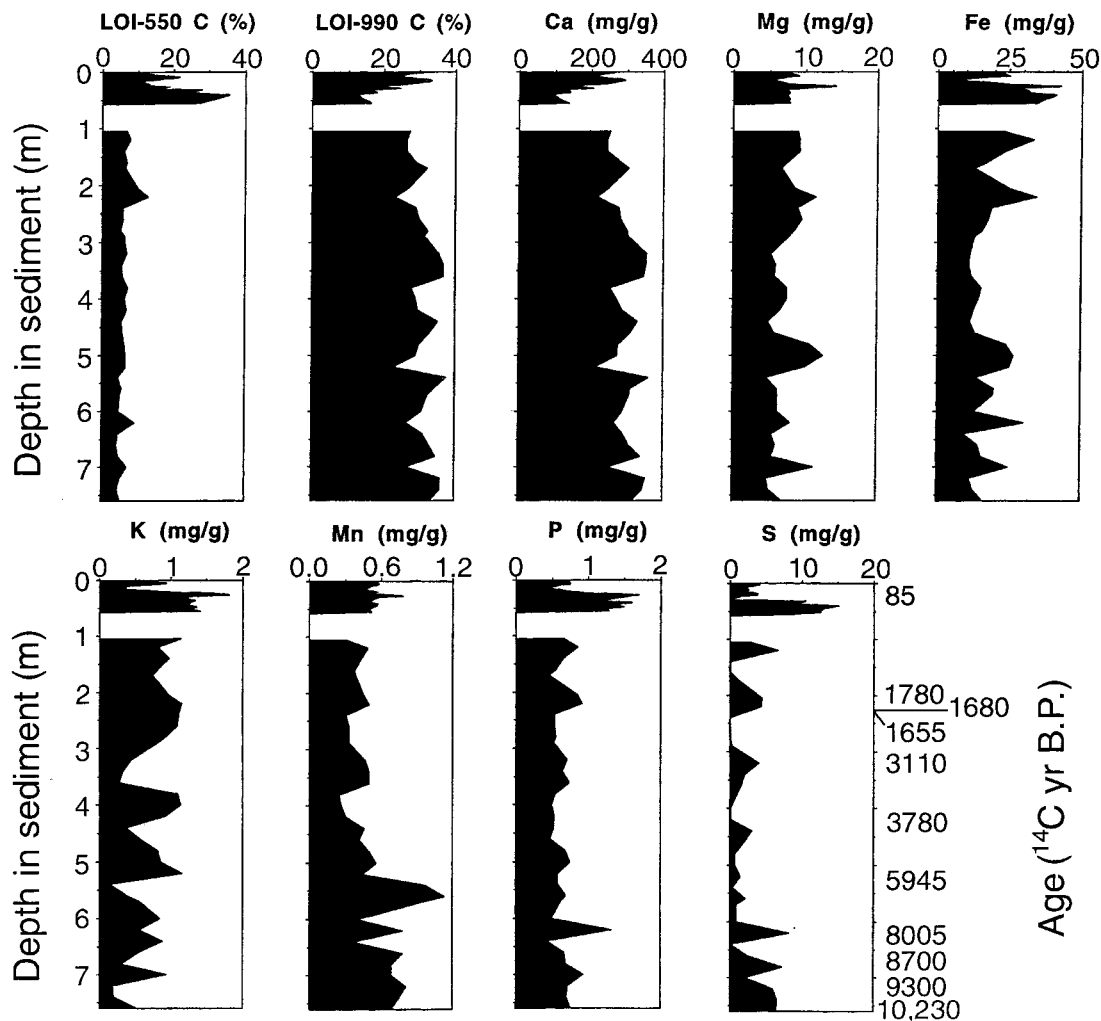
FIG. 3. Concentrations of organic matter (LOI 550°C), carbonate (LOI 990°C), calcium, magnesium, iron, potassium, manganese, phosphorus, and sulfur in the Lake Miragoane sediment core versus depth and HWLE-corrected AMS ^{14}C dates.

~40–80% of pollen at all depths (Fig. 5). Other arboreal elements include *Pinus,* poorly represented members of dry and moist forests, and cool-adapted *Podocarpus.* Rare taxa represent <1% of total pollen in all samples and were not included in the diagram. Arboreal taxa were assigned to habitat preference categories (Table 2) based on ecological information (Judd, 1987; Holdridge, 1945; Fisher-Meerow and Judd, 1989; Ekman, 1928; Howard, 1973) and were grouped in pollen diagrams to illustrate major climatic trends (Fig. 5). Moist forest pollen represents 0.3–7.5% of the pollen sum, and dry forest pollen represents 2–19% of the pollen sum throughout the core (Fig. 5). *Pinus* pollen probably belongs to fire-adapted *P. occidentalis.* Non-arboreal pollen comes from palms, shrubs, herbs, and aquatics (Table 3; Fig. 6). Herbs represent 0.3 to 53% of the pollen sum throughout the core. *Zea* (maize) grains were found at 0.72 m and in surface sediments (Fig. 6). Aquatic pollen represents 3.5–17.5% of the

total in samples from the short core, but ≤3.5% in deeper sediments.

DISCUSSION

Zone P1 = 7.6–6.6 m; 10,300–8200 ^{14}C yr B.P.

The Miragoane pollen record was divided into seven zones (Figs. 5 and 6). Zone P1 (7.6–6.6 m) has high pollen percentages of shrubs, Palmae, and *Podocarpus.* Other tree pollen in the zone comes from *Trema, Celtis,* and *Zanthoxylum.* Pollen of shrubs is dominated by *Miconia, Conostegia*-type, and *Gymnanthes*-type. Shrub and tree pollen in zone P1 comes from common components of montane hardwood forests above 800 m asl (Holdridge, 1945; Judd, 1987). Some species of *Miconia,* however, occupy dry, lowland habitats in Hispaniola (Howard, 1973), making it difficult to use the genus as a paleoenvironmental indicator.
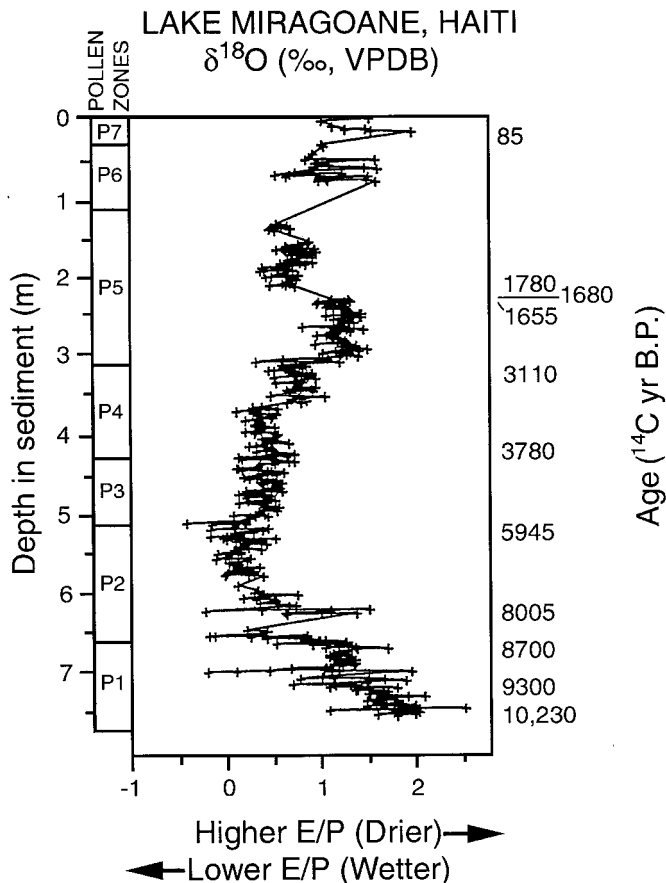
FIG. 4. The δ^{18}O of ostracod shells (*Candona* sp.) in the Lake Miragoane sediment core versus depth and HWLE-corrected AMS ^{14}C dates (modified from Hodell *et al.,* 1991). The profile shows a 5-point running mean and reflects long-term changes in E/P.

Podocarpus and *Conostegia*-type pollen are primarily restricted to zones P1 and P2. These zones are also characterized by low but persistent occurrence of Fabaceae pollen. Presence of poorly dispersed *Podocarpus* pollen in zone P1, together with relatively high abundance of grains from other highland taxa, indicates hardwood forests descended to low elevations under cooler conditions. Sediments of zones P1 and P2 have generally low charcoal concentrations (Fig. 7). Natural burning of Hispaniola's drier lowland communities occurred historically during the winter dry season (Holdridge, 1945). Lower temperatures and infrequent fires may have allowed fire-intolerant, dry-adapted, montane taxa to colonize sites below their modern elevational ranges.

Moist forests are represented by Moraceae and *Cecropia* pollen. Their percentages are low at the beginning of zone P1 but increase later in the zone. Low percentages of moist forest taxa suggest tree stands were small or far from the lake. High Palmae pollen percentages (Fig. 6) indicate palms grew near the lake. Several palm species in Hispaniola, including *Pseudophoenix vinifera,* occupy dry habitats (Holdridge, 1945), whereas other species are typical of moist areas. The open-

vegetation community supported a few dry forest trees (Fig. 5), including *Ampelocera, Guazuma,* Myrtaceae, and Fabaceae. Poaceae pollen is the most common herb taxon in zone P1, but it is nonetheless rare (Fig. 6).

At 7.0 m, *Cecropia* and Moraceae pollen increase slightly (Fig. 5), as does charcoal concentration (Fig. 7), whereas Palmae and shrub pollen decline (Fig. 6). Changes at this level may have been a consequence of fire. One member of the Moraceae, *Pseudolmedia,* comprises 5% of the pollen sum, and today grows in mature, humid forests and along streams. Pollen and δ^{18}O in zone P1 suggest a transition from cool, dry conditions to cool and somewhat moister conditions.

Zone P2 = 6.6–5.1 m; 8200–5370 ^{14}C yr B.P.

Zone P2 displays an increase in Chenopodiaceae/Amaranthaceae (Cheno/Am) pollen (Fig. 6). Shrub communities declined, but persisted in zone P2. Plant communities remained open and forest fires were still rare. The δ^{18}O record suggests increasing moisture availability between ~10,000 and 7000 ^{14}C yr B.P. (Fig. 4), but moist forest expanded only slightly. Dry forests were dominated by *Curatella,* a taxon now common in West Indian savannas (Holdridge, 1945). Among the other dry forest pollen types, percentages of Fabaceae, Myrtaceae, and Sapotaceae increase, while *Guazuma* and *Ampelocera* become rare. Cyperaceae pollen, which comprises most of the "other herbs" category, and Poaceae increase (Fig. 6).

Zones P3 and P4 = 5.1–3.1 m; 5370–2490 ^{14}C yr B.P.

Trema and *Cecropia* pollen dominate in zone P3 (5370–3950 ^{14}C yr B.P.), indicating the presence of upland and lowland moist forests (Fig. 5). Successional, mesic forests expanded around the deep lake, replacing palm- and shrub-dominated communities. *Spondias* and *Bursera* became regular components of the dry forest. The dry forest community included fire-resistant trees, such as *Curatella* and Sapotaceae species. Myrtaceae and *Guazuma* pollen are sporadic in the record after 5370 ^{14}C yr B.P. Pollen in zone P3 indicates generally moister conditions.

High percentages of Moraceae and other moist forest components (Fig. 5) in zone P4 (3950–2490 ^{14}C yr B.P.) reflect the wettest Holocene episode, an inference supported by low δ^{18}O values (Fig. 4). Combined percentages of Moraceae and *Cecropia* account for >50% of the pollen sum (Fig. 5). Moraceae pollen is represented equally by *Trophis*-type, *Chlorophora*-type and *Pseudolmedia,* probably *P. spuria. Trema* pollen remains common but has lower abundances than in zone P3 (Fig. 5). *Alchornea* and *Zanthoxylum* pollen represent moist forest. Pollen of *Celtis,* a deciduous, secondary forest tree, increases in the upper half of zone P4 and is common thereafter. Today, *Celtis* is found in dry mountain forests where deciduous taxa are common (Howard, 1973) and in dry, lowland areas. Dry, open forests near the lake were
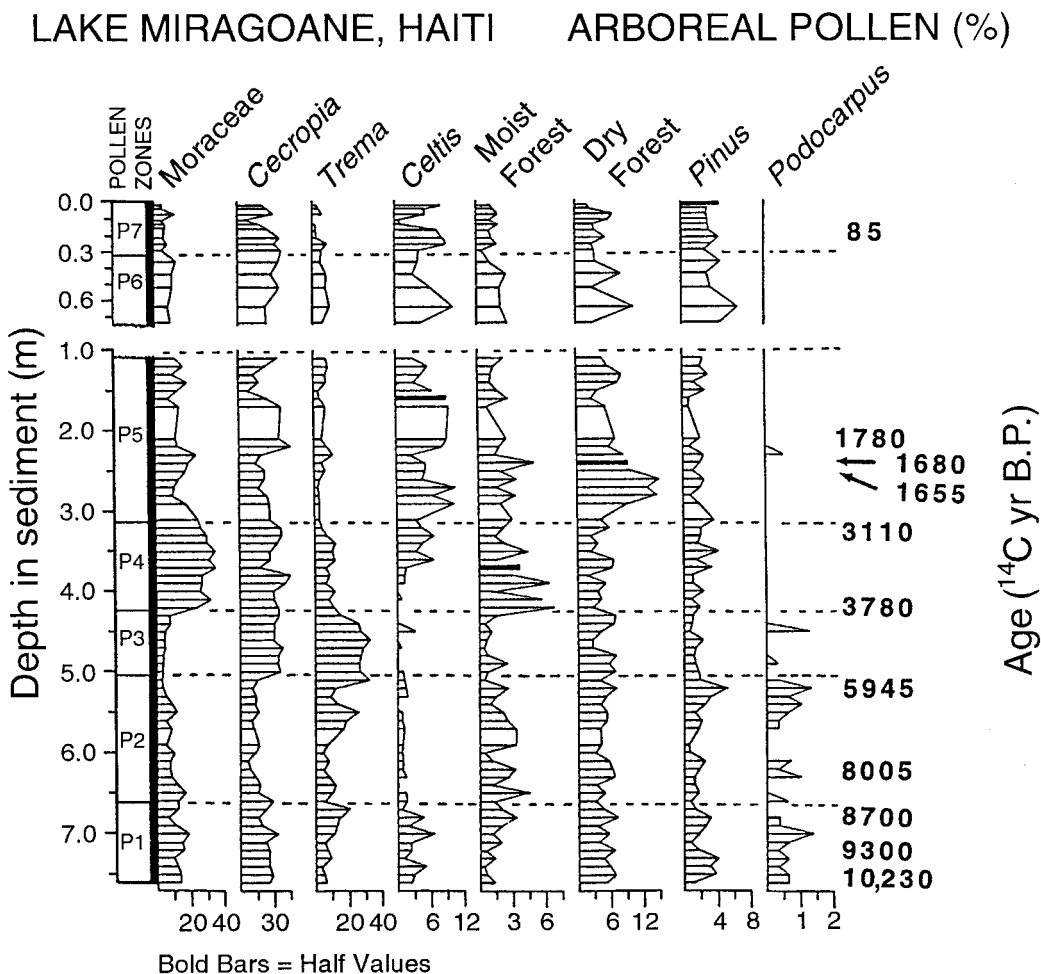
FIG. 5. Pollen percentages of major arboreal taxa or groups of taxa in the Lake Miragoane sediment core versus depth and HWLE-corrected AMS ^{14}C dates. Note depth scale change between the long core and the sediment–water interface core.

characterized by *Spondias* and *Ampelocera,* which are about equally represented and together account for half the dry forest pollen in zone P4. Percentages of other tree pollen of this community, such as *Curatella, Bursera,* and Fabaceae, decline. Poaceae and *Ambrosia* pollen dominate the herb taxa (Fig. 6).

Charcoal concentration increases in zone P3 (Fig. 7), along with palynological and isotopic evidence for increasing moisture availability. Pollen of *Ambrosia* (Fig. 6), a common genus in recently burned sites (Tsukada and Deevey, 1967), also increases. Sustained percentages of fire-tolerant *Pinus* pollen in zones P3 and P4 (Fig. 5) indicate increased fire frequency. Today, fire-adapted *P. occidentalis* is common on mountain summits and invades sites that burn repeatedly (Holdridge, 1945). Where burning is rare, fire-intolerant hardwood species are favored. Greater fire frequency in the middle Holocene occurred under wetter conditions. Although this association seems anomalous, it may be explained climatically. Seasonality in the northern hemisphere tropics was maximal in the early Holocene but remained high into the mid-Holocene (Hodell *et al.,* 1991). In the early Holocene, dry winters favored

lightning-induced ignition. However, fires may have been limited if fuel production was poor in the shrub-dominated communities and if summer storm frequency was low. By 5400 ^{14}C yr B.P., seasonality remained relatively strong, but the forest had expanded sufficiently to provide fuel for natural combustion. Alternatively, increased charcoal in zone P3 may signal early human disturbance, as was argued for the charcoal increase in Puerto Rico that began ca. 5300 cal yr B.P. (Burney and Burney, 1994). Although archaic artifacts were found along the coast of Haiti's southwestern peninsula, most are undated. The archaeological record is scanty but suggests human arrival on the peninsula between ~6000 and 4000 ^{14}C yr B.P.

Zone P5 = 3.1–1.1 m; 2490–640 ^{14}C yr B.P.

Zone P5 is characterized by pollen of *Celtis* and other dry forest taxa (Fig. 5). Forests declined and shrubs expanded in zone P5. In addition to pollen of pre-existing taxa *Curatella, Spondias, Bursera, Ampelocera,* and Fabaceae, dry forest is represented by pollen of *Phyllostylon, Cordia, Sapindus,* mem-

TABLE 2
Habitat Preferences of Arboreal Taxa Represented in the Lake Miragoane Pollen Record (see Fig. 5)

Moist-adapted	Dry-adapted	Cool-adapted
Moraceae	*Celtis*	*Podocarpus*
Pseudolmedia	*Pinus*[a]	
Chlorophora-type	**Dry Forest**	
Trophis-type	*Curatella*	
Ficus[b]	*Bursera*	
Cecropia	*Spondias*	
Trema	*Phyllostylon*	
Moist Forest	*Ampelocera*	
Zanthoxylum	*Guazuma*	
Alchornea	*Sapindus*	
Nectandra[b]	*Cordia*[b]	
	Meliaceae[b]	
	Bombacaceae[b]	
	Sapotaceae	
	Myrtaceae	
	Fabaceae	
	Prosopis	
	Caesalpinia	
	Mimosa	
	Cassia	

Note. Boldface indicates the category headings in the arboreal pollen diagram.

[a] Fire-adapted.

[b] Uncommon taxa.

bers of the Bombacaceae, Meliaceae (possibly *Swietenia*), and others.

Although drying commenced ~3200 ^{14}C yr B.P., the δ^{18}O record indicates a temporary return to moister conditions after ~1700 ^{14}C yr B.P. (Fig. 4). Higher percentages of *Cecropia* and *Celtis* pollen from ~1730 to 1000 ^{14}C yr B.P. (2.4–1.6 m) suggest forest re-expansion. Although wetter than present, this episode was not as mesic as mid-Holocene zone P4. Low pollen and charcoal concentrations at the beginning of zone P5 (Fig. 7) suggest rapid bulk sedimentation. Temporary return of forest after ~1730 ^{14}C yr B.P. stabilized watershed soils and reduced sedimentation rates, as reflected in high, mid-zone pollen and charcoal concentrations. By ~1000 ^{14}C yr B.P. (1.6 m), drier conditions returned and early agriculturists had colonized the area (Rouse and Moore, 1984).

Zone P6 = 0.72–0.30 m; 400–180 ^{14}C yr B.P.

According to the ^{14}C chronology (Table 1), sediments from 0.72 to 0.30 m depth were deposited after European arrival. The base of the short core (0.72 m) was previously estimated to be ~1000 years old, by extrapolation of the ^{210}Pb chronology (Brenner and Binford, 1988). It was thought to represent nearly the entire period of Taino and European settlement. We consider the ages of the zone boundaries tentative. *Zea* (maize) pollen at the base of the short core (Fig. 6) indicates near-shore

agriculture. Earlier maize cultivation cannot be corroborated because sediment from 1.10 to 0.72 m depth was not recovered.

Celtis, Pinus, and other dry forest elements, as well as *Cecropia,* persist from previous times and were the dominant trees (Fig. 5). *Pilea* and *Ambrosia* pollen are rare or absent in zone P6, while Poaceae pollen is abundant. *Acalypha* pollen is common and represents the majority of "other herbs" (Fig. 6). Agriculture may have been sparse or intermittent, and human impact on local plant communities remained modest.

Because there is little littoral development within Lake Miragoane, increased representation of aquatic pollen, mostly *Cladium* and *Typha* in zone P6 (Fig. 6), suggests marsh expansion. Prior to ~640 ^{14}C yr B.P. (1.10 m and below), these emergent taxa were rare. The δ^{18}O record (Fig. 4) indicates generally declining lake levels over the past three millennia. The marsh may have developed as a consequence of declining water levels and siltation associated with land clearance.

Zone P7 = 0.30–00.0 m; 180 ^{14}C yr B.P.–Present

Pollen and geochemistry in zone P7 reflect deforestation and soil erosion over the last ~200 yr. Forests are represented mainly by pollen of successional taxa, including *Celtis, Cecropia,* and the dry-adapted trees *Sapindus* and *Bursera.* At the beginning of zone P7, the decline in forest pollen suggests land clearance. Dry forests probably disappeared because they contained valuable timber species and occupied areas preferred for agriculture and livestock management. OM declined and carbonates increased in zone P7 (Fig. 3), reflecting watershed soil erosion.

According to the ^{210}Pb chronology, pollen concentration increased in sediments deposited between about A.D. 1850 and A.D. 1950 (0.08–0.06 m) (Fig. 7), and OM content increased relative to carbonates (Fig. 3). This trend may reflect brief

TABLE 3
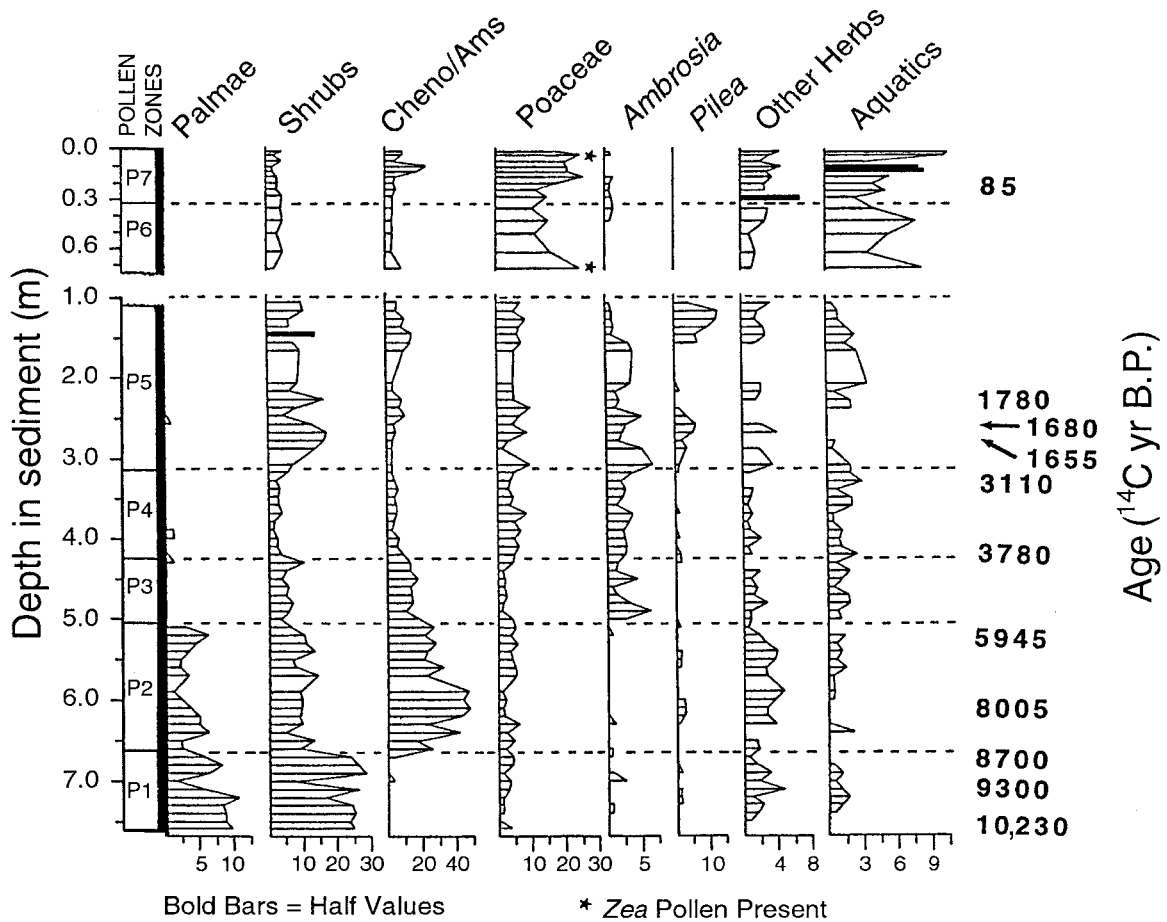### Non-arboreal Taxa Represented in the Lake Miragoane Pollen Record (see Fig. 6)

Palmae	Other herbs
Shrubs	Cyperaceae (non-*Cladium*)[a]
Melastomataceae	Solanaceae[a]
Miconia	*Acalypha*[a]
Conostegia-type	Umbelliferae[a]
Euphorbiaceae	Compositae (non-*Ambrosia*)[a]
Gymnanthes-type	**Aquatics**
Myrica	*Typha*
Anacardiaceae	*Cladium*
Cheno/Ams	*Sagittaria*[a]
Poaceae	*Nelumbo*[a]
Ambrosia	*Nymphaea*[a]
Pilea	

Note. Boldface indicates the category headings in the non-arboreal pollen diagram (see Fig. 6).

[a] Uncommon taxa.

LAKE MIRAGOANE, HAITI NON-ARBOREAL POLLEN (%)

FIG. 6. Pollen percentages of major non-arboreal taxa or groups in the Lake Miragoane sediment core versus depth and HWLE-corrected AMS ^{14}C dates. Note depth scale change between the long core and the sediment–water interface core.

forest recovery and reduction of siltation associated with land-use changes after Haiti's independence from France in A.D. 1804, when large, French-run plantations were divided into small, subsistence plots (Brenner and Binford, 1988). Small farms were created throughout the country and many highland sites were exploited for the first time (Woods, 1987). The ^{210}Pb dates indicate that the topmost 6 cm of sediment were deposited since about A.D. 1950. These carbonate-rich sediments have low pollen concentrations and document the most severe deforestation since agriculture began in the watershed ~1000 ^{14}C yr B.P. Today, local vegetation consists of small secondary forest patches separated by expanses of weedy, cultivated, and abandoned land. Watershed soils are severely eroded and steep slopes often display exposed bedrock.

PALEOCLIMATE SUMMARY AND BIOGEOGRAPHIC IMPLICATIONS

Pollen and δ^{18}O data from the Lake Miragoane core reflect environmental changes in southwestern Hispaniola since ~10,300 ^{14}C yr B.P. Vegetation changes that predate significant human settlement of the watershed ~1100 ^{14}C yr B.P. were climatically driven, whereas subsequent impacts on vegetation were a consequence of Taino and later European activities.

Mainland sites in northern South America and Central America remained relatively dry until ~10,500 ^{14}C yr B.P. (Leyden, 1984, 1985; Piperno et al., 1990). Early Holocene dryness persisted in Jamaica (Goodfriend and Mitterer, 1988), Florida (Watts and Hansen, 1994), and the Yucatan Peninsula (Whitmore et al., 1996). Filling of low-elevation lakes in Florida (Watts and Hansen, 1994) and the Yucatan Peninsula (Whitmore et al., 1996) about ~8000 ^{14}C yr B.P. is attributed to the combined effects of increased precipitation and sea-level rise. Onset of wetter conditions in Florida ~7000 ^{14}C yr B.P. was marked by the establishment of a more mesic vegetation assemblage (Watts and Hansen, 1994).

The δ^{18}O and trace metals in ostracod shells from the oldest part of the Miragoane core indicate high E/P. The δ^{18}O record

LAKE MIRAGOANE
HAITI

MICROFOSSIL
CONCENTRATIONS
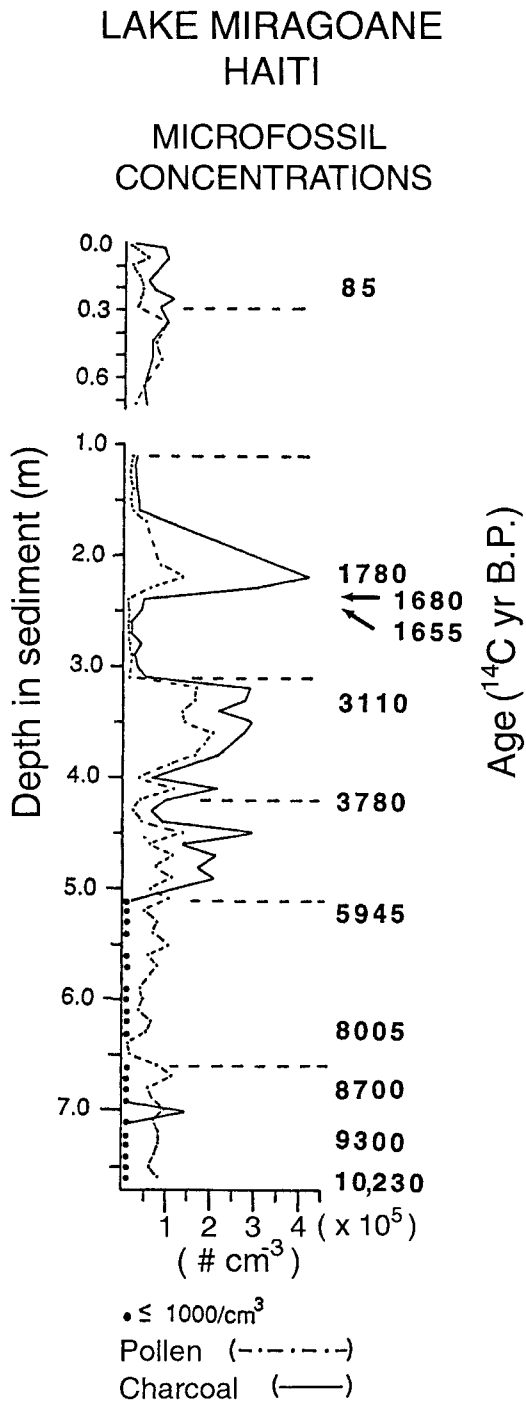
FIG. 7. Total pollen and charcoal concentrations (number cm^{-3}) in the Lake Miragoane sediment core versus depth and HWLE-corrected AMS ^{14}C dates. Horizontal dotted lines indicate pollen zone boundaries. Note the depth scale change between the long core and the sediment–water interface core.

indicates fairly steady, early Holocene lake-level rise, interrupted by brief reversals at ~9100–8500 and ~8000–7600 ^{14}C yr B.P. Lake filling in the early Holocene created shallow-water habitats where Cheno/Ams proliferated. As in Florida and Yucatan, higher lake levels were probably a response to

both increased rainfall and rising sea level (Taylor *et al.,* 1985; Mann *et al.,* 1984). Pollen of zone P1 shows that generally dry climate in Hispaniola persisted until at least 8600 ^{14}C yr B.P. Forest expansion thereafter was a consequence of increased rainfall, which is supported by δ^{18}O-inferred, deep-water lake conditions.

Fossil Jamaican land snails indicate that mean annual temperature in the early Holocene was >4°C higher than in the late glacial (Goodfriend and Mitterer, 1988). Pollen records from Panama (Piperno *et al.,* 1990), Guatemala (Leyden, 1984), and Venezuela (Leyden, 1985) date early Holocene warming at ~8500 ^{14}C yr B.P. Pollen data from the Panama Canal Zone indicate that cool-temperature indicators Ericaceae and *Symplocos* disappeared ~8500 ^{14}C yr B.P. (Bartlett and Barghoorn, 1973). Persistence of *Podocarpus* pollen late in zone P2 of the Miragoane record also suggests delayed Holocene warming. Differences in the timing of onset of warmer and wetter conditions at sites around the Caribbean may be a consequence of regional climatic differences, variable responses of indicator taxa, or dating inaccuracies.

The δ^{18}O record indicates gradually declining but high lake levels during pollen zones P3 and P4 (5370–2490 ^{14}C yr B.P.), when the vegetation reflects generally moist conditions. Water levels were higher than present and precipitation was sufficient to support moist forests, particularly in zone P4. Despite palynologically inferred moist conditions, climatic warming and consequent increased dry-season evaporation may account for lake-level decline at this time. Since ~3200 ^{14}C yr B.P. (3.7 m in zone P4), Lake Miragoane has desiccated gradually, a trend interrupted only by temporary returns to moister conditions (e.g., ~1700–1000 ^{14}C yr B.P.). The recent, general drying is consistent with trends reported for lowland neotropical Lakes Enriquillo, Dominican Republic (Taylor *et al.,* 1985; Mann *et al.,* 1984), Valencia, Venezuela (Bradbury *et al.,* 1981), Church's Blue Hole, Bahamas (Kjellmark, 1996), and Chichancanab, Yucatan, Mexico (Hodell *et al.,* 1995). The long-term pollen record from Lake Miragoane displays trends that are generally consistent with records from low-elevation, continental sites around the Caribbean, suggesting that insular plant communities responded to climate changes in a similar fashion to their continental counterparts.

Biogeographic patterns in the Caribbean islands reflect pre-Holocene environmental changes, but Holocene climate changes further modified the insular Caribbean flora and fauna. For example, early Holocene range reductions and extinctions of West Indian vertebrates are attributed to habitat alteration or elimination caused by the arid-to-mesic climate shift and sea-level rise (Pregill and Olson, 1981). Habitat modification after the climate transition is supported by the disjunct or restricted modern distributions of obligate xerophilic species, especially reptiles and birds. Late glacial fossils of these animals occur at sites beyond modern ranges (Pregill and Olson, 1981). Pollen data indicate xerophytic plant communities were more widespread between ~10,300 and 5370 ^{14}C yr B.P. At that time,

moist forest habitats were small and fragmented. Likewise, mesophilic animals had more restricted, disjunct distributions. As mesic forests expanded in the middle Holocene (~5370–2490 ^{14}C yr B.P.), xerophytic plant communities were fragmented, limiting the habitat for their associated faunas. Increasing fire frequency ~5400 ^{14}C yr B.P. also may have affected the Hispaniolan fauna.

Mid-Holocene expansion and coalescing of mesic plant communities promoted greater abundance of mesophilic animals and increased contact between previously isolated populations. The ~150-km-wide strip of lowland dry forest that currently separates the Massifs de La Hotte and de La Selle may have been occupied by mesic forests between ~5400 and 2500 ^{14}C yr B.P. Three species of the mammalian insectivore *Nesophontes,* that became extinct ~100 yr ago, show minor morphological differentiation in the massifs and in the intervening area, suggesting recent contact in the Miragoane region between formerly isolated populations of the massifs (C. A. Woods, personal communication, 1990). Sympatry probably occurred in the mid-Holocene, when mesic vegetation colonized the gap that separates the massifs.

Amerindian populations may have driven some vertebrate species to extinction by direct exploitation or habitat destruction, but the evidence is equivocal. Humans are thought to have arrived in the Greater Antilles as early as 7000 yr ago (Rouse, 1989), but colonization of Haiti's southwestern peninsula is poorly dated (Rouse and Moore, 1984). Early settlers were confined largely to coastal sites, and agriculturists with ceramic technology only came to the southern peninsula about 1400 ^{14}C yr B.P. (Rouse and Moore, 1984), suggesting that they had minimal impact on higher-elevation flora and fauna.

Fossils from southwestern Hispaniola show several extinct mammal species, including rodents, ground sloths, and a primate, persisted as late as ~3000 ^{14}C yr B.P. (Woods, 1989). Of the endemic rodents known from Hispaniola, 93% are now extinct, but most survived until about 3000 yr ago (Woods, 1989). Within the past few millennia, four bat species from the highlands of the Massif de La Selle have also gone extinct (Morgan and Woods, 1986). Extinction of some highland mesophilic animal species appears to predate significant human disturbance. Faunal extinctions coincide with an isotopically documented drying trend and pollen evidence for loss of mesic forests after 3000 ^{14}C yr B.P. Climatic drying, rather than human activities, may have been responsible for the disappearance of these taxa.

ACKNOWLEDGMENTS

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