Hydrobiologia **511:** 161–172, 2004.

Recent eutrophication in the Southern Basin of Lake Petén Itzá, Guatemala: human impact on a large tropical lake

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Received 21 August 2001; in revised form 27 June 2003; accepted 15 October 2003

Key words: carbon isotopes, eutrophication, Guatemala, human disturbance, lake sediment chemistry, nitrogen isotopes

Abstract

A ^{210}Pb-dated sediment core from a small bay in the southern basin of Lake Petén Itzá, Guatemala documents recent cultural eutrophication. Increased sediment accumulation beginning ∼1930 A.D. coincided with catchment population growth and was a consequence of watershed deforestation and increased surface run-off. At the same time, geochemical records from the Lake Petén Itzá sediment core indicate increased phosphorus loading and organic matter accumulation. High nutrient concentrations after 1965 A.D. coincided with lower sediment C/N ratios, suggesting an increase in the relative contribution of phytoplankton to the organic matter pool. This inference is confirmed by the dominance of eutrophic and hypereutrophic diatom species. Organic matter δ^{13}C values decreased after 1965 A.D., seemingly contradicting other indicators of recent eutrophication in the southern basin of Lake Petén Itzá. Relatively depleted δ^{13}C values in recent sediments, however, may reflect a contribution from ^{13}C-depleted sewage effluent. Increased δ^{15}N of organic matter after 1965 A.D. indicates changes in the dissolved inorganic nitrogen delivered to the lake. The relatively small increase in δ^{15}N (∼0.6‰) is less than might be expected with nitrate loading from sewage and soils, and might be offset by the presence of nitrogen-fixing cyanobacteria with low δ^{15}N values.

Introduction

Paleolimnological studies from lowland Petén, Guatemala document long-term impact of Maya populations on terrestrial and aquatic ecosystems as well as Pleistocene/Holocene climate change (Cowgill & Hutchinson, 1966; Deevey, 1978; Deevey et al., 1979, 1983; Leyden, 1984; Rice et al., 1985; Vaughan et al., 1985; Binford et al., 1987; Leyden, 1993, 1994; Islebe et al., 1996; Curtis et al., 1998; Rosenmeier et al., 2002). Few lake sediment records have been used to address recent environmental changes in Petén. A sound understanding of modern human impacts on Petén's ecosystems is necessary to manage the region's land and water resources in the future.

Post-Columbian Petén (i.e., after the 1500s) was sparsely populated until the mid-1960s. As late as 1964, the region, which encompasses 35 854 km^2, was inhabited by only about 25 000 people, about 45% residing in twelve small towns, and others living in still smaller rural villages (Schwartz, 1990). In the early 1960s, the central government pressured the FYDEP (Empresa Nacional de Fomento y Desarrollo

Económico del Petén) to colonize Petén rapidly, to ease land pressures in the highlands. By 1973, the regional population had swelled to nearly 65 000, and in 1986 the population was estimated at more than 300 000. Today there are probably more than one-half million people living in Petén.

Intensive agriculture, ranching, and commercial logging operations, both foreign and national, accompanied the demographic explosion in Petén. Government officials estimated that prior to 1960, 70–80% of the area was densely forested (Schwartz, 1990). Reports suggested that by 1989 as much as 60% of the forests had been cleared. Recent forest loss has contributed to increased surface run-off and accelerated soil erosion around Petén lakes. Nitrogen and phosphorus inputs from eroded soils, human and livestock wastes, and fertilizers have probably contributed to eutrophication of regional waterbodies.

In this study, recent eutrophication of a small bay in the southern basin of Lake Petén Itzá is reconstructed from a short (128-cm) ^{210}Pb-dated sediment core. Changes in material transfer to the lake bottom were calculated from bulk sediment accumulation rates and sediment composition. Changes in lake trophic state were reconstructed from fossil diatom assemblages and sediment nutrient concentrations. Stratigraphic variations in the carbon and nitrogen isotopic (δ^{13}C and δ^{15}N) composition of organic matter from the core were interpreted as reflecting changing lacustrine productivity and input of sewage effluents to the basin.

Study site

The Department of Petén occupies the northern third of Guatemala (Fig. 1a) and is characterized principally by low-lying karsted limestones of Cretaceous and Tertiary age (Vinson, 1962). The landscape is dominated by well-drained forest soils (mollisols) (Simmons et al., 1959) and tropical semi-deciduous and evergreen vegetation (Lundell, 1937). Terrain varies between 100 and 300 m above mean sea level and groundwater lies well below the land surface and is fairly inaccessible. Surface waters are perched, however, resulting in numerous lakes and seasonally inundated topographic depressions (Deevey et al., 1979). The lake district contains a number of terminal basins distributed along a series of east-west aligned *en echelon* faults at 17° N latitude. Principal water bodies of the lake chain extend approximately 100 km

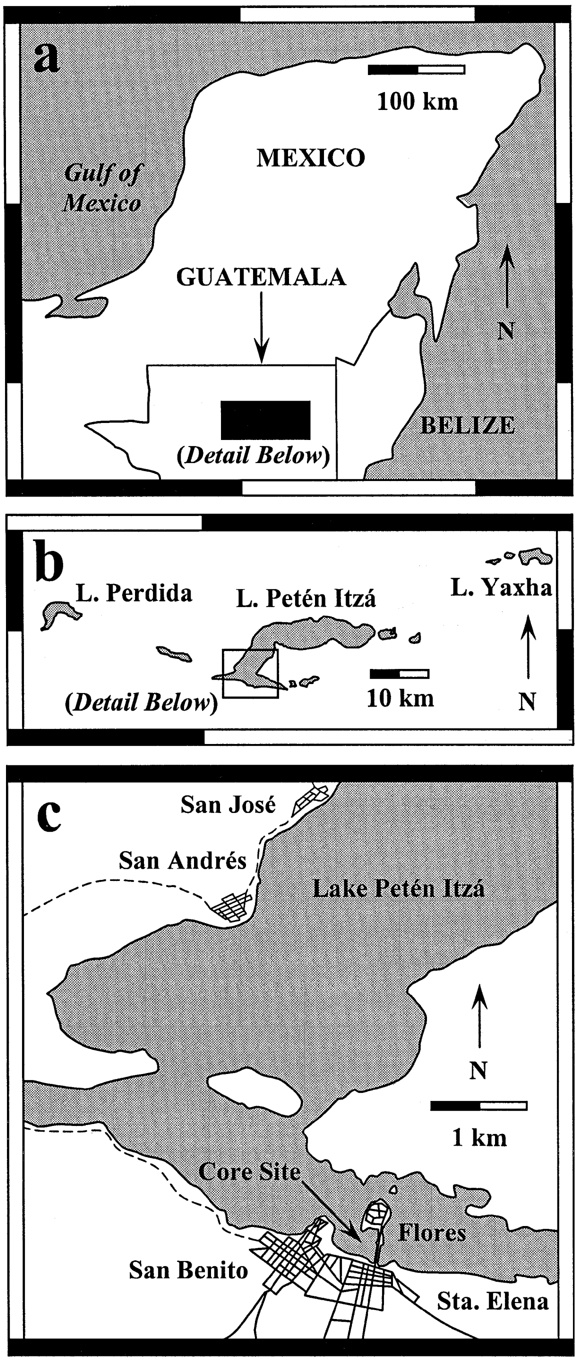

Figure 1. (a) Map of the Yucatán Peninsula showing lake study sites in northern Guatemala (black rectangle). (b) Petén lake district in Guatemala. (c) Southern basin of Lake Petén Itzá and sediment core site (N 16° 55′ 32″, W 89° 53′ 33″).

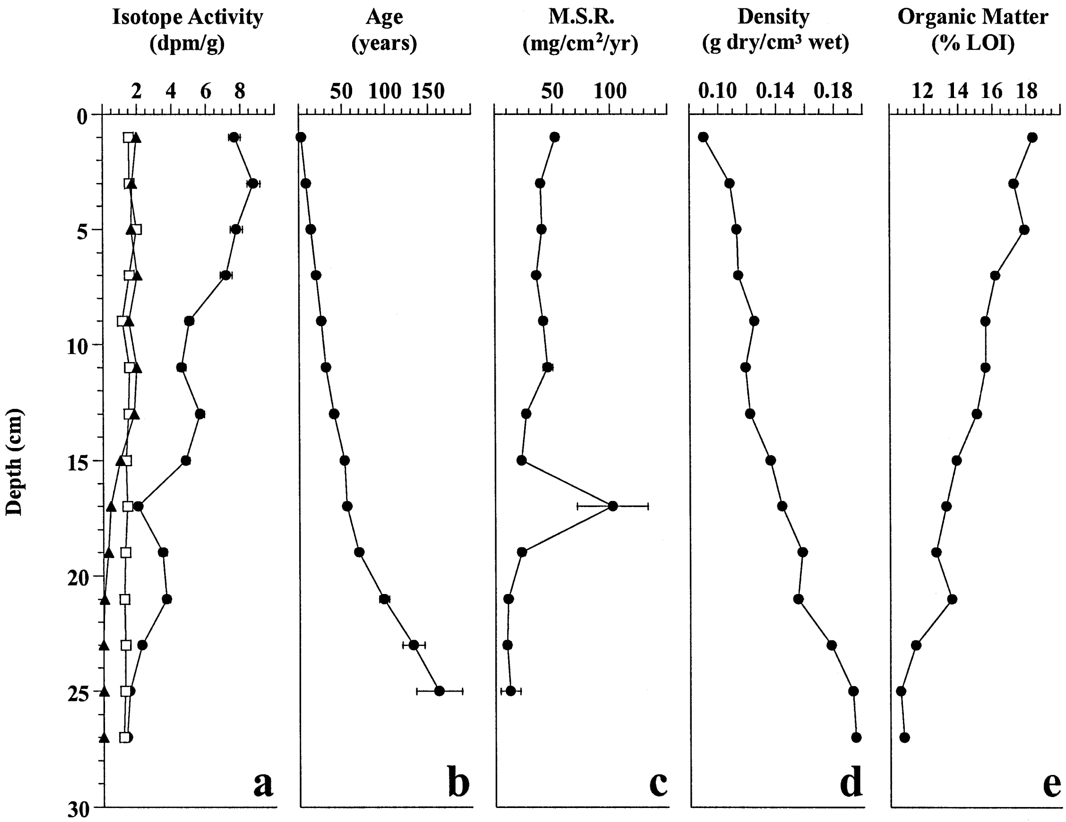

Figure 2. (a) Total ^{210}Pb (filled circles), ^{226}Ra (filled diamonds), and ^{137}Cs (open squares) activities versus depth in the Petén Itzá core. (b) Age versus depth values and (c) mass sedimentation rates (M.S.R.) derived from the constant rate of supply model. Error bars delineate one-standard deviation about the mean. (d) Bulk density and (e) organic matter concentration derived from loss-on-ignition measurements.

from the westernmost Lake Perdida eastward to the twin basins of Yaxhá and Sacnab (Figure 1b).

Lake Petén Itzá (16°55′ N and 89°50′ W) occupies two elongate basins within the central Petén lake district. The large northern basin is more than 20 km long, 3 to 4 km wide, and has a maximum depth of ~160 m (Anselmetti et al., 1999). The southern basin of Petén Itzá, which supports the densely populated towns of Santa Elena, San Benito, and Flores, extends 14 km east-west and has a maximum width of about 1.5 km. The lake is relatively fresh (400 mg l^{-1} TDS) with a pH of 8.4 and a surface conductivity of ~490 μS cm^{-1}.

Materials and methods

In July 1997, a sediment core was recovered in 6.0 m of water from a small embayment of the southern basin of Lake Petén Itzá, west of the two-lane gravel causeway connecting the island city of Flores and the mainland towns of Santa Elena and San Benito (Figure 1c). Sediments were collected with a piston corer designed to retrieve undisturbed sediment-water interface profiles (Fisher et al., 1992). The core was sectioned in the field at 2.0-cm intervals by upward extrusion into a sampling tray fitted to the top of the core barrel.

Sediment chronology and sediment accumulation rates were determined by ^{210}Pb dating. Radioisotope (^{210}Pb, ^{226}Ra, ^{137}Cs) activities were measured by direct gamma counting (Appleby et al., 1986; Schelske et al., 1994) using an EG & G Ortec GWL high purity germanium well detector. Radium-226 activity was measured at each depth to estimate supported ^{210}Pb activity. Unsupported ^{210}Pb activity was estimated by subtraction of supported activity from the total activity measured at each level. Sediment ages were determined using the constant rate of supply model (Appleby & Oldfield, 1978).

Total carbon (TC) and nitrogen (TN) in the sediments were measured with a Carlo Erba NA 1500 CNS

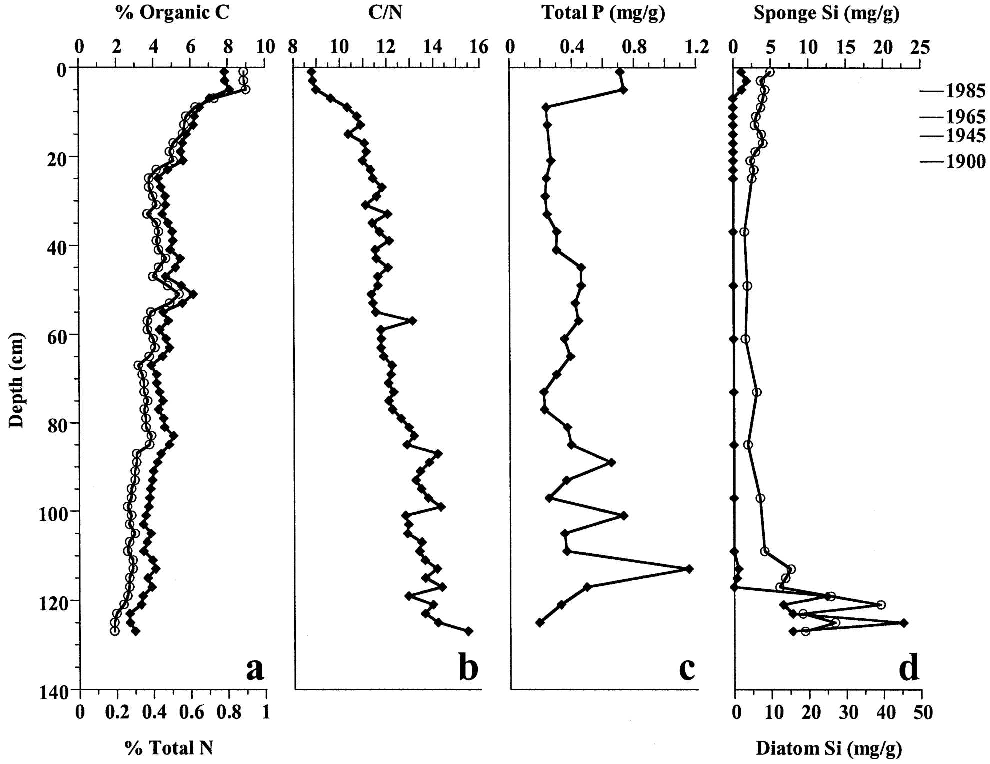

Figure 3. (a) Organic carbon (filled diamonds) and total nitrogen content (open circles), (b) C/N mass ratios, (c) total phosphorus concentration, and (d) sponge spicule biogenic silica (open circles) and diatom biogenic silica (filled diamonds) versus depth. Approximate sediment age is indicated to the right of the plot.

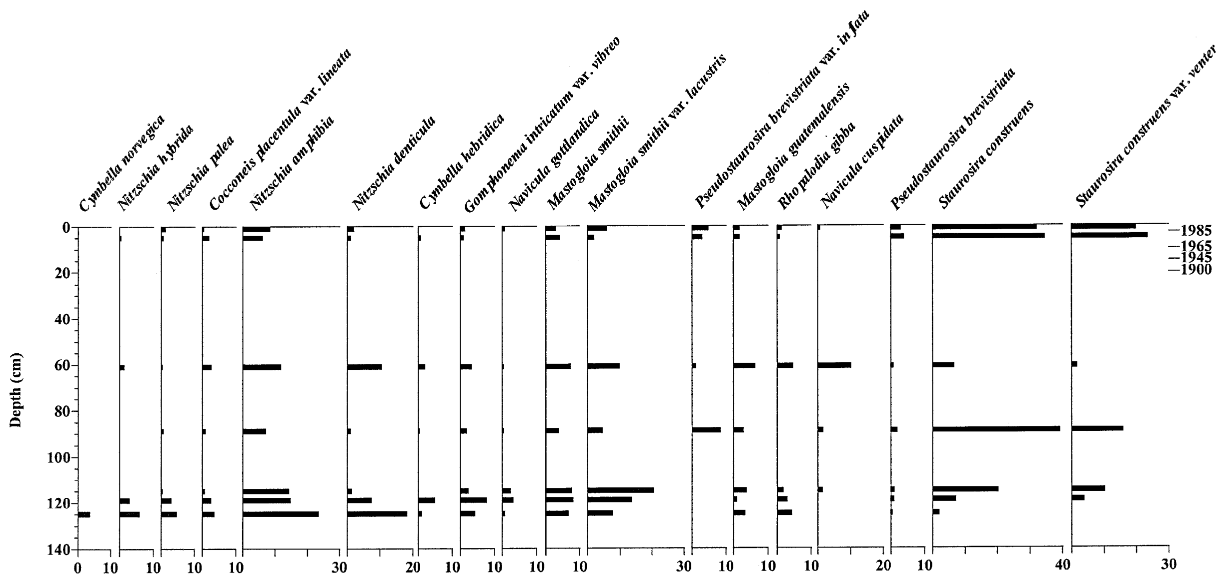

Figure 4. Relative abundance of dominant diatom taxa (diatom taxa with representation greater than 3% in at least one sample) versus depth in the Petén Itzá core. Approximate sediment age is indicated to the right of the plot.

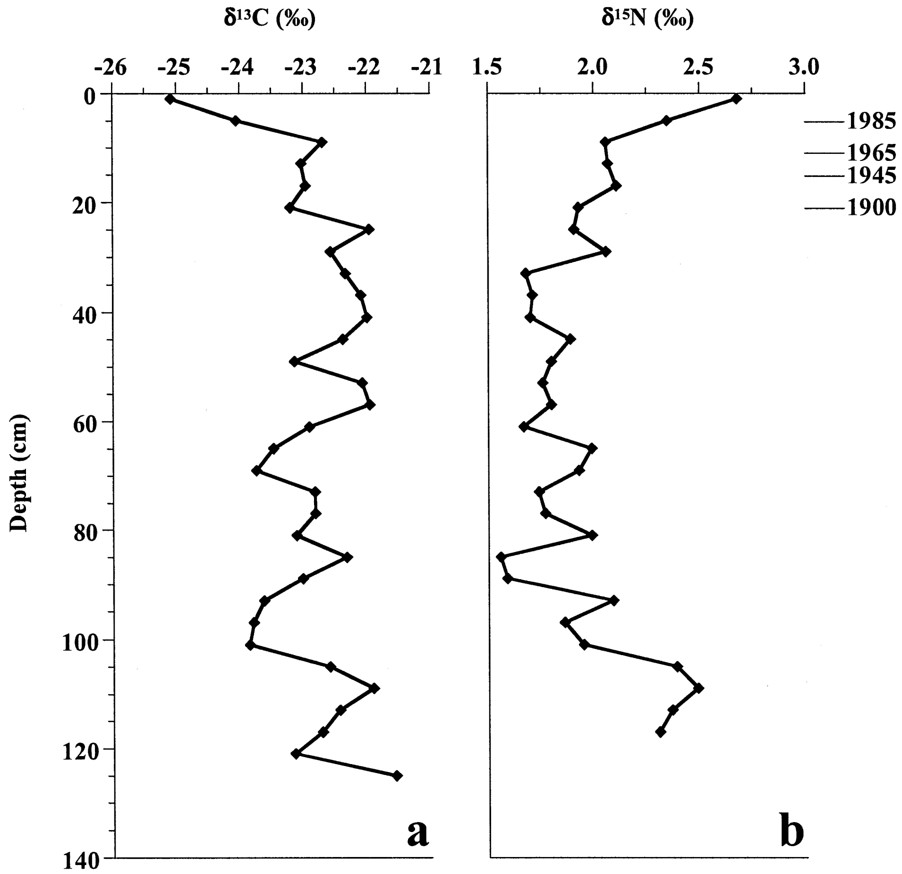

Figure 5. (a) Carbon and (b) nitrogen isotopic composition of organic matter versus depth. Approximate sediment age is indicated to the right of the plot.

elemental analyzer with autosampler. Inorganic carbon (IC) was measured by coulometric titration (Engleman et al., 1985) with a UIC/Coulometrics Model 5011 coulometer and coupled UIC 5240-TIC carbonate autosampler. Organic carbon (OC) was estimated by subtraction of IC from TC. Total phosphorus (TP) was measured using a Technicon Autoanalyzer II with a single-channel colorimeter, following digestion with H_2SO_4 and $K_2S_2O_8$ (Schelske et al., 1986). Biogenic silica from diatom frustules and sponge spicules was measured using the Technicon Autoanalyzer II and heteropoly blue method following digestion with Na_2CO_3 (Conley & Schelske, 1993).

Diatom samples were digested using H_2O_2 and $K(CrO_4)_2$ to remove organic material (Van der Werff, 1955). All samples were repeatedly settled, aspirated, and rinsed, and the supernatants were dried onto coverslips and mounted with Naphrax mounting medium. At least 500 valves were counted in each sample using phase-contrast microscopy at 1500× magnification.

Autoecological information for diatom taxa was obtained from several sources including Hustedt (1930, 1930–1966), Patrick & Reimer (1966, 1975), Lowe (1974), Whitmore (1989), Krammer & Lange-Bertalot (1991a,b), and Van Dam et al. (1994). Salinity ecological classification categories used were those of Gasse et al. (1987). Percentages of diatoms in salinity and trophic ecological categories were summed for each sample. The percentages of taxa that spanned more than one ecological category were divided equally among the ecological categories involved.

Acidified, carbonate-free sediment samples for stable carbon isotope analyses were measured with a Carlo Erba NA 1500 CNS elemental analyzer and VG PRISM II series mass spectrometer. Tin capsules containing 400–500 μg of sediment were combusted at 1040 °C in an O_2 atmosphere. Combustion gases were passed through a reduction column in a stream of helium gas and into a gas chromatograph where CO_2 was

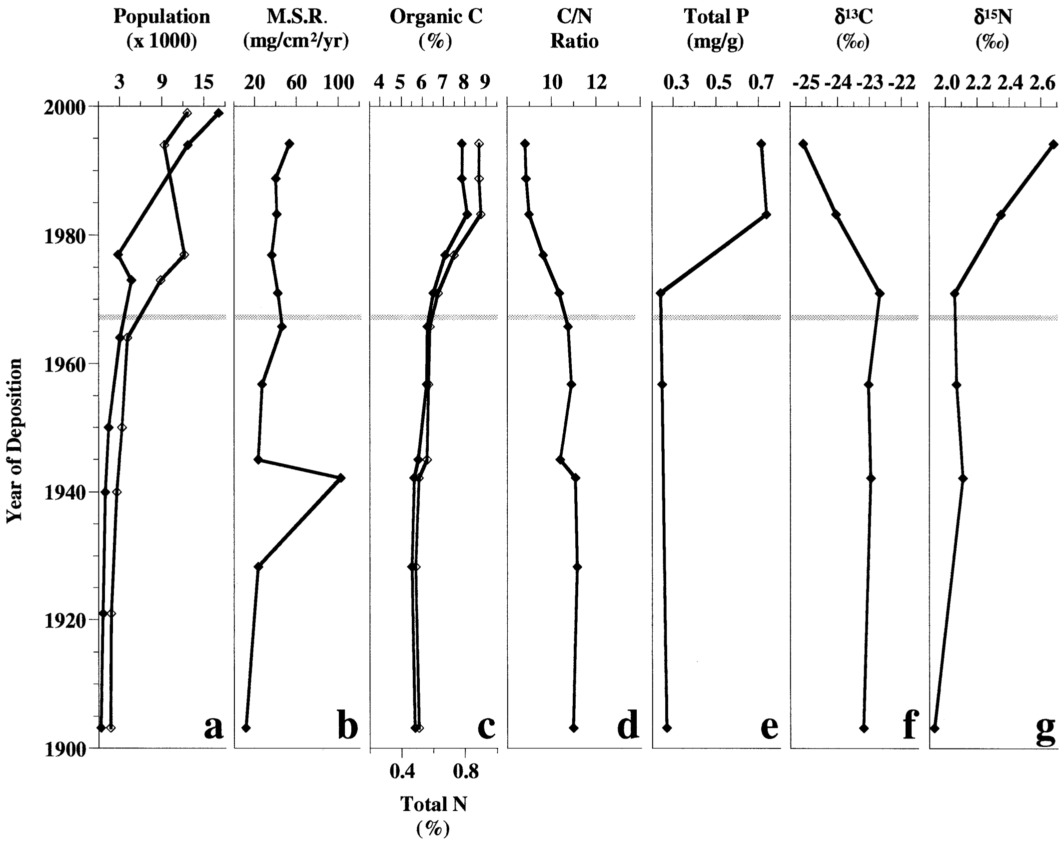

Figure 6. (a) Population growth in the towns of Flores (open diamonds) and San Benito (filled diamonds). Flores and San Benito occupy the southern basin of Lake Petén Itzá. (b) Mass sedimentation rate (c) organic carbon content (filled diamonds) and total nitrogen content (filled diamonds), (d) C/N ratios, (e) total phosphorus concentration, and (f) carbon and (g) nitrogen isotopic composition of organic matter verses calendar year. Gray line delineates the time of construction (1967) of the causeway to Flores.

separated. The gas stream then entered a VG PRISM II series mass spectrometer where the CO_2 was concentrated in a cryogenic triple trap. Upon warming, the CO_2 gas was analyzed in the mass spectrometer and compared to an internal gas standard. By international standard, $\delta^{13}C$ values are expressed in conventional delta (δ) notation as the per mil (‰) deviation from the Vienna PeeDee Belemnite (VPDB). Samples for $\delta^{15}N$ analysis were also combusted in the CNS Analyzer and generated N_2 gas was cryogenically trapped and introduced to the inlet of the mass spectrometer. The gas was analyzed and compared to an internal reference standard. Nitrogen isotope results are expressed in conventional delta (δ) notation as the per mil (‰) deviation from air. Precision for $\delta^{13}C$ and $\delta^{15}N$ of the samples analyzed was ±0.09‰ and ±0.03‰, respectively.

Results

Total ^{210}Pb activity in the core decreased from a subsurface maximum of 8.8 dpm g^{-1} to supported levels (~1.5 dpm g^{-1}) at ~25.0 cm depth (Fig. 2a). Cesium-137 activity in the core was <2.0 dpm g^{-1} and failed to display a definitive peak. Total residual unsupported ^{210}Pb-activity was 11.3 dpm cm^{-2}, from which a maximum datable age of 1835 A.D. at 25 cm was calculated (Fig. 2b). Rates of sediment accumulation varied nearly ten-fold through the core profile from 10 to 102 mg cm^{-2} yr^{-1} (Fig. 2c).

Paleoenvironmental proxies from the Lake Petén Itzá core are plotted against depth and time. Results are discussed as a function of age. Organic carbon concentration in the sediments was low prior to ~ 1900 A.D. and averaged 4.3% (Fig. 3a). Similarly, total nitrogen content was relatively low (averaging 0.35%) prior to ~1900 A.D. but increased nearly two-fold by

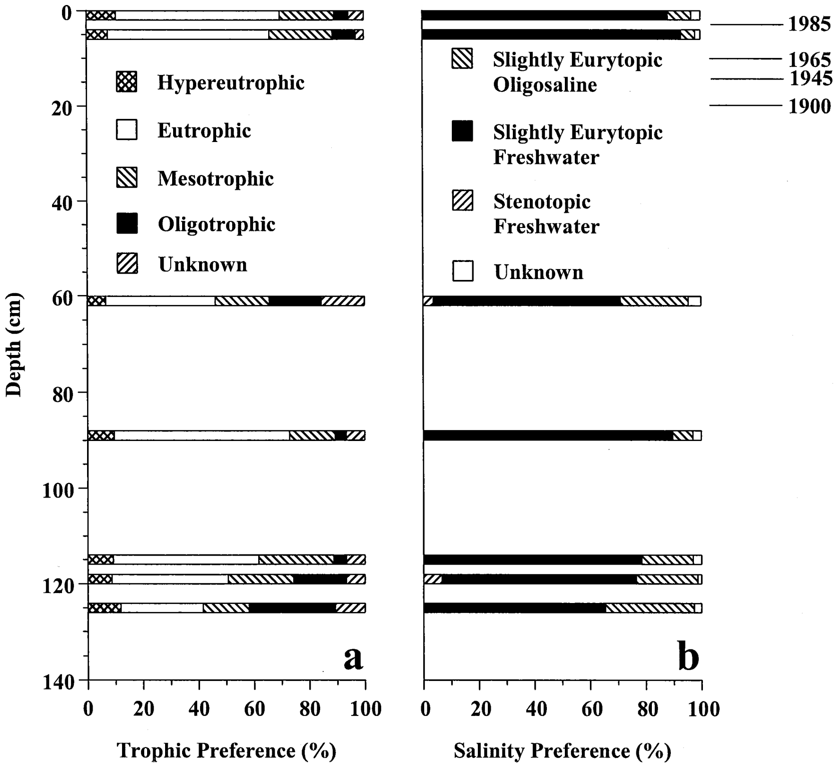

Figure 7. (a) Trophic state preference categories and (b) total ionic salinity preference categories versus depth in the Petén Itzá sediment core. Approximate sediment age is indicated to the right of the plot. Salinity ecological classification terms are those of Gasse et al. (1987). These salinity ranges include 0–15‰ for slightly eurytopic oligosaline, 0–5‰ for slightly eurytopic freshwater, and 0–0.5‰ for stenotopic freshwater.

1945 A.D. (Fig. 3a). Maximum organic carbon and total nitrogen concentrations occurred after 1965 A.D. Carbon/nitrogen ratios generally decreased through time (Fig. 3b). Bottommost sediments have C/N ratios >14, but values decreased to ~ 12 at mid-depth, and topmost sediments have C/N ratios <10.

Basal sediments in the Lake Petén Itzá core had relatively high and variable total phosphorus concentrations that decreased to <0.3 mg g^{-1} prior to $\sim$1965 A.D. (Fig. 3c). High phosphorus values occurred again after 1965 A.D. Diatom and sponge spicule silica was high in basal sediments, but decreased markedly sometime prior to 1900 A.D. and remained low to the present (Fig. 3d).

Seventy-five diatom taxa were identified in sediment core samples. Although samples were digested for diatom analyses at 5-cm intervals, only seven samples were analyzed because diatoms were extremely scarce or were obscured by clastic sediments. Dissolution and erosion of diatoms was likely the result of abrasion by clastic particles and low dissolved silica values within the lake. In many samples that showed evidence of diatom dissolution, information loss precluded reliable ecological interpretations.

Eighteen species of diatom taxa with varying trophic state and salinity preferences have dominated the flora of Lake Petén Itzá (Fig. 4). Several benthic taxa increase through time, notably *Pseudostaurosira brevistriata* (Grun.) Williams & Round, *P. brevistriata* var. *inflata* (Pant.) Williams & Round, *Staurosira construens* Ehr., and *S. construens* var. *venter* (Grun.) Williams & Round. *Staurosira construens* and *S. construens* var. *venter* represent $>30\%$ of the diatom assemblage in all but the oldest sediments, whereas species of *Nitzschia* and *Mastogloia* are most prominent in lower samples. Several species of *Nitzschia*, including *N. hybrida* Grun., *N. palea* (Kutz.) W. Sm., *N. amphibia* Grun., and *N. denticula* Grun. appear also in the lower portions of the sediment profile. *Mastogloia smithii* Thwaites ex. W. Sm., *M. smithii* var. *lacustris* Grun., *M. guatemalensis* Patr., *Rhopalodia gibba* (Ehr.) O. Mull., and *Navicula cuspidata* (Kutz.) Kutz. exhibit highest numbers in bottommost and mid-depth samples, with greatest representation mid-core.

N. amphibia and *N. denticula* also appear with greater abundance at mid-core depths.

The $\delta^{13}C$ of organic matter in Lake Petén Itzá south basin sediments was high and variable prior to 1900 A.D. and averaged −22.7‰ (Fig. 5a). In contrast, organic matter $\delta^{15}N$ was relatively low prior to 1835 A.D. (Fig. 5b). After 1900 A.D., nitrogen isotopic values increased steadily from 1.9‰ to 2.7‰. Minimum $\delta^{13}C$ values (−25.1‰) occurred after 1965 A.D.

Interpretation of sediment proxies

Changes in lake water chemistry, trophic state, and sediment geochemistry result primarily from variations in material output from the surrounding catchment, often due to land-use changes. For example, deforestation and agricultural production enhance the transport of soil nutrients and organic and inorganic matter to a lake, which is in turn reflected in sediment lithologic composition (Deevey, 1984; Binford et al., 1987). Land clearance accelerates alluviation and colluviation, and increases in sediment accumulation may reflect intensified watershed erosion. Nutrient ratios (e.g., C/N) can also be used to evaluate the relative contributions to sediments of terrestrial and aquatic organic matter sources (Kemp et al., 1977; Meybeck, 1982; Håkannson, 1985; Krishnamurthy & Bhattacharya, 1986; Nakai, 1986; Hassan et al., 1997). Moreover, sedimentary diatom assemblages and biogenic silica measurements provide insights into trophic state changes and shifts in the algal community composition (Stoermer et al., 1985; Schelske et al., 1986; Whitmore, 1989, 1991; Anderson et al., 1993).

Variations in the carbon and nitrogen isotopic ratio ($^{13}C/^{12}C$ and $^{15}N/^{14}N$) of sediment organic matter also indicate changes in lacustrine primary productivity (Stuiver, 1975; McKenzie, 1982, 1985; Hollander & McKenzie, 1991; Hollander et al., 1992; Schelske & Hodell, 1991, 1995; Hodell & Schelske, 1998). Phytoplankton preferentially remove the lighter ^{12}C and ^{14}N from the dissolved inorganic carbon (DIC) and nitrogen (DIN) of surface waters during photosynthetic uptake. As supplies of CO_2 and NO_3^- are depleted, phytoplankton discriminate less against the heavier $^{13}CO_2$ and $^{15}NO_3^-$ and sinking organic matter is progressively enriched in ^{13}C and ^{15}N. Changes in the $\delta^{13}C$ and $\delta^{15}N$ of organic matter can therefore be used to reconstruct productivity in surface waters.

Additional factors may influence the $^{13}C/^{12}C$ and $^{15}N/^{14}N$ of lacustrine organic matter. Changes in pH, temperature, species composition, nitrogen limitation or fixation, and growth rate can affect the $\delta^{13}C$ and $\delta^{15}N$ of phytoplankton (Hinga et al., 1994; Goericke et al., 1994; Laws et al., 1995). The isotopic signature of sedimented organic matter may be further altered by relative shifts in the organic matter source material (i.e., terrestrial vs. aquatic) contributed to the sediment pool and changes in the relative abundance of macrophytes and phytoplankton. Lastly, the stable isotopic signature of sedimented organic matter may be influenced by differential, post-depositional preservation of the various components of the organic matter pool, each of which may possess a distinctive isotopic value.

Discussion

Dramatic increases in the urban population surrounding Lake Petén Itzá are documented by FYDEP (1977) and the Instituto Nacional de Estadística (unpublished data) beginning ~1940 A.D. (Fig. 6a). Increased sediment accumulation in the southern basin of Lake Petén Itzá coincided with increased population growth and probably reflects clearance of forested shorelines and soil destabilization (Fig. 6b). For example, the period between 1934 and 1942 A.D. was relatively wet, characterized by ~2050 mm yr^{-1} of rain relative to the mean annual average of ~1600 mm yr^{-1} (Deevey et al., 1980). High lake level and consequent flooding in Flores in 1938 A.D. was probably associated with the unusually heavy rains (Penados, 1980). High sediment accumulation ~1940 A.D. correlates with the period of high rainfall and may reflect intensified erosion associated with shoreline deforestation. Mass sedimentation rates also increased at 1967 A.D. coinciding with the construction of the causeway that links the island of Flores with Santa Elena (Zetina, 1985).

Within the last century, geochemical records from the Lake Petén Itzá sediment core reflect nutrient enrichment and increased algal productivity. Organic carbon and total nitrogen content increased after 1940 A.D. and total phosphorus content increased markedly after 1965 A.D. (Figs 6c, 6e). Intensified basin occupation likely coincided with expanded agriculture and erosion of soil nutrients and fertilizers. Furthermore, in the mid-1960s, drains were first laid in the rapidly growing villages around the southern basin of Petén Itzá and discharge of nutrient-rich sewage effluent into the lake began. At present, the small streams and canals draining into the embayment near Flores exhibit very high phosphorus and nitrogen concentrations, averaging ~5700 and ~1800 μg l^{-1}, respectively. Run-off from urban areas and agricultural fields would enhance nutrient loading to the lake, causing increased algal productivity. Near-surface sediments contain organic matter with a mean C/N ratio of 9.9, typical values for plankton-derived sediments (Fig. 6d). Lower portions of the core exhibit values of ~15, suggesting a substantial contribution from terrestrial sources. Low C/N ratios in recent deposits indicate that phytoplankton productivity has increased in the last 30–40 years.

Fossil diatom remains in the Lake Petén Itzá sediment core provide some evidence for cultural eutrophication. Historical water quality inferences from the diatom assemblages indicate that the Flores embayment is dominated by benthic taxa, consistent with shallow water conditions. Representation of benthic taxa however does not seem to be determined by changing water level. For example, the percentage of oligotrophic individuals is greatest at depth in the sediment core (Fig. 7a) and the percentage of eutrophic individuals appears greatest in more recent sediments. In contrast, diatom derived salinity variations and inferred water level changes through time appear minimal (Fig. 7b). Greater representation of *Pseudostaurosira* and *Staurosira* spp. after ~1965 A.D. (Fig. 4) also suggests a slight increase in productivity because such taxa frequently indicate mesotrophic to eutrophic conditions (Whitmore, 1989; Van Dam et al., 1994). High phytoplankton counts (nearly 30 000 cells ml^{-1}) associated with sewage-induced nutrient loading were also noted near the island city of Flores in 1969 A.D., and led Brezonik & Fox (1974) to characterize the southern basin of Petén Itzá as highly eutrophic. Brezonik & Fox (1974) characterized the relatively uninhabited northern basin of Lake Petén Itzá as oligotrophic, noting a total phytoplankton count of only 185 cells ml^{-1}.

Organic matter $\delta^{13}C$ values in the Lake Petén Itzá sediment core decreased markedly after ~1965 A.D. (Fig. 6f). Depletion of organic matter ^{13}C contrasts with other indicators of recent eutrophication and nutrient loading. Increased primary productivity might be expected to enrich the $\delta^{13}C$ of organic matter. Another source of ^{13}C-depleted organic matter is therefore necessary to reconcile the carbon isotopic signature of organic matter within the lake. Sewage, like other terrestrial organic matter sources, is depleted in ^{13}C relative to organic matter produced by phytoplankton. In a study of a sewage dumpsite in the New York Bight, anthropogenic waste and marine organic matter were characterized by distinct $\delta^{13}C$ values (−26.2 and −22.0‰, respectively), such that the extent of sludge carbon distribution in the sediments could be mapped (Burnett and Schaeffer, 1980). Similarly, Gearing et al. (1991) found that sewage carbon accumulated in the sediments of estuarine mesocosms with added sewage sludge (−24.2‰) was significantly different from control stations (−21.6‰). The relatively light $\delta^{13}C$ values of organic matter (−22.5 to −25.2‰) in recent (post A.D. 1965) sediments of the southern basin of Petén Itzá probably reflect an increasing contribution to the sediment organic matter pool from sewage effluent. Sorting out the proportions of organic matter derived from lacustrine and terrestrial sources is not yet possible because end-member values for the area are not available.

The increase in $\delta^{15}N$ of organic matter from 1965 A.D. to the present may be related to an increase in the $\delta^{15}N$ of the dissolved inorganic nitrogen delivered to the lake. The $\delta^{15}N$ of sewage-derived ammonium and nitrate is ^{15}N-enriched with measured values typically +10 to +20‰ (Heaton, 1986; Aravena et al., 1993; Spaulding et al., 1993). Soil nitrate also tends to be relatively enriched in ^{15}N (measured values +3 to +12‰). Increased nitrate loading from sewage and soils may have contributed to the increased $\delta^{15}N$ of the sediment organic matter in the southern basin of the lake. The magnitude of the $\delta^{15}N$ change (~1‰), however, is not consistent with the expected change associated with anthropogenic effluents. Compensatory changes in productivity may have minimized shifts in the $\delta^{15}N$ values expected with increased sewage discharge. Cyanobacteria, particularly *Microcystis* sp. and *Lyngbya* sp., dominate the modern phytoplankton assemblages of the southern basin of Lake Petén Itzá (Brezonik & Fox, 1974). These nitrogen-fixing cyanobacteria show little isotope fractionation and have $\delta^{15}N$ values similar to that of atmospheric nitrogen (Peterson & Fry, 1987). High numbers of nitrogen-fixing cyanobacteria with low $\delta^{15}N$ (0‰), particularly under eutrophic conditions, may offset the increase in $\delta^{15}N$ associated with sewage input.

Conclusions

Recent changes in sediment accumulation and shifts in organic matter characteristics (C/N ratios, $\delta^{13}C$ and $\delta^{15}N$) in a core from a small bay in the southern basin of Lake Petén Itzá are temporally correlated with increases in human population densities in the surrounding watershed, suggesting an anthropogenic cause for changes in the sediment record. Logging and land clearance for agriculture have contributed significantly to forest loss in Petén since the 1950s. Recent vegetation removal was accompanied by increased catchment soil erosion, contributing to the nearly fourfold (average) increase in the rate of sediment supply to the southern basin of the lake. Increased eutrophication and organic matter accumulation are a consequence of excess nutrient loading caused by riparian deforestation by the rapidly growing population and subsequent agricultural and industrial activities. Furthermore, increasing sewage discharge from Flores, Santa Elena, and San Benito has increased nutrient concentrations in the southern basin of Lake Petén Itzá and contributed to greater algal production. Eutrophication in Lake Petén Itzá is presently confined to the Flores embayment, partly as a consequence of its shallow morphometry and hydrologic characteristics. Fill construction of the causeway between Santa Elena and Flores restricted water circulation. This problem has been only partially remedied by recent creation of culverts that permit some water exchange with the rest of the southern basin. Nevertheless, as population in the Petén Itzá watershed continues to increase, nutrient enrichment will likely be detected in other areas of the lake.

Acknowledgements

We thank Lic. F. Polo Sifontes and Sr. Byron Lemus of the Instituto de Anthropologia é Historia (IDAEH), Guatemala, for facilitating field work. Jason Curtis provided laboratory assistance. We thank David Hodell, Claire Schelske, and two anonymous reviewers for thoughtful comments on the manuscript. This work was funded by NSF grant EAR-9709314 and a grant from the National Geographic Society.

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