Quantification of soil erosion rates related to ancient Maya deforestation

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ABSTRACT

We used seismic and sediment core data to quantify soil erosion rates for the past ~6000 yr in the closed catchment of Lake Salpetén, in the tropical lowlands of northern Guatemala. The region was affected by ancient Maya land use from before ca. 1000 B.C. to A.D. 900. This period of human impact coincided with deposition in the lake of a detrital unit (Maya Clay) as much as 7 m thick that contrasts sharply with the relatively organic-rich gyttja deposited both before and after Maya occupation of the watershed. The greatest soil loss, with mean sustained values of ~1000 t/km^{2}yr^{-1}, occurred in the Middle and Late Preclassic Periods (700 B.C. to A.D. 250), associated with relatively low Maya population densities. Soil erosion slowed during the period of maximum population density in the Late Classic Period (A.D. 550–830), indicating a decoupling between human population density and soil erosion rate. The most rapid soil loss occurred early during initial land clearance, suggesting that even low numbers of people can have profound impacts on lowland tropical karst landscapes.

Keywords: soil erosion, lake sediments, land use, Maya, seismic stratigraphy, human impact.

INTRODUCTION

The impact of the ancient Maya civilization on lowland tropical karst landscapes has been cited as an example of long-term, human-induced environmental degradation (Beach, 1998; Binford et al., 1987; Redman, 1999). Previous studies in the central Petén region of northern Guatemala indicated that Maya-induced deforestation and intensified agricultural activity led to accelerated topsoil erosion, increased lacustrine sedimentation, rapid soil nutrient depletion, and declining crop yields (Deevey et al., 1979; Olson, 1981; Rice and Rice, 1990). It was even suggested that human-induced environmental degradation contributed to the collapse of the Maya civilization in the ninth and tenth centuries A.D. (Redman, 1999).

Here we quantify changes in soil erosion rates in a closed drainage basin by combining seismic and sediment core investigations of the lacustrine sediments in Lake Salpetén. The Salpetén catchment is a simple source-to-sink system where lake deposits reflect erosional and runoff processes in the catchment. Temporal patterns of soil loss were compared to estimates of ancient Maya population densities (Rice et al., 1985; Rice and Rice, 1990) and with vegetation changes inferred from pollen analysis (Leyden, 1987).

Previous studies investigated prehistoric human impacts on soil erosion in Central America (Fisher, 2005; Fisher et al., 2003; O'Hara et al., 1993) and identified periods of relatively higher and lower erosion (Beach et al., 2006; Deevey et al., 1979; Dunning et al., 1998, 2002). Our approach enabled us to both identify the timing of erosion rate changes and estimate quantitatively the amount of soil downwasting, which we related to changes in human population density and land clearance through time.

APPROACH

The amount of sediment accumulated in lake basins has been used to quantify sediment yield and denudation rates in various catchments (De Vente and Poesen, 2005; Einsele and Hinderer, 1997; McIntyre, 1993). We applied a limnogeological approach to the Lake Salpetén catchment in northern Guatemala (Fig. 1) to quantify soil erosion history in relation to ancient Maya occupation in the watershed. Lake Salpetén is a small water body (2.55 km^2) with a surrounding catchment of 3.81 km^2 (Brezonik and Fox, 1974). It has a maximum depth of 34 m and is at 104 m above sea level. The lake has no permanent inflows and receives surface runoff only during strong precipitation events. It has no surface outflows, making the lake an effective sediment trap. The small catchment size, in combination with a lack of significant sediment storage capacity, implies rapid transport of eroded particles from the catchment (i.e., source) to the lake (i.e., sink). Scale dependency of the erosion rate, as observed in large catchments and for longer time scales (De Vente and Poesen, 2005), is thus minimal.

Sediments in Lake Salpetén were imaged geophysically with a 3.5 kHz seismic reflection survey (Fig. 2). Multiple transects provided a quasi-three-dimensional (3D) image of the sediment architecture, and

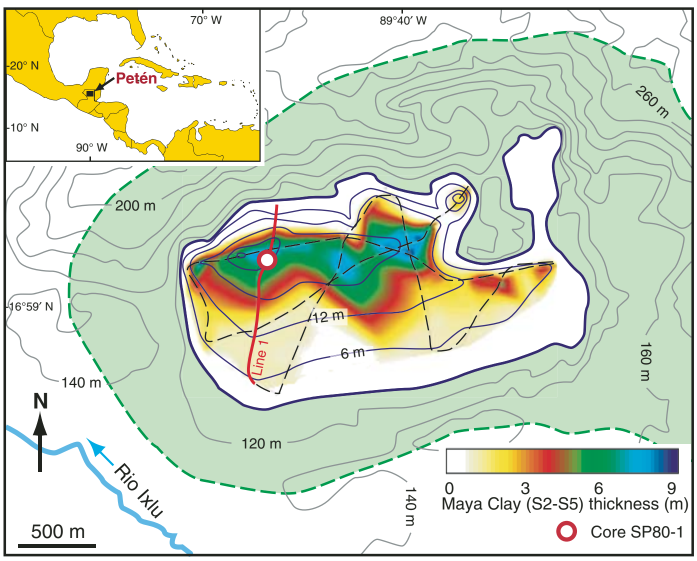

Figure 1. Bathymetry and catchment area of Lake Salpetén. Green area indicates lake catchment. Contour lines on land (gray) are plotted every 20 m. Bathymetric contour lines (blue) are 6 m intervals. Colored areas in lake indicate thickness of Maya Clay unit. Positions of seismic section (red line) displayed in Figure 2 and drill hole SP80-1 are also indicated. Inset shows lake location in Petén district of northern Guatemala. TOC—total organic carbon.

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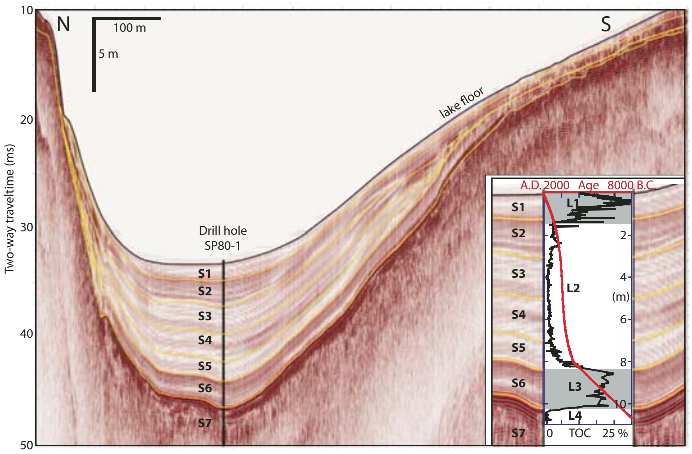

Figure 2. Seismic line 1 crossing the lake from north (left) to south (right) and location of drill hole SP80-1. Depth is given in two-way traveltime (ms). Seismic sequences S1–S7 are indicated by yellow lines (vertical exaggeration = 20×). Inset shows seismic to core correlation with coinciding lithologic units L1–L4 (L4—evaporites and/or clay; L3—Lower Gyttja, L2—Maya Clay; L1—Upper Gyttja). ^{14}C age data (in calendar k.y.; red dots) provide age model (red line) (Rosenmeier et al., 2002a, 2002b; Fig. DR1 [see footnote 1]). Total organic carbon curve (TOC, black line) indicates relatively sharp boundaries between lithologic units.

sediment volumes were quantified throughout the basin. Previous studies in Petén lakes that used single or even multiple sediment cores were unable to quantify basin-wide deposition because of sediment focusing and spatial variability in sediment thickness. Furthermore, chronological control in cores was poor because radiocarbon dates on bulk sediment were unreliable as a consequence of hard-water-lake error (Deevey and Stuiver, 1964). In this study, we combined information from seismic data with accelerator mass spectrometry (AMS) ^{14}C radiocarbon dates on lake sediment cores. We dated only terrestrial organic matter, enabling us to obtain a reliable sediment chronology (Rosenmeier et al., 2002a, 2002b; see GSA Data Repository Fig. DR1[1]).

SEDIMENT CORES

Lithologic and chronologic control was provided by an ~14 m core (SP80-1) that was recovered in Lake Salpetén in 1980 (Deevey et al., 1983) (Figs. 1 and 2). Because the uppermost 1.6 m of sediment were not recovered in SP80-1, a composite section was developed using two additional sediment cores collected in 1999 (Rosenmeier et al., 2002a; Table DR1, and the Composite Core and Age-Depth Model Construction in the Data Repository). All presented depths refer to this composite depth scale. Four main lithologic units were defined (L1–L4) on the basis of changes in sediment composition and chemistry (Rosenmeier et al., 2002b). Lithologic units were recognized by sharply contrasting organic matter content, as expressed by total organic carbon (TOC) concentrations (Fig. 2). Lowermost unit L4 (below 10.0 m) is composed of organic-poor, gypsum-rich lacustrine sediments. Units L3 (10.0–8.1 m) and L1 (1.5–0 m) are composed of dark-colored, organic-rich sediments (gyttja) with TOC values of ~20%. Between these two gyttja units is a thick, mostly inorganic deposit (L2; 8.1–1.5 m) that has been referred to as Maya Clay (Binford et al., 1987; Brenner, 1994; Deevey et al., 1979). L2 sediments consist mostly of fine-grained, partly laminated clays with variable amounts of carbonate and less organic matter (TOC value ~2%). This 6.5-m-thick package of clay-rich deposits is derived mostly from eroded soil that is interpreted to be a consequence of human deforestation of the watershed coupled with intense sediment focusing into deeper water (Brenner, 1994).

SEISMIC DATA AND SEDIMENT VOLUMES

Seismic profiles indicate a sediment geometry in the deep basin consisting of an ~10-m-thick package of regularly layered sediments that overlies a distinct high-amplitude reflection (lowermost yellow horizon in Fig. 2). Seismic stratigraphic analysis subdivides this sediment succession into seven seismic units (S1–S7) that are separated by traceable reflections (Fig. 2). The correlation of the seismic section to the core was achieved using the highest-amplitude reflection as a marker horizon (S6-S7) that coincides with the pronounced lithologic change at 10.22 m (L3-L4 boundary) and its sharp contrast in physical properties. The resulting acoustic velocity of 1560 m/s is a reasonable value for clay-rich lacustrine sediments at ~25 °C and was applied to the entire section. Using this core to seismic correlation, L1 corresponds to S1, L2 coincides with S2–S5, and L3 is equivalent to S6 (Fig. 2). In this study, the Maya Clay was subdivided into four seismic units (S5–S2) that are separated by reflections that can be traced with confidence throughout the basin.

To estimate the volume of deposits within seismic units S6–S1, sediment thicknesses for each unit were interpolated between the measured values along seismic lines and extrapolated to the edges of the basin (Table DR1). Sediment volumes were converted to dry sediment mass using a grain density of 2.5 g/cm^3 and average porosities of 90% and 70% for gyttja and clay, respectively, on the basis of empirical measurements in several Salpetén cores (Rosenmeier et al., 2002b). Using the seismic to core correlation and AMS ^{14}C age model (Rosenmeier et al., 2002a, 2002b; Fig. 2; Table DR2 and Fig. DR1), dates were assigned to the boundaries between units S6–S1, permitting the calculation of the mean annual mass sedimentation rate for each unit. We assumed that organic matter was of lacustrine origin and that inorganic components (carbonate and clays) were detrital. As a consequence, we did not include the average organic matter content in clay units (10%) or gyttja units (40%) to calculate detrital inorganic sediment yield (Table DR1). Erosion rates for the carbonate-poor, pre- and post-Maya gyttjas may be slightly overestimated, because much carbonate in these deposits is probably biogenic. However, the majority of the carbonate in the Maya Clay is detrital (Brenner, 1994). Unlike previous studies, for which site-specific changes in sedimentation rate were calculated from single, or even multiple cores, our 3D approach enabled us to estimate the total lake-wide sediment mass that was transported to this closed basin during various times that correspond to archaeologically defined periods of Maya occupation. Because the catchment size is known (Brezonik and Fox, 1974), we were able to use the annually deposited sediment mass to compute the average annual erosion rate of mineral soil ($t/km^2\ yr^{-1}$) and the vertical soil loss (in centimeters) in the watershed for the specified time intervals.

EROSION RATES

Our approach provides a sediment budget with a quantitative record of erosion rates in the Lake Salpetén catchment in six discrete steps from the pre-Maya period to modern time (Fig. 3; Table DR1). Average basin-wide erosion rates were low (16.3 $t/km^2\ yr^{-1}$) prior to ca. 2200 B.C., during the deposition of the pre-Maya gyttja. After ca. 2200 B.C., erosion rates increased consistently from 134 to 988 $t/km^2\ yr^{-1}$, representing high annual soil loss values that provided a substantial and sustained input of sediment to the lake basin. This intense phase of soil erosion began in the early Preclassic (2000–700 B.C.) and culminated in the late Preclassic Period

[1]GSA Data Repository item 2007226, Table DR1 (data of seismic units S1–S6 with resulting soil erosion and vertical soil loss values); Description of composite core and age-depth model construction; Table DR2 (list of AMS ^{14}C samples); and Figure DR1 (ages of terrestrial organic matter versus composite depth), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

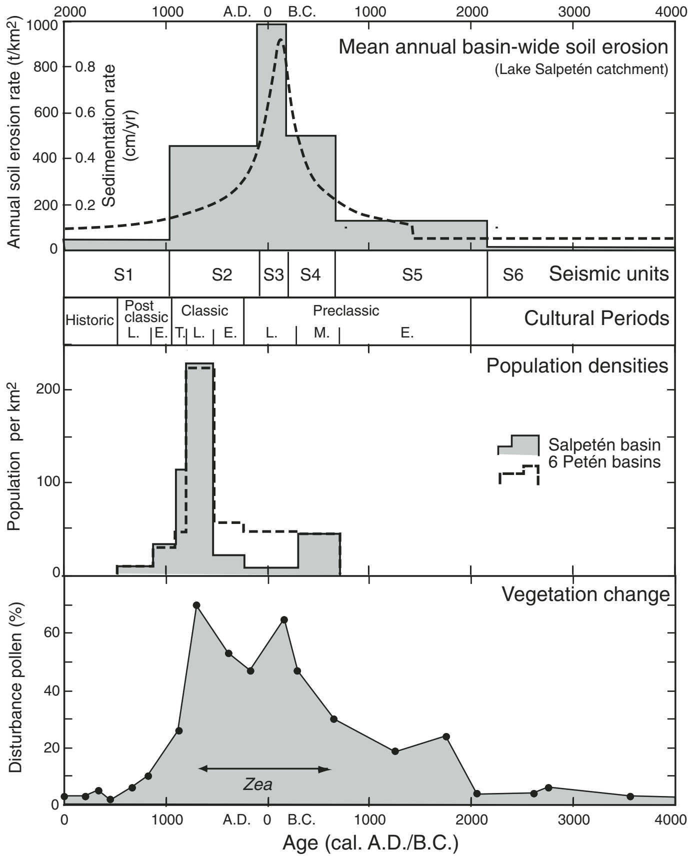

Figure 3. Salpetén basin variables plotted versus time for past 6000 yr (from top to bottom). Annual soil erosion rates are averaged over entire catchment (gray area). Black dashed line indicates lacustrine sedimentation rate at the coring site based on the applied age model (Rosenmeier et al., 2002a, 2002b; Fig. DR1 [see footnote 1]). Also shown are seismic units S6–S1; Maya cultural periods (E—Early; M—Middle; L—Late; T—Terminal) (Rice and Rice, 1990); population densities of Salpetén basin alone (gray area) and combined with five other Petén basins (black dashed line) (Rice and Rice, 1990); and disturbance pollen percentage (e.g., grass, weeds) from analysis of drill core SP80-1 in Lake Salpetén (Leyden, 1987) (black line and dots), indicating replacement of regular high-forest taxa. Occurrence of *Zea* (corn; black arrow) indicates nearshore anthropogenic land use.

(250 B.C.–A.D. 250). In the subsequent Classic Period (A.D. 250–950), the soil erosion rate dropped to 457 t/km^2 yr^{-1}, but nevertheless remained high relative to pre-Maya levels. After ca. A.D. 1000, i.e., following the Classic Maya collapse, soil erosion rates declined to 49 t/km^2 yr^{-1}. If the Maya Clay is treated as a single unit, the calculated mean anthropogenic erosion rate, sustained over a period of ~3100 yr, is 359 t/km^2 yr^{-1}, or ~22 times the pre-Maya baseline rate. Estimates of basin-wide soil erosion rate for the six discrete periods were compared to the coring-site–specific, age-model–based curve of sedimentation rate (dashed line in Fig. 3). Similar to the trend for soil erosion in the catchment, sediment accumulation in core SP80-1, taken in the depocenter of Lake Salpetén, also displayed a maximum in the late Preclassic.

DISCUSSION

The Salpetén basin is characterized mostly by mollisols, fertile mineral soils that possess a thin organic surface layer (Olson, 1981) and have a typical bulk density of ~1.4 g/cm^3 (Simmons et al., 1959). Taking a simple approach, we used this bulk density value to convert mass downwasting in t/km^2 yr^{-1} to soil loss in centimeters (Table DR1), without accounting for possible density variations within soil profiles or in different areas of the catchment. If Maya Clay units S5–S2 are combined, the resulting total soil loss amounts to ~80 cm averaged over the entire catchment. The northern shore likely underwent higher than average soil loss because of its steepness. About 71% of total soil loss, or ~56 cm of the soil profile, was removed prior to the Classic Period. Averaged over the entire catchment, a large fraction of available soil had been removed in an early phase of erosion, and almost all the soil above bedrock had been transported into Lake Salpetén by the end of the Classic Maya period. After the decline of the Classic Maya culture, soil recovered partially in the catchment; modern soil thickness is an average of 40 cm (Brenner et al., 2002), indicating higher soil formation rates than the ~7 cm/k.y. reported from some areas in northern Petén (Beach, 1998).

Calculated soil erosion rates were compared with pollen-inferred changes in vegetation from Salpetén core SP80-1 (Fig. 3) (Leyden, 1987), in which plant taxa were grouped into high forest and disturbance (e.g., grasses, weeds) categories. Coincident increases in disturbance taxa and soil erosion rates suggest a causal link between vegetation removal and soil loss. Maximum erosion rates during the Late Preclassic coincided with a peak in disturbance taxa (65%). Even though erosion rates decreased in the Classic Period, percentages of disturbance pollen taxa remained high, indicating continued regional land clearance. Both disturbance taxa and erosion rates decreased ca. A.D. 1000, when human populations declined and agricultural activities were curtailed.

These shifts in vegetation cover may have also been influenced to some degree by climate change. Geochemical climate proxies from lake sites on the northern Yucatan Peninsula reveal a series of dry events in Maya prehistory that might have affected initial forest decline, influenced human land-use practices, and even contributed to cultural demise in the ninth century A.D. (Hodell et al., 1995, 2005; Curtis et al., 1996). The dramatic 20–50× increase in soil erosion during the period of Maya occupation, however, cannot be explained by Holocene drying alone, and can only be accounted for by intense land use. To evaluate how human numbers affected soil removal, erosion rates were compared to estimated population densities that were reconstructed from dated house mounds along archaeological transects around Lake Salpetén and in other Petén catchments (Fig. 3) (Rice and Rice, 1990). Contrary to the previously hypothesized direct relationship between population numbers and soil erosion (Rice et al., 1985), our results from Salpetén indicate that greatest erosion occurred early, during the Preclassic Period when population in the basin was relatively low (Fig. 3). When population peaked in the Classic Period, soil erosion had already diminished. A large part of the soil profile was removed prior to the period of highest population density. Lake Salpetén has a relatively small watershed, and similar studies on quantified soil erosion have not yet been done in other Petén basins. Nevertheless, site-specific sedimentation rates derived from cores in other Petén lakes, such as Lake Petén Itzá, also indicate that an early pulse of sedimentation preceded maximum population densities in the Classic Maya Period (Fig. 3) (Hillesheim et al., 2005; Rice and Rice, 1990). Soil erosion pulses from other Petén basins (Beach et al., 2006; Dunning et al., 2002) and from the Patzcuaro Basin in the Mexican Altiplano (Fisher et al., 2003; O'Hara et al., 1993) also indicate substantial environmental impact during initial settlement. Estimated soil loss for the Salpetén catchment, however, is more than two orders of magnitude greater than values inferred for the Patzcuaro Basin (O'Hara et al., 1993), reflecting the high erodibility of Petén soils and the enormous pressure on riparian soils during the period of lowland Maya occupation.

CONCLUSION

This sediment study from the Lake Salpetén basin in the lowlands of northern Guatemala provides a 6000 yr record of quantified soil loss for the periods before, during, and after Maya occupation in the watershed. Early, rapid soil loss associated with initial land clearance probably made farming increasingly difficult during the subsequent centuries. Decoupling of population density and soil erosion through time in the Salpetén basin is explained by a pulse of intense erosion during initial land clearance in the Preclassic Period, when highly erodible soils were first exposed (Beach et al., 2006). After this rapid soil loss, erosion rate declined despite a growing human population, because erodibility deeper in the soil profile decreased. Soil erosion may have been recognized as an early environmental challenge and may have influenced ancient Maya agricultural practices. Declining erosion rates in the Classic Period may reflect not only decreased soil erodibility through time, but a change in agricultural strategies, from extensive slash and burn cultivation in the Preclassic Period, to more intensive practices that incorporated soil conservation techniques (Beach, 1998; Beach et al., 2006; Fisher et al., 2003). In any case, the ancient Maya had to contend with severe soil erosion long before their populations attained high densities in the Late Classic Period (A.D. 550–830) and then ultimately declined during the Terminal Classic Period (A.D. 830–950). Erosion rates decreased, and soils and forests recovered partially during the following Postclassic and Historic Periods when human disturbance declined substantially, contradicting the concept that abandonment leads to massive degradation of once-cultivated landscapes (Fisher, 2005). The ongoing population increase in Petén that began after the 1950s has once again increased deforestation (Schwartz, 1990), and presumably erosion rates, in the region.

ACKNOWLEDGMENTS

We thank Margaret Dix and Michael Dix of the Universidad del Valle de Guatemala and their students Lucía Corral, Oscar Juarez, Gabriela Ponce, Julia Quiñones, and Rodolfo Valdez for field assistance. Jason Curtis, Lico Godoy, and Jennifer Szlosek also helped in the field. Thomas Guilderson assisted with radiocarbon analysis under the auspices of the U.S. Department of Energy, University of California Lawrence Livermore National Laboratory (contract W-7405-ENG-48). We are indebted to the Consejo Nacional de Areas Protegidas (CONAP), the Instituto de Antropología e Historia (IDAEH), and the Wildlife Conservation Society (WCS), Guatemala, for facilitating field work. Barbara Leyden kindly provided pollen data. Prudence Rice and Don Rice provided assistance with paleodemographic data. The comments of Timothy Beach and two anonymous reviewers improved the manuscript. This work was funded in part by grants from ETH Zurich, Swiss National Science Foundation, the U.S. National Science Foundation (ATM-0117148), and the National Geographic Society. This is a publication of the University of Florida Land Use and Environmental Change Institute (LUECI).

REFERENCES CITED

Beach, T., 1998, Soil catenas, tropical deforestation, and ancient and contemporary soil erosion in the Petén, Guatemala: Physical Geography, v. 19, p. 378–404.

Beach, T., Dunning, N., Luzzader-Beach, S., Cook, D.E., and Lohse, J., 2006, Impacts of the ancient Maya on soils and soil erosion in the Central Maya lowlands: Catena, v. 65, p. 166–178, doi: 10.1016/j.catena.2005.11.007.

Binford, M.W., Brenner, M., Whitmore, T.J., Higuera-Gundy, A., Deevey, E.S., and Leyden, B., 1987, Ecosystems, paleoecology and human disturbance in subtropical and tropical America: Quaternary Science Reviews, v. 6, p. 115–128.

Brenner, M., 1994, Lakes Salpetén and Quexil, Petén, Guatemala, Central America, *in* Gierlowski-Kordesch, E., and Kelts, K., eds., Global geological record of lake basins: Volume 1: Cambridge, Cambridge University Press, p. 377–380.

Brenner, M., Rosenmeier, M.F., Hodell, D.A., and Curtis, J.H., 2002, Paleolimnology of the Maya Lowlands: Long-term perspectives on interactions among climate, environment, and humans: Ancient Mesoamerica, v. 13, p. 141–157, doi: 10.1017/S0956536102131063.

Brezonik, P.L., and Fox, J.L., 1974, The limnology of selected Guatemalan lakes: Hydrobiologia, v. 45, p. 467–487.

Curtis, J.H., Hodell, D.A., and Brenner, M., 1996, Climate variability on the Yucatan Peninsula (Mexico) during the last 3500 years and implications for Maya cultural evolution: Quaternary Research, v. 46, p. 37–47.

Deevey, E.S., and Stuiver, M., 1964, Distribution of natural isotopes of carbon in Linsley Pond and other New England lakes: Limnology and Oceanography, v. 9, p. 1–11.

Deevey, E.S., Jr., Rice, D.S., Rice, P.M., Vaughan, H.H., Brenner, M., and Flannery, M.S., 1979, Mayan urbanism: Impact on a tropical karst environment: Science, v. 206, p. 298–306, doi: 10.1126/science.206.4416.298.

Deevey, E.S., Brenner, M., and Binford, M.W., 1983, Paleolimnology of the Peten Lake District, Guatemala III. Late Pleistocene and Gamblian environments of the Maya area: Hydrobiologia, v. 103, p. 211–216, doi: 10.1007/BF00028454.

De Vente, J., and Poesen, J., 2005, Predicting soil erosion and sediment yield at the basin scale: Scale issues and semi-quantitative models: Earth-Science Reviews, v. 71, p. 95–125, doi: 10.1016/j.earscirev.2005.02.002.

Dunning, N., Rue, D., Beach, T., Covich, A., and Traverse, A., 1998, Human-environment interactions in a tropical watershed: The paleoecology of Laguna Tamarindito, El Petén, Guatemala: Journal of Field Archaeology, v. 25, p. 139–151.

Dunning, N.P., Luzzadder-Beach, S., Beach, T., Jones, J.G., Scarborough, V., and Culbert, T.P., 2002, Arising from the bajos: The evolution of a neotropical landscape and the rise of Maya civilization: Association of American Geographers Annals, v. 92, p. 267–283, doi: 10.1111/1467–8306.00290.

Einsele, G., and Hinderer, M., 1997, Terrestrial sediment yield and the lifetimes of reservoirs, lakes, and larger basins: Geologische Rundschau, v. 86, p. 288–310, doi: 10.1007/s005310050141.

Fisher, C.T., 2005, Demographic and landscape change in the Lake Patzcuaro Basin: Abandoning the garden: American Anthropologist, v. 107, p. 87–95.

Fisher, C.T., Pollard, H.P., Israde-Alcantara, I., Garduno-Monroy, V.H., and Banerjee, S.K., 2003, A reexamination of human-induced environmental change within the Lake Patzcuaro Basin, Michoacan, Mexico: National Academy of Sciences Proceedings, v. 100, p. 4957–4962, doi: 10.1073/pnas.0630493100.

Hillesheim, M.B., Hodell, D.A., Leyden, B.W., Brenner, M., Curtis, J.H., Anselmetti, F.S., Ariztegui, D., Buck, D.G., Guilderson, T.P., Rosenmeier, M.F., and Schnurrenberger, D., 2005, Climate change in lowland Central America during the late deglacial and early Holocene: Journal of Quaternary Science, v. 20, p. 363–376, doi: 10.1002/jqs.924.

Hodell, D.A., Curtis, J.H., and Brenner, M., 1995, Possible role of climate in the collapse of Classic Maya civilization: Nature, v. 375, p. 391–394.

Hodell, D.A., Brenner, M., and Curtis, J.H., 2005, Terminal Classic drought in the northern Maya Lowlands inferred from multiple sediment cores in Lake Chichancanab (Mexico): Quaternary Science Reviews, v. 24, p. 1413–1427.

Leyden, B., 1987, Man and climate in the Maya Lowlands: Quaternary Research, v. 28, p. 407–414, doi: 10.1016/0033–5894(87)90007-X.

McIntyre, S.C., 1993, Reservoir sedimentation rates linked to long-term changes in agricultural land use: Water Resources Bulletin, v. 29, p. 487–495.

O'Hara, S.L., Street-Perrott, F.A., and Burt, T.P., 1993, Accelerated soil erosion around a Mexican highland lake caused by preshispanic agriculture: Nature, v. 362, p. 48–51.

Olson, G.W., 1981, Archaeology: Lessons on future soil use: Journal of Soil and Water Conservation, v. 36, p. 261–264.

Redman, C.L., 1999, Human impact on ancient environments: Tucson, University of Arizona Press, 288 p.

Rice, D.S., and Rice, P.M., 1990, Population size and population change in the central Petén lakes region, Guatemala, *in* Culbert, T.P., and Rice, D.S., eds., Precolumbian population history in the Maya lowlands: Albuquerque, University of New Mexico Press, p. 123–148.

Rice, D.S., Rice, P.M., and Deevey, E.S., 1985, Paradise lost: Classic Maya impact on a lacustrine environment, *in* Pohl, M., ed., Prehistoric lowland Maya environment and subsistence economy: Peabody Museum Papers, v. 77, p. 91–105.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.H., and Guilderson, T.P., 2002a, A 4000-year lacustrine record of environmental change in the southern Maya lowlands, Petén, Guatemala: Quaternary Research, v. 57, p. 183–190, doi: 10.1006/qres.2001.2305.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.H., Martin, J.B., Anselmetti, F.S., Ariztegui, D., and Guilderson, T.P., 2002b, Influence of vegetation change on watershed hydrology: Implications for paleoclimatic interpretation of lacustrine $\delta^{18}O$ records: Journal of Paleolimnology, v. 27, p. 117–131, doi: 10.1023/A:1013535930777.

Schwartz, N.B., 1990, Forest society: A social history of Peten, Guatemala: Philadelphia, University of Pennsylvania Press, 320 p.

Simmons, C.S., Tarano, T., and Pinto, Z., 1959, Clasificacion de reconocimiento de los suelos de la Republica de Guatemala: Guatemala City, Guatemala, Ministerio de Agricultura, 1000 p.

Manuscript received 26 February 2007
Revised manuscript received 21 May 2007
Manuscript accepted 25 May 2007

Printed in USA