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Recovery of the forest ecosystem in the tropical lowlands of northern Guatemala after disintegration of Classic Maya polities

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ABSTRACT

We employed paleolimnological methods to investigate tropical forest recovery and soil stabilization that followed abandonment of agricultural systems associated with disintegration of Classic Maya polities ca. A.D. 800–1000. We used lithological, geochemical, magnetic, and palynological data from sediment cores of Lake Petén Itzá in the Maya Lowlands of northern Guatemala. Sediment core chronology was developed using radiocarbon dates on terrestrial wood and charcoal fragments. Our results indicate that in the absence of large human populations and extensive farming activities, Petén forests recovered under humid climate conditions within a span of 80–260 yr. Soil stabilization postdates pollen evidence of forest regrowth stratigraphically, and required between 120 and 280 yr. We conclude that the tropical forest ecosystem in the watershed of Lake Petén Itzá had been reestablished by the early Postclassic Period (A.D. 1000–1200).

INTRODUCTION

Ancient Maya population decline during the terminal Classic Period (ca. A.D. 800–1000) in lowland Guatemala (Fig. 1) was associated with abandonment of regional agricultural systems. This demographic decline occurred following a long episode of sustained occupation that began ca. 1000 B.C., and initiated regional forest recovery and soil stabilization. Several paleolimnological studies in the Maya Lowlands found evidence of environmental recovery associated with decreased anthropogenic pressure, but the exact timing and dynamics of forest regrowth and soil stabilization remained elusive, due to the difficulty of establishing reliable sediment core chronologies and to spatial and temporal variations of human impact on the landscape (Wiseman, 1985; Leyden, 1987; Brenner et al., 1990, 2002; Islebe et al., 1996; Johnston et al., 2001; Rue et al., 2002; Wahl et al., 2006). Dating lake sediment records from the region is challenging because radiocarbon dates on bulk sediments are confounded by hard-water-lake error (Deevey and Stuiver, 1964). The problem arises because old carbon from local limestone bedrock and soils can enter lake water as dissolved bicarbonate and be incorporated into lacustrine organic matter. Aside from the challenge of developing reliable core chronologies, it remained unclear whether reforestation after the Classic Maya Period (ca. A.D. 250–1000) was exclusively a consequence of reduced anthropogenic stress, as some have suggested (Deevey et al., 1979; Wiseman, 1985), or if it was associated, in part, with increasing regional rainfall (Hodell et al., 2000; Brenner et al., 2002). We investigated these complex interactions among climate, environment, and humans in the Maya Lowlands using a well-dated sediment record from Lake Petén Itzá that spans approximately the past 1000 yr.

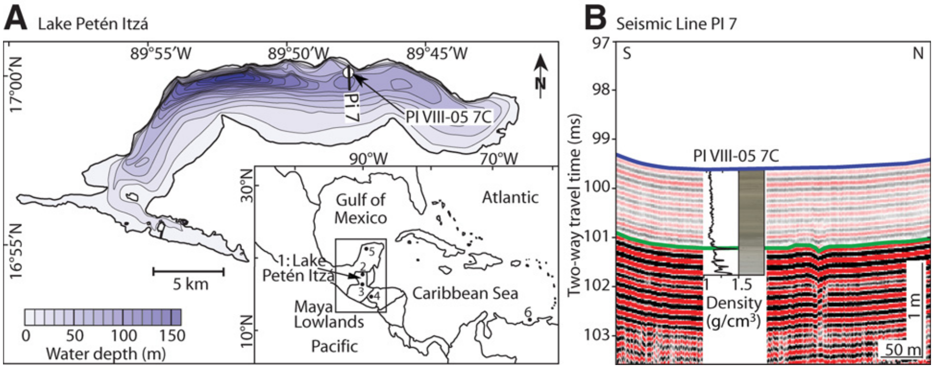

Figure 1. A: Bathymetric map of Lake Petén Itzá, with location of sediment core PI VIII-05 7C (core 7C) along seismic line PI7. Inset shows map of circum-Caribbean region with sites from the Maya Lowlands mentioned in this study: 1—Lake Petén Itzá (this study), 2—Mirador Basin (Wahl et al., 2006), 3—Laguna Las Pozas (Johnston et al., 2001), 4—Petapilla Swamp, Copan Valley (Rue, 1987), 5—Aguada X'caamal (Hodell et al., 2005), 6—Cariaco Basin (Haug et al., 2001, 2003). B: Bulk density with scan of core 7C superimposed on seismic image collected along seismic line PI7 (Anselmetti et al., 2006; location in A). Density contrast at transition from clay to gyttja results in high-amplitude reflection in seismic record.

Previous studies throughout the Maya Lowlands (Fig. 1) displayed considerable variability with respect to the apparent timing of forest recovery and soil stabilization after the Classic Period. Forest recovery is indicated in regional pollen records by a transition from a savanna-like landscape to a closed-canopy forest that appears similar to early Holocene, pre-Maya vegetation. Soil stabilization is marked by a reduction in inorganic detrital input, i.e., the end of rapid watershed soil erosion. Pollen studies from the shallow southern basin of Lake Petén Itzá (Islebe et al., 1996; Curtis et al., 1998) and from the Mirador Basin (Wahl et al., 2006) point to rapid forest recovery and soil stabilization within 150 yr after the disintegration of Maya political systems

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between A.D. 800 and 1000. Studies from the Petapilla Swamp, Honduras (Rue, 1987; Rue et al., 2002; Webster et al., 2005), and from Laguna Las Pozas in the Río de la Pasión drainage, Guatemala (Johnston et al., 2001), suggested that forest regeneration began after A.D. 1200, long after the decline of Classic Maya populations. Poorly dated pollen records from small, shallow lakes in the Petén savannas (Brenner et al., 1990; Leyden, 2002) even suggested that forest regrowth in Petén was delayed until the Spanish conquest in the sixteenth century A.D.

STUDY SITE

Lake Petén Itzá (16°55′N, 89°50′W) is the deepest and largest lake in the lowland Neotropics of Central America (maximum depth ~160 m, area ~100 km^2) (Fig. 1). It is located in the Department of Petén, northern Guatemala, in the heart of the Maya Lowlands. Lake Petén Itzá occupies a closed basin and its water level varies in response to the changing ratio between evaporation and precipitation (Hillesheim et al., 2005; Hodell et al., 2008). Lake Petén Itzá is located in a climatically sensitive region where rainfall is highly seasonal and related to the migration of the Intertropical Convergence Zone and the Azores-Bermuda high-pressure system (Hastenrath, 1984).

METHODS

In August 2005, short sediment cores were retrieved from Lake Petén Itzá with a gravity corer. Core locations were selected based on high-resolution seismic data collected in 1999 (Anselmetti et al., 2006). In this study we focused on core PI VIII-05 7C, hereafter referred to as core 7C. Core 7C was 106 cm long and was collected in ~60 m of water (Fig. 1). Past climate and environmental change was inferred from multiple variables, including sedimentology, elemental geochemistry, magnetic susceptibility, and pollen from the late Holocene sediment archive. The chronology for core 7C was based on ^{14}C ages of terrestrial wood and charcoal samples (Table DR1 in the GSA Data Repository[1]), thereby avoiding dating problems associated with hard-water-lake error (Deevey and Stuiver, 1964). Radiocarbon ages were measured using the accelerator mass spectrometry facility at ETH, Zurich. An age-depth model was developed using a depositional P sequence model (k = 3) of the OxCal 4.1 calibration program (https://c14.arch.ox.ac.uk). The approach assumes that depositional processes are random and incorporates a priori information on sample stratigraphic position, following a Bayesian mathematical approach (Bronk Ramsey, 2008). All dates are reported in calibrated calendar years B.C. or A.D. (2σ error ranges). Late Holocene vegetation changes in the region were inferred from shifts in fossil pollen assemblages throughout the sediment record. Pollen data were grouped by ecological preference: tropical forest elements, pine and temperate elements, disturbance elements, and spores and algae (see the Data Repository).

RESULTS

The calibrated calendar age at the base of core 7C (106 cm) is estimated to be between A.D. 880 and 1140 (Fig. 2). This indicates that the core represents deposition over a time span of 810–1070 yr. The average sedimentation rate in core 7C was ~1 mm/yr. Sedimentological and geochemical characteristics were used to divide core 7C into four lithologic units, I to IV, from bottom to top (Fig. 3). Lithologic units, variations in organic matter and carbonate content, changes in magnetic susceptibility, and shifts in calcium concentration are shown in Figure 3. The date on basal sediments of unit I (106–96 cm) has a range from A.D. 880 to 1140, and the date at the top of unit I is between A.D. 1020 and 1180. Sediments at the base of unit II (96–66 cm) were dated to between A.D. 1020 and 1180, while uppermost sediment in unit II was dated to between A.D. 1280 and 1410. Assuming a constant sedimentation rate, bottom sediments of unit III (66–28 cm) date to between A.D. 1280 and 1410, and topmost sediments date to between A.D. 1700 and 1760. Lowermost sediments of unit IV (<28 cm) were deposited between A.D. 1700 and 1760, whereas the youngest sediments at the top of unit IV are assumed to represent modern deposits.

Pollen results from core 7C are shown as a percentage diagram in Figure 2D (also see Fig. DR1 in the Data Repository). The pollen percentage diagram was divided into four zones from bottom (1) to top (4) on the basis of plant ecological preferences. Sediments at the base of pollen zone 1 (106–98 cm) date to between A.D. 880 and 1140, while those at 98 cm date to between A.D. 980 and 1160. Pollen was rare in this zone and relative abundances could not be calculated. Pollen zone 2 (98–79 cm) ranges from its lower boundary, dated to between A.D. 980 and 1160, to its upper boundary, dated to between A.D. 1160 and 1270. This zone is dominated by tropical, moist forest elements such as *Brosimum*

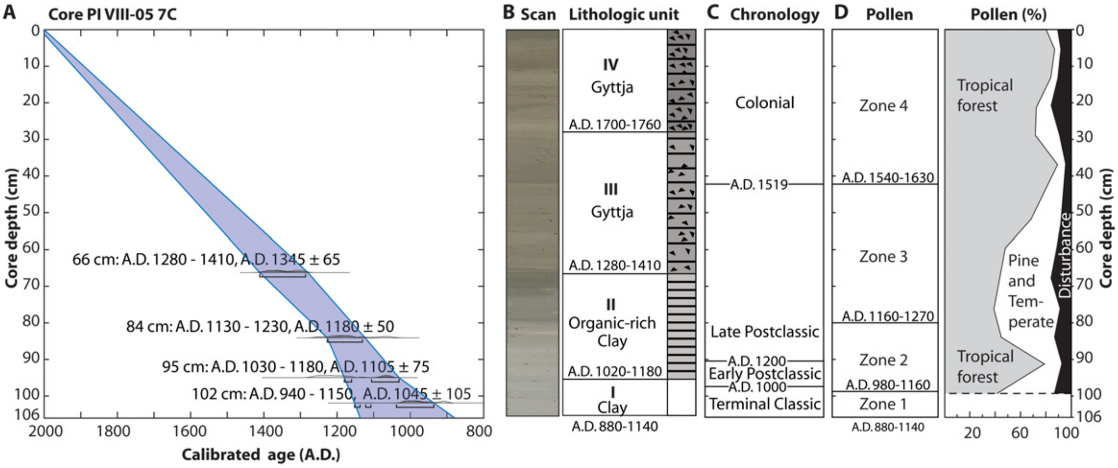

Figure 2. A: Calibrated ^{14}C ages (cal yr A.D.) measured on terrestrial organic matter (2σ error ranges) versus depth for Lake Petén Itzá core PI VIII-05 7C (core 7C). OxCal 4.1 depositional P sequence model (k = 3) after Bronk Ramsey (2008) was used to build age-depth model for the core. B: Stratigraphic column with lithologic units, with range of ages (cal yr B.P.) of boundaries, and photographic scan of core 7C. C: Generalized archaeological chronology (dates are from Rice and Rice, 1990, 2004; Demarest et al., 2004; Adams and MacLeod, 2000; Sharer and Traxler, 2006). D: Pollen zones and pollen percentage diagram of core 7C (detailed pollen diagram in Fig. DR1; see footnote 1).

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[1] GSA Data Repository item 2010150, methods, Table DR 1(AMS ^{14}C samples of core PI VIII-05 7C) and Figure DR1 (pollen percentage diagram for Lake Petén Itzá, core PI VIII-05 7C), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

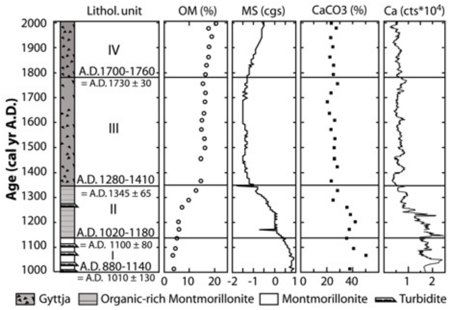

Figure 3. Lithologic, geochemical, and magnetic susceptibility data for Lake Petén Itzá core PI VIII-05 7C versus age in calibrated years A.D. From left to right: stratigraphic column with lithologic units, weight percent organic matter (OM, %), magnetic susceptibility (MS, cgs), weight percent calcium carbonate ($CaCO_3$, %), and calcium elemental (Ca) concentration (counts per second, cts × 10^4).

alicastrum, Moraceae, *Ficus*, Fabaceae, Euphorbiaceae, *Guettarda combsii*, Myrtaceae, Meliaceae, *Myrica*, and Sapotaceae. Local elements like fungal spores and Cyperaceae also occur in pollen zone 2. Pollen zone 3 (80–43 cm) has a lower boundary dated to between A.D. 1160 and 1270, and an upper boundary dated to between A.D. 1540 and 1630. In this zone, a change from dense forest vegetation to a more open, savanna-like landscape is indicated by a decline in relative abundance of tropical forest elements Moraceae and *Brosimum*, and a coincident increase in *Pinus* (pine), *Quercus* (oak), *Alnus*, Asteraceae, and Poaceae (grasses). Melastomataceae, typical in disturbance vegetation, have values between 1% and 6%. Other disturbance elements with low values in pollen zone 3 are *Croton*, *Celtis*, *Cecropia*, *Trema*, and Solanaceae. Pollen grains of *Ulmus* were detected in the sample at 56 cm depth. Pollen zone 4 (43–0 cm) is characterized by tropical lowland dry forest taxa that are typical of recent vegetation in Petén, with abundant *Brosimum alicastrum* and other Moraceae. Minor forest disturbance is indicated by *Cecropia*, *Celtis*, and *Ceiba*.

DISCUSSION

Human Ecology in Petén at the Terminal Classic to Early Postclassic Transition

Major economic, political, and demographic changes are evident in the archaeological record of the Petén Lakes region during the Terminal Classic (A.D. 800–1000) and Early Postclassic (A.D. 1000–1200) Periods (Rice and Rice, 1990, 2004; Demarest et al., 2004; Adams and MacLeod, 2000; Sharer and Traxler, 2006). These changes occurred at the end of a protracted, ~750-yr episode of population growth and political integration in the southern Maya Lowlands that was associated with the expansion of both intensive agriculture in the form of terraces and raised fields (Turner, 1974; Turner and Harrison, 1981) and extensive slash-and-burn clearance of tropical forest (Lentz and Hockaday, 2009). Such deforestation promoted increased soil erosion, leading to a characteristic inorganic detrital deposit in most lakes and wetlands in Petén termed Maya Clay (Deevey et al., 1979; Brenner et al., 1990; Beach et al., 2006; Anselmetti et al., 2007; Mueller et al., 2009).

Sediments of bottommost unit I, deposited between about A.D. 880 and A.D. 1180, possess characteristics of the Maya Clay. This clay unit thus indicates high detrital input into the lake, coinciding roughly with the Terminal Classic Period (Fig. 2). Hence, continued rapid clay deposition following the Classic Maya Period (A.D. 250–1000) indicates sustained unstable soil conditions, reflecting persistent open vegetation around Lake Petén Itzá during this period. This is in accord with the low pollen concentrations in unit I, as high detrital input further diluted the low influx of pollen grains in pollen zone 1, deposited between A.D. 880 and 1160. Open vegetation suggests persistent human disturbance around Lake Petén Itzá during the Terminal Classic Period. This finding is consistent with archaeological data that indicate people moved from the nearby Petexbatún and Río Pasión River areas into the Petén Lakes region during the Terminal Classic Period (Rice and Rice, 2004), and suggests that the Petén Lakes area was more politically stable and environmentally favorable than adjacent regions. Open vegetation in the Terminal Classic Period may, however, simply reflect delayed ecosystem recovery after widespread anthropogenic deforestation during the Classic Maya Period.

The transition from pollen zone 1 to zone 2 is dated between A.D. 980 and 1160, and represents the reestablishment of closed tropical vegetation, beginning in the Early Postclassic Period. The shift is characterized by tropical forest elements such as Moraceae, *Brosimum alicastrum*, and *Ficus*. The lithologic transition from unit I to unit II is dated between A.D. 1020 and 1180, representing the end of the phase of high detrital input, i.e., the end of rapid soil erosion in the Petén Itzá watershed, as indicated by decreasing magnetic susceptibility values (Fig. 3). Consequently, we suggest that since ca. A.D. 900, in the absence of large human populations and extensive agricultural activity, (1) Petén forests recovered within a span of 80–260 yr, and (2) soil stabilization required between 120 and 280 yr, stratigraphically postdating pollen evidence for forest recovery. This small discrepancy between the apparent timing of forest regrowth and soil stabilization may be a consequence of pollen rain reflecting regional vegetation shifts, while sedimentological and geochemical data reflect local, watershed-specific erosion intensity. Other studies that focused on agricultural expansion and deforestation on the southern Yucatán Peninsula over the past 50 yr (e.g., the Southern Yucatán Peninsular Region, SYPR Project) indicate that forest recovery to a pre-agricultural state might be reached in 50–90 yr, following agricultural abandonment (Turner et al., 2001; Lawrence et al., 2004).

Pollen assemblages of zone 2, deposited during the Early Postclassic Period, represent the period of reestablishment of closed tropical vegetation containing high percentages of *Brosimum alicastrum*, Moraceae, *Ficus*, *Guettarda combsii*, and Sapotaceae, suggesting moist climate conditions. Local elements like fungal spores and Cyperaceae in zone 2 indicate marsh-like shore vegetation, supporting the inference for wetter conditions at that time. Thus, we suggest that reduced forest clearance, combined with more humid climate conditions, promoted rapid forest regeneration around Lake Petén Itzá at the beginning of the Early Postclassic Period (ca. A.D. 1000). This differs from the conclusions of several previous studies suggesting that vegetation regrowth in Petén was attributable exclusively to reduced anthropogenic stress (Deevey et al., 1979; Wiseman, 1985). Our findings support the hypothesis proposed in some earlier studies, i.e., that climate also contributed to the reforestation process (Rue, 1987; Brenner et al., 1990, 2002; Hodell et al., 1995, 2000; Curtis et al., 1996). Increased humidity after A.D. 1000 has also been documented in other paleoclimate records from the circum-Caribbean region, and is associated with the phase referred to as the Medieval Warm Period, from ca. A.D. 950–1300 (Haug et al., 2001, 2003). Results of the SYPR Project suggest that the critical ecosystem nutrient affecting forest regrowth is phosphorus (Lawrence et al., 2007).

CONCLUSION

We used lithological, geochemical, magnetic, and palynological data from a sediment core spanning an ~1000 yr period, taken in Lake Petén Itzá, to reconstruct the dynamics of environmental recovery in the Guatemalan lowlands associated with demographic and political changes at the end of the Maya Classic Period. The pollen record indicates that tropical forest in Petén recovered within 80–260 yr after major demographic decline and abandonment of regional agricultural systems. Reforestation occurred during a relatively moist period, implying a climate contribution to the recovery process. Soil stabilization stratigraphically postdates pollen-documented forest regrowth, and required between 120 and 280 yr. We conclude that regional tropical vegetation had been reestablished and that soils were stabilized in the Petén Itzá watershed by the Early Postclassic Period (A.D. 1000–1200). The timing of post-Maya reforestation and soil stabilization in the Maya Lowlands probably varied somewhat across the landscape, depending upon the earlier intensity of human occupation and environmental characteristics such as water availability, topography, geology, and soil type. Nonetheless, this study provides important insights into tropical forest ecosystem recovery following a prolonged period of human vegetation disturbance.

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REFERENCES CITED

Adams, R.E., and MacLeod, M.J., eds., 2000, The Cambridge history of the native peoples of the Americas, Volume II, Mesoamerica, Part 1: Cambridge, Cambridge University Press, 571 p.

Anselmetti, F.S., Ariztegui, D., Hodell, D.A., Hillesheim, M.B., Brenner, M., Gilli, A., McKenzie, J.A., and Mueller, A.D., 2006, Late Quaternary climate-induced lake level variations in Lake Petén Itzá, Guatemala, inferred from seismic stratigraphic analysis: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 230, p. 52–69, doi: 10.1016/j.palaeo.2005.06.037.

Anselmetti, F.S., Ariztegui, D., Brenner, M., Hodell, D.A., and Rosenmeier, M.F., 2007, Quantification of soil erosion rates related to ancient Maya deforestation: Geology, v. 35, p. 915–918, doi: 10.1130/G23834A.1.

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

Brenner, M., Leyden, B.W., and Binford, M.W., 1990, Recent sedimentary histories of shallow lakes in the Guatemalan savannas: Journal of Paleolimnology, v. 4, p. 239–251, doi: 10.1007/BF00239697.

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.

Bronk Ramsey, C., 2008, Deposition models for chronological records: Quaternary Science Reviews, v. 27, p. 42–60, doi: 10.1016/j.quascirev.2007.01.019.

Curtis, J.H., Hodell, D.A., and Brenner, M., 1996, Climate variability on the Yucatan Peninsula (Mexico) during the past 3,500 years, and implications for Maya cultural evolution: Quaternary Research, v. 46, p. 37–47, doi: 10.1006/qres.1996.0042.

Curtis, J.H., Brenner, M., Hodell, D.A., Balser, R.A., Islebe, G.A., and Hooghiemstra, H., 1998, A multi-proxy study of Holocene environmental change in the Maya lowlands of Petén: Journal of Paleolimnology, v. 19, p. 139–159, doi: 10.1023/A:1007968508262.

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., 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.

Demarest, A.A., Rice, P.M., and Rice, D.S., 2004, The terminal classic in the Maya lowlands: Assessing collapses, terminations, and transformations, *in* Demarest, A.A., et al., eds., The terminal classic in the Maya lowlands: Boulder, University of Colorado Press, p. 45–572.

Hastenrath, S., 1984, Interannual variability and the annual cycle: Mechanisms of circulation and climate in the tropical Atlantic sector: Monthly Weather Review, v. 112, p. 1097–1107, doi: 10.1175/1520-0493(1984)112<1097:IVAACM>2.0.CO;2.

Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., and Roehl, U., 2001, Southward migration of the intertropical convergence zone through the Holocene: Science, v. 293, p. 1304–1308, doi: 10.1126/science.1059725.

Haug, G.H., Guenther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A., and Aeschlimann, B., 2003, Climate and the collapse of Maya civilization: Science, v. 299, p. 1731–1735, doi: 10.1126/science.1080444.

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.W., 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, doi: 10.1038/375391a0.

Hodell, D.A., Brenner, M., and Curtis, J.H., 2000, Climate change in the Northern American Tropics since the last ice age: Implications for environment and culture, *in* Lentz, D.L., ed., Imperfect balance: Landscape transformations in the Precolumbian Americas: New York, Columbia University Press, p. 13–38.

Hodell, D.A., Brenner, M., Curtis, J.H., Medina-Gonzalez, R., Rosenmeier, M.F., Guilderson, T.P., Chan-Can, E.I., and Albornaz-Pat, A., 2005, Climate change on the Yucatan Peninsula during the Little Ice Age: Quaternary Research, v. 63, p. 109–121, doi: 10.1016/j.yqres.2004.11.004.

Hodell, D.A., and 12 others, 2008, An 85-ka record of climate change in lowland Central America: Quaternary Science Reviews, v. 27, p. 1152–1165, doi: 10.1016/j.quascirev.2008.02.008.

Islebe, G.A., Hooghiemstra, H., Brenner, M., Curtis, J.H., and Hodell, D.A., 1996, A Holocene vegetation history from lowland Guatemala: The Holocene, v. 6, p. 265–271, doi: 10.1177/095968369600600302.

Johnston, K.J., Breckenridge, A.J., and Hansen, B.C.S., 2001, Paleoecological evidence of an Early Postclassic occupation in the southwestern Maya lowlands: Laguna Las Pozas, Guatemala: Latin American Antiquity, v. 12, p. 149–166, doi: 10.2307/972053.

Lawrence, D., Vester, H.F.M., Pérez-Salicrup, D., Eastman, J.R., Turner, B.L., II, and Geoghegan, J., 2004, Integrated analysis of ecosystem interactions with land-use change: The southern Yucatán peninsular region, *in* DeFries, R., et al., eds., Ecosystem interactions with land use change: American Geophysical Union Geophysical Monograph 153, p. 277–292.

Lawrence, D., D'Odorico, P., Diekmann, L., DeLonge, M., Das, R., and Eaton, J., 2007, Ecological feedbacks following deforestation create the potential for a catastrophic ecosystem shift in tropical dry forest: National Academy of Sciences Proceedings, v. 104, p. 20696–20701.

Lentz, D.L., and Hockaday, B., 2009, Tikal timbers and temples: Ancient Maya agroforestry and the end of time: Journal of Archaeological Science, v. 36, p. 1342–1353, doi: 10.1016/j.jas.2009.01.020.

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

Leyden, B.W., 2002, Pollen evidence for climatic variability and cultural disturbance in the Maya lowlands: Ancient Mesoamerica, v. 13, p. 85–101, doi: 10.1017/S0956536102131099.

Mueller, A.D., Islebe, G.A., Hillesheim, M.B., Grzesik, D.A., Anselmetti, F.S., Ariztegui, D., Brenner, M., Curtis, J., Hodell, D.A., and Venz, K.A., 2009, Climate drying and associated forest decline in the lowlands of northern Guatemala during the late Holocene: Quaternary Research, v. 71, p. 133–141, doi: 10.1016/j.yqres.2008.10.002.

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, 123–148.

Rice, P.M., and Rice, D.S., 2004, Late Classic to Postclassic transformations in the Peten lakes region, Guatemala, *in* Demarest, A., et al., eds., The Terminal Classic in the Maya lowlands: Collapse, transition, and transformation: Boulder, University of Colorado Press, p. 125–139.

Rue, D.J., 1987, Early agriculture and early Postclassic Maya occupation in western Honduras: Nature, v. 326, p. 285–286, doi: 10.1038/326285a0.

Rue, D.J., Webster, D., and Traverse, A., 2002, Late Holocene fire and agriculture in the Copan Valley, Honduras: Ancient Mesoamerica, v. 13, p. 267–272, doi: 10.1017/S095653610213210X.

Sharer, R.J., and Traxler, L.P., 2006, The ancient Maya (sixth edition): Stanford, California, Stanford University Press, 555 p.

Turner, B.L., II, 1974, Prehistoric intensive agriculture in the Mayan Lowlands: Science, v. 185, p. 118–124.

Turner, B.L., II, and Harrison, P.D., 1981, Prehistoric raised-field agriculture in the Maya Lowlands: Science, v. 213, p. 399–405.

Turner, B.L., II, and 16 others, 2001, Deforestation in the southern Yucatán peninsular region: An integrative approach: Forest Ecology and Management, v. 154, p. 353–370.

Wahl, D., Byrne, R., Schreiner, T., and Hansen, R., 2006, Holocene vegetation change in the northern Peten and its implications for Maya prehistory: Quaternary Research, v. 65, p. 380–389, doi: 10.1016/j.yqres.2005.10.004.

Webster, D., Rue, D.J., and Traverse, A., 2005, Early *Zea* cultivation in Honduras: Implications for the Iltis hypothesis: Economic Botany, v. 59, p. 101–111.

Wiseman, F.M., 1985, Agricultural and vegetation dynamics of the Maya collapse in central Petén, Guatemala, *in* Pohl, M.D., ed., Prehistoric lowland Maya environment and subsistence economy: Cambridge, Massachusetts, Harvard University Press, p. 63–71.

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