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Impacts of the ancient Maya on soils and soil erosion in the central Maya Lowlands

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Abstract

Many studies across the central and southern Maya Lowlands of Belize, Guatemala, Honduras, and Mexico have produced records of land degradation, mostly sedimentation and soil erosion, during the ancient Maya period from before 1000 BC to the Maya Collapse of c. AD 900. This paper provides new data from two sites (Blue Creek and Cancuén), synthesizes more than a decade of the authors' research in Guatemala, Belize, and Mexico, and synthesizes other findings from this region. These research projects analyzed more than 100 excavations in upland and depression sites, cored lakes and wetland sediments, and studied sediments in the field and laboratory using radiocarbon dating, a battery of soil chemistry tests, stratigraphic analysis, magnetic susceptibility, elemental analyses, and artifact identification. Our objective was to date when sedimentation and soil erosion occurred, identify stable surfaces, and correlate them with the state of knowledge about past land use. These findings indicate three general epochs of accelerated soil erosion and identified two major paleosols. The three waves of soil erosion occurred in the Preclassic period (c. 1000 BC to AD 250), the Late Classic (AD 550 to 900), and in the last several decades. The major paleosol ('*Eklu'um*') in these sites is a well-developed Mollisol or Vertisol that started forming in the early Holocene and was buried in either the Preclassic or Classic periods (AD 250 to 900). At some sites the *Eklu'um* paleosol lies beneath sediments with a fainter paleosol, which in turn lies buried below Classic period and later sediments. This picture shows higher than expected soil erosion linked to the region's first pioneer farmers in the Preclassic and less than expected soil erosion in the Late Classic when population peaked and land use was the most intensive. In other regions like Cancuén, Guatemala, however, most soil erosion occurred during the Maya Late Classic (AD 550–830). Erosion here was intense but short-lived: depressions record 1–3 m of aggradation in two centuries. A third epoch of accelerated soil loss and aggradation arose with the rapid land use changes brought by new pioneers during the last several decades.

Keywords: Soil erosion; Paleosols; Maya Lowlands; Maya Civilization; Land degradation

1. Introduction

Since the early 20th century some scholars have linked the thin soils of the southern Maya Lowlands (Fig. 1) with ancient Maya induced soil erosion and sedimentation, to which some even attributed the Maya Collapse of c. AD 900 (Bennett, 1926; Thompson, 1954; Morley, 1956). This proposition, however, did not consider that the region's limestone bedrock could naturally weather in this tropical climate and leave only thin residual soils behind. The hypothesis of severe ancient Maya land degradation, deforestation and soil erosion, evolved into subsequent notions of sound resource management by a complex civilization living in hostile environment of a seasonally dry tropical forest (Dunning and Beach, 2004b). Since the early 1990s, however, the so-called 'Pristine Myth' that Pre-Columbian peoples caused little environmental alteration has fallen to an onslaught of empirical studies showing long,

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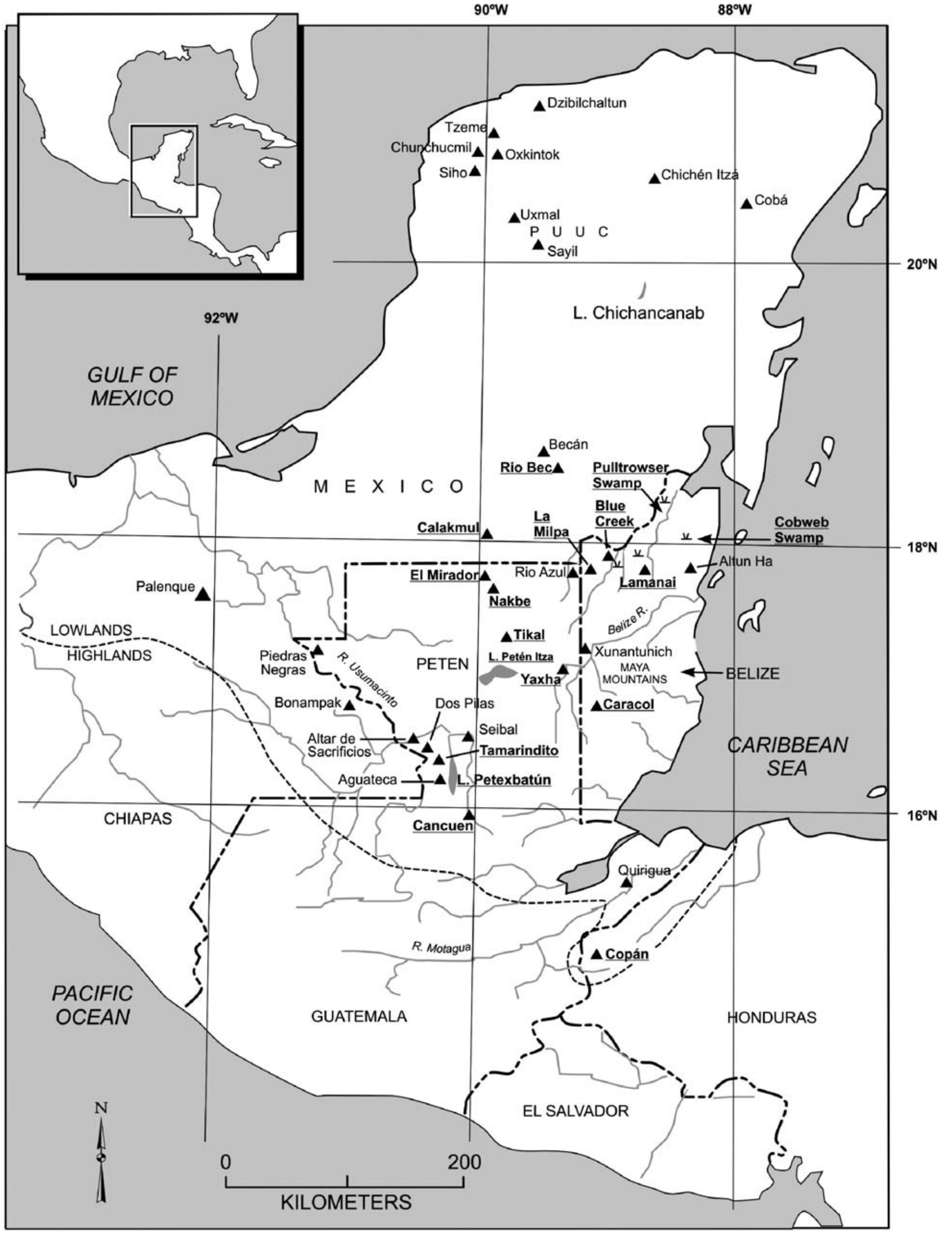

Fig. 1. The Maya Lowlands, sites mentioned in the text are underlined.

persistent human impacts (both land degradation and active conservation) on the slopes of Mesoamerica (Deevey et al., 1979; Butzer, 1992; Denevan, 1992; O'Hara et al., 1993; Beach, 1998a; Beach et al., 2002, 2003; Brenner et al., 2003; Fisher et al., 2003; Webster et al., 2004).

This article presents new data and synthesizes our own studies and other work about the magnitude and chronology of erosion and sedimentation in the central and southern Maya Lowlands (Fig. 1). In many cases, ancient Maya pioneer deforestation led to erosion and deposition that buried pre-Maya paleosols we designate collectively as *Eklu'um*, the Mayan term for "black earth" (Dunning and Beach, 2004a). Although the *Eklu'um* paleosol occurs widely in the central and southern Maya lowlands, this paper constructs a more complex picture that includes both extensive and abrupt ancient Maya episodes of soil erosion and sedimentation and equally as extensive ancient Maya land manipulation to maintain soil beds against erosion and the vicissitudes of water (Beach et al., 2002). This paper shows that ancient Maya impacts on this region's geomorphology varied greatly over time and location. Land degradation triggered by pioneer agriculture and forest clearance in the Preclassic was pervasive, but indigenous soil conservation that evolved into successful land management was also pervasive. Moreover, this widespread sequence of pioneering degradation and evolving conservation has played out in many, but not all, situations from antiquity to the present.

1.1. Background

Lake core and catena studies point to high levels of soil erosion in the Maya Lowlands during periods of land use change such as deforestation (Deevey et al., 1979; Furley, 1987; Wingard, 1996; Beach, 1998a). We have examined modern soil erosion by rill, interrill, and gully processes since 1991 in parts of this region, observing, for example, the complete truncation of soils to bedrock along the Petexbatun River in Guatemala's Petén over a ten year period (Beach and Dunning, 1995; Beach, 1998a). Two major factors limiting quantities of soil erosion here are the initial thinness of soils and the high infiltration rates into the porous limestone parent material. In the example above and another reported below from Blue Creek, Belize, soil erosion preceded rapidly after deforestation (removing whole soil profiles) but slowed significantly with reduced sediment supplies and when the porous limestone parent material became exposed, thus accelerating infiltration. In Blue Creek, however, gullying continued to incise into the limestone saprolite after complete soil removal.

The scientific literature includes much speculation about ancient Maya soil erosion, based on archaeological and geomorphological lines of evidence. For example, Stevens (1964: 301–302) in his *Soils of Middle America* argued that since many Maya sites across the Petén occur in association with the shallow Rendzina soils of the Yaxa Series (Simmons et al., 1959), the region's soils are still undergoing rejuvenation from accelerated erosion during the Maya Classic. Further, Stevens (1964: 302) mentioned the hypothesis that soil depletion caused the Late Classic Maya collapse as outlined by Morley (1956: 71) and proposed by H.H. Bennett (1926). Later, Bennett (1945: 166) estimated 50% of Mexico and 30% of Guatemala had been "ruined for cultivation, nearly ruined and severely affected". More recent studies have underscored the severity of soil erosion across this region, including Furley (1987) and Beach et al. (2003) in Belize, Abrams and Rue (1988) and Wingard (1996) in Honduras, and Deevey et al. (1979), Beach (1998a), and Rosenmeier et al. (2002) in Guatemala's Petén.

From outside the Maya Lowlands, and extending the implications of this paper, has been the debate about erosion at Lake Patzcuaro in Michoacan, Mexico. At this site O'Hara et al. (1993) used data derived from sediment cores to argue that erosion rates were at least as high during the Late Preclassic and the Postclassic as they were after the Spanish conquest and questioned whether indigenous methods held any meaningful environmental advantages for us today. In contrast, a study from the same lake basin by Fisher et al. (2003) used evidence from cores, trenches, and exposures to paint a different picture. They argued that the Preclassic degradation was the second most severe episode of soil erosion and that it was caused by initial land clearance rather than long-term land-use practices. Fisher et al. (2003) concluded that the most severe soil erosion occurred after the epidemics of the European conquest decimated indigenous populations and their ability to maintain soil conservation practices. They also argued that intensive management by high populations of Precolumbian Tarascans produced low levels of erosion.

Thus far for the Maya lowlands there are only a few syntheses and a handful of mostly unrelated studies and historical hypotheses for the trends of land degradation. The information available suggests that the relationship of humans and soil erosion in broader Mesoamerica is highly complicated and there are no simple correlations between population levels and geomorphic impacts (Beach et al., 2006).

2. Area descriptions

The Maya Lowlands is both a cultural and physical region, named after a series of related cultures that have occupied the region of generally low, limestone terrain with tropical wet and dry climates (Fig. 1). This section provides a brief cultural history to explain terms and possible trends of land degradation on soils over time. Evidence of human impacts in this region may date from as early as about 3000 BC, but Maya culture and its impacts on the environment started in the Early Preclassic by 1000 BC and have lasted with major ebbs and flows to the present (Pohl et al., 1996; Brenner et al., 2003). The Preclassic lasted till AD 250, followed by the Early Classic from AD 250–500, and the Late and Terminal Classic, which ran from AD 550 to 950. Scholars have proposed collapses and/or declines at the end of the Preclassic, between the Early and Late Classic (AD 500–550), and in the Terminal Classic (AD 830–950) in Guatemala's Petén and later in Mexico's Yucatán (Demarest et al., 2004), though millions of Mayan speakers still live across the region (Schwartz, 1990). The Maya attained extremely high population levels in the Late Classic, when many urban centers had sustaining dense populations that stretched far into the hinterlands (Culbert and Rice, 1990; Turner, 1990). This paper focuses on the central and southern Maya lowlands to understand the general erosion trends of a relatively broad (c. 100,000 km^2) and relatively flat, karst region, influenced by over 3000 years of human impacts.

The specific focus here is on the central and southern Maya Lowlands that range from 15.45°N to 19°N latitude and 88°W to 91°N longitude and from sea level to about 300 m in elevation (Fig. 1). This region is founded on the Cretaceous and Tertiary Yucatán platform. The platform ranges from little surface gradient and low elevation in the northern and coastal plains to a region with about 250 m of regional relief, structured by a series of normal faults and carved by karst dissolution and fluvial erosion (Fig. 2). Abrupt elevation change occurs along scarps near the fault lines and mogotes and dolines in the uplifted central platform. The central Yucatán is a karstic plain with internal

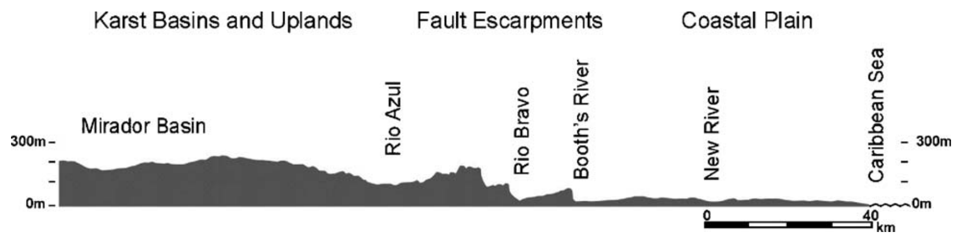

Fig. 2. Maya Lowlands topographic cross section from northern Guatemala through northern Belize (after Dunning et al., 2002, Fig. 2).

drainage and has no perennial rivers, but the peripheries have rivers and low gradient floodplains. This research focuses largely on depressions, including lowland floodplain and coastal plain areas below 20 m in elevation and upland karst depressions (regionally called *bajos* and *aguadas*, ranging in karst terms from ponors to poljes) up to 100 m elevation (Day, 1993). Many of the *bajos* are seasonally inundated, and many of the near sea-level dolines, floodplains, and coastal plain areas are perennial lakes and wetlands. The floodplain sites in this study are connected to the general fluvial and karst geomorphic systems that flow into the coastal plain and Gulf of Mexico or Caribbean. Sea-level changes have influenced sedimentation in these low lands and depressions (Pohl et al., 1996). The upland karst depressions, however, respond mainly to local geomorphic conditions since most connect to sea level only through ephemeral karst caves. Although there is low local relief, the wide range in drainage conditions and some soil variation supports a wide variety of ecosystems, from tropical deciduous forest to low scrub forest and saw-grass swamps (Brokaw and Mallory, 1993; Greller, 2000).

The soils of the region have similar factors of formation: limestone or carbonate parent materials, low relief (though short and steep karstic and scarp slopes), tropical forest vegetation, and high rainfall with a pronounced dry season. Rainfall varies from 1200 to more than 2500 mm, and average temperature varies only from around 26 to 29 °C. Annual rainfall variation from year to year is high, and the dry season lasts about half of the year from December to May. The region has both Udic and Ustic soil moisture regimes and has an Isohyperthermic temperature regime (Van Wambeke, 1987). Along the flat northern plain and short, steep Petén slopes, many soils are similar to the sequence in Beach (1998b) and the catena in Beach (1998a). Thin tropical Rendolls, some Alfisols, and Inceptisols occupy upland slopes and Histosols and Vertisols have formed in most depressions.

The study region includes five research areas across the southern Maya Lowlands: the Blue Creek Region, the adjacent Three Rivers area, the Pasión River area, the Northern Petén area, and the southern Yucatán area (Fig. 1). Another three areas across the central and southern Lowlands provide more information: the Copán area of Honduras, the Central Petén Lakes area around Tikal, and northern Belize. All of these areas, except Belize, have about 100–200 m of regional relief caused by the relative uplift associated with normal faulting. Belize has both lower relative relief on the coastal plain and much higher relief in the crystalline Maya Mountains in the south.

Factors that accelerate soil erosion across this region include frequent, intensive convective storms in the wet season, high runoff and piping in expanding clay soils (which naturally are well structured with blocky or granular structure), moderate slope lengths with some steep sections, tropical forests undergoing rapid deforestation, and little modern conservation. Like many other places, deforestation has accelerated typical slope processes such as raindrop impact, sheet, rill, gully, piping, waterfall, and mass wasting.

3. Methods

No full sediment budget is yet available for the Maya region (Beach, 1994), though much basic soils and geomorphic information is gradually coming into better focus from settlement archaeology projects (Dunning and Beach, 2004b). Our main proxies for erosion in this landscape are the parts of the sediment budget lost on slopes and retained in depressions, which represent a significant amount of the non dissolved load in the region's internally drained karst sinks that have few drainage connections to their underlying caves and aquifers. Since 1990, we have measured rills, gullies, and soil truncation, and excavated hundreds of trenches, auger holes, and archaeological units, many below the water table to bedrock, recording artifacts, ecofacts, and cultural and natural stratigraphy (Beach et al., 2002, 2003; Dunning et al., 2002).

Our field soil analyses for Cancuén and Blue Creek reported here and for the Petexbatun and Three Rivers region synthesized here included color, texture, structure, carbonate content (by HCl reaction), and other soil descriptive terms as outlined by the Soil Survey Manual (USDA, 1993). Samples were analyzed at the University of Wisconsin–Milwaukee Physical Geography and Soils Lab, the Milwaukee Soils Lab, and the Cornell Nutrient Analysis Laboratories, and analyses included pH, exchangeable and total *P*, concentration of K^+, Ca^{2+}, and Mg^+ cations by atomic absorption (*P* and *K* used the Bray 2 method because of high carbonate), particle size by pipette method, organic carbon (Walkley–Black), and Loss on Ignition organic content (Table 3). The Smithsonian Center for Materials Research and Education (SCMRE) provided further detailed analyses by inductively coupled plasma-mass spectrometry ICP-MS of the inorganic chemistry of soil samples from the Pasión River area (Fig. 5).

This regional synthesis discussed below uses both soil geomorphic studies based on soil excavation units and paleoenvironmental studies based on lake or wetland cores. The lake and wetland core studies used multiple methods including assays of sediment chemistry, grain-size analysis, sedimentation rates, and magnetic susceptibility, and many ecological proxies like pollen and oxygen isotopes (Deevey et al., 1979; Hodell et al., 1995; Dunning et al., 1998; Brenner et al., 2002; Rosenmeier et al., 2002). To estimate soil erosion, Furley (1987) and Beach (1998a) used soil catena studies; Dunning and Beach (1994) used the RUSLE (Revised Universal Soil Loss Equation) and soil truncation estimates; and Wingard (1996) modeled soil erosion and fertility depletion with the EPIC (Erosion Productivity-Impact Calculator) Model over time for Copán, Honduras. Most other studies trenched through aggraded depressions (Beach et al., 2002; Dunning et al., 2002), and profiled and dated strata, often identifying pre-Maya paleosols by darker colors, more organic matter, artifacts, changes in carbon isotope signatures, radiocarbon dating, and increased magnetic susceptibility and elemental concentrations (Fig. 4). Gunn et al. (2002), for example, distinguished the Preclassic stable soil surfaces with multiple proxies, especially in the lower profile heavy metal layers identified through elemental analysis by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

4. Results and analyses

The general soil profiles in these sites start from limestone or saprolitic limestone on which an indicator paleosol formed, which in turn lies beneath 50 to 200 cm of sediment with one or two later episodes of pedogenesis. The surface of the paleosol in most sites dates to 1000–2000 or more years ago and is well developed, meaning that it is thicker, darker, contains more clay, has well developed structure, and often has manganese and iron nodules. In most cases studied thus far, the sediments that cover the paleosol and the top of the paleosol have artifacts, generally horizontally laid potsherds, presumably deposited and worked in from above. Based on radiocarbon dates and the artifacts, the *Eklu'um* paleosol thus generally represents the first soils encountered by the ancient Maya and some group of processes over Maya times buried these soils.

The Blue Creek region lies where the coastal plain and the karst plateau meet (Fig. 3). The main site of Blue Creek, like many ancient Maya sites, hugs an escarpment ecotone between well drained uplands with dolines and mogotes, seasonally drained larger karst depressions (bajos), and perennially wet lower coastal plains. Excavations occurred in all three zones. In the perennial wetland excavations a widespread paleosol (often a Vertisol or Mollisol fringed by Histosols in lower areas) occurs buried about 90 to 180 cm. The representative sequence has a thick, black, organic clay-rich Ab horizon buried by 100 cm of lighter, coarser, often laminated sediments (Table 3). The Ab horizon usually has both a 10–15 cm-thick Ab1 and 20–40 cm-thick Ab2. The Ab1 is a mixed transition (mottled with light- and black-colored sediments) of the overlying sediments and the paleosol, which is usually black in color (N2/0 in Munsell), and has 4 to more than 10% organic carbon. The Ab2 and Ab1 both date to the Preclassic, and in the examples in Table 1, the Ab1 at a depth of 110 cm dated to 200 BC to AD 70 (calibrated, 2 sigma) and the Ab2 at 130 cm dated to 400 to 170 BC (calibrated, 2 sigma). These radiocarbon dates place the transition from a stable to an aggrading environment in the Late Preclassic (400 BC–AD 250). Artifacts do not contradict these dates because they are undatable or are Preclassic. The only evidence for dating the period of sedimentation are artifacts that date across the ancient Maya periods (1200 BC–AD 900), and a radiocarbon date from charcoal in the upper aggraded sediments of a nearby excavation (at a depth of 66 cm) that dates to the Early to Late Classic, AD 460–650 (calibrated, 2 sigma) (Beach et al., 2004). Ancient Maya ditches, probably Late Classic in origin, occur within the AD 460–650 date and run through almost the entire aggraded sequence of 90–180 cm. These lines of evidence point to Late Preclassic through

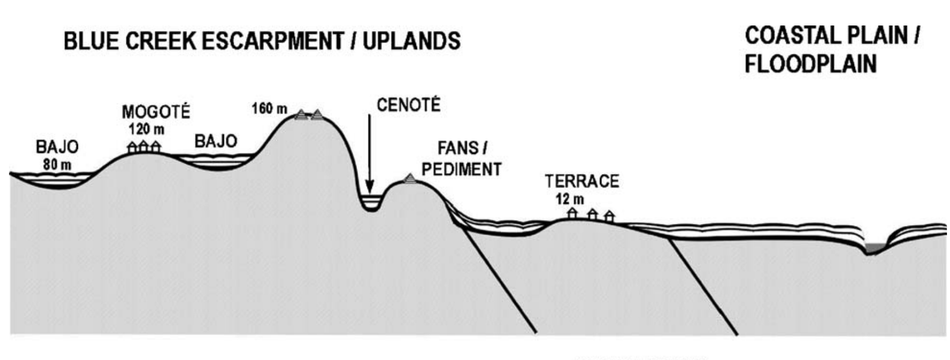

Fig. 3. Blue Creek Landscape Diagram.

Table 1
Paleosols: depths and dates

Location beta number	Environment	Depth to Eklu'um or Ab[a] (cm)	^{14}C dating, cal 2 sigma, wood or charcoal	Artifacts ceramics or lithics
Blue Creek Upland	Collapse doline			Preceramic Paleosol, all eras above
Beta-182608 AMS	Unit 66M Ab1	135	Modern	
Beta-183586 AMS	Unit 66M Ab	290	2140–1940 BC	
Beta-182610 AMS	Unit 66M Ab 5	350	2475–2195 BC	
Blue Creek Plain	Alluvial fan			Preceramic Paleosol, all eras above
Beta-195854 AMS	Unit 66S Ab2/3	147	930–810 BC	
Beta-195856 AMS	Unit 66S Ab5	306	2590–2450 BC	
Blue Creek Plain	Floodplain wetlands			Preclassic Paleosol, all eras above
Beta-195857 AMS	Unit 66 R	66	AD 460–650	
Beta-158427	Unit 56 E Ab1	110	200 BC–AD 70	
Beta-158428	Unit 56 A Ab2	130	400–170 BC	
Cancuén				
Beta-167477	Dissolution doline	110–140	AD 530–680	Late Classic to Paleosol
Cancuén	Backslopes	40–48		Late Classic to Paleosol
Cancuén	Footslopes	125–180		Late Classic to Paleosol

[a] Ab: buried A horizon.

Late Classic aggradation with erosion and gypsum precipitation, which coincides with the periods of high population densities and drying conditions (Brenner et al., 2003). The current surface soil is thick and also has strong melanization, which implies a significant, but difficult to quantify, period of pedogenesis. The only evidence to quantify this period of pedogenesis comes from a regional estimate that Histosols formed about 1 mm year^{-1}, which yields a 400 year formation for the deepest, 40 cm-thick O horizons (Kim and Rejmánková, 2002).

Also at Blue Creek, we excavated a ~4 m deep trench to study sedimentation rates in a collapsed doline and a 3 and 2 m deep trench in two alluvial fans (Fig. 3). The sinkhole excavation was down to limestone saprolite at about 4 m deep. Just above this at 351 cm lay the top of the oldest paleosol (identifiable by melanization) that had lithics and abundant charcoal, which dated to 2475–2195 BC (calibrated, 2 sigma). This also corresponds to the date for a stratum of increased charcoal in core taken from a nearby swamp. Charcoal from another paleosol above this at 290 cm dated to 2140–1900 BC (calibrated, 2 sigma) and the upper most paleosol at 130 cm dated as modern. Extensive modern erosion in the region starting with the first clearance in 1958 (Hinckley, 1997) probably aggraded the upper 130 cm. This sinkhole shows both the early start of erosion even before the Preclassic Period and significant modern erosion.

The alluvial fans represent a more complicated erosion and deposition environment, because the two excavated ones contain four and five paleosols. In fan excavation unit 66S, charcoal from Ab5, the lowest paleosol, at a depth of 307 cm dated to 2450 to 2590 BC (calibrated, 2 sigma) and one from just below the upper paleosol at 147 cm dates to 810 to 930 BC (calibrated, 2 sigma). All the paleosols except the lowest and oldest have ancient ceramics (unidentifiable in most cases) embedded through them. The few ceramics in the lowest eroded sediments are consistently Preclassic in style, whereas ceramics above the upper paleosol are mixed. Thus in both the doline and fan sediments, charcoal dates the lowest paleosols to mid Holocene at least 2000 BC and much of the subsequent aggradation, from c. 3 m to about 1 m, occurs through the Preclassic period, since ceramics occur through these soils. These dates and sediments show two major points: the Holocene's first major erosion event occurred at the outset of the Maya era, and less sedimentation occurs in the Classic period, despite much higher populations and more intensive land uses (Adams et al., 2004).

The Three Rivers area to the south of Blue Creek has similar environments except for no coastal plain, though it does have low lying river valleys that run into the nearby coastal plain. Across this region's upland and lowland depressions are two buried soils, a lower paleosol, 95 to 180 cm deep, that generally dates from Preclassic and earlier (55–2465 BC) and an upper Paleosol, 50–75 cm deep, that generally dates to the Early Classic or early Late Classic (AD 15–555) (Beach et al., 2003: 151; Dunning et al., 2002). This sequence suggests two episodes of erosion and sedimentation: an early episode between the Preclassic and Late Classic and a later phase that occurs with the Classic period. The Preclassic phase has about the same depth of sediment accumulation (between 50–75 cm), suggesting similar quantities of soil erosion even though human populations were much lower in the Preclassic.

In the large karst depressions (called *bajos*) of northern Guatemala considerable variability exists both between and within basins. A bajo adjacent to the large Preclassic site of Nakbe yielded a paleosol interpreted as an ancient Histosol buried by disturbance associated with nearby urbanization (Jacob, 1995; Hansen et al., 2002). In contrast, in a bajo adjacent to the nearby Preclassic city of El Mirador, paleosols occurred in some soil excavations within localized depressions, but not in others (Dahlin et al., 1980; Dahlin and Dahlin, 1994). Paleosols occur widely through the sediments of the sprawling Bajo La Justa north of the ancient city of Yaxha (Dunning et al., 2002, in press). In a section of the huge Bajo de Santa Fe, however, there was a Preclassic paleosol in one group of trenches, but none in another group located in nearly identical topographical contexts separated by 1 km (Dunning et al., in press). The area investigated within the Bajo de Santa Fe has very little local relief and the paleosol lies generally at less than 50 cm depth. The variability between bajos clearly reflects the variation in human impacts and different drainage hydrology within these karst depressions even before the arrival of the Maya. The two oldest paleosols yet discovered within bajos are an apparent Histosol dated to 9610±360 BC (uncalibrated) buried at about 4 m depth in the Bajo de Santa Fe near Tikal (Cowgill and Hutchinson, 1963) and an Oxisol dated to 13,480 to 12,300 BC (uncalibrated) buried at a similar depth within the Dumbbell Bajo of northwestern Belize. The variability and complexity of environmental histories evident within bajos show that these sinks must be studied individually in order to understand the regional erosion histories (Dunning et al., in press).

In the Petexbatun region of the central Petén, a complex record of environmental impacts shows more early environmental change and less than expected change in the Late Classic (Dunning et al., 1998). Soil erosion and sedimentation evidence exists around upland fields and in lake cores taken at Laguneta Tamarindito that started by about 1000 BC. Our lake cores also showed surprisingly lower quantities of sedimentation in the Late Classic when human populations here reached their highest level. This period of lower than expected lake sedimentation correlates with a vast expansion of ancient Maya agricultural terraces as well as a soil landscape truncated by previous erosion (Beach, 1998a).

Finally, at Cancuén, in Guatemala's southern Petén state, soil stratigraphy in six separate depression and footslope excavations showed well developed paleosols buried at 110 to 180 cm (Fig. 4). Even some backslope soils have a distinct buried soil, though only at c. 40–50 cm depth. Cancuén's occupation is dominated by a short period of the Late Classic (Kovacevich et al., 2003), and indeed these excavations only yielded Late Classic artifacts down to the paleosols and no horizontally deposited ceramics below this (though some vertical or diagonal ceramics are embedded in the buried Vertisols through cracks). The buried soils at Cancuén are also easily distinguished by their chemical composition, which is evident in the aggraded sequence of a karst depression (Table 3) because the overlying Late Classic Maya sediments have at least three times more total *P* than the paleosol. Cook et al. (in press) demonstrated that the Late Classic soil floors overlying buried soils have significantly altered heavy metal and rare earth element (REE) chemistry. The elevated concentrations of heavy metals and REEs from areas of ancient human occupation not only aids in their distinction from the buried soils (Fig. 5), but also provides specific information on the location and nature of Maya land use in antiquity.

Fig. 4. Photo of Cancuén footslope excavation. Daesha Ramachandran is pointing to the Late Classic (AD 550–850) paleosol.

Radiocarbon dating of charcoal near the top of a paleosol buried at 1.1 m in a small karst depression (Table 3) dates it to the early part of the Late Classic (AD 530 to 680, calibrated, 2 sigma). At Cancuén the evidence suggests significant environmental change occurred over a short time period in the Late Classic because all of the colluvium is choked full of Late Classic artifacts and is sandwiched by the well developed pre-Late Classic paleo Vertisol and the surface Rendoll (Tables 1–3). Much of the erosion at this site must have been caused by urbanization since about half of the buried soils occurred close enough to the highly built up site core. Several sites with buried soils, nonetheless, occurred at significant distance from the urban construction and must have been covered by ancient agricultural erosion since they have both well developed buried paleosols and surface soils.

4.1. Regional synthesis

Essentially equivalent to the paleosols described here and the sediments that bury them are the 'Maya Clays' that occur in many depressions in the southern Maya Lowlands (Table 2) (Dunning et al., 1998). For example, in the coastal plain of northern Belize and the floodplain of the Belize River Valley comparable sequences of Preclassic surfaces are buried by Classic "Maya Clay" fill (Jacob and Hallmark, 1996; Pohl et al., 1996; Pope et al., 1996; Holley et al., 2000; Gunn et al., 2002).

Similarly, lake cores from the central Petén show evidence of these Maya Clays (Table 2) (Rice, 1996; Rosenmeier et al., 2002). The first major change in the sedimentation record comes from lake core pollen evidence

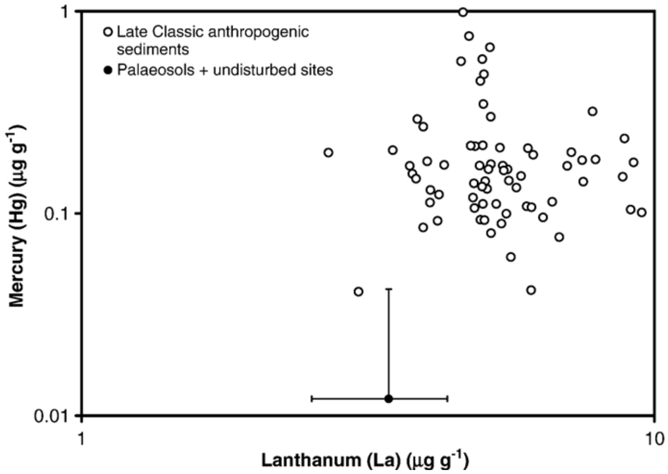

Fig. 5. Bivariate plot of the concentration of Mercury (Hg) and Lanthanum (La) in soils sampled from the floors of 2 Late Classic jade production workshops ($n=70$) and from palaeosols and undisturbed sites ($n=7$) at Cancuén, Guatemala.

of waning forests and waxing savanna at 3660 BC (Islebe et al., 1996) and lake core sediment derived from eroded soils by about 1000 to 1400 BC (Early Preclassic: 1500–900 BC) (Rosenmeier et al., 2002; Brenner et al., 2003). The early pollen evidence could be from the natural drying of the later Holocene, which was more conducive to savannas; yet as early as 1400 BC, upland erosion is finding its way into the lake basins and vegetation change shows widespread disturbance indicators. Indeed, many lake cores from this region show sediments associated with the upland diffusion of Archaic and Preclassic Maya deforestation and agriculture as thick and dense clay mineral layers sandwiched by much thinner organic sediments from the earlier Holocene below and Postclassic above (Brenner et al., 2003: 59). The evidence paints a picture of erosion and sedimentation starting soon after deforestation, despite the Preclassic's lower populations and meager stone tools. The sediments arrive with increased charcoal and pollen of maize and disturbance taxa.

In the broader Mesoamerican context, the first evidence of accelerated soil erosion appears after the Formative or Preclassic Period (2000 BC to AD 250). For example, soil erosion from land clearance occurs after 1600 BC, with clays deposited in the Mexican highland Lake Patzcuaro (O'Hara et al., 1993), and with wetland soil manipulation for agriculture in the Archaic and the Early Preclassic both in the Maya Lowlands and central Mexico (Sluyter, 1994; Jacob, 1995; Pohl et al., 1996).

The evidence from most of the studies of Maya Clays only gives us a broad date for the early phase of burial of the soil surface and a *terminus post quem* date when aggradation occurred. This sequence with the occasional upper paleosol strewn with artifacts suggests five general soil formation episodes: (1) early Holocene soil formation under tropical forest, (2) Preclassic and earlier erosion and sedimentation from pioneer farmers, (3) some cultural hiatus of stable soil formation at the end of Preclassic to the Late Classic, (4) Late Classic soil erosion and sedimentation, intense at some sites like Cancuén and Copán and less so in some places with extensive conservation like the Petexbatun, and (5) finally stable soil formation and recovery after the Maya Collapses in the 10th and 16th

Table 2
Paleosols and aggradation in literature with depth and dates

Location	Environment	Depth (cm) Sedimentation	Dating sedimentation or Paleosol	Citations
Pulltrouser and Cobweb, Northern Belize	Perennial wetland	Paleosol 140 75–200	1770–1950 BC 250 BC–AD 900 artifacts and ^{14}C	Pohl et al., 1996; Jacob, 1995; Pope et al., 1996
Douglas Swamp	Perennial wetland	Paleosol 140	1750–1590 BC	Pope et al., 1996
Nakbe, Northern Petén	Karst bajo-seasonal wetland	50–150	0–500 BC? artifacts and ^{14}C	Jacob, 1995; Hansen et al., 2002
Mopan R. Valley, Central Belize	Fluvial	140–190	350 BC–AD 550 artifacts	Holley et al., 2000
Rio Bravo, Northern Belize	Fluvial	90–105	250 BC–AD 250 ^{14}C	Beach et al., 2003
Sierra de Agua	Fluvial	74	1490–940 BC ^{14}C	Beach et al., 2003
La Milpa Bajo	Karst bajo-seasonal wetland	90–170	1885–1620 BC ^{14}C	Beach et al., 2003
Calakmul, southern Yucatán	Karst bajo-seasonal wetland	90–110	370–780 BC ^{14}C	Gunn et al., 2002
Petén, Bajo La Justa	Karst bajo-seasonal wetland	80–290	AD 75 ^{14}C	Dunning et al., 2002
Belize Three Rivers	Karst bajo-seasonal wetland	Ab1[a]=30–60 Ab2=100–130	Ab1=AD 400 ^{14}C Ab2=390 BC ^{14}C	Dunning et al., 2002
Copán, Honduras	Fluvial	70–>200	AD 700; EPIC modeling	Wingard, 1996: 229

[a] Ab: buried A horizon.

Table 3
Typical soil profiles: Cancuén, Blue Creek, and La Milpa[1]

Cancuén Doline Horizon depth cm	Texture % clay	% Sand	% Silt	Soil St[2]	Munsell color	pH	Exc K^+ Mg kg^{-1}	Exc Ca^{2+} Mg kg^{-1}	Exc Mg^+ Mg kg^{-1}	% OC (LOI × .56)	Total P Mg kg^{-1}	Periods: artifacts and ^{14}C
A1 0–12	C 57	13.1	29.7	gr	10YR2/1	5.3	250	6248	1023	4.5	781	Late Classic
A2 12–40	C	–	–	sbk	10YR2/1							
A/C 40–52	C 67	8.1	25.4	col	10YR4/1	6.4	198	6625	2461	3.5	347	
Cg 52–110	C 84	3.2	12.6	col	Mottled 5Y4/1 and 10YR6/8	7.6	247	10 065	1690	2.4	325	Late Classic
Ab 110–150	C 89	3.8	7.7	Gr/ma	N2/0	7.9	166	9660	3026	3.4	89	Late Classic
2Cg 150–190	C 74	8.7	16.9	ma	5GY4/1	8.1	226	8725	3340	1.7	143	No artifacts
Blue Creek Floodplain 56 B horizon dpth cm	**Texture[§] % Clay**	**% Sand**	**% Silt**	**Soil Sr[2]**	**Munsell color**	**pH**	**Exc K^+ Mg kg^{-1}**	**Exc Ca^{2+} Mg kg^{-1}**	**Exc Mg^+ Mg kg^{-1}**	**% OC (LOI × .56)**	**Av P Mg kg^{-1}**	**Periods: Artifacts and ^{14}C**
Ap 0–17	SiL 2	21	76	gr	10YR3/1	7.8	37	40151	566	4.5	60	Mixed
Oy 17–41	SiL 26	19	55	pl	5Y4/1	7.7	180	48146	2688	30	43	Mixed
Cgy1 41–84	C 64	21	15	pl	N4 mottled 7.5YR5/6	7.6	71	39614	1054	7.4	45	none
Cgy2 84–89	fSL	–	–	pl	5Y4/1 10YR2/2	7.7	–	–	–	–	–	none
Ab1/Cy3 89–100	SiL 7	22	71	pl	2.5Y4/0 mottled 10YR8/2	7.7	46	27898	507	9.3	17	Preclassic
Ab2 100–135	C 74	3	23	gr/pl	2.5Y3/0 motted 10YR8/2	7.6	104	18980	1157	8.7	10	Preclassic
2Cg 135–180+	C 69	6	25	ma	5GY6/1	7.7	123	15966	1180	4.4	12	none
La Milpa[1] Floodplain RB2–10 dpth cm	**Texture % Clay**	**% Sand**	**% Silt**	**Soil Sr[2]**	**Munsell color**	**pH**	**Exc K^+ Mg kg^{-1}**	**Exc Ca^{2+} Mg kg^{-1}**	**Exc Mg^+ Mg kg^{-1}**	**% OC (WB)**	**Total P Mg kg^{-1}**	**Periods: Artifacts and ^{14}C**
Oe 0–1				gr	10YR2/1							Mixed
A 1–34	C 93.8	0.5	5.7	sbk	10YR2/1	6.9	49	11094	2894	1.3	14	Mixed
C 34–91	C			sbk	10YR4/1							Mixed
Ab 91–119	C 71	6.4	22.6	sbk	2.5Y3/0	8.0	25	9200	3798	1.2	58	Preclassic
Cg 119–158	C			ma	N5/Gley	–	–	–	–	–	–	None

[1]Beach et al., 2003: 152.
[2]C = clay, SiL = silt loam, fSL = fine sandy loam.
[3]Gr = granular, co = columnar, sbk = subangular blocky, ma = massive.

centuries AD (Beach et al., 2003). These soil trends are not universal, but they are widespread at both urban and rural archaeological sites.

4.2. Modern soil erosion

There have been few direct studies of soil erosion in the Maya Lowlands; yet high rates of modern soil erosion are obvious across the region (Table 4). To link our studies of ancient erosion with modern evidence, we surveyed gully and sheet and rill erosion at three sites. On 18–25° slopes near Blue Creek in northwestern Belize cleared for housing, gullies in 2004 forming over five years were 40 to 110 cm deep, 80–260 cm wide, and 10–30 m long. This recent gullying and earlier sheet and rill erosion removed all the 20–45 cm of soil from the 30% of the slopes in channels and was incising into bedrock limestone. Similarly, recent gullying after clearance at the site of Cancuén, Guatemala created a

Table 4
Soil erosion measurements

Region	Slope position	Type	Depth, width, length m; shape	Citations and dates
Blue Creek	Shoulder, back, 18–25 degree slopes	Gullies cut through soil into rock	D:.4–1.1; .9–2; 8–40; trapezoidal	Measurements 2000–2004; 5 yrs
Cancuén	Shoulder, back, 18–20 degree slopes	Gully cut through soil into rock	D:1.3–2.4; 2–6; 28; u-shaped to trapezoidal	Measurements 2002; recent
Petexbatun	Shoulder, back, 3–14 degree	Rill, interrill	.01–.02 truncation per year	Beach and Dunning, 1995; Beach, 1998a
Belize	Shoulder, back	Rill, interrill	0–.05 truncation per year	Furley, 1987

gully 130–240 cm deep, 2–6 m wide, and 28 m long. Beach and Dunning (1995) and Beach (1998a) reported rill and interrill and gully erosion in the Petexbatun uplands that in one case eroded soil to bedrock over the shoulder and backslopes, and truncated more than 35% to more than 70% of soil profiles in a decade after clearance. Furley (1987) working on karst slopes in central Belize reported more modest erosion, though after just one milpa cycle of 2–3 years. He reported this graphically, which showed the first 7 of the 11 soil depths truncated by c. 2 to 10 cm.

4.3. Ancient soil conservation

The Maya Lowlands also provide a long history of slope conservation (Turner, 1974), reported since the 1920s (Cooke, 1931). In studies over the last decade, scores of ancient Maya agricultural terraces dated to the Classic and mostly to the Late Classic (Beach and Dunning, 1995, 1997; Beach et al., 2002). These excavations show at least six different types of land use management techniques and as many construction techniques. The Maya built them at the household to the corporate group level, and in some places, such as like Caracol, terrace systems dominate the landscape a thousand years after abandonment. In other parts of the Maya Lowlands like Tikal and Copán, with equally complex city-states and erosive landscapes, the literature records little evidence of conservation (Beach et al., 2002). Indeed, some modern studies, like Wingard (1996) and Abrams and Rue (1988), have recalled the closer links between collapse and landscape degradation presented by Bennett (1926) (Dunning and Beach, 2000). Where extensive, complex terracing of the Classic period occurred (northern Belize and the Petexbatun of Guatemala), there was also less sedimentation evidence at this time (Beach, 1998a; Beach et al., 2002, 2003). Where and when no such conservation features occurred (such as Cancuén in the Late Classic), there was ample erosion and sedimentation evidence. For Copán, Wingard (1996) also published evidence for high rates of erosion and sedimentation in the Late Classic with limited conservation features, but here he linked it to population growth and farmers expanding up the slopes for the first time, after taking up the large expanses of fluvial bottomland. In the case of reduced sedimentation in the Late Classic period, the causes may have been both exhausted sediment supply (Gilbert, 1877) and the expanding conservation features. Certainly the terraces hold more soils from antiquity (including dated paleosols, see Beach et al., 2002), but given the tendency of modern erosion to truncate soils to bedrock, Preclassic erosion also may have stripped much of the sediment supplies where early farmers moved onto hillslopes.

5. Discussion and conclusions

This study brings together a number of empirical studies that show the extent and timing of Maya impacts on geomorphology or land degradation in terms of sedimentation and indirectly soil erosion. Sedimentation in karst depressions and floodplains started before, or in the Early Preclassic periods in many parts of the Maya Lowlands. Here many depression soils that had formed in equilibrium since the start of the Holocene were now beginning to be covered by artifact-laden sediment eroded from surrounding slopes. Likewise, many lake cores show the so-called 'Maya Clay' starting to deposit over the organic sediments that had slowly accumulated since the start of the Holocene. In the examples where archaeological evidence shows Preclassic and earlier occupation, the records of sedimentation also start in these early periods. In some sites (the Petexbatun, the Three Rivers, and the Belize River), the lake core and soil evidence show lower than expected rates of soil erosion in the Late Classic, when populations were highest. This correlates with the wide diffusion of many types of terracing that may have conserved soils when ancient Maya populations were greatest (Turner, 1990; Beach et al., 2002). This may also be partly the result of sediment exhaustion, in which erosion may have already removed the readily erodible component of upland soils. All the sites show a return to low levels of soil erosion after the Maya Collapse of the 9th and 10th Centuries AD. Lake sediments return as slowly accumulating organic gyttja and the aggraded sediments start to form topsoils generally 1 to 2 m above the buried pre-Maya topsoils. Hence, until the 20th Century the ancient Maya were the major agent of geomorphic change, both in accelerating erosion and modifying slopes with terracing to conserve soils.

The aggradation that buried soils in the Maya Lowlands was human induced because the epochs of erosion so obviously parallel the Maya expansions in the Preclassic and Late Classic. The later period also corresponds to the general drying associated with the Classic Period Maya droughts (Hodell et al., 1995, 2001), which could have contributed to increased erosion. But the present state of knowledge about climate change over the Maya period is insufficient to suggest how it might have changed soil erosion rates, given the unambiguous connection between accelerated erosion and deforestation in the contemporary landscape. At present, land use causes of soil erosion are clearer than climatic ones. Based on the propinquity of some of the research sites to urban areas and the fact that erosion/deposition occurred during periods of Maya urban development, urban construction must have some role in this aggradation. Nonetheless, most of the buried paleosol sites in this study are far from major urban sites and must have been buried by erosion from rural land-use.

In examples from this paper, human impacts on the Maya Lowlands were the largest agents of change in the Holocene. Soil erosion occurred over much of this region as pioneer farming and urban construction expanded onto slopes in the Preclassic and Classic in many areas, or during the Classic period alone at Cancuén and Copán. This caused aggradation of depressions and valleys that buried once stable soils and lacustrine sediments that had formed through the Holocene. At Cancuén, collapse came before the Maya could respond with conservation. At Copán and the central Petén lakes region, the Maya built few conservation features (footslope terraces and artificial benches) around depressions to counteract accelerated erosion. In many other regions, like the Petexbatun, the Three Rivers Region, Caracol, the Belize River Valley, and the Rio Bec region, the Maya manipulated their landscapes into terraces and diversions mainly during the Late Classic. This stemmed upland erosion, and the sheer number and labor implications of these terraces suggest their value to the Maya. The fact so many terraces are still in place after more than 1000 years shows the geomorphic longevity of their slope management and the surprisingly slow rate of slope movement under the thick cover of tropical forest. The main cause of slope movement during the last millennium of high forest stability has been creep and tree fall and root throw (Beach, 1998a). A new cycle of erosion has returned in the last decades as new groups of pioneers in increasing numbers have once again deforested the slopes, and rain drops, sheets, rills and gullies have increased slope movement dramatically.

A distant correlation within Mesoamerica is with Lake Patzcuaro in the Mexican highlands. Our findings here parallel those of Fisher et al. (2003) for Lake Patzcuaro in three ways: they show evidence for very early sedimentation and erosion, geographic and chronological connections to urban development, and less-than-expected soil erosion during periods of high populations and intensive indigenous management. The urban connection is especially true around Cancuén and the urban sites of northwestern Belize like La Milpa, and the lower erosion and intensive land use connection is especially true for northwestern Belize and Tamarindito. Since these regions have very different and heterogenous environments and histories, any correlations are interesting and may give us insight into the broad processes of land degradation.

There are both costs and benefits in synthesizing research. The prevailing idea of the first part of the 20th C. that Precolumbian Maya environmental impacts were small was not a universal view. Indeed, Bennett (1926) proposed soil erosion as a cause of the Maya collapse, which Huntington (1915) had already ascribed to climatic change. There is ample evidence for large-scale soil erosion from uplands and sedimentation in depressions that followed a pioneering path through the Maya Lowlands and that it started before the Late Classic when population pressure was highest. There is also ample evidence for lower soil erosion at several sites during the periods of highest human populations and intensive land uses (Beach et al., 2002). Precolumbian people obviously caused widespread geomorphic change, both in terms of soil erosion and soil conservation. But their impacts started near the beginning of their civilization, which persisted more than a thousand years beyond the start of the sediment cascade.

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