1 **ANCIENT MAYA IMPACTS ON THE EARTH'S SURFACE: AN EARLY**
2 **ANTHROPOCENE ANALOG?**

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22 **Abstract**

23 The measure of the “Mayacene,” a microcosm of the Early Anthropocene that occurred from *c.*
24 3000 to 1000 BP, comes from multiple Late Quaternary paleoenvironmental records. We
25 synthesized the evidence for Maya impacts on climate, vegetation, hydrology and the
26 lithosphere, from studies of soils, lakes, floodplains, wetlands and other ecosystems. Maya
27 civilization had likely altered local to regional ecosystems and hydrology by the Preclassic
28 Period (3000-1700 BP), but these impacts waned by 1000 BP. They altered ecosystems with vast
29 urban and rural infrastructure that included thousands of reservoirs, wetland fields and canals,
30 terraces, field ridges, and temples. Although there is abundant evidence that indicates the Maya
31 altered their forests, even at the large urban complex of Tikal as much as 40% of the forest
32 remained intact through the Classic period. Existing forests are still influenced by ancient Maya
33 forest gardening, particularly by the large expanses of ancient stone structures, terraces, and
34 wetland fields that form their substrates. A few studies suggest deforestation and other land uses
35 probably also warmed and dried regional climate by the Classic Period (1700-1100 BP). A much
36 larger body of research documents the Maya impacts on hydrology, in the form of dams,
37 reservoirs, canals, eroded soils and urban design for runoff. Another metric of the “Mayacene”
38 are paleosols, which contain chemical evidence for human occupation, revealed by high
39 phosphorus concentrations and carbon isotope ratios of C₄ species like maize in the C₃–
40 dominated tropical forest ecosystem. Paleosol sequences exhibit “Maya Clays,” a facies that

41 reflects a glut of rapidly eroded sediments that overlie “Ekluum” paleosols. This stratigraphy is
42 conspicuous in many dated soil profiles and marks the large-scale Maya transformation of the
43 landscape in the Preclassic and Classic periods. Some of these also have increased phosphorous
44 and carbon isotope evidence of C₄ species. We synthesize and provide new evidence of Maya-
45 period soil strata that show elevated carbon isotope ratios ($\delta^{13}\text{C}$), indicating the presence of C₄
46 species in typical agricultural sites. This is often the case in ancient Maya wetland systems,
47 which also have abundant evidence for the presence of several other economic plant species.
48 The “Mayacene” of c. 3,000 to 1,000 BP was thus a patchwork of cities, villages, roads, urban
49 heat islands, intensive and extensive farmsteads, forests and orchards. Today, forests and
50 wetlands cover much of the Maya area but like so many places, these are now under the
51 onslaught of the deforestation, draining, and plowing of the present Anthropocene.

53 **Introduction**

54 Since Crutzen and Stoermer (2000) coined the term “Anthropocene,” studies using the term
55 have proliferated. Indeed, the term is now widespread in the mass media and across academic
56 disciplines, with at least three journals (*The Anthropocene*, *The Anthropocene Review*, and
57 *Elementa: Science of the Anthropocene*) and three Museum exhibits, planned and underway
58 (Scott Wing, pers. com.). The US National Research Council (NRC) has recognized that one of
59 their ‘grand challenges’ is to understand the nature of earth surface evolution in the
60 Anthropocene (NRC, 2010). Multiple disciplines are addressing the issue. Both scientists and
61 the broader public are aware that humans are having profound effects on Earth, but to quantify
62 the scale and rate at which human impacts are altering the planet, we must know about
63 background conditions and the chronology of change. One aspect of the Anthropocene
64 discussion has been its timing, i.e. when did the period of large-scale human impact begin? This
65 discussion has many precedents, from G.P Marsh’s (1864) *Man in Nature*, to Carl Sauer et al.’s
66 symposium in 1955 that led to *Man’s Role in Changing the Face of the Earth* (Thomas, 1956), to
67 B.L. Turner et al.’s (1993) *The Earth Transformed by Human Action*, to *The Americas before*
68 *and after 1492* (Butzer, 1992, 1993). Today, the concept of the Anthropocene transcends human
69 impacts on Earth surfaces to include planet-changing greenhouse gases especially since the start
70 of the Industrial Revolution (Ruddiman, 2013).

71 One expression of the ‘Early Anthropocene’ is in Central America, where the ancient Maya
72 had profound impact on a globally important tropical forest (Figs. 1, 13). Here we focus on the
73 “Mayacene” or Maya Early Anthropocene and on a reckoning of environmental changes caused

by ancient Maya Civilization from 3,000 to 1,000 BP, its global impacts, and its ‘golden spikes’ (i.e. stratigraphic markers). The “Mayacene” period had both natural and human drivers of environmental change, thus data from geomorphic and paleoecological records have elements of equifinality. The lines of evidence for how much the Maya changed their environment are the geomorphological, archaeological, paleoclimatological, and paleoecological records. Environmental changes inferred from pollen and plant macro-remains, transported sediment, altered soils, animal remains, human skeletal material and cultural artifacts, and models of land-surface and climate changes. Despite decades of research, we are still in our infancy for understanding these metrics of Maya environmental impact.

The “Mayacene” has at least six stratigraphic markers that indicate the period of large-scale change, and all have a common connection to Maya accelerated fires. One is the so-called “Maya Clay” (Deevey et al., 1979) (Fig. 6). We use the term “Maya Clay” to describe the clay-rich facies dated to the Maya period in lakes, karst sinks, floodplains, caves and wetland deposits, which are all variably aggrading environments. Other markers, sometimes categorized under the rubric of “Maya Clay,” are paleosol sequences (Fig. 6), which may be depositional or erosional under different circumstances, but both often indicate human land-use change (Beach et al., 2008). These include Anthrosols, or perhaps even ‘Mayasols’ (Fig. 11). Certini and Scalenghe (2011) argued that the “golden spikes” for the Anthropocene are anthropogenic soils, because they so clearly show changes from stability to instability in the geological record. A third marker of Maya Civilization are profiles of carbon isotope ratios that show increased $\delta^{13}\text{C}$ values in depositional sediments radiocarbon-dated to the Maya period (Table 2). These may occur in aggrading or equilibrium soil surfaces because the zone of ^{13}C enrichment from C_4 species occurs from the top to the rhizosphere, ~30 cm below the surface. Surface soils revert to

lower $\delta^{13}\text{C}$ values when C_3 forest species returned after the decline of Classic Maya culture. The fourth marker includes the remains of building materials and landscape modifications in the form of houses, terraces, roads, walls, and wetland fields, many of which are still evident on the landscape (Figs. 10, 12, 13). In the carbonate terrain of the Maya Lowlands, these markers are mostly limestone and its derivatives like plaster, ceramics, and fainter evidence of wattle and daub, with associated plant materials. Lidar mapping of these features has eclipsed past incremental improvements in remote sensing, and our knowledge of infrastructure markers of the “Mayacene” will soon accelerate (Chase et al., 2014). The fifth ‘golden spike’ is the widespread fingerprint of chemical enrichment of such elements as phosphorus and mercury, in sediments from the Maya era (Table 1). Although other elements are enriched by human activities, the greatest focus has been on phosphorus, with growing interest in heavy metals. A sixth metric of the “Mayacene” is the evidence for Maya-induced climate change.

All paleoenvironmental studies in the Maya region completed to date are still insufficient to quantify long-term human impacts relevant to global change research. Most work in the Maya area has focused on individual sites or site clusters, which undermines attempts to up-scale the findings. New efforts, however, through IHOPE-Maya, are addressing the global role of this past civilization (Chase and Scarborough, 2014).

1. Maya Environments

The Maya region covers about 350,000 km² and the Lowlands encompass about half this total. Mayanists often distinguish between the highland and lowland zones, but recognize that Maya civilization was not monolithic in time or space (Fig. 1). Here we focus on the tropical lowlands.

The Maya region is environmentally diverse in both its highland and lowland regions (Figs. 1, 2). The highlands include igneous, metamorphic, and sedimentary rocks built from volcanism, thrusting, folding, and tension. Structuring much of the lowlands is the Yucatán Platform, which is mostly Cretaceous and Tertiary marine limestone and evaporites (Hartshorn et al., 1984; Marshall, 2007; Perry et al., 2009). *Sascab*, a saprolitic limestone, often with a case-hardened outer surface, covers the limestone bedrock to variable depths (Darch, 1981).

Chicxulub Impact ejecta (King et al., 2004) crops out in late Cretaceous layers of the central and southern Maya Lowlands. Perry et al. (2009) suggested this as a possible source for sulfate-rich groundwater in the eastern part of the peninsula, which is down-aquifer from the numerous large karst sinks called *bajos* or *poljes* (Fig. 1). Minerals like gypsum and celestite make up the sulfur-rich material in these rocks, and dissolve readily in groundwater as it passes through the regolith on its way to the aquifer. The region's carbonate and evaporite rocks have evolved into an array of karst landscapes, each influenced by factors like the amount of rainfall, the composition of the carbonate rock (especially the amounts of calcium, magnesium and sulfur), the presence of faults and escarpments, the groundwater table elevation, the zone of interaction with sea water and interactions with soil and overlying vegetation (Marshall, 2007; Day, 2007).

Three west-east transects across the Yucatán Peninsula epitomize regional geomorphology (Fig. 2). Transect A crosses the north-central Yucatán through a low, Tertiary carbonate zone that has only ~100 m of local relief, mostly fashioned by the higher platform of the Sierrita de Ticul. This swath runs from the low elevation of the west coastal plain to the 100-m rise of Puuc and Sierrita sites and then down to the karst plain, 10-30 masl, to the slightly uplifted east coast. The karst landscape here is subtle, from the Maya sites of Canbalam to

Chunchucmil (Fig. 10), but well developed, with mogotes and dolines near Uxmal and Oxkintok, to the elongated caves systems near Tulum. Transect B from the west bisects the low deltaic plain of the Usumancinta River and rises up to 400 masl in the elevated interior of high escarpments and *bajos* before descending along a series of tilted normal faults and their magnesium-rich and hardened escarpments (Brennan et al., 2013) and valleys into the low-lying river valleys and high sandy pine savannas of northern Belize. The escarpments are weathered into steep mogote hills and depressions that range from ponors to *poljes* or *bajos* (Dunning et al., 2002). Transect B runs from the wetlands at the foot of Palenque to the escarpment and *bajo*-edge sites like Calakmul and down to the wetland-edge sites such as Blue Creek and the coastal plain sites, from Cuello to the Belize barrier reef. Transect C runs from the folded Cretaceous highlands through the low Cretaceous sedimentary rocks of central Petén and rises up the Maya Mountains and its Paleozoic intrusive pluton and surrounding metamorphic and igneous rocks, before it descends to the Belize reef. This swath runs from sites like Toniná in the Chiapas highlands to Ceibál in the Petén, south of the lake district, to Caracol and across the Maya Mountains to the reef. A series of east-west half grabens created the Petén lakes, near the boundary where the Tertiary marine sediments border Cretaceous deposits to the south (Mueller et al., 2010).

The two north-south transects (Fig.2) bisect the karst plain in the northern lowlands and rise into the elevated interior, crossing the Petén lowlands and the volcanic highlands of Guatemala and the Maya Mountains, where transect E continues through the Motagua River and ridges of its drainage basins. These swaths cover the northern sites of Chichén Itzá and Dzibilchaltún to the north and the great volcanic highland site of Kaminaljuyú and the river sites of Copán and Quiriguá to the south. Additionally, the Pacific side has a complex array of rivers

and alluvial fans on its coastal plain, and Maya sites, some dating to the Early Preclassic (Neff et al., 2006).

Ecosystems

A north-to-south transect through the Maya Lowlands shows a general increase in precipitation and temperature, and in vegetation height and diversity (Fig. 4). At the northwest coast, mangroves and beach-ridge ecosystems give way to a 20-km swath of estuarine wetlands, where fresh groundwater discharges at the surface into scattered *petenes*, i.e., islands of tropical forest in the expanse of sawgrass and mangroves. Inland, the coastal swath transitions to thorn woodland-savanna that grades into a seasonal deciduous forest. The deciduous forest then grades into a band of semi-evergreen forest and an evergreen seasonal forest, also called “tropical very dry forest” that stretches from central Yucatán to northern Petén (Murphy and Lugo, 1995: 17). This dry forest breaks up into a savanna zone around La Libertad in the north-central Petén, which merges southward into the species-rich tropical moist forest of the southern two-thirds of the Petén (Murphy and Lugo, 1995; Hartshorn, 1988; Dunning et al., 1998).

Guatemala’s Petén has several major vegetation zones (Holdridge, 1967). These include Tropical Dry Forest in the northern Petén around the Maya Biosphere Reserve, Tropical Savanna around La Libertad, and Tropical Moist Forest in the central and southern Petén, including the Petexbatún region (Murphy and Lugo, 1995; Hartshorn, 1988). Hartshorn (1988) includes the southern Petén in the lowland perhumid forest zone. Although not true rainforest, these forests are the most species-rich in Mesoamerica, averaging ~100 species ha⁻¹, one quarter of which are understory palms. With respect to tree species at breast height, forests across the landscape vary from 46-91 species ha⁻¹ (Brewer and Webb, 2002), depending on rainfall amount and whether they exist in uplands, along waterways, in *bajos*, or along ecotones (Brokaw et al., 1993).

Though often difficult to recognize, these forests often have three tree canopies. Some upper canopy species such as *Ceiba pentandra* and *Tabebuia guayacan* are deciduous and flower during the dry season (Fig. 13). Strangler figs (mostly *Ficus*, Moraceae) and numerous other epiphytes are common. Up to half of all tree species depend on forest gaps from tree-falls for regeneration. A study of gap dynamics at La Selva, Costa Rica indicates that the primary, perhumid forest, similar to that along the Pasión River, Guatemala has an average turnover rate of 118 years (Hartshorn, 1988). Hartshorn (1988; p. 377) noted that the millennium since ancient Maya abandonment is long enough for succession to have produced “climax” vegetation, though some studies show the Maya absence only began four centuries ago, with small populations persisting through that time.

Savannas are interspersed among forests throughout the region (Figs. 4, 5). Climate is not the determining factor because adjacent forests exist under the same climate conditions. The pine (*Pinus caribaea* var. *hondurensis*) savannas, which are dominated by grasses, but may have up to 30% forest cover, are much smaller in Mesoamerica than in South America and can exist within both the Tropical Dry and Moist Forest life zones (Hartshorn, 1988: 379). At least three explanations exist for these anomalous grasslands: 1) they are Pleistocene relicts, 2) they are a consequence of ancient Maya deforestation, and/or 3) they are edaphically or lithologically induced. Lundell (1937: 81) linked the savannas of Petén, Guatemala to older Cretaceous carbonates (Peterson, 1983: 11), whereas Kellman (1985) linked them with Oxisols or other infertile soils, and regular fires. Sauer (1957) thought many of the Mesoamerican savannas were human-induced, but Hartshorn (1988: 379) argued they were natural. Savannas also occur on the sand plains of northern Belize, and share many characteristics with those of Petén, i.e. frequent fires, similar grasses, oak, pine, and palmetto ecosystems, and infertile soils, in this case a

consequence of sandy texture rather than deep weathering. Distinct from these ecosystems are the wetland savannas dominated by sedges, found in the perennial wetlands of the coastal plain (Rejmánková et al., 1995; Bridgewater et al., 2002).

Climate and Water

The Maya region has a tropical wet and dry climate, influenced by the Intertropical Convergence Zone, the subtropical high, land-sea interactions, and the easterly trade winds. Annual rainfall varies tremendously, from ~500 mm on the NW coast to >4000 mm in the highlands. Mean annual temperature ranges from 26° C in January to 32° C through most of the summer. The wet season runs from June to December, with highest rainfall from July to September. The dry season usually spans January through May, with large moisture deficits from March through May.

One variable too often ignored in studies of earth surface processes is water chemistry, because it is difficult to evaluate changes over time and because it leaves little record. We can only study the historical data we have, i.e. modern geologic factors that influence water characteristics, and indirect evidence from past land use. Most of the region is karst and groundwater flows through sulfate-rich, carbonate aquifers. Regional waters often have high ionic concentrations, particularly of calcium and sulfate, and have great potential for pollution caused by rapid runoff from human-disturbed surfaces under intensive land use (Luzzadder-Beach, 2000).

Historical Overview

Human interactions with the Mesoamerican landscape began before the Holocene (Valdez and Aylesworth, 2005). Organized forest clearance and agriculture in the Maya Lowlands of

233 Central America began around 5000 BP (Pohl et al., 1996; Jones, 1994), and spread throughout
234 the region between 4000 and 3000 BP, in the Early Preclassic (Pohl et al., 1996). Ancient Maya
235 imprints on the landscape thus began in the Preclassic Period, around 3200 – 1700 BP, a time
236 Hammond (2005) has termed the Maya *landnam*, when population was largely rural, though
237 permanent settlements increased in size and slash-and-burn agriculture was typical in the Middle
238 Preclassic (3000 to 2400 BP). Population and land use surged in the late Preclassic (2400-1750
239 BP, Adams et al., 2004: 329), with a marked Terminal Preclassic population downturn at 1800
240 BP (Dunning et al., 2012). Population fluctuated in some regions during the Early Classic (1750-
241 1400 BP) (Adams et al., 2004; Guderjan, 2004) with general political transformation around the
242 central Mexican city of Teotihuacan (Stuart 2000), then grew strongly during the Late Classic
243 Period from 1400 to 1100 BP, supported by widespread, intensified agriculture, land
244 manipulation and conservation efforts in the form of terracing and water management
245 (Scarborough, 1993; Beach et al., 2002; Luzzadder-Beach and Beach, 2009). This period also
246 saw agriculture expand into engineered wetland environments (Luzzadder-Beach et al., 2012),
247 underscoring the relationship between water resources and hydraulic Maya society (Houston,
248 2010). Population declined dramatically and settlements and agricultural fields were abandoned
249 in many parts of the Maya world in the late and Terminal Classic into the Postclassic, from 1100
250 BP onward (Valdez and Scarborough, 2014; Turner and Sabloff, 2012; Guderjan, 2004;
251 Guderjan et al., 2009). Postclassic populations were smaller, less sedentary and had less impact
252 on the landscape. A few communities like Lamanai in Belize persisted until the European
253 Conquest (Graham et al., 1989). Abandoned Maya agricultural landscapes and urban sites of the
254 Central Maya Lowlands began to return to forest in the Postclassic, and some landscapes

recovered to full forest by the time of European arrival (Hodell et al., 2000: 32; Luzzadder-Beach and Beach, 2009; Mueller et al., 2010)

2. Methods

This review of ancient Maya environmental impacts draws on multiple methods and proxy environmental variables to synthesize the data from a large region. We discuss each paleoenvironmental proxy variable and refer to the articles that describe its use in detail. For new data from our own soil and sediment work, we described soil profiles in USDA terms, including texture, structure, color, and HCl reaction but present only stratigraphic and carbon isotope data (Beach et al., 2008, 2011). For carbon isotope analysis, we collected soil samples in plastic bags and dried them. We sieved the samples to 2 mm (10 mesh), crushed and sieved 5 gram subsamples to 0.25 mm (60 mesh), and removed carbonates with 1 M HCl. Next, to remove calcium and magnesium carbonates, the lab immersed the samples in a water bath heated to 70 °C for at least 2 h. Next, we removed humic and fulvic acid fractions of the soil organic matter (SOM) by the alkaline pyrophosphate extraction method (Webb et al., 2004, 2007). The stable carbon isotope ratio ($\delta^{13}\text{C}$) of the remaining soil humin was measured with a Finnigan Delta Plus isotope-ratio mass spectrometer, connected to a Costech elemental analyzer (EAIRMS) (Wright et al., 2009). Recent articles discuss these laboratory methods in detail (Webb et al., 2004, 2007; Johnson et al., 2007a, b; Sweetwood et al., 2009; Wright et al., 2009; Balzotti et al., 2013). For dating, we used only accelerator mass spectrometry (AMS) radiocarbon determinations on terrestrial organic remains or charcoal. The carbonate terrain of the Maya area possesses little quartz and feldspar for optically stimulated luminescence (OSL) dating.

4.1 Synthesis: “Mayacene” Climate

The ancient Maya lived through multiple dry periods during the Preclassic, Late Classic, and Postclassic Periods (Fig. 3). For nearly a century, scholars have speculated that drought played a role in the cultural transformations evident in the archaeological record between the Classic and Postclassic Periods (Luzzadder-Beach and Beach, 2012). Gunn et al. (1994) modeled evidence for drier conditions in the Terminal Classic at the Rio Candelaria in Campeche, Mexico. They retrodicted decreased river discharge based on a model of global insolation, atmospheric patterns and volcanic emissions. Soon after, empirical evidence for Late to Terminal Classic drying came in the form of the relative abundance of gypsum (CaSO_4) (or sulfur [S]) to calcium carbonate (CaCO_3) in Yucatán lake sediments, along with shifts in the oxygen isotope ratios ($\delta^{18}\text{O}$) of ostracod and gastropod shells (Hodell et al., 1995, 2000, 2001, and 2005; Escobar et al., 2010). Hodell et al.'s (1995) study of a sediment core from Lake Chichancanab indicated sulfur peaked and $\delta^{18}\text{O}$ ratios were relatively high in the Late Preclassic and both peaked in the Late Classic. Also, Hodell et al. (2005) inferred 15th-Century drying based on historical information and uninterrupted $\delta^{18}\text{O}$ data over the last millennium in three of four Yucatán lake core records. Hodell et al. (2001) suggested that late Holocene droughts were cyclic and had been modulated by solar variation. Carleton et al. (2014) called this into question but did not dispute whether the droughts had occurred. Recently the newer proxy of the δD of leaf waxes from Lake Salpetén in Guatemala and Lake Chichancanab in Yucatán (Fig. 3) reinforced the finding of severe drying in the Late Preclassic to Early Classic and Late Classic to Postclassic (Douglas et al., 2015).

From the epicenter of Classic Maya Civilization in Petén, Guatemala, $\delta^{18}\text{O}$ lake core data suggest greater Terminal Classic evapotranspiration, which alternatively may reflect reforestation (Yaeger and Hodell, 2008: 187–242). Haug et al. (2003) used variations in titanium

(Ti) and iron (Fe) concentration in marine sediments from the Cariaco Basin, north of Venezuela, to infer past runoff and erosion from the continent (Fig. 3). The record is unequivocal with respect to wet and dry periods, but the record is ~2000-km distant from the Yucatán Peninsula. The marine record shows variability between *ca.* 3800 and 2000 BP (1850 BCE to 50 BCE), stability between *ca.* 2000 and 1300 BP (50 BCE to 650 CE), low deposition of Ti and Fe, suggesting drought, from 1300 to 1000 BP (650-950 CE), and very low deposition from about 500-200 BP (1450-1750 CE), during the Little Ice Age.

Cave speleothem studies in Belize and Yucatán have started to clarify paleoclimate conditions. Kennett et al. (2012) analyzed a stalagmite in southern Belize and found evidence for long-term drying in the Late Preclassic, several dry episodes in the Early and Terminal Classic, and the longest and most severe dry period in the Early Postclassic (1010-1100 CE). Webster et al. (2007) also found speleothem evidence in Belize for Preclassic climate instability from dry to wet, Late Preclassic (5 BCE and 141 CE) deep drying, and severe drying again in the Late Classic through early Postclassic (780, 910, 1074, and 1139 CE). About 450 km north of these southern Belize records, near the Postclassic Maya site of Mayapan, a cave record indicates eight multi-year droughts from the Terminal Classic to early Postclassic (Medina et al., 2010). The authors estimated that average precipitation declined by 52% to 36% during the dry periods centered near 806, 829, 842, 857, 895, 909, 921, and 935 CE. In the Mesoamerican highlands of Central Mexico, Stahle et al. (2011) used Montezuma bald cypress (*Taxodium mucronatum*) to produce a dendrochronology record that shows Late Classic drying from about 810 to 860 CE and Terminal Classic drying from 897 to 922 CE.

Scholars have long suspected that ancient Maya land use could have been a driver for past climate change. The ancient Maya altered landscapes in ways that could have affected the

323 atmosphere. Widespread deforestation and other landscape changes like urbanization and
324 wetland farming can change albedo, greenhouse gas cycles, atmospheric particulate matter and
325 evapotranspiration. We have been limited by insufficient knowledge of the extent of these
326 landscape changes, and the best we can do is model scenarios with assumed land-use percentages
327 based on pollen and other proxy evidence. Evidence shows several vegetation trends in Maya
328 prehistory, including forest declines in the Late Archaic, the Preclassic and Classic. There is
329 evidence from the Petén lakes and Mirador region for reforestation within 80-260 years as Maya
330 populations declined during the Terminal Classic and early Postclassic (Mueller et al., 2010;
331 Islebe et al., 1996; Curtis et al., 1998; Wahl et al., 2006). Other studies in the Maya Lowlands
332 suggest reforestation was delayed until after 750 BP (Johnson et al., 2001; Rue et al., 2002) or
333 even as late as 400 BP, the latter perhaps after human diseases were introduced during the 16th-
334 Century European conquest (Brenner et al., 1990; Leyden, 2002; Dull et al., 2010; Nevle et al.,
335 2011). Ruddiman (2013) has even argued that New World population decline in the 16th Century
336 was a possible driver for the Little Ice Age, when CO₂ concentrations in the atmosphere dropped
337 by ~10 ppm and CH₄ levels fell by 100 ppb.

338 There are four studies that have modeled climate change induced by Maya deforestation
339 (Oglesby et al., 2010; Hunt and Elliot, 2005; Cook et al., 2012; Griffin et al., 2014). Oglesby et
340 al. (2010) modeled the climate effects of complete deforestation and found both decreased
341 precipitation (15-30%) and increased temperature, thus increased human-induced drought. Hunt
342 and Elliot's (2005) model, however, indicates large-scale drought could occur stochastically, i.e.
343 by chance, within the normal parameters of the region's climate. Cook et al. (2012) modeled a
344 5-15% rainfall decline and found that 60% of the drying in the Maya Terminal Classic was
345 attributable to deforestation. Lastly, Griffin et al. (2014) modeled the effects of declining forest

density on local climate and agricultural production. These studies indicate that Maya deforestation could have been an important factor in climate change, much like widespread forest removal is involved in climate change today.

4.2 Synthesis: Impacts on Vegetation

Maya civilization altered forests, savannas, and wetlands, probably with greater intensity than did ancient peoples of Amazonia, as suggested by the much greater density of sites in the Maya area (Fig. 14). Nonetheless, there have been many ecological studies of human impacts on Amazonian forests (Roosevelt 2013), but as in the Maya region, we have only a preliminary assessment of these anthropogenic forests. Paleoecological and botanical studies have attempted to get at the long-term impacts of the Maya on regional forests, and a few botanical studies have focused on the what the current forest can tell us about the past (Lambert and Arnason, 1982; Gomez-Pompa et al., 1987; McSweeney, 1995; Ross et al., 2011; Hightower et al., 2014; Lentz et al., 2015; Schulze and Whitacre, 1999; White and Hood, 2004; Hayashida, 2005; Campbell et al., 2006; Thompson et al., 2015). The legacy of “Mayacene” forest impacts may take many forms, such as greater dominance of useful species due to ancient plantation remnants or non-useful species because of ancient over-harvesting. But impacts vary greatly as a function of land use intensity, plant introductions to new habitats, habitat transformations, complicated ecosystem responses, and the time since abandonment, from the Late Preclassic at Mirador, to the last few centuries at Lamanai. A large ancient city like Caracol had pervasive impacts that declined with abandonment, but the legacy of these impacts continues to the present day because of the alteration of the soil parent materials and slopes by terraces (Hightower et al., 2014). Outside of ancient Maya cities, ecosystem impacts are still clear in areas where there was severe erosion and

sedimentation. For example, ancient Maya colluvium that chokes river valleys can change stream flows and ecosystem processes (Beach, in review).

Maya agroecosystems evolved as a patchwork or mosaic across space and through time. Ancient Maya land uses included ‘natural’ and managed forests, swidden agriculture, orchards, terraced and wetland fields, urban development and kitchen gardens, all of which required active management through tending, seeding, burning, and watering. Time since abandonment at different sites ranged from 2000 BP to present, i.e., in the Preclassic to Terminal Classic, during European Conquest, and in some areas, never. At least some modern forests and savannas, therefore, must be the product of this patchwork and its many generations of seeds, even if there is rapid turnover and succession in these tropical forests (Hartshorn, 1988).

The earliest European recognition of Maya impacts on ecosystems goes back to de Landa (1978) and other early Spanish chroniclers in the 16th Century, who mentioned planted trees and orchards in Yucatán. Some early studies in the Maya Lowlands considered ancient impacts and their ecological legacies. Lundell (1937) discussed savannas and forests and considered human impacts and edaphic conditions as explanations for why savannas exist in the wet Petén. Puleston (1978) hypothesized that the high frequency of ramón or breadfruit (*Brosimum alicastrum*) scattered among Maya ruins was as an example of relict orchards, possibly with selected genotypes (Peters, 1983), but others concluded the trees simply expressed an ecological preference for limestone surfaces (Lambert and Arnason, 1982). Similarly, some have speculated about Maya-induced distribution of the useful Cohune palm (*Attalea cohune*), though there are again multiple factors that account for its modern distribution (McSweeney, 1995). But one cannot escape the fact that ancient Maya land use expanded the habitat for species such as

ramón, creating distinct forest types (Bartlett, 1935) and thus altering the Maya forest over the long term.

Two specific examples of the possible legacy of ancient Maya impacts are pines in the Petén forest and savannas within forests. First, a Caribbean pine stand in the *bajos* northeast of Tikal could be a relict stand from ancient Maya management, or alternatively, the product of edaphic factors such as sandy or otherwise xeric soils (Lentz et al., 2015). Dvorak et al. (2005) concluded these pines are relicts of dryer times and lower sea levels, but there is evidence of nearby Maya occupation and perhaps forest management (Lentz et al., 2015; Fialko, 2001). A second example relates to savanna formation in the northern Neotropics (Lundell, 1940; Dull, 2004; Brenner et al., 1990; Stevens, 1964; Sauer, 1957). Lundell (1938) argued that the savannas of Petén, Guatemala were a consequence of edaphic factors, whereas Sauer (1957) and Stevens (1964) argued they were created by humans, through soil alteration or fire management. Dull (2004) carried out a multi-proxy study that provided a complex explanation for the existence of a savanna in El Salvador, but fire was a key factor.

Indigenous and “feral gardens” are two other examples of continued Maya impacts. The former may include pockets of economic species found outside their usual distribution range. For instance, the moist microenvironments of sinkholes in northern Yucatán harbor cacao, which indigenous Maya farmers continue to maintain and may have done so for many years (Gomez-Pompa et al., 1991). The “feral garden” concept comes from Ross (2011) and Ross and Rangel (2011), who found greater diversity of useful tree species to be correlated with denser Maya sites, which they attributed to long-term impacts of ancient Maya forest use. Also, Hightower et al. (2014) used Lidar to study forest canopies at Caracol and found terraced slopes gave rise to

significantly different forests, which had more vertical diversity, greater height, and fewer gaps, as we would expect where soils are thicker, younger, and can store more water and nutrients.

Lentz et al. (2015) estimated that about 40% of the forest remained intact at Tikal, even in the Late Classic. Balzotti et al.'s (2013) work on soil carbon isotope ratios and remote sensing conform to evidence for little ^{13}C enrichment at Tikal (Lentz et al. 2015), indicating there was a large expanse of land with C_3 (i.e. forest) species. Lentz and Hockaday (2009) also noted that Tikal temples had very large beams from old forest stands, perhaps indicating careful forest management through the time of Late Classic population growth, until the middle of the 8th Century. Lentz et al. (2015) also found cellular evidence that indicated most charcoal came from large trees rather than from pioneer species like *Cecropia*. Evidence for the persistence of forest through the period of high population in the Late Classic lends credence to the “garden city” concept of Maya urban-garden patchworks in the Classic period (Dunning and Beach, 2010; Lentz et al., 2015).

Zooarchaeology

Evidence for “Mayacene” environmental changes also comes from human and animal remains. Zooarchaeology can be informative about Maya impacts in many ways, providing insights into the changing size of animal populations and human nutritional status, which reflects changes in animal use, evidence for long-distant trade of species, genetic bottlenecks in populations, incorporation of new species into the human diet, changes in body size (Emery and Thornton, 2008), or species introductions, as with the Mexican turkey (*Meleagris gallopavo gallopavo*) at Preclassic El Mirador (Thornton et al., 2012). Several studies showed that maize or other C_4 species were components of deer and peccary diets, and this and other

434 zooarchaeological evidence suggests that a patchwork of forests, fields, and successional plants
435 surrounded Maya sites (Emery, 2008; Emery and Thornton, 2008; Somerville et al., 2013).

436 Excavations at the volcanically buried Classic Maya village of Cerén, in El Salvador, also
437 show this patchwork of well-tended and organized gardens. At Cerén, excavators found small,
438 intensive ridged plots of beans, squash, maize and manioc, along with fruit trees like avocado,
439 cacao, guava and hog plum (Lentz and Ramírez-Sosa, 2002; Sheets, 2008). Beyond the village,
440 Sheets et al. (2012) excavated larger-scale manioc and maize fields. There is growing evidence
441 for this patchwork of diverse and intensive farm-scapes at other sites such as Chan, a Maya
442 village in Belize (Robin, 2012).

443 We know from ecology and geomorphology that apex predators (e.g., wolves in
444 Yellowstone, Beschta and Ripple, 2009) and niche constructors (e.g., leaf-cutter ants) play major
445 roles in landscapes, but we have little information on such species over the course of Maya
446 prehistory. Leaf-cutter ants, for example, are dominant and invasive at forest edges and
447 disturbed sites (Dohm et al., 2011) and they have large impacts on soils. They are probably
448 expanding their coverage today and likely did so in the “Mayacene,” but we have no studies to
449 document this.

450 Characteristics of human bones might indicate patterns of stress, food abundance, disease and
451 population age structure, which may also provide evidence for the state of the ecosystem. But
452 research on this subject is equivocal. Studies have inferred the health status of the ancient Maya
453 using bones from different sites, deposited at different times. Conclusions vary from the worst
454 health detected in any group in the Americas at Copán (Steckel and Rose, 2002) to evidence of
455 nutritional stress (Saul, 1973). But Wright and White (1996) concluded that osteology showed

no evidence for declining health or nutrition through the Maya Terminal Classic or differential health and nutrition between urban and rural sites.

4.3 Hydrosphere Impacts

Perhaps the greatest challenge for humanity today is water management, for drinking and agricultural use. Both water quantity (too little or too much) and quality present serious problems. The ancient Maya faced these same issues. Indeed, some have argued that the trajectory of Maya Civilization was organized around water management, from initial passive use of water in concavities (lowlands near natural sources) during the Preclassic, at centers like El Mirador, to active control on convex land surfaces (uplands with engineered sources) in the Classic, as at Tikal (Scarborough, 1993). Evidence for Maya impacts on the hydrosphere includes research on lakes, wetlands and rivers, and municipal water management. Maya iconography is also replete with water imagery (Finamore and Houston, 2010; Lucero, 2002).

Limnological Change

Limnological study of the Maya Lowlands started with the work of G.E. Hutchinson and colleagues at Yale University (Cowgill et al. 1966; Tsukada and Deevey 1967). This work led to the seminal study by Deevey et al. (1979) on the environmental impacts of ancient Maya urbanism and a later study by Binford et al. (1987), which set the stage for research that has continued to the present. A persistent model of Maya-environment interaction emerged from this work (Figs. 5a and 5b in Binford et al., 1987). The diagrams correlate Maya population density, deforestation, soil erosion, sedimentation, organic chemistry, phosphorus loading, and lacustrine productivity. Estimates of ancient Maya population density over time came from ten archaeological transects around Lakes Yaxha and Sacnab, and sediment characteristics in cores

from six basins. The Binford et al. (1987) diagram shows a transition from predominantly tropical forest pollen taxa to more savanna-like ‘disturbance’ pollen throughout the Maya period, from *ca.* 3000 to 400 BP. Deforestation was accompanied by increased soil erosion, lacustrine sedimentation and phosphorus loading, and depleted lacustrine productivity, which all reversed course after 400 BP, or perhaps earlier, because hard-water effects compromised the dating of the cores.

Deevey et al. (1979) and Rice et al. (1985) also compared two adjacent lake basins in Petén, Guatemala and found the more urbanized Yaxhá Basin showed greater anthropogenic impacts relative to the non-urbanized Sacnab Basin, though the latter also experienced considerable land clearance and associated degradation. In comparison, far to the north at Michoacán, México, Fischer and others (2003) found that anthropogenic impacts from early urbanization and concomitant population concentration at a site on the shore of Lake Pátzcuaro, dwarfed the regional land-change signal expressed elsewhere in the basin. These findings illustrate that despite regional patterns of low-density urbanism, environmental impacts were accentuated in urban areas, especially as populations grew to levels that approached local and regional carrying capacity, such as at the Maya city of Tikal (Lentz et al. 2015). Accordingly, the persistent effects of land use on vegetation, soils, and hydrology are typically more pronounced across ancient urban landscapes.

After Deevey et al. (1979), subsequent paleolimnological studies in the Maya Lowlands found similar patterns of human disturbance, though a ~5-m core from a pond near Copán (Fig. 1) produced conflicting results based on pollen and charcoal (Rue et al., 1989; McNeil et al., 2010). Nevertheless, all the studies bolster the case for the “Mayacene.” Rue et al. (1989; 2002) argued for long-term and large-scale human impacts, whereas McNeil et al. (2010) showed

501 evidence for long-term human alteration with *Zea mays* and deforestation in the deepest core
502 levels (2900 BP). McNeil et al. (2010) interpreted increased pine pollen to indicate reforestation
503 in the Late Classic, and thus Maya slope management during the period of highest population.
504 Rue et al. (2002) found high quantities of charcoal in the lowest levels of the core at 5700 BP
505 and *Zea mays* by 4300 BP, compared with *Zea mays* at 5400 BP in their earlier cores at Lake
506 Yojoa, 90 km E of Copán (Rue et al., 1987). Rue et al. (2002) point out the age discrepancy of
507 *Zea* pollen showing up by 5400 BP, but archaeological evidence not appearing until 3300 BP in
508 the region (Rue et al., 2002). Morell-Hart et al. (2014), nonetheless, provide archaeological
509 evidence in Honduras for use of plants that later became cultigens extends back to 8500 BP,
510 though *Zea mays* came much later.

511 At Lake Salpeten, Peten, Guatemala, Anselmetti et al. (2007) used seismic imaging to
512 determine the three-dimensional distribution of “Maya Clay” in the basin. In the deepest part of
513 the lake (~32 m), the clay layer is about 7 m thick (Fig. 6) and is sandwiched between much
514 thinner layers of organic-rich sediment in the 10-m Holocene section. A complete Holocene
515 sediment core from the deep-water site, collected in 1980 (Deevey et al., 1983; Leyden et al.,
516 1987; Brenner, 1994), provides “ground-truth” for interpretation of the seismic data. Maya
517 erosion started early, but slowly, in a seismically defined zone dated to 4000-2700 BP, rising
518 from 16.3 to 134 t km² yr⁻¹, then increased through two successive zones to 500 t km² yr⁻¹,
519 peaking early in this sequence at 988 t km² yr⁻¹ in the Late Preclassic, until 1700 BP. Erosion
520 declined to 457 t km² yr⁻¹ through the Classic Period, but declined by nearly an order of
521 magnitude to 49 t km² yr⁻¹ after the Terminal Classic. Hence, peak erosion did not correlate with
522 archaeologically estimated population density, but did correlate with percent disturbance pollen.
523 Erosion levels declined, but were still far above background levels during the Late Classic, when

population densities were greatest and there was a second peak in disturbance. These findings are interesting in that they suggest that even low numbers of people can have profound consequences with respect to soil erosion. The later decline in soil export, coincident with a growing human population, suggests that either much of the erodible material had washed out of the watershed, or that people had begun to take steps to prevent erosion.

Other paleolimnological studies in the Central Maya Lowlands show large increases in multiple variables after *c.* 5,000 BP, including economic and weed pollen, charcoal and magnetic susceptibility, the latter reflecting a shift from organic to mineral deposition (Wahl et al., 2007a, 2014; Fleury et al., 2014). Two multi-proxy, high-resolution core studies from Petén serve as examples. At Puerto Arturo, Wahl et al. (2014) showed the trends described above, along with evidence for drying after 4,600 BP. At Laguna Tuspan, near the Maya site of La Joyanca in northwest Petén, Fleury et al. (2014) showed the familiar pattern of Maya clay corresponding to the period of Maya occupation. They used micropaleontology, clay mineralogy and geochemistry to show four main episodes of accelerated erosion between *c.* 3000 and 1280 BP, with the largest occurring by 1280 BP, well before the Terminal Classic. The Central Petén studies all show significant declines in erosion and sedimentation after the Terminal Classic, even though this coincides with some of the records most extreme climatic fluctuations such as the highest magnitude and duration droughts in the Postclassic and Little Ice Ages and higher rainfall of the Medieval Climate Anomaly (Kennett et al., 2013; Haug et al., 2001; Hodell et al., 2005).

Wetter *bajos* and Maya-induced desiccation

Bajos provide another perspective on the “Mayacene.” Since at least the 1930s, researchers have noted the aggregation of Maya centers around so-called *bajos* or large karst

sinks in central Petén (Dunning et al., 2002). The plethora of such sites shows that the Maya preferred these localities, although many investigators have commented that *bajos* were inhospitable – a perception that stems from how difficult it is to traverse these areas because of dense swamp-forest vegetation and seasonal inundation.

Research on *bajos* goes back to the earliest Maya environmental archaeology. In 1931, Ricketson excavated a deep pit in the Bajo de la Juventud, adjacent to the ruins of Uaxactún (Ricketson 1937: 11). Based on the stratigraphy of the pit, geologist Cooke (1931) concluded that Maya-generated erosion and eutrophication had transformed *bajos* from shallow lakes to seasonal swamps. In 1959, biologist Cowgill and colleagues excavated a >5-m-deep pit in the Bajo de Santa Fe near Tikal and concluded there was no evidence for the existence of a former lake, at least in that part of the *bajo* (Cowgill and Hutchinson, 1963). Harrison (1977) revived the “*bajos* as lakes” hypothesis based on the presence of large complexes of wetland fields detected via aerial photography in several *bajos* in southern Quintana Roo, Mexico. A model of the *bajos* as breadbaskets within the central Maya heartland soon arose (Adams et al., 1981), but Pope and Dahlin (1989) argued that the southern Quintana Roo *bajos* were hydrologically anomalous and that conditions within most elevated, interior *bajos* were not conducive to wetland agriculture – a conclusion based in part on field work by Dahlin and soil scientist Foss in the El Mirador Bajo, Guatemala (Dahlin et al., 1980; Dahlin and Dahlin, 1994).

We cannot generalize findings from one *bajo* to all *bajos*, or even many *bajos*. Research that began in the mid-1990s indicates a great deal of variability in the hydrology, vegetation and edaphic conditions among *bajos* and even within individual depressions (Dunning et al., 1999, 2002, 2003, 2006, 2009; Kunen et al., 2000; Beach et al., 2003, 2008, 2009). Furthermore, data show that the environmental histories of individual *bajos* have varied greatly, an important

consideration for trying to correlate paleoenvironmental conditions with cultural history in the Maya Lowlands (Jacob, 1995; Dunning et al., 2006).

Several studies have shown that Maya-induced soil erosion led to clay deposition in karst sinks, which aggraded the margins of larger depressions and possibly plugged smaller sinks (Dunning and Beach, 1994, Beach et al., 2003). Thus, human impacts would have altered the hydrology of the sinks, leading to desiccation or flooding. So soil erosion probably did transform some erstwhile shallow lakes and perennial wetlands of some *bajos* into the seasonally desiccated wetlands of today (Fig. 7). This model explains well the transformations in some *bajos*, especially smaller ones, only a few km² in area (Dunning et al., 2006; Beach et al., 2008).

A core collected from a *cival* (herbaceous perennial wetland) near El Zotz and its Preclassic neighbor Palmar reflects some of the variability in the environmental history of *bajos*. The core showed evidence for human disturbance even in its basal deposits at 300 cm dated to 3680-3460 cal BP, with high amounts of charcoal and *Zea mays* by 280 cm, modeled to c. 3000 BP. The Maya clays here extend from 250 to 55 cm, and span the Late Preclassic to the Classic, with evidence for high sedimentation rates, pulses of higher magnetic susceptibility, and pollen of many economic species, including *Zea mays* reaching high levels in the Preclassic and Classic periods. The rapidly deposited Maya clays transition to peat by the Classic period at this site, which had little Classic period occupation (Luzzadder-Beach et al., in Review).

The greatest environmental diversity exists within the region's most expansive depressions. Many of the largest *bajos* in the Maya Lowlands are structural in nature, owing their origins in part to normal faulting and preferential dissolution of gypsum-rich limestone. Examples include El Mirador Bajo in Petén, Guatemala (Dahlin et al., 1980), El Laberinto Bajo

in Campeche, Mexico (Gunn et al., 2002), and Bajo de Ázucar in Petén, Guatemala (Dunning et al., 2008; Dunning and Griffin, 2008). These *bajos* cover hundreds of square kilometers and are delimited on at least one side by steep fault scarps (Fig. 7). In these places, faulting has apparently penetrated deeply buried evaporite beds including large quantities of gypsum (Perry et al., 2009). As a consequence, these large *bajos* had floors of clay with high quantities of sulfate and chloride, which made agriculture across much of the *bajos* problematic and reduced water quality, thereby posing significant challenges to early occupants. As forests were cleared across adjacent uplands, Ca-rich soils were eroded and redeposited in the *bajos*. As these cumulic, base-rich soils expanded and deepened over time, they became vital agricultural resources for Maya farmers. Along the margins of the Bajo de Santa Fe, Maya farmers from Tikal invested heavily in the cultivation of maize as well as root crops beginning in the Late Preclassic and continued to cultivate these lands into the 11th century CE when the nearby urban center was all but abandoned (Dunning et al., 2015 a and b), a pattern that may be reflective of wider trends in the *bajos* around Tikal (Balzotti et al., 2013).

These *bajo*-edge Maya sites in the Maya heartland of Petén and nearby Belize and Mexico declined in the Preclassic and Terminal Classic. Ultimately, the *bajos* we have studied show several trajectories from human induced landscape instability to adapted land use management in the “Mayacene,” but some sites never recovered their urban pasts.

Wetland Fields, Canals, Dams, and Diversions

Maya manipulation of wetlands is still understudied, but it is clear that a large area of wetlands show complex Maya interactions (Fig. 1, 9). Research since the 1960s has shown field systems in perennially wet environments, especially on the Coastal Plain of northern and eastern

614 Belize, the low-lying *bajos* with near-surface water tables near the Rio Hondo in the Mexican
615 State of Quintana Roo, and along the Usumacinta River and Río Candelaria lowlands (Siemens
616 and Puleston, 1972; Jacob, 1995; Pohl et al., 1995; Siemens, 1982, 1992; Gliessman et al., 1983;
617 Liendo-Stuardo, 1999). Researchers have reported wetland fields at many sites (Sluyter, 1994;
618 Luzzadder-Beach et al., 2006, 2012; Beach and Luzzadder-Beach, 2013), and research is
619 ongoing in several places. Early on, scholars recognized landscape patterns that appeared to be
620 wetland fields, like the extant *chinampas* at Xochimilco, Mexico, but may be features that owe
621 their origin to both natural and anthropogenic processes (Luzzadder-Beach et al., 2006; Beach et
622 al., 2009a).

623 We have excavated many wetland fields and found evidence for agriculture in several
624 places in northern Belize, including Sierra de Agua, Chawak, Chan Cahal, Birds of Paradise, and
625 Lamanai (Fig. 1) (Beach et al., 2009a, 2013a and b, 2014, in Review; 2008, 2012; Luzzadder-
626 Beach et al., 2009a, 2012). Maya engineering in these landscapes included ditch building, field
627 raising, damming, water storage and draining for crop production, from tubers to maize to fruit
628 trees.

629 Wetland patterns run from irregular forms, such as at Chawak (Beach et al., in review), to
630 cobweb forms such as Cobweb Swamp (Jacob, 1995) at Chan Cahal (Beach et al., 2014), and to
631 rectangular forms as at Birds of Paradise (Fig. 9). We have mapped reservoirs in group of fields
632 and others lie along streams or lagoons. In profile, all the fields we have studied have complex
633 strata formed from both natural processes and human agency. We can generalize the cross-
634 sectional strata of the fields from bottom to top as an Archaic or Preclassic paleosol buried under
635 1-2 m of gypsum and fine sediments with an intervening Classic-period paleosol at 50-100 cm
636 below the surface (Fig. 9). The fields vary widely in surface area from 100 to 3000 m² (Beach et

al., 2013). The ancient ditches or canals are 1.5-3 m wide and 1-2 m deep and are filled by Terminal Classic to present sediments in all cases we have studied (Beach et al., 2013: 52).

Recent studies near Blue Creek, northwestern Belize, indicate that most of these are Classic-period phenomena, but dating wetland fields is complicated and the most reliable dates come from ditches and field sequences. Fields would be easier to date if the Maya built them by piling material above the prominent paleosol sequences that date to the Late Preclassic, about 2000 years ago, but many fields were steadily aggraded by active deposition after that time, which may have been both natural and Maya-induced (Beach et al., 2009a, 2015). Some of the wetland fields have unconformities, with older radiocarbon dates on top of younger ones from the Late Classic, which may indicate field building in the Late Classic and possibly before, as early as the Late Preclassic (Beach et al., 2014). Deepest levels in the ditches date only to the Late and Terminal Classic, but this may simply indicate when the ditches started to fill after abandonment. Earlier research north of Blue Creek indicated a wide chronology of wetland formation, some even dating to the Archaic period, but some became abandoned soon after because of insurmountable inundation and salinity (Pohl et al., 1996; Berry and McAnany, 2007).

The Belize sites we excavated and surveyed represent about 10 km², and aerial study along the Rio Hondo suggests there are many more with similar surface patterns. Guderjan et al. (2011) used aerial survey and found at least ten areas of wetland field patterns along the river, which may add up to 50-100 km² of fields across northern Belize. But, we think the timing and formation of these ten new areas may produce surprising results because the chronologies and patterns of wetland fields varied so much to the south (Beach et al. 2009a, 2014) and earlier work came to divergent conclusions about the origin of the northern wetland fields (Berry and

MacAnany, 2007; Harrison, 1996; Pohl et al., 1996). Ongoing studies are estimating the area, chronology, hydrology, and changing ecology of these wetland systems, and are quantifying greenhouse gas exchanges to estimate the climatic relevance of Maya agroecosystems.

Fluvial Valleys and Floodplains

In a predominantly karst landscape like the Maya Lowlands, some areas like the northern Yucatán have no rivers. Yet the igneous and metamorphic highlands of the central spine of Central America and the Maya Mountains produce tremendous runoff and fluvial systems that flow into the Maya lowlands, as seven major and many minor rivers: Motagua, Belize, Pasión-Usumacinta, Hondo, Candelaria, Agua Dulce-San Pedro, and Ulua. There has been very little research on the natural science of these rivers (Beach et al., 2008, in review). This means only rudimentary studies of sediment budgets, floodplain formation, alluvial fans, and deltas exist. There are also few geoarchaeology studies, which include Gunn et al., (1995) on flow and climate, Siemens et al. (2002) on ancient dams, van Nagy (2003) on delta formation and a study on fluvial terrace sequences by Solís-Castillo et al. (2013). Below, we summarize the work on rivers near La Milpa, Copán, Quirigua, the Usumacinta, the Candelaria, and the Belize River (Beach et al., 2008).

Beach et al. (2015; in review) studied the floodplain and wetland fields of the Rio Bravo (Figs. 4, 8), a tributary of the Rio Hondo in northwestern Belize near La Milpa. They completed excavations along four floodplain transects through this fluviokarst watershed. Their excavations indicate Maya impacts starting in the Preclassic, when paleosols and natural floodplain swamp sequences became aggraded and sedimentation rates increased. The Rio Bravo studies determined the following diachronic sequence: the Archaic to Preclassic

sedimentation rates ranged from 0.82 mm yr⁻¹ to 1.5 mm yr⁻¹ on the floodplain. The Late Preclassic through Classic rates rose to 0.98-2.03 mm yr⁻¹, and the Classic rates ranged from 1 mm yr⁻¹ to as high as 9.12 and 16.27 mm yr⁻¹ at ancient Maya wetland field sites. Ancient Maya canals, abandoned in the Late Classic, provided Postclassic floodplain sedimentation rates of 0.65 mm yr⁻¹ at Chan Cahal, 1.5 mm yr⁻¹ at Sayap Ha, and 1.7-2 mm yr⁻¹ at the Birds of Paradise fields. Two caveats for inter-site comparison are that canals create higher trap efficiencies and thus display greater deposition rates than open floodplains and none of the canals date to periods before the Late Classic. We also estimate that accumulation in the last Terminal Classic field activity areas in floodplains, from *c.* 1000 BP, ranged from 50-90 cm, which yields an estimated sedimentation rate of 0.45 to 0.82 mm yr⁻¹ for the Postclassic. Thus we estimate a 2-fold or more increase in sedimentation, with the highest amount in the floodplains during the Classic period, though the lag effect of watershed erosion (Beach, 1994) can mean that much of the sedimentation wave could have started earlier.

A few studies have noted fluvial aggradation elsewhere in Belize. Lietzke and Whiteside (1981) reported a paleosol sequence buried by 69–86 cm in the Swazi River floodplain in southern Belize. But most work has been near to and part of archaeology projects in the Belize River Valley. At least three studies discuss aggradation over Maya times in the Belize River system, starting upstream near the site of Xunantunich, next to the Rio Mopan. There, a series of excavations and an electromagnetic conductivity survey found a clay-rich paleosol buried by a 140-190-cm-thick wedge of high-energy deposits that had well developed top soils (Holley et al. 2000: 22). Based on artifacts, Holley et al. (2000) ascribed the alluviation to Preclassic through Late Classic watershed degradation, and found no evidence for landscape stability during this period.

Farther downstream, Willey et al. (1965), with the pioneering Harvard settlement archaeology survey, argued the ancient Maya around the site of Barton Ramie in the Belize River Valley deforested watersheds and increased flooding and aggradation that reached upper fluvial terraces (Olson, 1981). They based this on a paleosol sequence in the upper stream terraces that consist of a thick, black paleosol buried by ~1 m of lighter brown sediments, mantled with well developed, black, clayey top soils (Willey et al., 1965). They also found Preclassic structures built on the thick black paleosol and Classic period structures built into the upper sediments and farther uphill, away from the river. They argued that aggradation happened in the Preclassic and during or since the Classic period. The lower paleosol was 70 cm thick, which is a cumulic Ab horizon indicative of alluvial or colluvial fill; hence in the early Preclassic or even earlier there experienced some deposition, but not enough to bury the A horizon as during the period of Classic construction. The surface A horizon shows evidence of stability after site abandonment.

Many other sites in the Belize River and adjacent streams hold great potential for fluvial research, and one study along the Xibun River in Belize reported paleosol sequences buried by ~1 m of alluvium on two middle and late Holocene fluvial terraces. Bullard (2004: 319) also found that on one terrace 5-6 m above the river, sand and silt with little soil development covered Late Classic architecture (1120–1000 BP), but obtained no dates for either episode of burial.

Other areas with some research are near the sites of Copán, Honduras and Quirigua, Guatemala. The Motagua is a particularly important drainage basin. It lies at the boundary of the Caribbean plate, has high ecological diversity, is a source area for many resources such as jade (Harlow et al., 2004) and is a major link between the highlands and the cities of Copán and Quirigua. These sites and others in the region linked by the Copán and other Motagua tributaries are enticing because they are located on terraces and floodplains that could possibly help us

understand fluvial response to human impacts. Unfortunately, there has been little such work that could clarify these interactions.

Much research at Copán has referenced environmental change, but there have been too few studies devoted to this topic. Study of the Copán river valley's history indicates a soil chronosequence. The late Pleistocene, upper fluvial terraces, left too high by early Holocene incision for continued sedimentation, have well developed soils classified as Inceptisols (Oxic Ustropepts) (Turner et al., 1983). The broad lower terrace had a paleosol often buried ~1 m, built in younger alluvium classified as a Entisols (Mollic Ustifluvents), dated to *c.* 3000–2000 BP (Preclassic), which Turner et al. (1983: 198, Fig. T-23) considered the main pre-Maya valley surface. There was an upper paleosol buried by what they interpreted as modern or historic aggradation. They concluded this surface was buried by aggradation from flooding and channel migration in the Preclassic and Classic periods. The Copán Maya were not passive inhabitants during “Mayacene” environmental changes because they diverted the river after 1300 BP, only to have their diversion unravel after the site's decline *c.* 1200 BP. Perhaps as sediment starvation occurred with watershed recovery in the Postclassic, the river cut down through the Maya sediments to form a lower floodplain and eroded the site of Copán, and modern gullying and excavations exposed the paleosol sequence. Engineering of the river continued up to the 1930s as the Carnegie Institution of Washington diverted the river again to preserve the site.

At the site of Copán, some studies showed ~2 m of sediment covering Late Classic, low-elevation parts of the Las Sepulturas group (Wingard, 1992, p.184; Abrams et al., 1996, pp 55-75; Webster et al., 2000; Webster, 2005: 48). Elsewhere in the Copán Pocket, Wingard (1992:184) described one sequence of 70 cm of sandy loam sediments covering a clayey-textured paleosol. Likewise, Olson (1981:113-114) found buried paleosols with Maya artifacts

at 107 cm in the fluvial sediments of the nearby Rio Amarillo and the Valle de Naco. McNeil et al. (2010) disputed erosion and sedimentation evidence for Copán using pollen evidence from Petapilla pond, which indicated high pine presence throughout the entire period of occupation. But there are no dates on the sediments or in-depth analyses of the soils that covered the buildings, nor are there long-term sedimentation rates calculated for the pollen cores, and firm conclusions about erosion and sedimentation at Copán and surroundings will have to await further research.

Downstream, after the Copán River enters the Motagua River in Guatemala, archaeological research at the ancient Maya site of Quirigua suggests large-scale sedimentation in this floodplain site (Ashmore, 1984; 2007: 23) and tantalizing information on river response. An irrigation project excavated many 2-m-deep canals across this floodplain, and research teams were able to study ancient settlement distribution in these exposures. Alluvium enveloped all but the major architecture of this important site. The investigators found sites built after 1300 BP buried by ≤ 1 m of alluvium, sites before 1300 BP buried by 2 m along the north side of the site, and below the 2-m canals on the south side, in the river's direction. Postclassic sedimentation declined to as low as 20% of Classic sedimentation.

The Usumacinta River is the largest in Mexico, but we know little of its geomorphic evolution. One study by Solís-Castillo et al. (2013) investigated soils and human interactions on the river's lower Pleistocene and Holocene terraces. The study defined a soil chronosequence in these terraces, showing that Vertic characteristics and Vertisols occurred in the oldest soils with artifacts from the Preclassic. Two other soil studies provide insight into Usumacinta geomorphic instability. Fernandez et al. (2005) described a soil profile located in the floodplain of the Usumacinta near Piedras Negras, Guatemala. They discovered a buried A horizon from 94 to

125 cm, AMS-dated on soil organic matter to 2200 $\pm$ 70 BP. Balzotti et al. (2013) described three 3 m deep soil cores from the Usumacinta flood plain at the site of El Kinel near La Tecnica, Guatemala. These cores dated only broadly to the ancient Maya period by artifacts lying on beach sands buried at the 3 m depth. Contrary to these finding of ancient Maya aggradation, work by Munoz-Salinas et al. (2013) on delta formation in the Usumacinta and Grijalva Rivers indicated only a very late Anthropocene signature because deposition increased most in the last century of a 1600-year sequence.

4.4 Water Management Features

Maya civilization existed in a climate with pronounced dry and wet seasons, and there is ample evidence that the Maya had specific strategies to manage during both. Water research has focused both on Maya centers and in hinterlands, where water management features may be less discernible in landscapes obscured by karst landforms (Siemens, 1978). Researchers have written about Maya water features for more than 400 years. Fr. Diego de Landa reported on them in the 16th Century, and Stephens encountered Maya *aguadas* with stone-lined floors at Rancho Noyaxche and Jalal in 1842 (Stephens, 1843, 138-141). Wetland field and urban reservoirs were discussed in Beach et al. (2014, 2015). Although ecological research lags in Central America, a rich area of investigation developed around water management of Maya centers and regions (Matheny, 1976; Scarborough et al., 1993, 2012; Luzzadder-Beach, 2000; et al., 2012; Siemens et al., 2002; Lucero, 2002; Weiss-Krejci, 2002; Fash and Davis-Salazar, 2006; Davis-Salazar, 2003; Fedick and Morrison, 2004; Johnstone, 2004; Akpinar, 2011; Akpinar-Ferrand et al., 2012; Luzzadder-Beach et al., 2012; Wyatt, 2014). Many of these studies have also tied water management features to climate trends, including the cities that flourished in Classic period with elaborate reservoirs built during and after the Late Preclassic droughts (Dunning et al., 2012).

An inventory of all water-management features would include reservoirs, dams, canals, wells, *chultunes*, and soil-building features like terraces and *aguada* fills, because these hold soil moisture and the Maya built pits and wells to collect seepage into *aguada* fills (Akpinar, 2011: 41). Summing up the total moved sediment for ancient reservoir or *aguada* construction would need to account for the dams, berms, cisterns, floors, sediment removal and buildup, diversions, and the dredged materials over time. Despite the long history and recent upswing in studies of these features, most of them are hidden under forest canopies and others have been destroyed by drain-and-plow activity. Recent work at Tikal has started to remedy this with a landscape-level approach through excavation, mapping and multiple lines of paleoecological analysis. This work has found impressive evidence for water management, with a significant part of the urban infrastructure devoted to managing for too little or too much water, and even for water quality (Scarborough et al., 2012).

The Maya literature describes several dams and types of dams, such as a dam in the Cayo District of Belize (Healy, 1983), the Copán Valley of Honduras (Turner and Johnson, 1979), the massive Palace Reservoir dam at Tikal (Scarborough et al., 2012), La Milpa (Scarborough et al., 1995), and at Tamarindito (Beach and Dunning, 1996). Siemens et al. (2002) described a series of dams or weirs perpendicular to flow in a region of wetland fields, in the flat coastal plain of the Candelaria River (Figs. 1, 2), which they inferred were drought adaptations for channeling water. Similarly, a series of dams channeled water at ancient Chau Huiix, Belize (Pyburn, 2003).

We know of cisterns or *chultunes* from archaeology and from the early chronicler de Landa in the 16th Century and explorer J. L. Stephens (1843, p. 227) who described a series of *chultunes* in reservoir (or *aguada*) sediments, which acted as seeps in the dry season. From recent archaeology at the Puuc site of Kiuic, where Stephens visited in the 1840s, Simms et al.

(2012) wrote that *chultunes* are in every building complex and could have held enough water to last through the 4-5-month dry season. In many places, *chultunes* are plentiful and had multiple functions, beyond water storage (Matheny, 1971; Dahlin et al., 2005; Wyatt, 2014).

Scarborough (1993) has likened Classic Maya urban landscapes to “water mountains,” designed to efficiently drain and collect water. Such a model includes the limestone and plaster surfaces and high-runoff, drainage systems, diversions away from fields, and reservoirs to hold water and protect water quality, with evidence for filtration ponds and sand filters. Such cities as La Milpa (Dunning et al 1999), Tikal (Scarborough et al., 2012) and El Zotz (Beach et al., 2015) fit this pattern. In contrast, at Palenque the goal was drainage of excess water. This city had elaborate drainage systems in this wet region of Chiapas (French and Duffy, 2010; French et al., 2012).

Maya-built water features had much greater complexity and many purposes, from storage and preservation of water quality to defense, erosion control, flood control, aquaculture and ritual (Scarborough, 2003; Akpinar, 2011; Scarborough et al., 2012; Wyatt, 2014). *Aguadas*, for example, are important for their impacts on the landscape, including how much they are part of the built environment: floors or linings (Adams 1981; Akpinar-Ferrand et al. 2012; Beach et al. 2015), dams and filtration ponds and boxes (Scarborough et al. 2012), erosion and dredging and changing landscapes from dry to wet (Beach et al. 2015). We do not know the total number of *aguadas* constructed, but they occur at most Maya sites. They even occur next to rivers, such as at Cancun, Guatemala and above shallow water tables, such as at Chunchucmil, Yucatán (Beach et al. 2006; Beach 1998). Akpinar (2011) reviewed 45 *aguadas* and found most had human-modified features, ranging from highly engineered to more natural karst sinks or former quarries.

842 It is likely that there are thousands of such features, but our small sample number skews what we
843 can say about their chronology and uses.

844 One *aguada* at the Maya site of Zotz, 20 km west of Tikal, provides a case study of a
845 reservoir in the city's midst and the pattern of passive water management changing to more
846 active management from the Preclassic to Classic. The El Zotz *aguada* coincides with the start
847 of the city. Nearby Palmar, in a broad structural lowland, next to a seasonal lake (cival), waned
848 in the Late Preclassic, whereas El Zotz waxed in the Early Classic, on the escarpment edge. El
849 Zotz built its *aguada* with a berm around its edge, separate holding ponds, and lined the natural
850 sink with dressed stone, ceramic and clay, thus preventing infiltration and holding water from
851 runoff and rainfall (Fig. 8). The *aguadas* at Uxul, NW of El Mirador, Campeche, Mexico
852 (Seefeld, 2013) and Zacatel, between Nakbe and El Mirador, Guatemala had floors and complex
853 architecture and at Kinal, Petén, 100 km east of Nakbe, there was a silting pond (Wahl et al.,
854 2007b).

855 The main reservoir at Zotz held about 47,228 m³ of water, which makes it nearly as large
856 as the great Palace Reservoir at Tikal (Scarborough et al., 2012). Perhaps like the hypothesized
857 filtration system at Tikal (Scarborough et al., 2012), its well-constructed floor and possible
858 dams and holding tanks were engineered to maintain quality as well as to decrease losses from
859 percolation (Beach et al., 2015). Still, the Zotz reservoir aggraded through the Classic period
860 from a depth of 230 to 100 cm below the surface, when the Late Classic Zotz Maya built another
861 floor, this time of inferior construction, which then filled another 100 cm to the surface. An
862 *aguada* excavation at the Late Classic site of Xultun, northeast of Zotz, uncovered a similar Late
863 Classic floor (Akpınar et al., 2012). Although several reservoirs show signs of dredging, many

like the Zotz and Zacatel *aguadas* (Wahl et al., 2007) filled up with clay, possibly because they still held plenty of water into the Postclassic (Beach et al., 2015).

4.5 Lithospheric Impacts

Lithosphere impacts include Maya soil impacts, quarrying and Maya building or other uses of stone. Maya stone use involved large-scale impact because there are numerous Maya centers (Fig. 14) with stone buildings (Abrams, 1994), and the amounts of lime required to make plaster for the buildings and wood to make plaster were also high (Schreiner, 2002; Wernecke, 2008). Few studies, however, have quantified the tons of limestone or hours of human labor (Abrams, 1994) required for such constructions, though Dahlin et al. (2006) produced such estimates for the site of Chunchucmil. Lithic assemblages (Barrett, 2011; Dahlin et al., 2011) can also provide insights into patterns of resource depletion.

Mayasols: Soil Impacts

The Maya region has seen growing interest in the study of anthropogenic soil changes (Beach et al., 2006). In this large area, small-scale soil surveys for the central Maya Lowlands (9, 14, 15 on Fig 1), such as King et al., 1992: 221), map the Yaxa soil suite and Yalbac subsuite as dominants in the Central Petén, and Beach (1998a) characterized a catena of these soils in the central Petén (Fig. 2). Slopes mainly have Lithic and Vertic Rendolls (Mollisols), which are black, calcareous, fertile soils with smectite or vermiculite clays, and formed from allochthonous limestone impurities like chert and autochthonous Saharan dust and volcanic ash (Cabadas et al., 2010; Bautista et al., 2011; Tankersley et al., 2011). Depressions have cumelic Mollisols at their foot slope margins and Vertisols with 2:1 clays and some Histosols (Beach, 1998a; Beach et al., 2003; King et al., 1992, 223). In the northern Karst Plain, *Boxluum*

soils are dark, organic, fertile Mollisols, and *Kankab* soils are clayey, red Alfisols (Dunning, 1990; Beach, 1998b; Sweetwood et al., 2009).

In the Maya Lowlands, soils produced a clear ‘golden spike’ for the Anthropocene (Kennett and Beach, 2013; Certini and Scalenghe, 2011), because they preserve visual, chemical, and fossil evidence of system change. The changes we can relate to human impacts include soil enhancement and depletion, erosion and aggradation. Most of the evidence for erosion and aggradation comes from lake sediments and the Maya clay therein (discussed elsewhere), but we consider soil erosion, anthrosol formation and chemical alteration here.

Stevens (1964: 301, after Simmons, 1959: 986) speculated that many of the thin Rendoll soils of the Central Maya lowlands are still undergoing rejuvenation from accelerated erosion during Classic times because many Maya sites across the Petén occur in association with the shallow soils of the Yaxa Series. The few catena studies represent too small a sample size to characterize slope sequences in the large area of the Maya Lowlands, but >40 soil-depth measurements in the Petexbatun area of Guatemala yielded a depth range of 0-11 cm with a mean of ~7 cm (Beach, 1998a). Similarly, we found soils depths of 0-12 cm, formed since Classic times, near Chunchucmil, Mexico (Sweetwood et al. 2009). Olson (1977) reports about the same depth of soil formation (7.6 cm) on well-drained upland architecture (sampling sites 9, 17, 27 on top of structures at Tikal). Fernández et al. (2005) report 10 and 11 cm of soil formation above flat stucco surfaces over about the same time period at Piedras Negras in northwest Petén. These estimates give a soil formation rate of ~0-10 cm ka⁻¹ on level limestone, which is close to the total depth of some Petén soils.

Stevens (1964: 302) also considered the hypothesis that soil depletion caused the Late Classic Maya collapse, as outlined by Morley (1956:71) and introduced as early as 1926 by H.H.

Bennett (1926). Beach et al. (2008) observed complete soil profile truncation in the Petexbatun area and Belize in less than a decade, and Beach (1998) showed soils were 7.9 to 17.5 cm thinner on deforested slopes compared with forested slopes in Petén, Guatemala. Furley (1987) also found high soil loss rates in a *milpa* on comparable karst limestone slopes in Belize after only one planting (2-3 yr) and fallow (6-7 yr) cycle.

Although studies have considered Anthrosols across the Maya world (Graham, 2006; Beach et al., 2009b), we have yet to find a sizeable area of *terra preta* soils like those of Amazonia (Sweetwood et al., 2009). Studies have attempted to find equivalent Maya *terra preta*, but the remarkable enrichment found in Amazonian soils is rare. The site of Marco Gonzales, Belize provides some evidence (Beach et al., 2009b), but other areas with large ancient populations, such as Chunchucmil, do not display the levels of enrichment that define *terra preta* (Sweetwood et al., 2009). We also found similarly low black carbon levels for a small number of El Zotz soils and Birds of Paradise wetland field soils. Nonetheless, there are many examples of conspicuously melanized and nutrient-enhanced ‘black earth’ soil profiles (Beach et al., 2009b). Two main areas where we observe ‘black earths’ are in profiles where soils tend to be red, as around Chunchucmil and Mayapan, and where soils are light-colored, like the coastal sites of Marco Gonzales and Wits Cah Ak’al (Murata, 2011) (Fig. 11). In the area characterized by black Rendoll and Mollisol soils, melanization is obscured, though there is often evidence of activity layers in dark-colored soils, such as in wetland field soils (Fig. 9), which often have high $\delta^{13}\text{C}$ values (Table 2), elemental concentrations, and SOM (Beach et al., 2009b; 2011). Indeed, many of the black soils around Chunchucmil developed on Maya buildings, in plaster, refuse and possibly, intentional organic inputs (Beach, 1998b; Dahlin et al., 2005; Beach et al., 2009b; Sweetwood et al., 2009). The high calcium content of the construction

materials of ancient structures leads to formation of calcium humates, a very stable form of soil organic matter (Olk, D.C. 2006). Sweetwood et al. (2009) reported average organic C contents for Boxlu'um, saklu'um, and kancab soils of 151, 88, and 64 g/kg, respectively. There were significant correlations between soil organic carbon as soil levels of Ca, Mg, and clay increased. At Mayapan, there is a similar pattern, but it is more apparent because of occupation as recent as c. 500 BP, at least 500 years after Chunchucmil's occupation (Brown, 1999). In the Puuc Hills region, contemporary Maya farmers use the Yukatek term *kakab* ("high earth") to describe the dark, culturally enriched soils that formed on and amidst ruins (Dunning, 1992). Another site, Wits Cah Ak'al, was focused on salt production on the coastal plain (Murata, 2011), and the soils formed on the site are built from the scatter of clay ceramic materials that bury and alter virgin soils (Fig. 11). Both Marco Gonzales and Wits Cah Ak'al also have high quantities of sodium chloride (NaCl, i.e. salt), which may be a factor in SOM preservation.

Slope Sequences

There have been many studies of soil impacts by the Maya. Most have focused on sediments in depositional environments and reveal two typical strata, the "Maya Clay" and the "*Ekluum* Paleosol," which signify the "Mayacene" in some places. Beach and colleagues (1995, 1998, 2002, 2003, 2006, 2008, 2009, 2011, 2013, 2014) identified sequences of buried soils dating to ancient Maya periods in agricultural terraces, floodplains, karst sinks, and alluvial fans based on physical evidence like Munsell color, textural differences, magnetic susceptibility, pollen, phytoliths, charcoal, and chemical changes. For example, some floodplain sequences have buried paleosols, clearly identifiable by light-colored sediments, aggraded from upslope erosion that buried dark, organic Maya-period soils (as in Fig.12), which developed for millennia based on their black, organic-rich top soils and evidence for weathering to clay-size particles.

955 These paleosols do not occur in all depositional sequences for several reasons: erosion-produced
956 aggradation does not occur everywhere, some soils lose their black color as organic matter
957 decomposes, some profiles may have been truncated, and others may have aggraded too steadily
958 for strong contrasts in melanization. Other factors like soil texture, structure, and magnetic
959 susceptibility (m.s.) may also help identify paleosols in dated sequences, and thus indicate
960 transformations that may become preserved in the long-term geological record. For example,
961 many buried soils display increased magnetic susceptibility through buried top soils because the
962 top soil developed for millennia on the surface, where it received metals from aeolian deposition
963 and was magnetized further by surface burning, both of which would decrease in rapidly
964 aggrading segment (Luzzadder-Beach and Beach, 2009). Similarly, soil texture should be finer
965 and more weathered from long-term weathering at the surface, as opposed to in rapidly derived
966 sediments that are deposited during erosion and aggradation cycles. Human application of mulch
967 can, however, complicate interpretations.

968 Cancuen, Guatemala was a largely Late Classic site with an erosion and deposition cycle
969 revealed in buried soils on footslopes and in depressions that date to the Late Classic (Fig. 11;
970 Beach et al., 2006). Indeed, footslopes there (Fig. 11) expose the facies intersection of a
971 floodplain cumilic soil with an abruptly buried slope soil. Erosion occurred earlier in paleosol
972 sequences around Blue Creek and the Programme for Belize in northwestern Belize, where
973 examples come from both the Preclassic and Classic periods. For example, one footslope at
974 Chawak in the Programme for Belize had a paleosol dated to the Late Preclassic, but facies-
975 changing aggradation to the Late Classic, topped with mature topsoil (Fig. 11) (Beach et al., in
976 review). These examples show both the “Mayacene” and modern “Anthropocene” because
977 recent gullying through sediments exposed the paleosols and modern topsoils at deforested sites

in the Petén and Blue Creek, but excavation exposed them in the forest preserves in the Programme for Belize.

These examples indicate the “Mayacene” upland equivalent of Maya Clay is the change in geomorphic process from mostly karstic to mostly fluvial (Luzzadder-Beach and Beach, 2008). Soil sequences in the Programme for Belize, in the Petexbatun area, and at Cancuen and elsewhere display evidence for slow, mostly karst processes under forested conditions before and after the “Mayacene,” when runoff was internal and carbonic acid was high from soil respiration. Deforestation, however, led to fluvial runoff dominance, lowered infiltration, and more erosion and aggradation (Beach, 1998a; Beach et al., 2008). Modern soil erosion has exposed some soil sequences, which exhibit the geomorphologic metamorphosis that accompanied both the “Mayacene” and “Anthropocene.”

Ancient Maya Terraces

Intensive agricultural systems took the form of wetland field systems and terrace systems and both imply large amounts of labor and planning (Beach et al., 2002; 2008; 2009). There were also forest gardens (Ford and Nigh, 2009) and even *milpas*, managed under the considerable knowledge of *milperos* (Nigh and Diement, 2013). Terraces and wetland fields can break down and become ineffective if poorly constructed or subject to extreme events. There are multiple types, functions and possible uses of terraces (Beach et al., 2002), and increasingly, studies of these systems are showing earlier use and more extensive coverage. The main areas of terracing are Caracol and the Vaca Plateau, northern Belize, the Petexbatun area of Petén, and the Rio Bec region of southern Campeche and Quintana Roo, Mexico, but there is a lack of terraces at Tikal and Copán (Beach et al., 2002, 2008). It required traditional archaeology at Mininha (Macrae and Iannone, 2011) to reveal the chronology of terracing, but Lidar (Chase et al., 2014) indicates

widespread coverage of terrace systems at Caracol, which will probably be extended with more ground-truth field checking.

Aspects of interest with regard to terraces are the anthrosols that form, the wall and drainage construction, how well they conserve soils, and whether their Late Classic use correlates with decreased erosion (Anselmetti et al., 2007) and can stand as an example of sustainable landesque capital. In some cases, terracing started in the Preclassic as at Bajo Donato near San Bartolo, Guatemala (Beach et al., 2009b) and Mininha, Belize (Macrae and Iannone, 2011). But more terraces developed later with higher populations in the Classic period (Beach et al., 2002; Holley et al., 2000) and dwindled in the Postclassic at Mininha (Macrae and Iannone, 2011). Despite the advantages of terracing (Fig. 12), there are still some areas with few terraces even in steep terrain at Tikal and Copán, though Dunning et al. (2015) recently reported a few terraces near Tikal. Areas with terracing that persisted over time would have developed landesque capital with use, and ecological capital with disuse, as at Caracol, Belize (Hightower et al., 2013) and the Rio Bravo (Beach et al., 2002, in review). The Maya may have used other slope conservation techniques, like forest conservation or vegetative berms, but some areas, perhaps those with skeletal soils today, simply eroded during use and developed thin soils since abandonment. Such scenarios would leave juvenile, thin soils on the slopes, with $\delta^{13}\text{C}$ signatures of tropical forests and buried sequences with complicated $\delta^{13}\text{C}$ signatures of mixed forest and C_4 species including *Zea mays* (Webb et al., 2004).

Geochemical markers in *Mayasols*

The pre-Hispanic Maya left a distinct impact on the inorganic chemistry of soils and sediments across a diverse range of landscapes. These markers include evident changes in the

amounts of Cu, Fe, Mn, Pb, Zn (Beach, 1998b; Coronel et al., 2014; Dahlin et al., 2007; Eberl et al., 2012; Hutson and Terry, 2006; Luzzadder-Beach et al., 2011; Manzanilla, 1996; Middleton, 2004; Middleton and Price, 1996; Parnell et al., 2002 a and b, Terry et al., 2004), Au, Hg, and the Rare Earth Elements (REEs) (Beach et al., 2006, 2008; Cook et al., 2006; Kovacevich et al., 2004; Wells et al., 2000) in soils that are coincident with the Classic Maya period (*c.* 1700-1100 BP). The greatest research focus, however, has been on the measurement and interpretation of phosphorus (P) in the ancient Maya environment.

In the lowlands of Mexico, Guatemala and Belize, the clay-rich tropical soils and limestone parent material are typically low in elemental P (Beach, 1998a, Beach et al., 2006; Cook et al., 2006). Pedoarchaeological research there has shown that soils contain micro-debitage, ceramics, plant and animal remains, dyes and food material that impart distinctive and persistent chemical signatures, including P concentrations that exceed the ‘natural’ background level. Since the early work of Cowgill and Hutchinson (1963) and Cook and Heizer (1965), more than 20 ancient Maya sites have reported elevated levels of P across Mexico, Belize, Guatemala, Honduras, and El Salvador, an area of ~350,000 km², nearly the size of Japan (Fig. 1). These elevated concentrations of P in Mayasols average **329** mg kg⁻¹ (geometric mean), with values as great as 11,000 mg kg⁻¹ detected in the Maya world (Table 1). These data include P concentrations determined via strong acid digestion and/or complete decomposition (Total soil P) and weak acid (extractable soil P) methods (Holliday and Gartner, 2007). Care needs to be taken when comparing geochemical data obtained by different methods. Our soil P compilation, therefore, is an underestimate of the real magnitude of elevated P in Maya-impacted soils.

Anthropogenic P, identifiable as elevated P concentrations in soil profiles contemporaneous with the Maya civilization, may thus be considered a regional-scale

chemostratigraphic marker of the Maya Anthropocene (Certini and Scalenghe, 2011; Gałuszka et al., 2013 and Gale, 2009).

There is nearly a century of research worldwide that reports the use of soil P analysis as an indicator of past human activity (Holliday and Gartner, 2007; King, 2008; and Mejía and Barba, 1988). Human activities redistribute and concentrate P derived from human and animal excretions, bones and plant remains that are reworked into sediments and soils (Arrhenius, 1963, Cook and Heizer, 1965; Deevey et al., 1979; Eidt, 1977, Gale et al., 2004; Gale and Carden, 2005; Gale and Hoare, 2011). Ethnographic and anthropological studies in the Maya world suggest that a number of specific human activities may leave measurable P signals in soils, including the establishment of home gardens (Flores-Delgadillo et al., 2011) and the generation of *terra preta and mulata*, animal pens (Barba and Lazos, 2000) and craft manufacture (Wells, 2004). Although some have interpreted elevated soil P in archaeological contexts as evidence of former cooking and living areas (e.g., from Mehlich-extractable P data, Parnell et al., 2002a: 386), earlier work by Middleton and Price (1996) (using Total soil P data) found little evidence of elevated soil P from modern Maya household activities. Further conflicting results comes from the ethnoarchaeological study of modern household areas in Guatemala (Fernández et al. (2002) and Mexico (Dore and Varela, 2010), and from the analysis of soils from food preparation areas in marketplaces by Dahlin et al. (2007). We are still uncertain if crop-based agriculture depleted or enhanced P in soils, though certain fractions would become occluded and persist in the soil (Arnason et al., 1982; Beach, 1998b, Dunning et al., 1997; Johnson et al., 2007). Agriculture has the potential to both concentrate and deplete soil P: heavy maize production without fertilizer depletes P in soil, whereas growing legumes and fertilizing enhances P levels even though legumes do not fix P as they do N (Nuruzzaman et al., 2006).

Mapping P concentrations across broad swaths of landscape indicates both positive and negative correlations between elevated P levels and ancient agricultural spaces, a finding that suggests a mix of land use practices, including fertilization (Ball and Kelsay, 1992; Dunning, 1992; Dunning et al., 1997; Killion et al., 1989; Smyth et al., 1995).

Soils across the Maya Lowlands are phosphate-poor in general and, thus, increases in P levels are good indicators of environmental change. Much of P residing in regional soils is of aeolian origin, derived from Saharan dust (Gross et al., 2015) and volcanic ash or recaptured from burned vegetation. Removal of forest cover severely retards the capture of airborne particulates and deprives soil of replenishing P (Lawrence et al., 2007; Das et al., 2011). Hence, ancient deforestation would likely have had a negative consequence in addition to those already noted, namely a steady decline in P levels and innate fertility (Dunning et al., 2012; Turner and Sabloff, 2012). One consequence of declining fertility in some areas is the invasion of undesirable fern species that are difficult to eradicate (Dunning and Beach, 2010).

Overall, studies in the Maya area show elevated P alone is not diagnostic of any specific past human activity because of the equifinality of process-response relationships (Walkington, 2010). Interpreting the Maya P record may be complicated by the numerous and often indistinguishable potential sources, and the potential for P mobility in both natural and modified soils and sediments (Cook et al., 2006). Nonetheless, by correlating patterns of P enrichment in soils with archaeological data (architecture, artifacts, human or animal remains, microdebitage), important insights into ancient Maya activities have been made. Developments in the analysis of P, to include step-wise extraction techniques to examine the multiple forms of P in archaeological soils, have proven useful in pinpointing the causes of elevated P at Maya sites (Beach, 1998b; Hutson et al., 2009; Luzzadder-Beach et al., 2011). Regardless of the exact

origins or pathways from humans to soils, the detection of elevated P at so many ancient Maya sites gives us confidence that it is a reliable marker of past human activity. The fact that P is a region-wide marker of ancient Maya activity makes it a robust metric for the Anthropocene in the Maya world.

If elevated P in soils and sediments across the Maya world is a ‘golden spike,’ then at what time do we hammer it in? The overwhelming majority of our understanding of P and the ancient Maya comes from Classic period contexts. The nature of Maya anthrosols and soil floors means the geochemical imprint of the “Mayacene” occurs mainly on the last site modification before abandonment. Although the first phase of human activity at a site leaves a physical or geochemical imprint, each successive phase of human activity may modify or even erase it, unless there are sealed contexts (Entwistle et al, 1998). In effect, much of the research on P in ancient Maya soils represents either the most recent records of ancient human activity or a cumulative effect (Wells et al, 2000). The study of buried anthrosols offers insights into past soil-human interactions during early Maya prehistory (Beach et al., 2006, 2008, 2009; Cook et al., 2006; Kennett and Beach, 2013; Luzzadder-Beach and Beach, 2009; Solís-Castillo et al., 2013).

Although soil and activity-area studies provide some spatial extent of P enrichment during the “Mayacene,” there is little temporal detail because of the Classic period overwriting. Understanding the history of anthropogenic input of phosphorus to the environment, especially the onset of significant inputs as a geochemical marker, is vital to establish the timing of the “Mayacene.” Lake sediment cores, mostly from the Yucatán (Mexico) and Central Petén (Guatemala), have been the primary source of data for reconstructing the Holocene history of environmental change and human impacts. The majority of this work has focused on developing

1115 stable oxygen isotope records on lacustrine biogenic carbonates (Covich and Stuiver, 1974;
1116 Curtis et al., 1996; Hodell et al., 2005) and identification of pollen to develop proxy records of
1117 past vegetation and climate change (Leyden, 2002). Far fewer studies, however, have produced
1118 inorganic geochemical time series (including phosphorus) capable of confirming the chronology
1119 of anthropogenic P time-horizon(s). Lake and *bajo* sediment records collected from the Central
1120 Petén region suggest that the first rise in anthropogenic P in the environment predates the Classic
1121 Period soil and activity-area data by millennia. Extensive coring of lake basins there since the
1122 1960s (Cowgill and Hutchinson, 1963) shows that phosphorus levels began increasing above
1123 long-term ‘natural’ background levels as early as *c.* 3000 BP (Preclassic), but reached their late
1124 Holocene peak *c.* 1000 BP (Late Classic) (Dunning et al, 1998). In the nearby Petexbatun region,
1125 a 10-ka record of environmental change from Laguna Tamarindito shows minor increases in
1126 phosphorus above the long-term background in the late Archaic period, *c.* 4000 BP. The greatest
1127 increase in P flux to the lake, however, dates from *c.* 2000 BP, in the Late Preclassic, which
1128 reflects the coeval large-scale forest clearance recorded in the pollen record (Dunning et al,
1129 1998).

1130 Based on the quantities of Maya house mounds, population densities in the Preclassic
1131 Period were relatively low (Rice and Rice, 1990), so the clear rise in P dating to this period
1132 highlights the sensitivity of the sediment records to early human activity. Indeed, the rise in P in
1133 the environment after 3000 BP is an indirect marker of human activity, associated with early
1134 vegetation clearance by the Maya and the rapid erosion and transport of top soils into lake
1135 basins, resulting in the deposition of the ‘Maya Clay’ (Anselmetti et al., 2007; Beach, 1998a;
1136 Beach et al., 2006; Beach et al., 2008; Deevey et al., 1979; Dunning et al., 2002). Nonetheless,
1137 the Late Preclassic P signal stands as a clear anthropogenic marker preserved across much of the

1138 Maya world. Although this first spike in P marks the onset of measurable anthropogenic P, P
1139 concentrations in lake sediments across the Petén increase by as much as 40 times in the
1140 millennia that followed, reaching maximum concentrations by the Late Classic (Dunning et al.,
1141 1998).

1142 Several Yucatán records also show the long-term record of P enrichment in the
1143 environment. In a core from Lake Coba, P slowly rises from *c.* 3000 BP to a maximum in the
1144 Late Classic period, *c.* 1200 BP (Whitmore et al., 1996). Farther northwest in the Yucatán
1145 Peninsula, the Lake Sayaucil record shows increasing phosphorus in the basin from *c.* 3000 BP,
1146 and as at Tamarindito, sharply increasing P in the Late Preclassic, coeval with human settlement
1147 (Whitmore et al., 1996). The P histories from Coba and Sayaucil are broadly similar to those
1148 recorded in the Central Petén, though P concentrations in Petén also spike briefly at their Archaic
1149 bases. Most concluded these early peaks in P were connected to discrete pulses of minerogenic
1150 material deposited during initial lake filling (Whitmore et al., 1996). In coastal Veracruz,
1151 Mexico, the history of anthropogenic P exhibits some departures from the pattern recorded
1152 further east in the Maya world. In the sediments from Laguna Caterina, P rises sharply after
1153 about 3000 BP, doubling in concentration within a century. Here, the greatest concentration of
1154 sediment P dates to *c.* 1500 BP (Classic Period) and declines thereafter (Sluyter, 1997).

1155 In lake sediment records, post-depositional interactions between P and Fe, and to some
1156 extent Ca, have resulted in lake redox conditions that influence the sedimentary P record
1157 (Engstrom and Wright, 1984; Anderson and Rippey, 1994). In the Maya world, the first rise in P
1158 above long-term background levels in lake sediments comes with the sudden influx of
1159 terrigenous material, following deforestation by the Preclassic Maya (Dunning et al., 1998). This
1160 is supported by parallel changes in pollen and diatom records from the same sediment cores,

1161 recording initial large-scale forest clearance in the late Preclassic. This provides support for the
1162 claim that the rise in P recorded during this period reflects environmental conditions at the time,
1163 rather than an artifact of post-depositional mobility in the sediments.

1164 In the lakes and *bajos* of central Petén and Yucatán, P concentrations increase through
1165 the Classic Period, despite many sites recording reductions in soil erosion and sediment flux to
1166 lakes. One explanation for this decoupling of Maya soil erosion and P flux in the Classic is the
1167 additional P input from the large populations and intensive land uses. Some support for this
1168 hypothesis comes from the increased quantities of charcoal and economic macrobotanical
1169 remains found in sediments from this period (Beach et al., 2008).

1170 **Carbon Isotopes in Dated Profiles**

1171 The last proxy we consider for the “Mayacene” is ^{13}C enrichment in dated soil profiles.
1172 Many papers have described the methods to analyze stable carbon isotope ratios of soil humin,
1173 identified as the oldest and most distinct SOM fraction to study (Webb et al., 2004; Awiti et al.,
1174 2008; Beach et al., 2009a, 2011). Beach et al. (2009, 2011, 2015) presented many profiles of
1175 $\delta^{13}\text{C}$ in dated sequences. Here we review these and other findings and add many new ones
1176 (Table 2). These sequences include ancient Maya wetland fields, terraces, *bajos* and *aguadas*
1177 (reservoirs), because these are all depositional environments that would have accumulated soils
1178 with organic matter that reflected the vegetation of the dated layers. For comparison, we add a
1179 new study of slopes that possess little evidence for Maya use.

1180 The $\delta^{13}\text{C}$ value can increase by approximately 1–3 ‰ in deeper soil horizons through soil
1181 microbial decomposition, and tropical soil processes can accelerate microbial activity, thereby
1182 increasing $\delta^{13}\text{C}$ by 3 or 4‰ (Ågren et al., 1996; Martinelli et al., 1996; Van Dam et al., 1997;

Balzotti et al., 2013). A $\delta^{13}\text{C}$ increase of 3 or 4‰ or more in a profile is a standard for C_4 species enrichment, above the expected value of about -27‰ for C_3 plants (Beach et al., 2011; Fernandez et al., 2005; Lane et al., 2004; Webb et al., 2004; Wright et al., 2009). To estimate the % C_4 vegetation contribution to soil humin we used the following equation (Nordt, 2001: 423; Wright et al., 2009):

$$\% \text{ SOC obtained from } \text{C}_4 \text{ vegetation } (\text{C}_{\text{C4}}) = 100 * (\delta^{13}\text{C}_{\text{soc}} - \delta^{13}\text{C}_{\text{C3}}) / (\delta^{13}\text{C}_{\text{C4}} - \delta^{13}\text{C}_{\text{C3}})$$

Sites: Slope Sequences

We include a new area as a baseline because it was relatively little influenced by the ancient Maya. The Cave slope area ($\sim 17^\circ 52'$ N Latitude) near Blue Creek, Belize lies about 1 km from small-scale Maya sites and yielded no artifacts. The slopes at the cave site had an average $\delta^{13}\text{C}$ of -26.7 ‰ in the A horizons and -25.1 ‰ in the C horizons of the Rendoll soils on steep slopes. Six of 10 soil profiles had simple, 20-cm or thinner O and A horizons over limestone and *sascab*. The exceptions were two deeper samples, a 50-cm-deep footslope soil and a 35-cm-deep soil in a back-slope rock cavity, and both showed increased $\delta^{13}\text{C}$, to -24.5 ‰ and -23.7 ‰. These numbers do not reflect the 4‰ criterion for C_4 enrichment, but indicate 16.7 to 22 % C_4 vegetation on these soils, where most today have minimal C_4 input.

A similar group of soil testing transects on the Sierrita de Ticul produced comparable results in an area with little to no Maya architecture and artifacts. Here again the transect slopes had an average $\delta^{13}\text{C}$ of -24.7‰ overall ($N = 35$), -25.6‰ for A horizons ($n = 24$), and -22.8 for lower horizons ($n = 11$), a ~ 3 ‰ increase in $\delta^{13}\text{C}$ of these profiles. Most soils had only A and AC horizons, but depression soils had deeper sequences, including a 60-cm-deep soil that changed from -26.3‰ in its upper A horizon to -22.3‰ and -21.8 ‰ at 25 and 45 cm, respectively. This

was an increase of 4.5 ‰, perhaps indicative of earlier maize agriculture in this deep *Kankab* soil. Another depression profile showed a similar pattern, with a surface value of -26‰, which increased to -22.7‰ at 25 cm, -22.3‰ at 45 cm, and -22.6 ‰ at 75 cm (Table 1).

Most of the slope soils display little $\delta^{13}\text{C}$ change in their stable isotope ratios with depth, because most are thin soils. Several deep soils, however, show significant increases in isotope values with depth. Balzotti et al. (2013) and Lentz et al. (2015) also found little change with depth around slope sites near Tikal, and they argued this was because the ancient Maya preserved forests on slopes. Dunning et al. (2015) studied summits and back slopes near Tikal, on the edge of the Bajo de Santa Fe and the Perdido Bajo, which showed no evidence for inputs of maize or other C_4 species. They also found the only profiles with evidence of C_4 species inputs were at foot slopes with $\delta^{13}\text{C}$ shifts of 3.3 to 6‰, the former similar to the cave slope. All of these slope soils may have been truncated, having developed only since the Late Classic in the *sascab* parent material under tropical forest cover. For example, Beach et al. (2008) observed complete soil profile truncation within five years of forest clearance on similar slopes just 1 km from the Cave slope.

Another Catena sequence behind the main plaza at La Milpa, Belize provided new slope evidence just beyond a dense Maya site. There, the back slope Rendolls have thin soil profiles, 30-40 cm deep, and display minimal $\delta^{13}\text{C}$ increase with depth. At the footslope site, a plaza excavation, in this sequence was an increase of the $\delta^{13}\text{C}$ to -24.4‰, similar to the Cave site's foot slope level of increase but below the 4‰ threshold of C_4 enrichment.

Another region with equivocal evidence for increased $\delta^{13}\text{C}$ is the region around Chunchucmil, Yucatán, Mexico (Sweetwood et al., 2009). There, soil profiles of $\delta^{13}\text{C}$ values

varied little across the entire landscape, despite the site's large population and likely high maize demand. The largest departure in $\delta^{13}\text{C}$ throughout the soil sequence was only 2.4‰ and the median was only 0.3‰. There were, however, significant spatial differences ($P < 0.01$) in $\delta^{13}\text{C}$ values according to soil type and vegetation zone. In a transect from the Gulf of Mexico through Chunchucmil, the coastal wetland with mainly C_3 species averaged -27.2‰ , one savanna zone averaged -25.4‰ , a site with anthropogenic soils averaged -23.7‰ , another zone with *kankab* soils averaged -22.6‰ , and buried soil under structures averaged -24.0‰ . The latter sites today all have mixtures of C_3 and C_4 species and have pronounced bioturbation, which has mixed SOM, possibly expunging evidence of ancient intensive maize farming.

Agricultural Terraces

Terraced slopes in the Central Maya lowlands are dominated today by C_3 species, but compared with un-terraced slopes, show more C_4 increases in their profiles. All of the terrace sequences have increased $\delta^{13}\text{C}$ values deeper soils, with top soil averaging -27.8‰ and the dated Classic levels averaging -23.6‰ , producing a mean C_4 plant contribution to the Classic soils of 23%. Three of the terraces produce buried profiles with $\delta^{13}\text{C}$ values $>4\text{‰}$ greater than in topsoil (Table 2). One other profile at Chawak, northwestern Belize had a $\delta^{13}\text{C}$ enrichment of 3.7‰ to -23.3‰ , which indicates $\sim 25\%$ increase in C_4 species through layers dated by two AMS analyses to the Late Classic (Beach et al., in review). At the La Milpa slope discussed above, the top of the slope profile near a terrace wall was clearly human-altered, with buried soil A horizons and a $\delta^{13}\text{C}$ increase from -28.9 to -22.6‰ , which would indicate an increase of up to 29% in the contribution from C_4 species. Because this was so near the Maya site, the values may reflect a *Zea mays* infield or preparation area.

Aguadas

Sediments in ancient Maya reservoirs showed little change in Classic period layers at Diablo (El Zotz, Guatemala), to some of the greatest levels of ^{13}C enrichment at a Cancuen *aguada*, Guatemala (61%). The Diablo case is just downhill from a precipice site of royal tombs, an unlikely place for maize production. Six of ten *aguadas* had greater than 4‰ above the C3 limit of -27 ‰. The Palmar cival near a Preclassic site with abundant evidence of maize agriculture had it highest levels (3.61 ‰ increase) in the Preclassic, which declined in the Classic period (Luzzadder-Beach et al. in Review). Five *aguadas* displayed a strong central tendency, with 27-28.4% C4 inputs in the Classic period deposits, although two others had from 11.7-18.2 %. Three profiles with high C4 inputs in the buried soils had similarly high C4 inputs in the surface soils, indicating modern C4 inputs or perhaps disturbance of the uppermost soil from bioturbation.

Bajos

Bajos around NW Belize produced equivocal results about C4 enrichment, but those around Tikal provide evidence for C4 species enrichment, especially at foot slopes and margins (Dunning et al., 2015 a and b). Previously we found that *bajos* had 3.8 to 26 % of their ancient soil humin derived from C4 species, and two new samples from *bajo* margins near sites in northwestern Belize and a third from Guatemala had similarly low C4 inputs. It should not be a surprise that *bajos* and other sites display a range of C4 (^{13}C) enrichment because they cover large expanses in the central Maya Lowlands, where ancient crops were both C4 and C3 species, and there were many other Maya land uses, involving mainly C3 species.

Floodplains

Floodplain soil $\delta^{13}\text{C}$ values can reflect local vegetation or that of the broader watershed from flood-deposited organic matter. Thus, floodplains may have mixed isotope signals unless

they have dating-constrained activity areas. At the little-disturbed Rio Bravo, NW Belize, three floodplain transects produced a range of results. The two sites that had significant $\delta^{13}\text{C}$ enrichment ($\sim 4\text{‰}$ and 26.5-33.3% increase in C_4 species) were Vertisol sites (GC 3 and Chawak 3) on slightly elevated stream terraces in the upper and lower Rio Bravo (Table 2). Floods rarely reach these sites and, thus, flood deposition is low. These sites may reflect ancient terrace and levee agriculture. Another site had higher $\delta^{13}\text{C}$ values (40.7 % C_4 inputs in the Preclassic), but it also had an elevated surface $\delta^{13}\text{C}$ value even though modern vegetation is largely C_3 species (Beach et al. 2011). The other floodplain sites showed slightly increased $\delta^{13}\text{C}$ values through Classic sediments before decreasing in Preclassic sediments.

The two Usumacinta aggrading floodplain sites discussed earlier also contained buried $\delta^{13}\text{C}$ isotopic signatures of C_4 species in ancient Maya paleosol levels. The site near Piedras Negras, Guatemala had a strong $\delta^{13}\text{C}$ isotopic signature of C_4 species at 94 to 125 cm in a buried A and BW sequence dated to the Late Preclassic, c. 2200 $\pm$ 70 BP (Fernandez et al., 2005). Also, three floodplain cores at the site of El Kinel near La Tecnica, Guatemala produced strong isotopic evidence of C_4 species at depths of 45-90 cm and 180 to 210 cm, dated broadly to the ancient Maya period. In contrast, all sediments deposited in the past 1000 years at these sites have the signatures of C_3 vegetation (Balzotti et al., 2013).

Wetlands and wetland fields

Beach et al. (2009, 2011, 2015, in review) studied wetland fields and canals at Chan Cahal, Sayap Ha, Chawak, and Birds of Paradise. Chan Cahal and Sayap Ha present a challenge because the wetland fields and canals there have been plowed and drained and planted in tropical grasses dominated by C_4 species since at least 1970, and as early as the late 1950s (Beach et al.,

2015). For example, Para grass (*Urochloa mutica*) is a common grass of wetlands and margins in Belize, and this tropical African grass uses the C₄ photosynthetic pathway (Douglas and O'Connor, 2004). In Kenya, Awiti et al. (2008) reported $\delta^{13}\text{C}$ increases in soils over 17 to 60 years, from $24.3 \pm 0.2\text{‰}$ in forest to $-16.3 \pm 0.4\text{‰}$ under cropland. Hence, soils in the Maya Lowlands with parallel land use changes may have similarly increased inputs in C₄ species and $\delta^{13}\text{C}$ through their surface to rhizosphere.

One site, 66T, still under canopy had a surface $\delta^{13}\text{C}$ of -28.34‰ , which rose to -24.09‰ moving downward into Terminal Classic sediments with *Zea mays* pollen, before dropping in underlying Preclassic sediments (Beach et al., 2009a). A field and canal that had only been converted to pasture for 10 years had surface $\delta^{13}\text{C}$ values of -26.45 and -26.68‰ , which rose to -25.37 and -25.13‰ through Terminal Classic sediments. These indicated small ancient C₄ inputs, but also had surface soils that may reflect the early shift to C₄ grass pastures. The areas under 40-50 years of C₄ pastures at Chan Cahal and Sayap Ha, all had surface soils strongly influenced by C₄ inputs. The Sayap Ha Field and canal had surface $\delta^{13}\text{C}$ values that were -17.08 and -16.63‰ and Terminal Classic values that were -20.30 and -18.63‰ . If surface soils were altered by C₄ grasses, then ancient soils reflect $\delta^{13}\text{C}$ increases of 6.3 and 6.52 ‰ and reflect inputs of 44.7 and 55.8 % from C₄ species. One other wetland field had a surface $\delta^{13}\text{C}$ of -21.86‰ and a Late Classic $\delta^{13}\text{C}$ of -21.51‰ , and a raised field platform from the Terminal or Postclassic had a similarly elevated $\delta^{13}\text{C}$ soil surface value of -18.1‰ . Three other sites at an *aguada* under pasture (Tamarindito, Guatemala) and a grassland-affected *aguada* and cival (Bejucal) had significantly higher $\delta^{13}\text{C}$ in the upper horizons. We note that two other tropical

forest floodplain sites (GC 50 and 250) had increased $\delta^{13}\text{C}$ in their upper horizons, but only to values about -23‰, and had $\delta^{13}\text{C}$ in Classic and Preclassic soils of -24.1 to -20.9‰.

The Birds of Paradise fields yielded $\delta^{13}\text{C}$ values with the highest percent contribution from C_4 species during the Classic period. Each of six $\delta^{13}\text{C}$ profiles had strong C_3 surface signatures and C_4 signatures at least 3.76‰ higher in the Late Classic field and canal levels (Beach et al., 2011). The Late Classic values indicated a range from 25 to 64% C_4 species input and had pollen evidence of maize and other grasses in this area, today dominated by C_3 species.

The Chawak wetland field site produced similar results to Birds of Paradise with a $\delta^{13}\text{C}$ increase of 5.5‰, which represents ~36.5% C_4 species input through the well dated paleosol and activity layer from the Late Classic. This site had poor pollen preservation because of seasonal oxidation, but grass pollen was dominant through the field levels and depths with greater $\delta^{13}\text{C}$ values (Beach et al., in review).

Overall, agricultural terraces, *bajo* margins, footslopes, stream terraces, and wetland fields and the fill in canals that dates to the Late Classic indicate C_4 enrichment in soil humin. Wetland fields and canals exhibited the strongest evidence for C_4 inputs compared to other sites, over time and several have maize and other economic pollen at the same levels, which together with the labor investments in field and canal construction indicate these fields were intensive farming systems. This was also the most potent agricultural proxy of the “Mayacene,” with evidence of up to 64% of the Late Classic vegetation being C_4 species in areas that are today dominated by C_3 tropical forests. Indeed, the wetland sites at Chan Cahal provide evidence for both the “Mayacene” and the Anthropocene with C_4 species significantly influencing the ancient Maya paleosols, and modern top soils under pasture grass.

5. Conclusions

Maya exceptionalism has a long history (Turner, 1993; Dunning and Beach, 2004), implying that Maya civilization was transcendent in one way or another. We make no claims for Maya exceptionalism, though we do define the “Mayacene” as a period based on stratigraphic changes that are both negative, i.e. degradation through soil erosion, and positive, i.e. building sustainable landesque capital like terracing. In most cases degradation part lowered the worth of the landscape for the Maya of the past and today. Many aspects of Maya landscapes can have negative impacts, including sedimentation on slopes, valleys, wetlands and lakes, and pollutants such as mercury and potentially phosphorus, if the latter is high enough to produce harmful algal blooms. Some of the byproducts of Maya land use could be positive such as landesque capital from Maya alterations that improved their use of the environment, including garden cities, forest gardens, reservoirs, terraces, roadways, wetland fields, anthrosols, and even slope erosion that built up footslope soils and *bajo* margin cultivation.

We considered five major ‘golden spikes’ and one line of modeling for the “Mayacene.” The first is the so-called “Maya Clay,” which is a facies that appears abruptly, and represents a shift from stable surfaces to unstable deposition in lake, wetland, floodplain, and even slope sediments. This represents a landscape that had been stable for millennia, becoming unstable, with “Mayacene” erosion and deposition. In some places this represented a largely karstic landscape becoming largely fluvial through some part of the Mayacene, before turning karstic again after Maya impacts waned. In some lakes and wetlands this may have started in the Middle Holocene with pollen evidence showing the changeover from peak forest to diminished forest taxa. The cause may have been the natural drying of Late Holocene climate or the first anthropogenic flush of agriculture indicated by *Zea mays* and charcoal by 5400 BP in Honduras,

and archaeological evidence for use of plants that later became cultigens extends back to 8500 BP (Morell-Hart et al., 2014). However early this might have been, *Zea mays*, disturbance pollen, and Maya clay are in full force from 3000 BP through at least the Terminal Classic period and in some places up to the European conquest, which ironically may have ushered in reforestation in some areas. We must now separate pollen, phosphorus, and charcoal evidence from sedimentation evidence because sedimentation decreased during periods with the highest population densities in the Late Classic (Dunning et al. 2002; Anselmetti et al., 2007; Fleurie et al., 2013). This may have been a consequence of Maya response to erosion and better slope management, or possibly to source reduction, but evidence for the rise of terracing argues for the former.

The second golden spike is the paleosol sequence (Fig. 6), from deposition on low slopes and erosion on steep slopes. We have shown buried paleosols from upper floodplains to footslopes, to alluvial fans, to large floodplains and wetlands. These paleosols usually date to the Preclassic as at La Milpa, where there is a strong Preclassic presence, or to the Classic as at Cancuen, where Classic occupation prevailed. As Certini and Scalenghe (2011) argue, these are visual “golden spikes” for the Anthropocene, but slope erosion is harder to trace because of the wide network of sediment flow and lack of watershed-level research. The thin, upland Rendoll soils of the region, as suggested early in Maya research, may be the upslope evidence of the “Mayacene.”

The third marker for the “Mayacene” are soil profiles of carbon isotope ratios that show a bulge of higher $\delta^{13}\text{C}$ values from increased input of C_4 species like maize in sediments dated to the Maya period. These are intercalated between deposits with lower $\delta^{13}\text{C}$ values, indicating predominant contribution from C_3 forest species, before and after the Maya period.

1384 Unsurprisingly, sites with the largest contribution to SOM from C₄ species are terraces, *bajo*
1385 edges, and especially wetland field systems, though all sites show considerable variability and
1386 our sample locations could not explain the whole region. Most slope profiles reflect modern C₃
1387 species, which may be evidence for Maya forest conservation on these sites or evidence of slope
1388 erosion and soil formation after reforestation in these often thin soils.

1389 The fourth marker includes the building materials and other indicators of human activity in
1390 the form of housing, terraces, roads, walls and wetland fields that are still present on the
1391 landscape. There has been little quantification of these features, but recent Lidar mapping has
1392 improved our overall understanding of the infrastructural landscape, which will improve even
1393 more with expanded coverage. Thus, early generalizations about areas of terracing, roads,
1394 reservoirs, and fields may greatly change in the coming decades. The largest body of literature
1395 has been on water management features, with remarkable evidence of full landscape water
1396 planning at Tikal and Palenque, and a growing number of reservoir and cistern studies that
1397 contribute to our understanding of ancient Maya water management in the face of climate
1398 change.

1399 The fifth golden spike is the widespread fingerprint of chemical enrichment of phosphorus in
1400 sediments that date to the Maya period. There are of course other elements enriched by human
1401 activities, e.g. mercury, but the greatest emphasis to date has been on phosphorus, with a
1402 growing interest in heavy metals. Phosphorus increased 3-4-fold through Maya-age sediments
1403 in a landscape with meager P in its bedrock.

1404 The last “Mayacene” evidence comes from modeled Maya impacts on climate, with an
1405 emerging consensus on the role of drought throughout Maya prehistory. There are still too few

climate modeling studies and too little known about the changes in vegetation and soils, but more upscaling of site studies will help better model surfaces and past climates. There are only a handful of studies on how the modern vegetation still reflects ancient Maya forest practices, but landscapes were certainly altered and are still dominated by stone temples, stripped soils, aggraded soils, terraces, and locally wetter or dryer conditions. Likewise, there are only a few, conflicting studies of human bones, and too few animal bone and shell records. Bringing these records together with better infrastructure mapping and surface modeling, as is underway with IHOPE-Maya, will help get at the measure of the “Mayacene” and its role in understanding modern global change.

6. List of Figures and captions

1. Map of the Maya Lowlands showing physiographic sub-regions and sites mentioned in the text. (Numbers refer to sub-regions: *1 North Coast; 2 Caribbean Reef and Eastern Coastal Margin; 3 Northwest Karst Plain; 3+ Chicxulub impact feature; 4 Northeast Karst Plain; 5 Yalahau; 5+ Holbox Fracture; 6 Coba- Okop; 7 Puuc-Santa Elena; 8 Puuc-Bolonchen Hills; 9 Central Hills; 10 Edzna-Silvituk Trough; 11 Quintana Roo Depression; 12 Uaymil; 13 Río Candelaria-Río San Pedro; 14 Peten Karst Plateau and Mirador Basin; 15 Three Rivers Horst and Graben; 16 Rio Hondo; 17 Lacandon Fold; 18 Peten Itza Fracture; 19 Libertad Anticline; 20 Río de la Pasión; 21 Dolores; 22 Belize River Valley; 23 Vaca Plateau; 24 Maya Mountains; 25 Hummingbird Karst; 26 Karstic Piedmont; 27 Motagua and Copán Valleys.* (After Dunning et al. 1998; Beach et al. 2008)

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Table 1:

Replace with the following table. NOTE: the changes in numbering in column 1, and that we need to update the location map with

Site and map reference	Maximum P (mg kg ⁻¹)	Background P (mg kg ⁻¹)	Data source
Aguateca, Guatemala (1)	45		Terry et al. (2004)
Blue Creek, Belize (2)	60		Beach et al. (2006)
Cancuen, Guatemala (3)	781		Beach et al. (2006)
Cancuen, Guatemala (3)	419		This study
Chunchucmil, Mexico (4)	1479		Dahlin et al. (2005)
Chunchucmil, Canbalam, Mexico (4)	272 ^a	5.1	Dahlin et al. (1997; 2007); Beach (1998)
Chunchucmil, Mexico (4)	120		Luzzadder-Beach et al. (2011)
Chunchucmil, Mexico (4)	40 ^a		Hutson and Terry (2006)
Chunchucmil, Mexico (4)	1231		Hutson, Beach, et al. (2009)
Copan, Honduras (5)	879	4.9	Canuto et al. (2010)
Dos Hombres, Belize (6)	101		Beach et al. (2002)
Ejutla Oaxaca, Mexico (7)	11000 ^b		Middleton and Price (1996)
El Ceren, El Salvador (8)	405 ^a	13	Parnell et al. (2002b)
El Coyote, Honduras (9)	4116		Wells (2004)
El Kinel, Guatemala (10)	127		Balzotti et al. (2013)
La Milpa, Guatemala (11)	101		Beach et al. (2003)
Nacimiento, Guatemala (1)	151	6.5	Eberl et al. (2012)
Petexbatun, Guatemala (12)	311		Dunning et al. (1997)
Piedras Negras, Guatemala (13)	125 ^a	20-30	Wells et al. (2000)

Piedras Negras, Guatemala (13)	241 ^a		Parnell et al. (2001)
Piedras Negras, Guatemala (13)	65 ^a		Parnell et al. (2002a)
Piedras Negras, Guatemala (13)	3000		Parnell et al. (2002a)
Piedras Negras, Guatemala (13)	2476		Terry et al. (2000)
Piedras Negras, Guatemala (13)	125 ^a	17-25	Terry et al. (2000)
Ramonal, Guatemala (14)	16 ^a		Burnett et al. (2012)
Xtobo, Guatemala (15)	117 ^a	5.2	Anderson et al. (2012)
Yaxha, Guatemala (16)	689		Deevey et al. (1979)
Geometric Mean ^c	329		

Table 1: Phosphorus in soils modified by the ancient Maya. This compilation includes all known results from peer-reviewed studies that include raw geochemical data.

^a Soil phosphorus determined using weak extraction methods and/or qualitative approaches. These values are likely to underestimate the total amount of phosphorus in these samples.

^b Estimate based on the recalculation of absolute P concentrations from Middleton and Price (1996)

^c The geometric mean is employed here to describe the central tendency of the P data compilation due to its applicability to non-normally distributed population and resilience to the influence of extreme values (after Cook et al., 2006)

Sites	Vegetation	Top soil	Maya Classic ^a Soil	Preclassic and earlier Soils	Maximum increase >-27	Estimated ^b max C ₄ vegetation Ancient
		$\delta^{13}\text{C} \text{ ‰}$	$\delta^{13}\text{C} \text{ ‰}$	$\delta^{13}\text{C} \text{ ‰}$	$\delta^{13}\text{C} \text{ ‰}$	%
1. Aguadas						
Cancuen, G ^c	Pstr ¹	-25.05	-17.75	-25.83	7.3	61.7
	1990s					
La Milpa, B ^c	TF ²	-27.46	-24.23	-26.45	3.23	18.5
*Zotz, G ^c	TF	-30.25	-25.41	-25.25	5	11.7
*Diablo, G ^c	TF	-29.40	-26.27		3.13	4.9
Tamarandito, G ^c	Pstr	-23.89	-22.89		1	27.4
	1990s					
*Zotz Ag 2, G ^d	TF	-26.92	-22.88	-23.91	4.04	27.5
*Zotz Ag berm, G ^d	TF	-29.82	-22.92	-24.54	6.9	27.2
*Bejucal Aguada, G ^d	TS ³	-22.05	-22.74		0	28.4
*Bejucal Cival, G ^d	TS	-24.71	-22.76		1.95	27.2
*Palmar Cival, G	TF/S	-27.65	-25.97	-23.39	3.61	24.1
Mean Aguadas		-26.72	-23.38	-24.90	3.62	25.86
2. Bajos						
D05, B ^c	TF	-26.65	-23.10	-25.43	3.55	26
Dumbbell, B ^c	TS	-29.54	-26.10	-24.64	4.9	15.7
Guijarral, B ^c	TF	-29.52	-25.45	-26.43	4.07	3.8
Palmar, G ^c	TF	-28.74		-25.80	2.96	8
Hammond Bajo edge	TS	-24.4	-24.8			<u>?</u>
	Pstr					
	2012					
Hammond Bajo	TS	-25.2	-25.2			<u>?</u>
	Pstr					

		2012				
Mean Bajos		-27.34	-24.93	-25.58	3.87	13.38

3. Floodplains

*BOP 2 2010 ^d	TS	-25.7	-23.1	-25.9	3.9	26
*GC 50 ^d	TF/S	-22.7	-22.8	-20.9	6.1	40.7
*GC 250 ^d	TF	-24.95	-24.1	-24.3	2.9	19.3
*GC 500 m ^d	TF	-26.3	-22.0	na	5	33.3
*Chawak 3 ^e	TF	-26.75	-23.62	-23.02	3.98	26.5

Mean Floodplains		-25.28	-23.12	-23.53	4.38	29.16
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4. Terraces

D17 ^c	TF	-26.43	-24.55		1.88	16.3
Guijarral ^c	TF	-28.70	-23.36		5.34	24.3
Medicinal Trail ^c	TF	-28.82	-25.79		3.03	8.1
Mohagany Ridge ^c	TF	-27.33	-21.67		5.66	35.5
*Chawak Foot sloped	TF	-26.8	-23.3	-25.8	3.7	24.67
La Milpa Crest terrace 2012	TF	-28.9	-22.6	-29.30	5.4	29.3
Mean Terraces		-27.62	-23.73	-27.55	3.92	21.77

5. Wetlands Canals and Fields

66J Field ^c	Pstr 2005	-26.45	-25.37	-25.62	1.08	10.9
66J Canal ^c	Pstr 2005	-26.68	-25.13		1.55	12.5
66T Canal ^c	TF	-28.34	-24.09	-27.22	4.25	19.4

BOP 1 Canal ^c	TF/S	-27.30	-19.59		7.71	49.4
BOP 3 Canal ^c	TF/S	-27.31	-19.61		7.7	49.3
BOP 3 Field ^c	TF/S	-27.41	-22.50		4.91	30
BOP7 Field ^c	TF/S	-27.31	-22.62		4.69	29.2
BOP 7 Canal ^c	TF/S	-25.96	-17.40		8.56	64
BOP 10 Canal ^c	TF/S	-28.03	-23.24		4.79	25.1
Chawak 1Field ^e	TF/W ⁴	-27.54	-21.53	-21.82	6.01	36.5
Sayap Ha Field ^e	Pstr 1960	-17.08	-18.63	na	9.92	55.8
Sayap Ha Canal ^e	Pstr 1960	-16.63	-20.30	na	10.37	44.7
Chan Cahal Vibracore						
Tomb 5 Field ^e	Pstr 1960	-21.86 35cm	-21.51	-25.78	5.49	
Tomb 5 Canal ^e	Pstr 1960	26.8 50cm	-26.1	-25.3	1.7	
Wetland Field Platform ^e	Pstr 1960	-18.1	-26.2	-25.1	8.9	
Mean Field		-23.68	-22.62	-24.58	5.86	32.48
Mean Canal		-25.88	-21.99	-26.26	5.25	37.77

6. Slopes

Hammond backslope	TF 2012	-26.1	-27.1	na	0.9	
Hammond Bajo edge	TF/S 2012	-24.4	-24.8	na	2.6	
Hammond Bajo	TF/S 2012	-25.2	-25.2	na	1.8	
La Milpa 2012 depression	TF	-27.3	-24.4	-24.4	2.9	19.3
Cave slope A mean	TF	-26.7	-25.1	na	1.9	

Cave Slope 1 (depression)	TF	-27.1	-24.5	na	2.5	16.7
Cave Slope 2 (shoulder depression)	TF	-26.7	-23.7	na	3.3	22
Cave Slope 3 (back)	TF	-26.6	-25.6	na	1.4	
Cave Slope 4 (back)	TF	-26.4	-26	na	1	
Cave slopes 5 crest-backs on 5-15 cm deep soils	TF	-26.0		na		
		-26.8		na		
		-27.8		na		
		-26.6		na		
		-26.3		na		
		-27.5		na		
Mean Slopes		-26.5	-25.16	-24.40	2.03	19.33

Table of Carbon Isotope values in soil Profile after (Beach et al. 2011) but with new data in bold.

^a Dated to the Late Classic.

^b % SOC obtained from C₄ vegetation (C_{C4}) = $100 * (\delta^{13}C_{soc} - \delta^{13}C_{C3}) / (\delta^{13}C_{C4} - \delta^{13}C_{C3})$

^c Beach et al. 2011.

^d Beach et al., in review.

^e Beach et al., 2014.

¹ Pasture with many C₄ species.

² Tropical Forest with few C₄ species.

³ Tropical Savanna with few C₄ species.

⁴ Wetland with few C₄ species.

Figure %

Figure 8

Figure 3

Figure'

Figure)

Figure**

Figure +

Before Deforestation

After Deforestation

Figure 1

Figure:-

Figure`%\$

Figure %%

A

B

C

D

Figure 1

1. Pre-agricultural tropical forest

2. Preclassic deforested

3a. Classic reforested

3b. Classic reclaimed

A

B

Figure 1

Figure 4