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Margin for error: Anthropogenic geomorphology of *Bajo* edges in the Maya Lowlands

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ABSTRACT

Many early Maya cities developed along the edges of large structural or karst depressions (*bajos*). This topographic position aided growing populations to more effectively capture and store rainwater, a necessity for year-round occupation of interior portions of the Maya Lowlands of Mexico and Central America. Ancient Maya forest clearance on sloping terrain led to accelerated soil loss and the aggradation of the *bajo* margins. These newly created margins of colluvial lands became a focus of subsequent intensive agriculture and helped underwrite further urban expansion. We document this long-term landscape transformation with data derived principally from field investigations at Tikal, Guatemala, and Yaxnohcah, Mexico, but with reference to other Maya centers in the Elevated Interior Region (EIR). Data are derived from field investigations, interpretation of lidar imagery, and laboratory analyses. We present a model of three variants of bajo margin landscape change with differences attributable to topography, lithology, hydrology, and cultural processes. We present preliminary data on crops that were cultivated on bajo-margin soils. We further describe how agriculture was adapted to evolving bajo margins as evidenced by systems of field walls, terraces, and ditches.

1. Introduction

Karl W. Butzer suggested years ago that metastable equilibria provided a useful model to track the fluctuating arcs of ancient civilizations (Butzer, 1980). Over time, Butzer's modeling of the long-term accommodation of cultures to environmental change, including anthropogenic change, became more nuanced (e.g. Butzer, 1996), presaging the introduction of resilience models in cultural and political ecology (e.g., Berkes and Folke, 1998; Holling and Gunderson, 2002; Chaffin and Scown, 2018). Ultimately, such modeling has led to a more refined understanding of the ways imbalances can lead to societal transitions (Butzer and Endfield, 2012). This way of thinking underlies the understanding we have developed of the complex way in which ancient Maya communities interacted with *bajos*, depressions with a range of wetland types within the interior of the Yucatan Peninsula. Specifically, scores of generations of human activity took place within a landscape that was partly the product of natural forces, but also was a cultural inheritance that included transformations made in the soilscape, hydrology, and vegetation, and sometimes enduring landesque capital (Dunning et al., 2006; Beach et al., 2015, Figs. 7, 12). Cultural inheritance also included the traditions of agricultural strategies, and included social and political systems that structured economic forces such as land tenure and the control of labor and goods (Webster and Murtha, 2015).

We report on investigations in and around Tikal (Guatemala) and Yaxnohcah (Mexico), two ancient Maya cities that developed on the margins of large bajos, and compare our findings to those from other sites in the Elevated Interior Region (EIR) of the Maya Lowlands (Fig. 1). We use changes in the soilscape to document the course of Maya interaction with these landscapes, including degradation and aggradation processes, as well as human response to these processes. This is a remarkable story of human adaptation to what initially may have seemed an incremental catastrophe involving soil erosion and related changes, but which evolved into a foundation for population growth and urbanization.

Yaxnohcah arose as an important urban center early on in the course of Maya Civilization, with evidence for the construction of monumental

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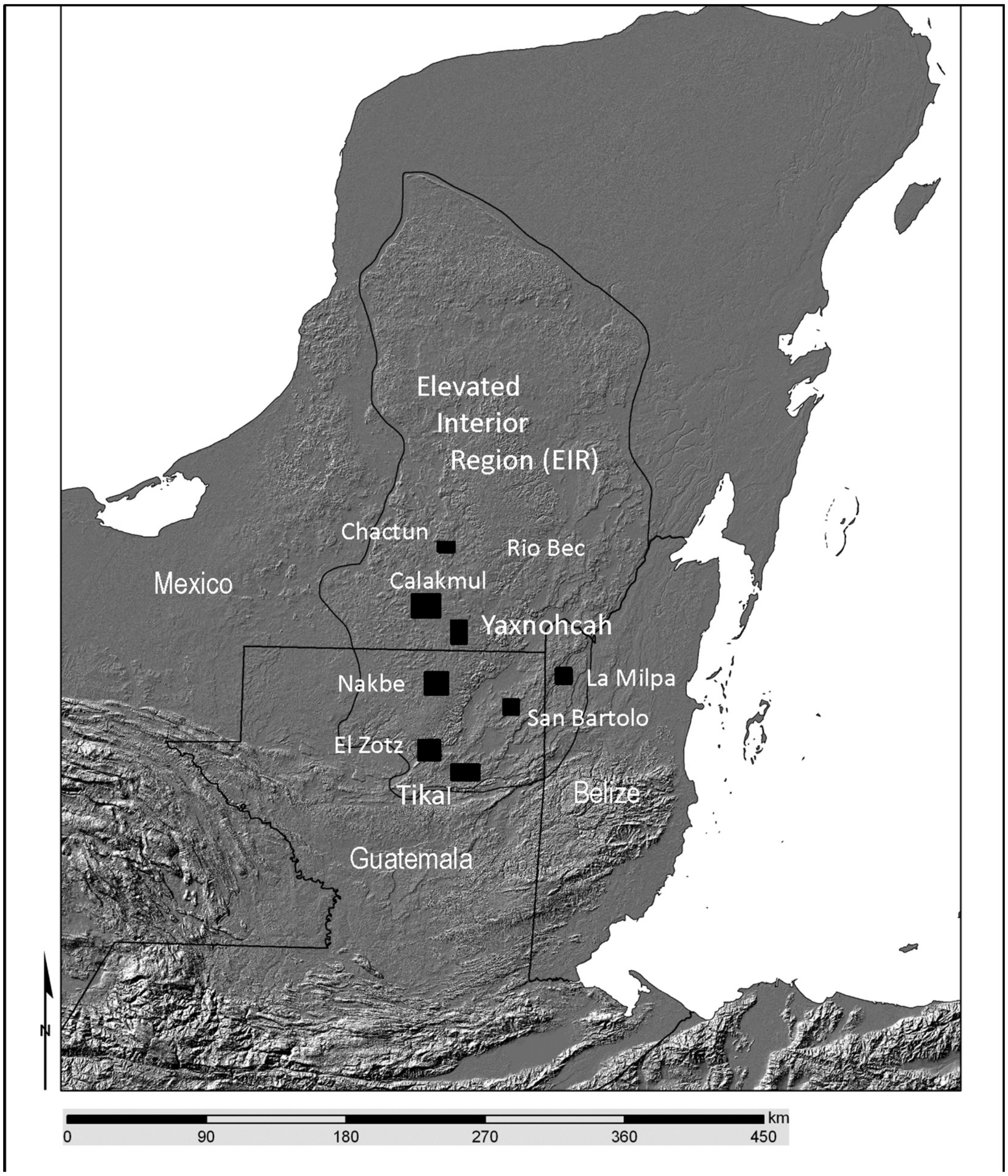

Fig. 1. Map showing the location of the Elevated Interior Region (EIR) within the Maya Lowlands and sites mentioned in the text.

architecture and a large central reservoir sometime between 800 and 700 BCE (the beginning of the Maya Middle Preclassic period). The city continued to grow through the Late Preclassic, probably peaking in the second century CE (Reese-Taylor et al., 2015, 2016a; Anaya Hernández et al., 2017). While Yaxnohcah continued to be occupied by a sizeable population during the ensuing Classic period, its fortunes had apparently declined and little investment in monumental construction took place; nearly complete abandonment occurred after 900 CE. Tikal grew at a slower rate in the Preclassic but became a sizeable center in the Late Preclassic (Martin and Grube, 2008; Dunning et al., 2015a). Unlike, Yaxnohcah, Tikal continued to grow through much of the Classic period, with some notable hiccups, becoming one of the most powerful centers in the Maya Lowlands, until it too declined abruptly in the ninth century CE (Martin and Grube, 2008; Lentz et al., 2014). These two large urban centers with their varying cultural trajectories offer insights into the interactions of the ancient Maya with the soilscape in the EIR. Examining bajo margins at other sites within the EIR sheds further light on ancient Maya adaptations to a changing landscape.

2. Regional setting

2.1. Physiography

Ancient Lowland Maya Civilization occupied the Yucatan Peninsula of Mexico and contiguous areas of Belize, northern Guatemala, and eastern Honduras and El Salvador, a region collectively referred to as the Maya Lowlands. Within this broader area lies an irregular physiographic province often called the Elevated Interior Region (EIR), a karst area characterized by an acute lack of perennial surface water and almost no access to the groundwater table (Dunning et al., 2012). The carbonate bedrock that underlies the EIR is chiefly Cenozoic limestone, though pockets of older beds (e.g., Cretaceous limestone, sandstone, and gypsum beds) crop out in some places by faulting. This ancient faulting has strongly controlled karst solution processes in some areas, including inducing the development of the largest bajos (Perry et al., 2009).

Bajos are a common feature within the EIR. While many use the term *bajo* for all low-lying swampy terrain, here we specifically address those depressions lying in the elevated (80 m or more above msl) interior portions of the EIR. Bajos range in size from less than a square kilometer to several hundred square kilometers. This size difference in part reflects different origins. Smaller bajos (aka pocket bajos) are strictly the product of limestone and sometimes evaporate dissolution, whereas the largest bajos have a significant structural component. Many of these larger bajos are associated with normal faults with prominent scarps protruding out on at least one side. Dissolution and erosion modifies grabens within these fault systems into rugged, complex karst landforms (Marshall, 2007). These depressions extend into the northern portions of the EIR, but in the north a combination of better drainage, less faulting and jointing, and less rainfall inhibit wetland development. The sites addressed in our research lie within the central to southern portion of the EIR.

Bajos cover between 40 and 60% of the landscape across the southern and central parts of the EIR (Siemens, 1978; Pope and Dahlin, 1989; Quintana and Wurster, 2001; Magee, 2011). Drainage within the EIR is largely internal and deranged in this karst region, though a few seasonally active river systems are present with infrequent streams dissected into limestone uplands; within bajos sluggish channels are entrenched in the deep Quaternary sediments.

Intriguingly, the bajo zone in the EIR became the heartland of Preclassic Maya civilization as urbanism took hold in the region beginning about 800 BCE. One advantage a bajo margin location held for urbanization is that sloping terrain and seasonal stream channels could be used to funnel runoff into reservoirs constructed to take advantage of the slow permeability of clay soils on the bajo floor; such reservoirs were necessary for year-round settlement because of the 5-month-long dry season and scarcity of perennial water sources (Dunning et al., 2018a). Several studies indicated that the soils the Maya originally encountered in and around bajos would have been largely unattractive for farming, but over time soils along the margins changed in ways that made them more suitable for cultivation (Dunning et al., 2002, 2006; Gunn et al., 2002). We examine these changes in the soilscape below.

2.2. Climate

The climate of the Maya Lowlands is tropical and isothermal (e.g., Dunning and Beach, 2010; Beach et al., 2018b). Within the EIR, rainfall is highly seasonal and spatially variable, structured by the annual migration of the ITCZ. Typically 90% of precipitation falls during a summer-fall wet season. Average annual rainfall increases southward across the lowlands and diminishes westward across the Yucatan Peninsula. In the southern half of the EIR, annual rainfall is normally 1500–2000 mm. One common driver of interannual variability in precipitation is tropical storms/hurricanes, which are frequent visitors to the region. Growing and compelling evidence now exists that the Maya Lowlands have been beset with episodic periods of intense drought that made the environment riskier for the ancient Maya, especially within the EIR (e.g., Hodell et al., 1995, 2005; Haug et al., 2003; Wahl et al., 2007, 2014; Dunning et al., 2012, 2014; Kennett et al., 2012; Medina-Elizade and Rohling, 2012; Griffin et al., 2014; Douglas et al., 2015; Luzzadder-Beach et al., 2016; Bhattacharya et al., 2017). The highly seasonal distribution of rainfall in the Maya Lowlands made collecting and storing rain water in interior regions essential for permanent settlement and urbanization in the EIR (Dunning et al., 2018a).

2.3. Topography, soils, and vegetation

The limestone in the EIR is nearly pure calcium carbonate, consequently producing relatively little in the way of residuum as it weathers in place. Several studies suggest that much of the mineral fraction of the soils in the EIR comes from eolian inputs including ash from various Central American and Mexican volcanoes, Saharan dust, and North American loess over long periods of time (Cabadas et al., 2010; Bautista et al., 2011; Tankersley et al., 2015, 2016). In the present day, soils on slope crests and backslopes on karst uplands are typically shallow, often skeletal Entisols, with Rendolls in local solution pockets and slope breaks. Over the course of the Quaternary, deep, smectite-rich clay sediments accumulated within bajos providing the parent material for Vertisols, the dominant soil type in these depressions and other, more stable surfaces (Beach et al., 2018a, 2018b). Some bajos also contain pockets of Histosols in areas with perennial moisture. The development of soils at the slope interface between uplands and bajos varies depending on the abruptness of the slope break, local drainage, and history of Holocene land cover. Present day soils along bajo margins are predominantly Cumulic Haplorendolls and Haplustolls (Fig. 2). The former typically overlie bedrock, whereas the latter often developed over buried Vertisols. Some bajo edges as at Tulix Mul, Belize, were less susceptible to geomorphic change because their gradients were too low for much slope erosion and deposition. Here Vertisols formed over 7 to 2° backslopes rather than Rendolls (Beach et al., 2018b). As will be discussed below, Vertisols also tend to redevelop on toeslopes where burial was less pronounced or drainage remained slow.

Today, the distribution of natural vegetation follows regional patterns of precipitation, drainage, and soils. Well-drained upland terrain is mantled by several subtypes of *upland forest* (following Brokaw and Mallory, 1993) that has been called variously *climax forest* (Lundell, 1937), *deciduous seasonal forest* (Wright et al., 1959), and "*montaña*" (a term used widely in the Peten; Ford, 1986). The canopy is typically 15–20 m high with some taller trees. *Manilkara zapota* (L.) P. Royen, *Brosimum alicastrum* Sw., *Pouteria reticulata* (Engl.) Eyma., *Drypetes brownii* Standl., *Sabal morrisiana* Bartlett ex. L.H. Bailey, *Hirtella americana* L., *Ampelocera hottlei* (Standl.) Standl., and *Pseudolmedia* sp. are among the dominant tree species (Thompson et al., 2015). Considerable spatial variability exists in the species composition depending in part on the microtopographic situation. Areas within bajos that are subject to the greatest extremes in soil moisture levels have *scrub swamp forest* (following Brokaw and Mallory, 1993). Other terms used for this forest assemblage include *bajo forest* (Lundell, 1937), *low marsh forest* (Wright et al., 1959), and *tintal bajo* (Ford, 1986). Trees in this assemblage are typically 3–5 m in height, with *Haemotoxylum campechianum* L. and *Croton* sp. most prevalent; a thick ground cover of sedges (*Cladium* sp.) and sawgrass (*Scleria bracteata* Cav.) is often present. A large variety of transitional forest types exist between the upland forest and scrub swamp forest extremes. Such transitional forests typically resemble upland forest in their structure but with a lower canopy and species composition that also includes examples of scrub forest types. Often the mid-story is dominated by escoba palm (*Cryosophila stauracantha*

Fig. 2. Photo of a pocket bajo south of Tikal National Park. Shallow soils on the crest and backslope have been left in forest. Deeper soils on the footslope (recently harvested in background as well as planted in citrus trees) and toeslope (maize field in foreground) are being used for intensive cultivation.

(Heynh.) R. Evans), so that this assemblage has been referred to as *escobal transition zone* (Lundell, 1937) and *escoba bajo* (Ford, 1986; Kunen et al., 2000). Other palm species are occasionally dominant, most notably concentrations of cohune or corozo palm (*Orbignya cohune* Mart.). Considerable variability exists among transition forest composition. For example, the region around Yaxnohcah in southern Campeche has very few palm-dominated areas (Lundell, 1937; Reese-Taylor et al., 2016b) Transitional forest types typically are characteristic of pocket bajos and frequently located on the aprons of gently sloping lands with deep colluvial soils found along the margins of many bajos, big and small. Pocket bajos are often present within the upland, montaña, areas.

3. Materials and methods

3.1. Field methods

Geoarchaeological excavations occurred at Tikal, Peten, Guatemala, in 2009 and 2010 as part of the University of Cincinnati Tikal Project. Excavations reported here from Yaxnohcah, Campeche, Mexico, were undertaken in 2016 and 2017 as part of the Proyecto Arqueológico Yaxnohcah. We designed these excavations to reveal stratigraphy associated with ancient landscape change and to recover paleoenvironmental proxies and cultural artifacts associated with that sequence of change. Landscape analysis and placement of geoarchaeological excavations at Tikal was guided by the use of a GIS derived in part by digitizing and georectifying maps created by the University of Pennsylvania Tikal Project in the 1960s (Carr et al., 2015). Landscape analysis and placement of geoarchaeological excavations at Yaxnohcah was facilitated initially by ground-based mapping by the Proyecto Reconocimiento Arqueológico en el Sureste del Estado de Campeche (Šprajc, 2008), further mapping by the Proyecto Arqueológico Yaxnohcah, and, after 2014, a lidar-derived DEM of a 34-km^2 area covering much of the site and its immediate hinterland (Reese-Taylor et al., 2016b).

Lidar data collection for Yaxnohcah was conducted by the National Center for Airborne Laser Mapping (NCALM) in 2014. Complete details of the data collection and processing for this work are discussed elsewhere (Reese-Taylor et al., 2016b). The lidar data were collected with an Optech Gemini terrain mapping system set to a pulse repetition frequency of 125 kHz. The nominal shot density was 15 shots/m^2. The *classify ground* function of Terrasolid's TerraScan software was used to identify the ground points—nominally 1.5 returns/m^2. The ground returns were converted to a 0.5-m pixel DEM by kriging. As is typical in the Maya area, the *ground points* category includes both the ground surface and the ruins of ancient Maya structures. Lidar data for Chactun were also acquired and processed by NCALM. The G-LiHT lidar data were acquired and processed by NASA as part of its biomass assessment program, with methods detailed elsewhere (Cook et al., 2013; Golden et al., 2016). The G-LiHT flight lines were manually scanned at the University of Cincinnati, and visible archaeological features were digitized; full details of methods are reported elsewhere (Ruhl et al., 2018). Excavations at Tikal and Yaxnohcah were carried out as part of larger programs of research investigating the history, development, resource management, and paleoecology of these ancient cities. The excavations reported here targeted the toe-, foot-, and sideslopes around bajos, including terraces put in place to retain soil and moisture. The general loci for these excavations were determined by pairing these operations with nearby *aguada* (ancient reservoir) investigations or excavations in residential groups in an attempt to form an overall picture of ancient land use. We recorded stratigraphy in the field in hand-measured profile drawings, photographs, visual and tactile description, and visual comparison with Munsell soil color charts. Soil samples for lab analysis were collected in reference to field-defined soil horizons. Samples were collected for flotation, pollen, and phytolith analyses at regular intervals (e.g., every 10 or 20 cm). Flotation was carried out in the field, and recovered organic material was saved and transported to the University of Cincinnati along with soil samples. Results from the analysis of macrobotanical remains recovered at Tikal are reported elsewhere (Lentz et al., 2014, 2015). Results from macrobotanical and phytolith analysis for Yaxnohcah will be forthcoming.

Artifacts were cleaned and initially recorded and classified in our field labs at Tikal and Yaxnohcah respectively. Artifacts from Tikal were transported to the Instituto de Antropología e Historia in Guatemala City for further examination, cataloguing, and curation. Artifacts from Yaxnohcah were transported to the Universidad Autonóma de Campeche in Ciudad Campeche for further examination, cataloguing, and curation. Additional geoarchaeological excavations at Tikal and Yaxnohcah have been reported elsewhere (Anaya Hernández, 2013; Geovannini-Acuña, 2013; Dunning et al., 2015b, 2016).

Research at Tikal and Yaxnohcah has included excavations or coring (depending on water level in a given season) in *aguadas*, the degraded remains of ancient Maya reservoirs. Some of these investigations have occurred in bajo-margin reservoirs and are referenced here because pollen recovered in some reservoir sediments bears on bajo-margin land cover and agriculture.

3.2. Laboratory methods

Radiocarbon dating of stratigraphically collected charcoal and organic sediment samples was performed at Beta Analytic Inc. and International Chemical Analysis Inc., both in Miami, Florida.

Laboratory testing of subsamples was carried out at the University of Cincinnati, Dept. of Geography, and at Spectrum Analytic Inc. (Washington Courthouse, Ohio). All samples were air dried at 105 °C for 24 h to determine dry weight. Organic matter percentage (OM%) was determined using loss-on-ignition (LOI): samples were heated to 550 °C for 1 h for OM (Dean Jr, 1974). Samples were then ground and the Bouyoucos hydrometer method was used to determine particle size percentages of remaining inorganic material (Bouyoucos, 1936). Phosphorus was extracted and measured using the Mehlich-3 ICP method (Mehlich, 1984). The Mehlich-3 extraction method was chosen because of the high carbonate content of many of the cores. Soil phosphates have been an important correlate of ancient land use used in archaeology for many decades (e.g., Eidt and Woods, 1974; Dunning et al., 1998; Beach et al., 2015). Additionally, in the Maya Lowlands, P is usually the nutrient most critically in short supply and a key variable in soil fertility (Lawrence et al., 2007; Das et al., 2011). Pollen and phytoliths were processed following standard procedures (Pearsall, 1989; Piperno, 2006).

4. Results

The eleven soils reported here all developed on or near bajo margins at Tikal or Yaxnohcah. Field descriptions and laboratory results on these soils are summarized in Table 1.

4.1. Operation 12B, El Pinal, Bajo de Santa Fe, Tikal

Operation 12B at Tikal was excavated in 2001 in one of the pine and palmetto savannas in the Bajo de Santa Fe at the extreme northeast corner of Tikal National Park - about 16 km NE of central Tikal (Dunning, 2001). This acidic, gypsic, nutrient poor soil lies beyond the toeslope on the eastern flank of a large island within the bajo. Though not a bajo-margin soil, it is included here to provide contrast with the other soils. The Op 12B soil is provisionally classified as a Chromic Dystraquaerts, a Vertisol with atypically high acidity, a pale Ochric epipedon, and redox features caused bt significant seasonal inundation. The pronounced vertical displacement of horizons within the soil profile is attributable to two primary processes: (i) shrinking and swelling of clay visible in pronounced slickensides, conical ped structures, and deep surface cracking (not indicated in the profile, but present throughout the area); and (ii) further *inflation* of vertic thrust cones created by the uneven precipitation of gypsum in emergent cones (Fig. 3).

Table 1
Characteristics of 10 bajo-margin related soils from Tikal, Guatemala, and Yaxnohcah, Mexico.

Site/operation	Horizon	Depth (cm)[a]	Color (Munsell)	pH	% Clay	% Sand	OM	P (mg/kg)	Notes
Tikal/El Pinal Op 12B									
	E	0–20	10YR8/1	5.1	95.0	2.3	2.1	22	Includes 1–2 cm O horizon rich in pine needles and duff
	C1	20–50	10YR6/2	4.9	94.3	3.4	0.8	18	±10% yellowish red mottles
	C2ss	50–190	10YR6/1	5.3	91.5	5.0	0.1	19	±10% yellowish red mottles
	C3yss	190–350+	10YR6/1	5.0	83.7	14.2	0.1	6	±25% yellowish red mottles; gypsum crystals as large as 20 cm across unevenly distributed, many in vugs
Tikal Op 5C									
	A	0–30	10YR2/1	7.6	88.1	4.8	12.7	112	
	AC	30–40	10YR3/1	7.7	90.0	4.4	10.2	100	
	Css	40–65	2.5Y4/1	7.9	66.4	22.0	7.0	63	±20% gravel; abundant weathered sherds and lithics
	2Abgss	65–72	Gley 2.5/N	6.9	87.2	9.0	8.5	75	Radiocarbon date: 2850 ± 40 BP
	2ACbss	72–95	2.5Y6/1	6.4	76.2	15.3	3.6	45	
	2Cbss	95–102	2.5Y8/2	5.1	59.8	21.5	1.8	31	
	R	102+							Weathered cherty limestone
Tikal Op 5B									
	A	0–15	7.5YR3/2	7.5	85.1	7.7	7.1	165	
	AC	15–40	7.5YR3/2	7.8	77.3	18.2	5.5	201	±25% small stones
	R								Weathered cherty limestone
Tikal Op 10A									
	A	0–16	10YR2/1	7.5	71.0	18.1	8.7	126	
	C	16–58	10YR5/1	7.6	65.0	22.5	4.0	49	In matrix of ±50% cobbles and gravel
	2Ab	58–65	Gley 2.5/N	5.0	69.3	20.4	6.9	18	
	R								Weathered gypsic limestone
Tikal Op 8I									
	A1	0–14	7.5YR2.5/1	6.9	91.3	2.4	11.7	149	
	A2g	14–28	Gley 2.5/N	7.0	89.8	5.1	10.1	133	
	AC	28–34	7.5YR4/1	7.1	82.0	4.9	7.0	97	
	C1	34–42	7.5YR4/2	7.4	41.7	38.3	3.2	73	±50% gravel
	C2	42–68	7.5YR4/2	7.2	48.8	40.0	2.9	75	Color varies by strata; 7.5YR4/2 is most common
	2Abgss	68–95	Gley 3 N	6.8	88.2	8.9	6.7	102	
	2ACbss	95–112	10Y6/1	7.0	87.1	4.3	3.3	94	
	2Cbss	112+	10YR6/1	7.3	90.5	5.6	3.0	76	
Tikal Op 8R									
	A	0–12	7.5YR2.5/1	7.5	84.2	31.1	8.6	101	
	AC	12–22	7.5YR4/1	7.8	58.4	29.2	5.1	65	
	R								
Tikal Op 8H									Weathering marly limestone
	A	0–8	7.5YR3/1	7.6	82.7	11.2	9.0	97	
	AC	8–14	7.5YR4/2	7.7	59.0	31.1	5.2	78	
	R								Weathering limestone
Yaxnohcah Op19R									
	A	0–30	10YR2/1	7.5	84.3	3.4	8.6	235	
	AC	30–45	10YR4/1	7.7	74.0	6.6	5.8	143	
	Css	45–60	10YR6/1	8.0	59.8	32.0	3.9	107	
	2Abss	60–70	10YR3/1	7.7	79.5	7.5	4.6	118	Radiocarbon date: 2040 ± 30 BP
	2Cbss	70–110	10YR7/1	7.8	64.1	31.1	3.1	75	
	3Abss	110–130	10YR3/2	6.9	79.2	10.4	5.0	80	Radiocarbon date: 2510 ± 30 BP
	3C1ss	130–150	10YR7/2	8.0	84.3	9.8	1.7	58	
	3C2ss	150–190	10YR5/2	8.2	78.2	12.9	0.9	42	Abundant Mn oxide stains
Yaxnohcah Op 19L									
	A1	0–8	7.5YR2.5/1	7.7	88.1	4.5	13.1	131	
	A2	8–16	7.5YR3/1	7.7	81.6	9.0	9.2	124	
	AC	16–29	7.5YR3/1	7.8	65.0	20.8	8.1	97	Abundant gravel
	C1	29–40	7.5YR4/1	7.9	72.3	13.3	6.4	89	Feint laminate structure
	C2	40–50	7.5YR6/1	8.0	60.4	26.6	4.4	68	In matrix of limestone rubble and gravel
	2Ab	50–53	7.5YR4/1	6.8	77.7	16.1	6.9	140	
	2Cb	53–58	7.5YR6/1	7.7	63.3	24.3	3.8	111	In matrix of limestone rubble and gravel
	3Ab	58–63	7.5YR4/1	7.0	83.8	11.0	6.3	169	
	R								Hard limestone

(continued on next page)

Table 1 (*continued*)

Site/operation	Horizon	Depth (cm)[a]	Color (Munsell)	pH	% Clay	% Sand	OM	P (mg/kg)	Notes
Yaxnohcah Op 30B									
	A1	0–15	7.5YR2.5/1	7.3	88.5	4.1	10.3	140	
	A2	15–25	7.5YR3/1	7.2	87.0	5.6	8.6	129	
	ACss	25–50	7.5YR5/1	7.0	76.4	12.5	5.8	75	
	Css	50–70	7.5YR6/1	7.1	79.2	16.8	3.7	101	±5% cherty gravel
	2Abgss	70–90	Gley 4/N	6.9	90.3	4.4	7.5	124	Radiocarbon date: 1580 BP
	2Cbgss	90–120+	Gley 8/1	6.7	65.8	21.1	2.8	62	
Yaxnohcah Op 30C									
	A1	0–10	7.5YR2.5/1	7.5	89.8	2.7	9.2	304	
	A2	10–30	7.5YR3/1	7.8	87.5	4.0	8.0	270	
	ACss	30–60	7.5YR4/1	7.7	90.4	1.8	6.6	213	
	Css	60–70	7.5YR5/1	7.5	90.7	5.1	5.6	98	
	R								Hard, cherty limestone

[a] Depths given are for representative portions of the profile. In some cases depths varied widely, especially in Veritisols.

Repeated seasonal precipitation of gypsum adds mass and elevation to the rising thrust cone – a process that has been dubbed *gyp-heave* (Jacob, 1995). Local topography is extremely hummocky. Humification is negligible; a thin O horizon of pine needles and duff apparently decomposes rapidly and does not lead to the development of a significant A horizon. This area of the Bajo de Santa Fe has several extensive pine/palmetto savannas (Dvorak et al., 2005).

Gypsiferous Vertisols have also been described in the large Bajo Laberinto between Yaxnohcah and Calakmul (Gunn et al., 2002) and observed in other large, deep bajos including Bajo de Azúcar (Dunning et al., 2017). These large bajos exhibit strong structural control associated with normal faults. The grabens within these fault systems appear to either expose or come in close contact with thick gypsum beds lying near the Cretaceous-Paleogene boundary within the bedrock structure of the EIR, leading to gypsum saturation of groundwater, which is tapped within the deepest bajos (Perry et al., 2010). Gypsiferous sand dunes have developed in a few areas of these giant bajos.

Darker clay Vertisols are also common in the larger bajos, including the Bajo de Santa Fe (Cowgill and Hutchinson, 1963). While still acidic and gypsic, these soils experience humification associated with dry season deciduous leaf fall under characteristic scrubby swamp forest and develop Umbric and sometimes Mollic epipedons.

4.2. Operation 5C, Aguada de Terminos Area, Bajo de Santa Fe, Tikal

Operation 5C was excavated into the footslope of a peninsula of upland terrain projecting into the Bajo de Santa Fe some 4 km east of central Tikal and close to the ancient reservoir known as the Aguada de Terminos (Fig. 4) (Dunning et al., 2015b). Here, a dark clay Vertisol was rapidly buried by overwashing coarse colluvium on which a dark Vertirendoll soil gradually developed (Fig. 5). Soil organic matter within the 2Abss horizon exposed in Op. 5C produced a calibrated radiocarbon age range of 1310–1040 BCE at a depth of 70 cm (Table 2). This date probably indicates that forest clearance associated with Early-Middle Preclassic colonization and cultivation of the area resulted in destabilization of soil and regolith on the overlying slope and rapid burial of the bajo margin soil. Similar slope destabilization, soil erosion, and downslope aggradation is evident elsewhere around Tikal (Dunning et al., 2015b) and at other investigated sites in the EIR (Dunning and Beach, 2000; Beach et al., 2002, 2003, 2006, 2008, 2009, 2015, 2018b; Dunning et al., 2002, 2006, 2009; Garrison and Dunning, 2009).

4.3. Operation 5B, Aguada de Terminos area, Tikal

Operation 5B trenched a terrace constructed of chert quarry rubble on a ± 4% slope south of Aguada de Terminos (Fig. 4). This feature is part of a network of rubble terraces that also lie northeast of the ancient reservoir and are the only agricultural terraces thus far documented at Tikal. The excavation revealed the terrace to be a simple berm constructed of cherty limestone rubble with small boulders at its core and smaller stones heaped on top (Fig. 6). The terrace retained a cumulic Rendoll soil. Given the low slope and skeletal nature of soils lying above the terrace, the soil behind the terrace wall possibly may have been enhanced by the intentional transfer of topsoil from elsewhere. Pollen recovered from the Aguada de Terminos indicates nearby cultivation of maize and probably achira (*Canna indica* L.) in the Late Preclassic and Late Classic periods (see discussion further below). Neither this terrace nor another exposed in Op. 5E produced datable cultural or organic material (Dunning et al., 2015b).

4.4. Operation 10A, Puleston's Peninsula, Bajo de Santa Fe, Tikal

Operation 10A probed into another footslope at the base of a peninsula projecting in the Bajo de Santa Fe about 6 km east of central Tikal (Dunning et al., 2015b). In this case, the excavation exposed a shallow Rendoll developed on a projecting shelf of limestone, which had been rapidly buried by colluvial deposition (Fig. 7). We have no dates from this soil, but comparison with other buried footslope soils around

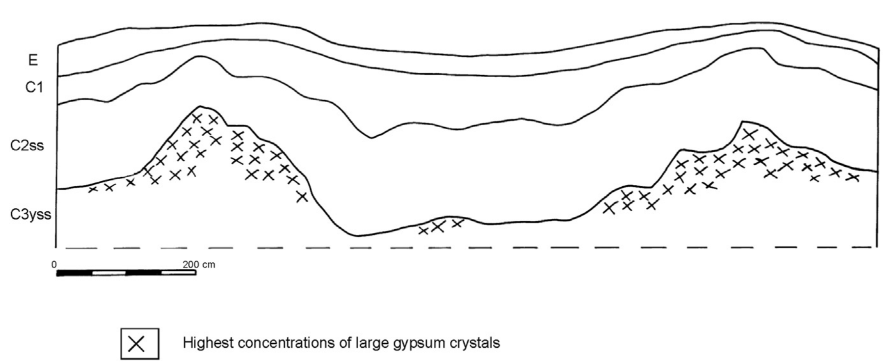

Fig. 3. Tikal Op. 12B profile: trench excavated in a pine/palmetto savanna in the Bajo de Santa Fe northeast of central Tikal.

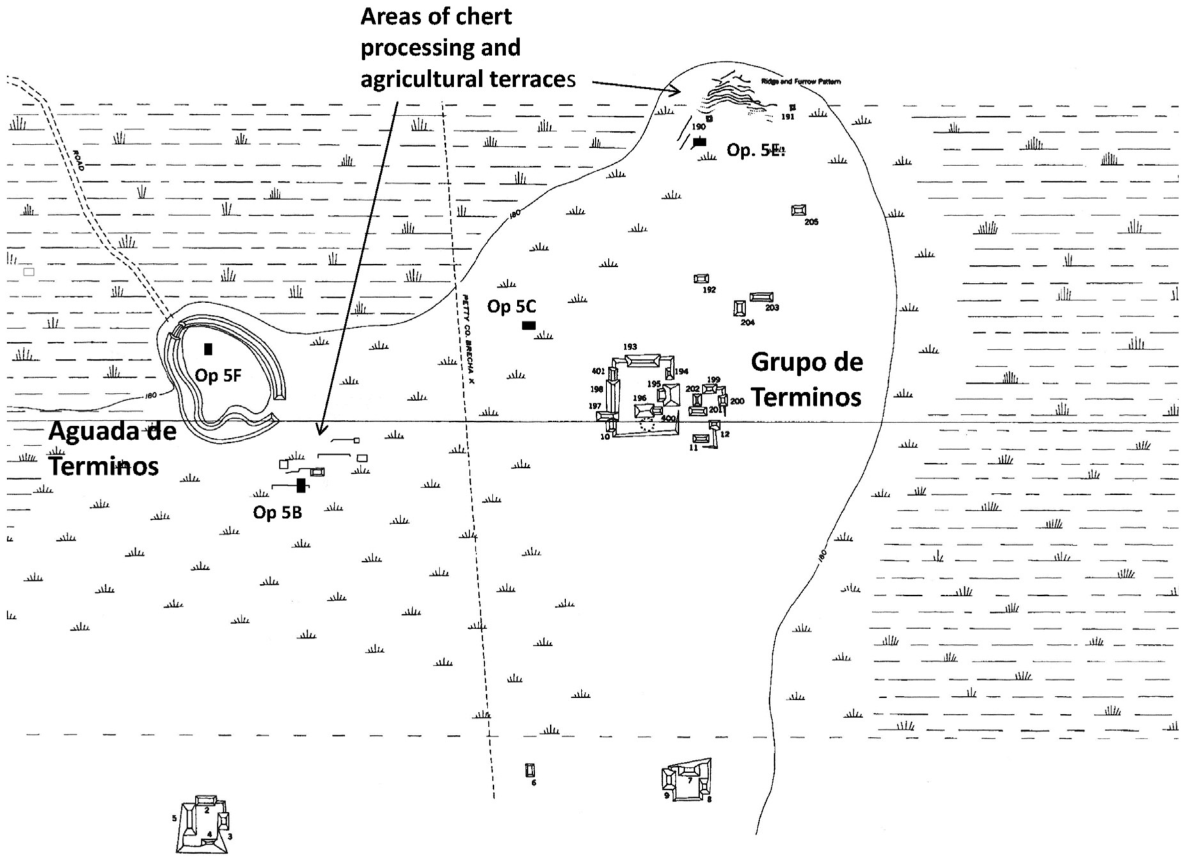

Fig. 4. Map of the area around Aguada de Terminos, Tikal, Guatemala. Base map adapted from Puleston (1983).

Tikal and other EIR sites (e.g., La Milpa, Belize: Beach et al., 2018a) suggests that it may be another example of aggradation linked to Preclassic forest clearance and resultant slope destabilization.

4.5. Operation 8I, Perdido Pocket Bajo, Tikal

The Perdido Pocket Bajo is an enclosed basin of about 2 km^2 lying below and just south of the Mundo Perdido complex of central Tikal; the Perdido Reservoir lies at the north end of the pocket bajo (Fig. 8). Operation 8I was one of a pair of soil pits, along with Op. 8D excavated into the floor of the pocket bajo a few hundred meters southwest of the reservoir. Operation 8D exposed a dark clay Vertisol typical of pocket bajos, though in this case the A horizon had been severely truncated, then buried by successive coarse alluvial deposits (Dunning et al., 2015b, Fig. 6.10). Operation 8I, situated on slightly higher ground on the bajo floor, exhibits a similar profile but without evident truncation of the 2Abss horizon and with fewer overlying alluvial strata (Fig. 9). A charcoal sample from alluvium immediately above the truncated 2Abss horizon in Op. 8D produced a calibrated radiocarbon age range of 400–570 CE (Table 2), that is the second half of the Maya Early Classic period. Evidence suggests that Perdido Reservoir dates to the Early Classic and that the Maya designed it to collect rainwater runoff channeled from the superadjacent Mundo Perdido plaza (Scarborough et al., 2012). A combination of excavation data from the reservoir and the pocket bajo suggests that the reservoir intake could be deliberately blocked in the event that heavy runoff (e.g. from a tropical storm/hurricane) threatened to damage the reservoir infrastructure. The coarse alluvium in the pocket bajo may be the result of diverted stormflow and successive flood events. The lack of truncation of the 2Abss horizon and lesser amount of coarse alluvium in Op. 8I relative to Op. 8D probably relates to the slightly higher elevation of the Op. 8I area. Stable

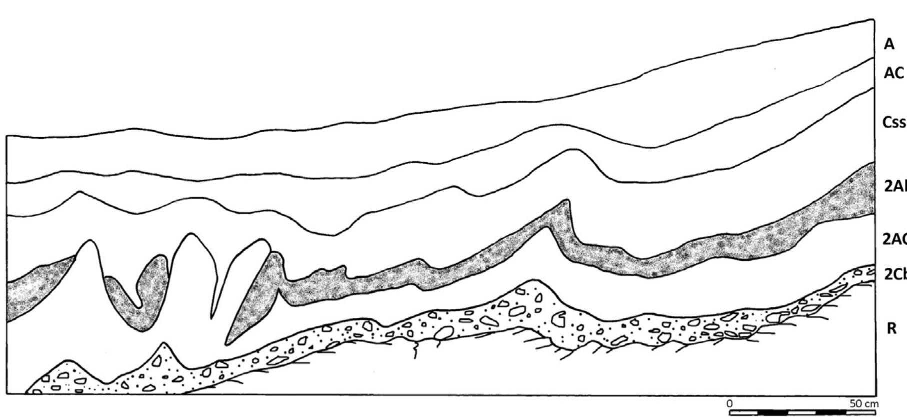

Fig. 5. Tikal Op. 5C: Excavation in a footslope, Bajo de Santa Fe, Guatemala.

Table 2
Radiocarbon dates associated with soil profiles detailed in Table 1.[a]

Site/stratum	Exc. unit	Depth (cm)	Lab sample #	Material	Conventional radiocarbon age	Calibrated age range (2 sigma)
Tikal/2Abss	5C	70	Beta-266126	SOM	2850 ± 40 BP	1310–1040 BCE
Tikal/2Abss	8D[b]	77	Beta-281748	WC	1570 ± 40 BP	400–570 CE
Yaxnohcah/2Abss	19R	65	ICA-17OS/1234	SOM	2040 ± 30 BP	160 BCE – 40 CE
Yaxnohcah/3Abss	19R	120	ICA-17OS/1235	SOM	2510 ± 30 BP	800–540 BCE
Yaxnohcah/2Abss	30C	80	ICA-17OS/0942	SOM	1580 ± 30 BP	410–550 CE

[a]All dates based on AMS. Calibrations determined with INTCAL13 (Reimer et al., 2013). SOM = soil organic matter. WC = wood charcoal. [b] The 2Abss horizon corresponds to the same horizon in Tikal Op 8I, which is discussed in the text.

carbon isotope analysis of samples taken from a line of soil cores across the pocket bajo indicate periods of intensive maize cultivation (Dunning et al., 2015b). No pollen was preserved in the sediments of Perdido Reservoir.

4.6. Operation 8R, Perdido Pocket Bajo, Tikal

Operation 8R was excavated into a footslope on the eastern flack of the Perdido Pocket Bajo exposing a Cumulic Rendoll (Dunning et al., 2015b). Although shallow, colluviation appears to have added mass to this low slope soil (Fig. 10).

4.7. Operation 8H, Perdido Pocket Bajo, Tikal

Operation 8H was excavated in the backslope above Op. 8R. Lying on a 12% slope, truncation has played a role in the history of this soil with some of its former mass transported down slope in to the vicinity of Op. 8R (Fig. 11). This soil is representative of backslope soils in the EIR. Much of the present-day soil may have formed in the millennium since Maya abandonment within sediment accumulated during Maya slope disturbance (Cook et al., 2017).

4.8. Operation 19R, Bajo Tomatal, Yaxnohcah

The ancient Maya city of Yaxnohcah straddles a broad ridge of uplands between the enormous Bajo Laberinto and the Bajo Tomatal. Bajo Tomatal is a large pocket bajo covering some 4 km^2 and is situated at a higher elevation than Laberinto, into which it seasonally disgorges runoff. Bajo Tomatal is bounded by steep scarps on several sides and ringed by ancient Maya settlement remains, including several large groups of monumental architecture. Operation 19R was excavated into a toeslope lying below Grupo Carmela, a monumental group constructed largely in the Late Preclassic period (ca. 500 BCE - 150 CE), though possibly originating earlier (Fig. 12). The scarp below Grupo Carmela appears to have been heavily quarried for limestone in ancient times.

Operation 19R exposed two buried soils within the toeslope (Fig. 13). The 3Abss soil is a well-developed dark clay Vertisol developed from clayey Holocene sediment. Soil organic matter in this horizon produced a calibrated radiocarbon age range of 800–540 BCE, during the Maya Middle Preclassic period, when monumental architectural groups were being constructed on nearby bluffs overlooking Bajo Tomatal (Table 2; Morton, 2016; Reese-Taylor, 2017). The 3Abss soil surface lies buried by variably coarser and finer colluvium and alluvium (the latter being discharge from the Middle Preclassic Brisa Reservoir). An apparent period of greater landscape stability induced the formation of a more weakly developed soil surface (2Abss); soil organic matter in this horizon produced a calibrated radiocarbon age range of 160 BCE – 40 CE, or the Maya Late Preclassic period. Landscape instability resumed, and the 2Abss soil was buried by colluvium, including large amounts of limestone rubble and gravel undoubtedly a byproduct of stone quarrying along the scarp-like edges of the bajo some 150 m west of Op. 19R.

4.9. Operation 19L, Bajo Tomatal, Yaxnohcah

Operation 19L was one of a pair of excavations in an ancient terrace built at the base of the scarp on the northwest edge of Bajo Tomatal (Fig. 12). Operation 19K sectioned the broad terrace wall, while Op. 19L exposed the cumulic soil behind the terrace. Footslope terraces were commonly built by the ancient Maya at the base of steep slopes in order to capture soil eroded from above (Dunning and Beach, 1994; Beach and Dunning, 1995). At least two buried soil surfaces are evident in the Op. 19L profile (Fig. 14). The 3Ab soil is a thin, compressed Rendoll developed on a projecting shelf of hard limestone. This surface was buried in part by the construction of a terrace wall of limestone rubble and by coarse colluvium (2Cb) washing down from the quarried slopes above. A clear, abrupt boundary occurs between the top of the 2Cb and base of the 2Ab horizons. The thin 2Ab horizon bears a strong resemblance (color, texture, and OM) to the A horizon material of a dark clay bajo Vertisol and, given that the terrace is immediately adjacent to Bajo Tomatal that topsoil was possibly intentionally added behind the terrace wall. The 2Ab soil was in turn buried by coarse colluvium (C2) after which additional dark clay soil (C1) appears to have been incrementally added, and eventually a cumulic Mollisol developed. Pollen recovered from Aguada Little Tom to the east of the terraces indicates nearby maize cultivation in the Late Preclassic period (see below for further discussion).

4.10. Operation 30B, Yaxnohcah

The southern margin of the Bajo Laberinto at Yaxnohcah includes a number of inlets, where fingers of bajo protrude into the uplands. Operation 30B was excavated in one such bajo inlet near Grupo Fidelia, a large Preclassic monumental platform and associated reservoir (Fig. 15). Operation 30B exposed a dark clay Vertisol and an underlying buried dark clay Vertisol (Fig. 16). The 2Abss soil surface is irregular, broken, and distorted by argilloturbation. Soil organic matter in this

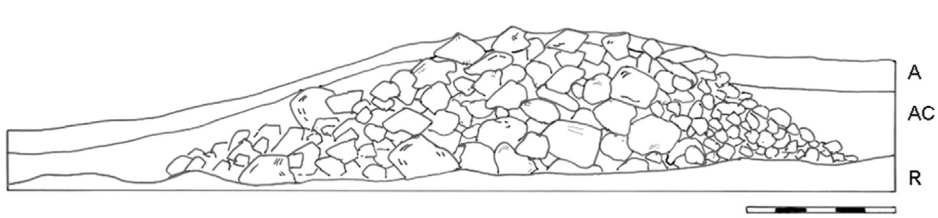

Fig. 6. Op. 5B, Tikal, Guatemala: cross section excavation of terrace wall and soil near the Aguada de Terminos.

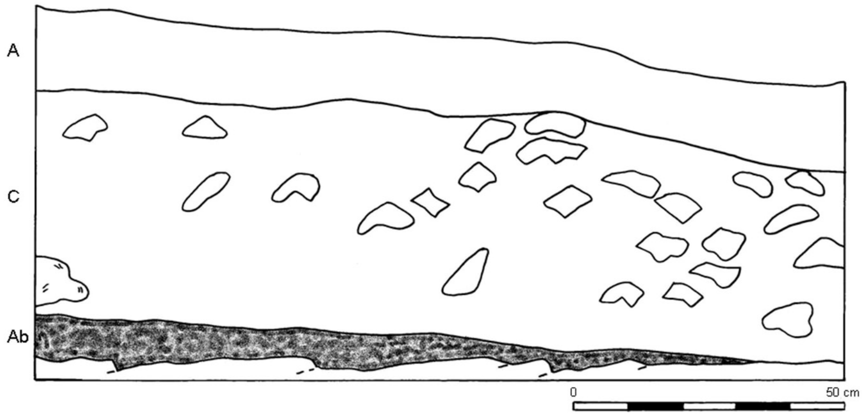

Fig. 7. Tikal Op. 10A: Excavation in a footslope, Bajo de Santa Fe, Guatemala.

horizon produced a calibrated radiocarbon age range of 410–550 CE, the latter half of the Maya Early Classic period. This soil was rapidly buried by largely fine sediment from which another Vertisol developed. Much of the high ground immediately north of Op. 30B was sealed with masonry construction in the Middle and Late Preclassic periods, hence sedimentation in the small basin that the excavation penetrated was likely generated by colluvial/alluvial transport from higher ground to the east or by eolian means. Pollen recovered from Late Preclassic sediment in Fidelia Aguada included maize and cotton (see further discussion below).

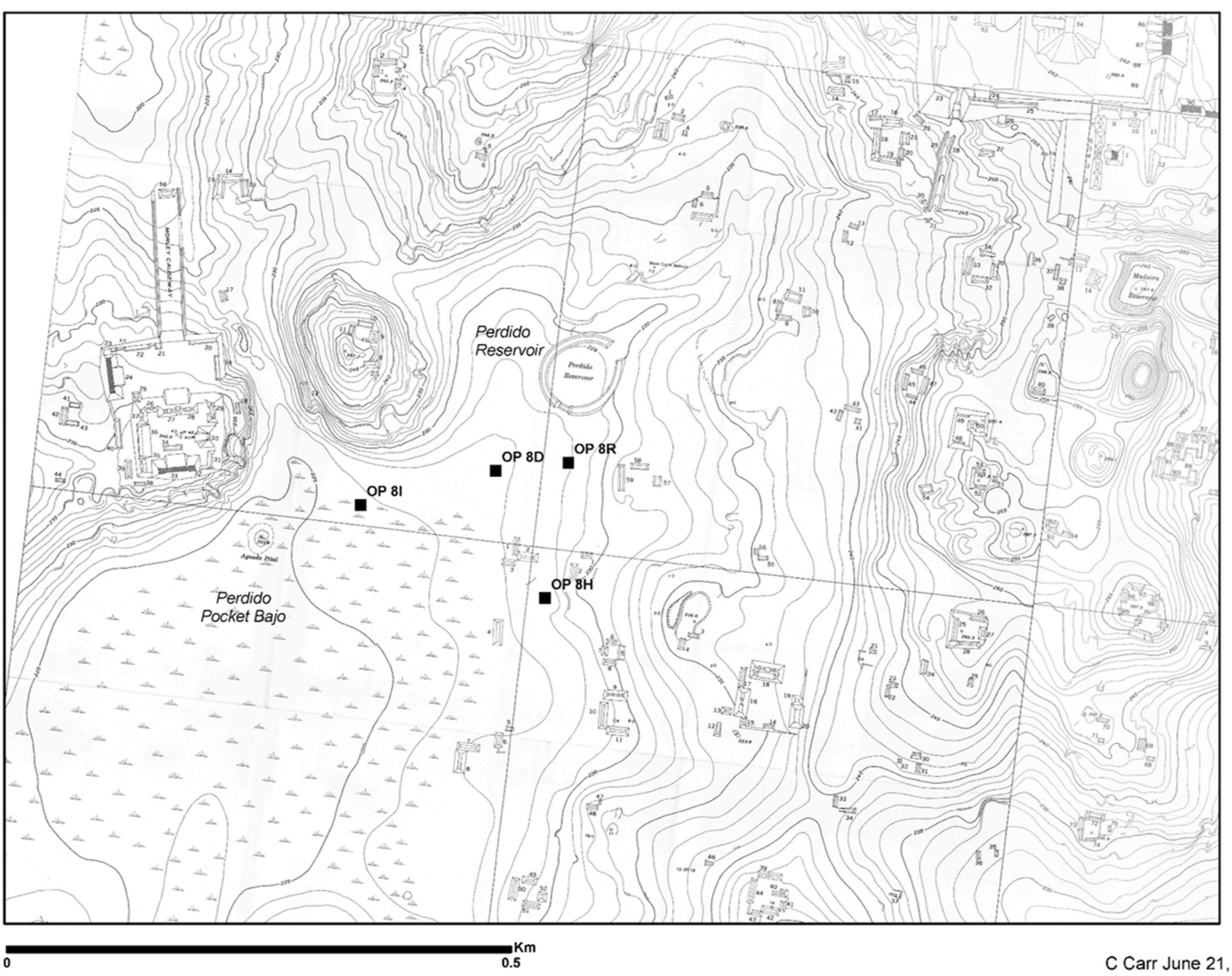

Fig. 8. Perdido Pocket Bajo area, Tikal, Guatemala.

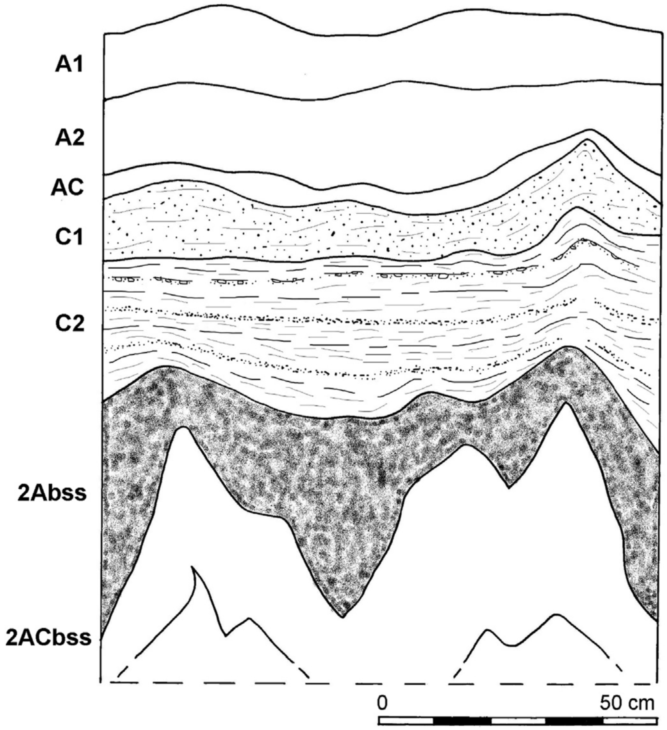

Fig. 9. Tikal Op. 8I. Excavation into toeslope, Perdido Pocket Bajo, Guatemala.

4.11. Operation 30C, Yaxnohcah

Operation 30C was excavated at the juncture of footslope and toeslope positions in a low-lying area near the Aguada Mucal. The soil exposed here is a cumulic Vertirendoll, which appears to have steadily gained mass via gradual colluviation from a nearby low hillock (Fig. 17); slope on the toeslope is about 2%; grading upward to 5% on the footslope and 12% on the backslope of the hillock.

5. Discussion

In the 1980s and 1990s, prevailing models linked soil erosion rates to population density in the Maya Lowlands, with a lock-step signal for land degradation and rising population pressure peaking around 800 CE at the end of the Late Classic (e.g., Rice, 1996). However, evidence steadily mounted that soil erosion rates in many areas peaked during the Preclassic and declined in the Classic period (e.g., Dunning et al., 1998; Dunning and Beach, 2000, 2010; Anselmetti et al., 2007; Beach et al., 2008, 2018b). Studies also found evidence that soil conservation strategies, including terracing, emerged in some areas in the latter Preclassic and became widespread in the Classic period (e.g., Beach et al., 2009; Dunning et al., 2009).

As the extent of Preclassic soil erosion was becoming evident, the degree to which aggradation affected bajos within the EIR was also being documented (e.g., Dunning et al., 1999, 2002, 2006; Gunn et al., 2002;

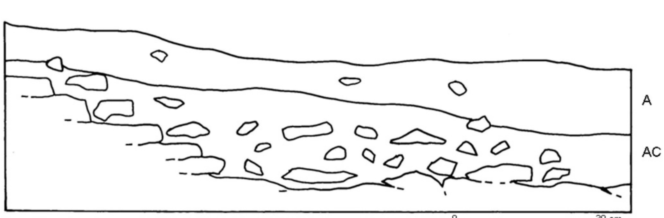

Fig. 10. Tikal Op. 8R: Excavation into footslope, Perdido Pocket Bajo.

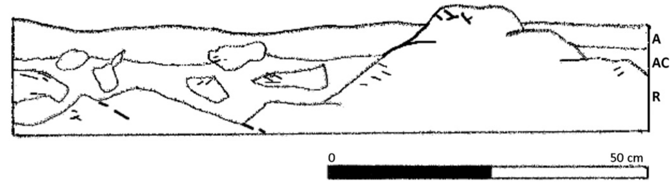

Fig. 11. Tikal Op. 8H. Excavation into shallow backslope, Perdido Pocket Bajo.

Hansen et al., 2002; Beach et al., 2003, 2008, 2015; Carozza et al., 2007). Data indicate that in some bajos, or parts of bajos, aggradation severely altered local hydrology resulting in the transformation of once shallow lakes or perennial wetlands into seasonal swamps - a process that was likely abetted by climate drying in the Late Preclassic period (Dunning et al., 2002; Hansen et al., 2002; Beach et al., 2009). However, continued investigations within EIR bajos also demonstrated that significant variability exists in the environmental history of these depressions, many of which never appear to have accommodated lakes or perennial wetlands (Dunning et al., 2006; Beach et al., 2015). As will be discussed further below, this variability can be attributed to differences in bajo origins, hydrology, and history.

Archaeologists and ecologists working in the Peten District of northern Guatemala in the mid-twentieth century noted the spatial correlation of large ancient Maya cities and the edges of bajos (e.g., Lundell, 1937; Morley, 1937; Bullard, 1960), though this relationship was found to be puzzling because of the perception that bajos were resource-poor environments. However, that perception did not recognize several potential resource advantages provided by bajos and wetlands, including natural water sources, potential for water collection and storage, agricultural opportunities, hunting and gathering, and wood harvesting. Later in the twentieth century, perceptions of bajos changed as their variability and agricultural potential became increasingly apparent, though the nature of that potential was not always clear, in large part because of soil data limitations (e.g., Fedick and Ford, 1990; Kunen et al., 2000). As geoarchaeological excavations began probing bajo margins and interiors, the highly variable nature of soils, hydrology, and environmental history became even more apparent (e.g., Dunning et al., 2002, 2006; Beach et al., 2003).

Today, some bajos contain pockets of perennial surface water, and evidence suggests that such water resources were more widespread in the Preclassic when cities were being established and growing (see above). Additionally, the seasonal rivers and streams that meander through some bajos often have deep pools where water persists long after inflow has stopped. In the Bajo de Santa Fe and surrounding areas, such pools were the loci of many sites established early in the Preclassic and of sites that persisted longer in the Terminal Classic (Fialko, 2000). Bajo-edge locations allowed growing populations to more effectively capture and store rainwater, a necessity for year-round occupation of interior portions of the Maya Lowlands, a process that began at an early date (Scarborough, 1993). For example, the Brisa Reservoir at Yaxnohcah, constructed ca. 800–700 BCE, had a holding capacity of about 84,000,000 L (Dunning et al., 2018a). Early Maya settlers in the EIR undoubtedly observed water running down slope into bajos and pooling in low areas with thick clayey soil- essentially providing a natural model for the construction of the earliest form, *depression-filling* reservoirs, most of which were built along bajo margins (Dunning et al., 2018a).

Edaphic conditions within bajos varied greatly over space and time as did suitability for cultivation, a topic which we address in more detail below. Although poorly suited for most seed and root crops, many native arboreal species can tolerate the challenging edaphic conditions in the interior regions of larger bajos. Bajos likely played an important role in supplying fuel and timber. Wood demand in ancient Maya society was tremendous, with firewood by far the highest and most constant need. At Tikal, a population of 45,000 (a conservative estimate of peak population), some 42.8 million kg/yr were needed (Lentz et al.,

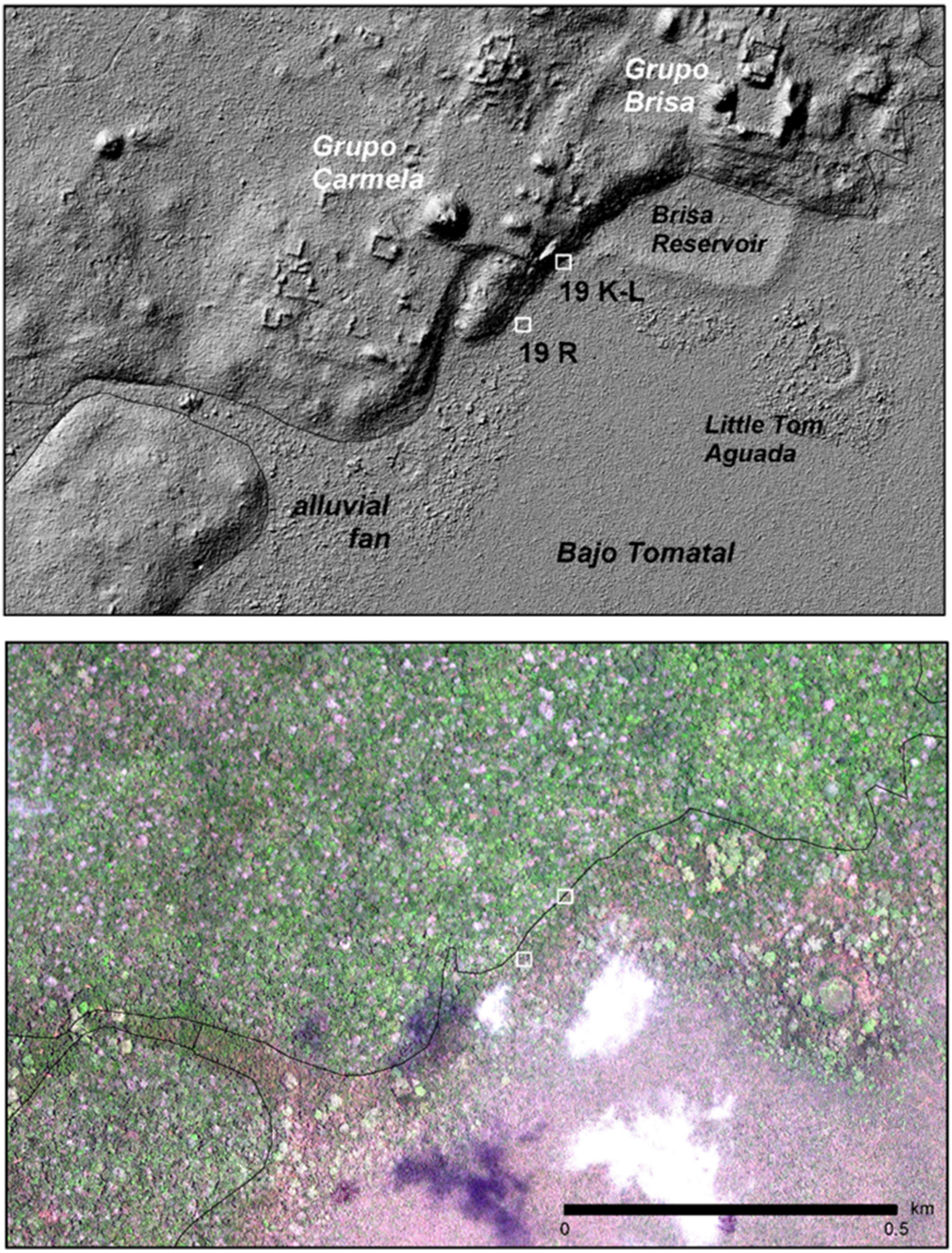

Fig. 12. Northwest section of Bajo Tomatal, Yaxnohcah, Campeche, Mexico: (above) hillshade of lidar-derived DEM; (below) Worldview 2 multispectral image (black line is a break line separating the steep backslope from the more gradual footslope).

2014). To remain even marginally sustainable, some 47% of the landscape around Tikal would have needed to remain in forest in order to meet wood needs. Much of that wood reserve was likely found in bajos. Wood collection in remote areas of the 600 km^2 Bajo de Azúcar may have been the impetus for canalization in areas of the bajo that would have been problematic for agriculture (Dunning et al., 2017).

Examination of the data presented above from investigations around Tikal and Yaxnohcah, in conjunction with data from other EIR sites, suggests three models of bajo margin development (Fig. 18). Large bajos occupying grabens are often bordered by sharp scarps on one or more sides. These bajos typically are deeper, often reaching the gypsum-rich bedrock that is lower in the regional bedrock stratigraphy. In combination, this topography and lithology led to the development of bajos containing areas of poorly drained, acidic, gypsiferous Vertisols (Laws, 1961; Dahlin et al., 1980; Dunning, 2001; Gunn et al., 2002; Dunning et al., 2006) (Fig. 18a), typified by the soil exposed in Tikal Op. 12B (Table 1; Fig. 3). Only a restricted number of native plants are tolerant of these acidic, seasonally inundated, and low CEC soils, including importantly the Caribbean pine (*Pinus caribaea*) an economically important wood to the ancient Maya (Lentz et al., 2005; Morehart et al., 2005). Accelerated erosion of the shallow Rendolls that mantled adjacent uplands, beginning around 1200 BCE in some parts of the EIR and coincident with the spread of agriculture and forest clearance, generated sedimentation that was heaviest at the slope breaks along bajo margins.

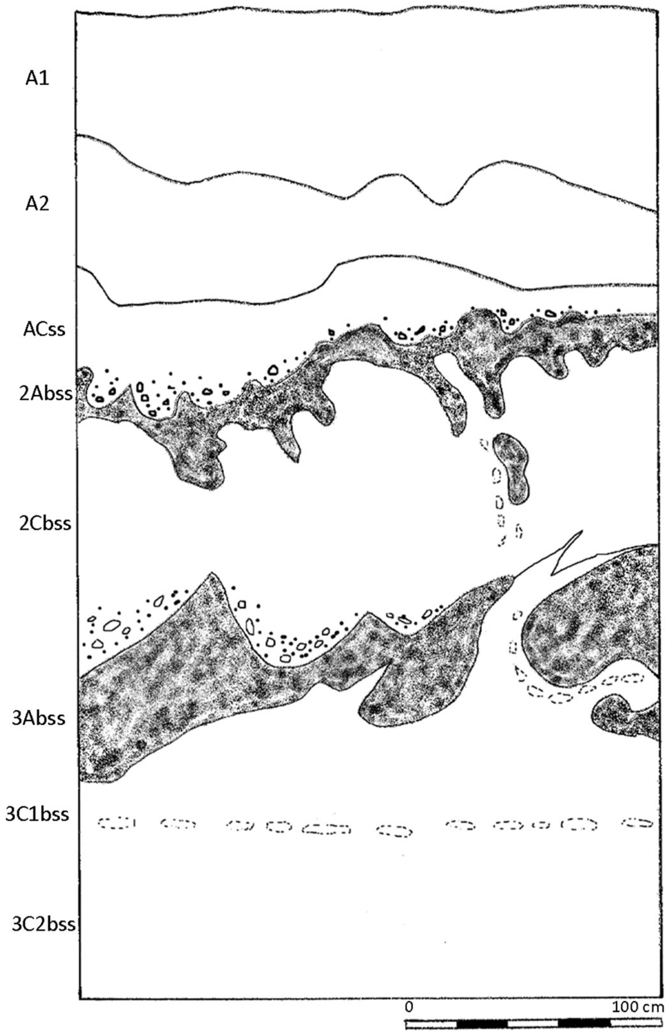

Fig. 13. Yaxnohcah Op. 19R: Excavation into toeslope, Bajo Tomatal, Mexico.

Tikal Op. 8H typifies the truncated Entisols found on backslopes and slope crests above bajo margins (Table 1; Fig. 11). Burial of soil surfaces along such bajo margins appears to have been fairly rapid effectively preserving buried soils such as the shallow Rendoll exposed in Tikal Op. 10A (Table 1; Fig. 7). Some smaller bajos are also bounded by steep scarp such as that which surrounds portions of the Bajo Tomatal at Yaxnohcah, where centuries of stone quarrying further steepened back slopes.

Quarrying may correlate with two episodes of aggradation, including coarse colluvium, in a toeslope probed by Yaxnohcah Op. 19R (Table 1; Fig. 13). The abrupt transition from backslope to footslope along this margin of the Bajo Tomatal was altered by the construction of a footslope terrace (Table 1; Fig. 14), probably to shield the spillway of the Brisa Reservoir from colluviation but also creating a stable planting bed. In many cases, limestone-derived sediment was deposited in aprons from a few tens to a couple hundred meters in width, but sometimes more. In parts of the Bajo Laberinto near Calakmul, aprons of more than a kilometer in width developed in places (Gunn et al., 2002; Geovannini-Acuña, 2008). Soils that developed on the colluvial aprons are cumulic Mollisols grading downslope into Vertisols. These new anthropogenic soils had much higher agricultural potential than the gypsic soils they mantled, whereas the less-altered central parts of the bajos remained agriculturally problematic.

Bajos with lower backslope angles also produced rapid aggradation on foot- and toeslopes in many instances (Fig. 18b). Near the Aguada de Terminos at Tikal, a backslope with 17% grade produced a surge of colluvium that buried a dark clay Vertisol during the outset of forest clearance and settlement in the Early Preclassic (Table 1; Fig. 5). At Yaxnohcah, the 10–12% backslope of a bajo margin generated sedimentation that rapidly buried a dark clay Vertisol near Grupo Fidelia ca. 500 CE as revealed in Op. 30B (Table 1; Fig. 16). Internal drainage in these cumulic bajo-margin soils varies from well-drained positions on upper footslopes to increasingly slower on lower toeslopes.

The burial of a dark clay Vertisol in the Perdido Pocket Bajo was more complex as revealed in Tikal Op. 8I (Table 1; Fig. 9). The Perdido Pocket Bajo receives channelized runoff from the Mundo Perdido plaza in central Tikal, including occasional high-energy stormflow documented by stratified coarse sediments. A nearby soil pit (Op. 8D) included partial truncation of the dark clay Vertisol ca. 500 CE before progressive burial (Dunning et al., 2015b). After channelization was initiated in the Early

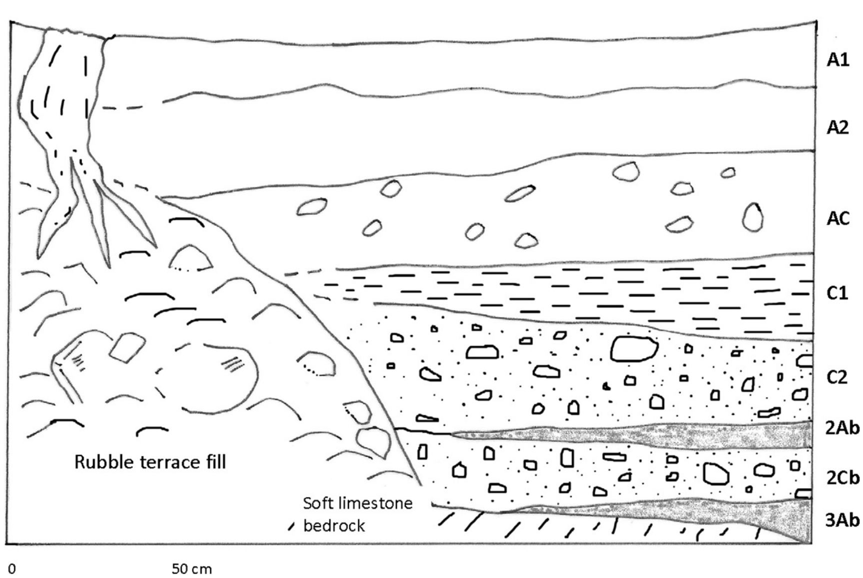

Fig. 14. Yaxnohcah Op. 19L. Excavation behind agricultural terrace at footslope, Bajo Tomatal, Mexico.

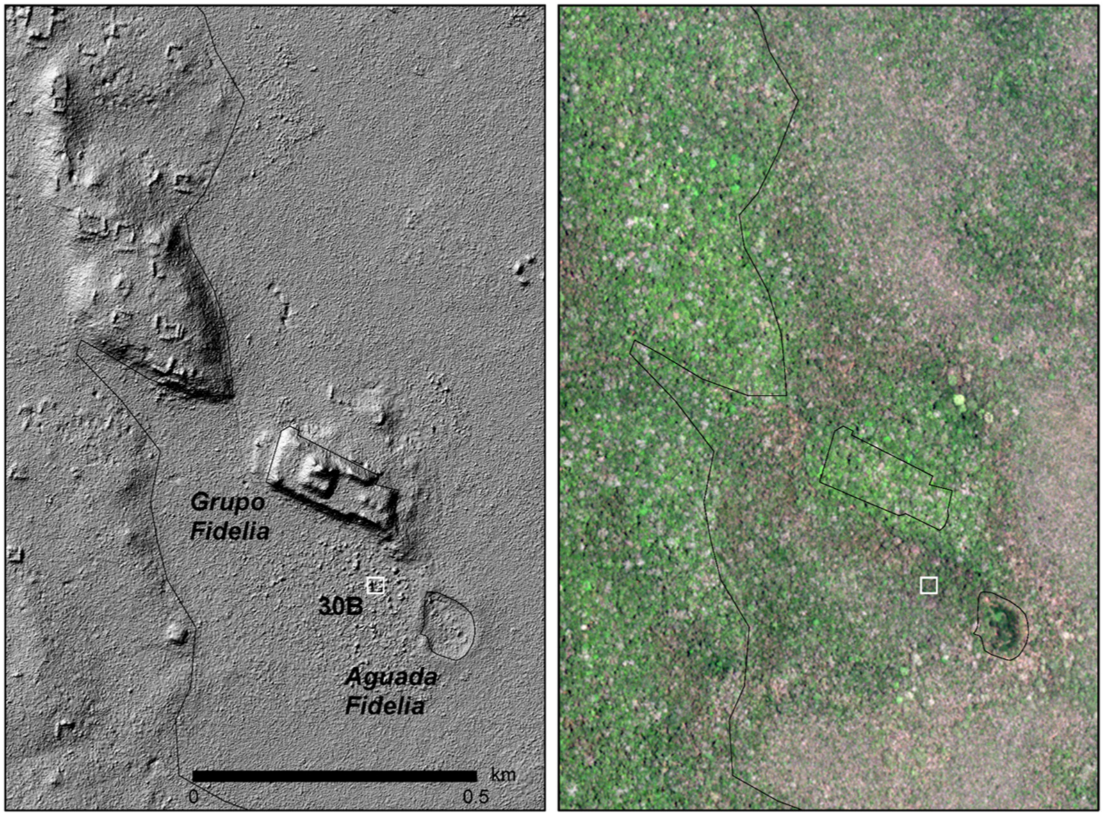

Fig. 15. Area around Grupo Fidelia, Yaxnohcah, Mexico: (left) hillshade of lidar-derived DEM; (right) Worldview 2 multispectral image (black line is a break line separating the steep backslope from the more gradual footslope).

Classic period, direct runoff into the bajo occurred chiefly during storm events; generally, runoff was directed into the Perdido Reservoir.

Bajo margins with shorter or more gently sloping backslopes are characterized by the development of cumulic Rendolls or Vertirendolls on footslopes and toeslopes (Fig. 18c). Tikal Op. 8R and Yaxnohcah Op. 30C illustrate these cumulic soils (Table 1; Figs. 10, 17). The greater accumulation of soil mass at Yaxnohcah Op. 30C is likely attributable to its position near the base of a significantly longer slope than that above Tikal Op. 8R.

In addition to aprons of cumulic soils formed in colluvium on foot and toeslopes surrounding bajos, aggradation also occurred in the form of alluvial fans at the mouths of arroyos, for example, where arroyos discharge abruptly from entrenched channels within the escarpment onto the floor of the Bajo Tomatal at Yaxnohcah (Fig. 12). Footslopes and fans are manifest topographically as well as vegetatively in several types of transitional forest types, often with a much higher percentage of palms, especially escoba (*Cryosophila stauracantha*). Cohune or corozo palm (*Attalea*

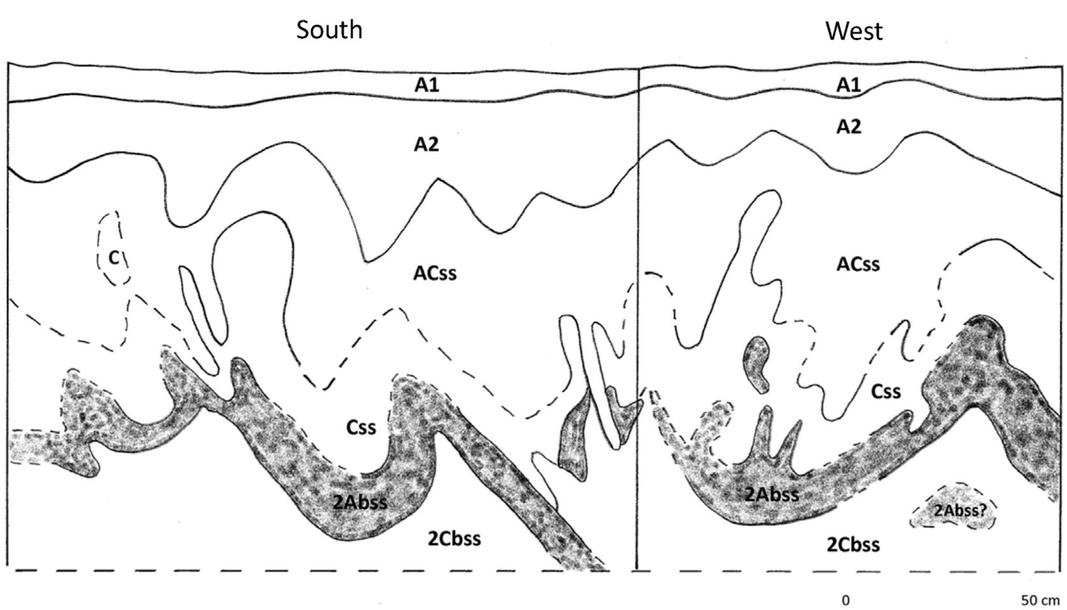

Fig. 16. Yaxnohcah Op. 30B: Excavation into toeslope near Grupo Fidelia.

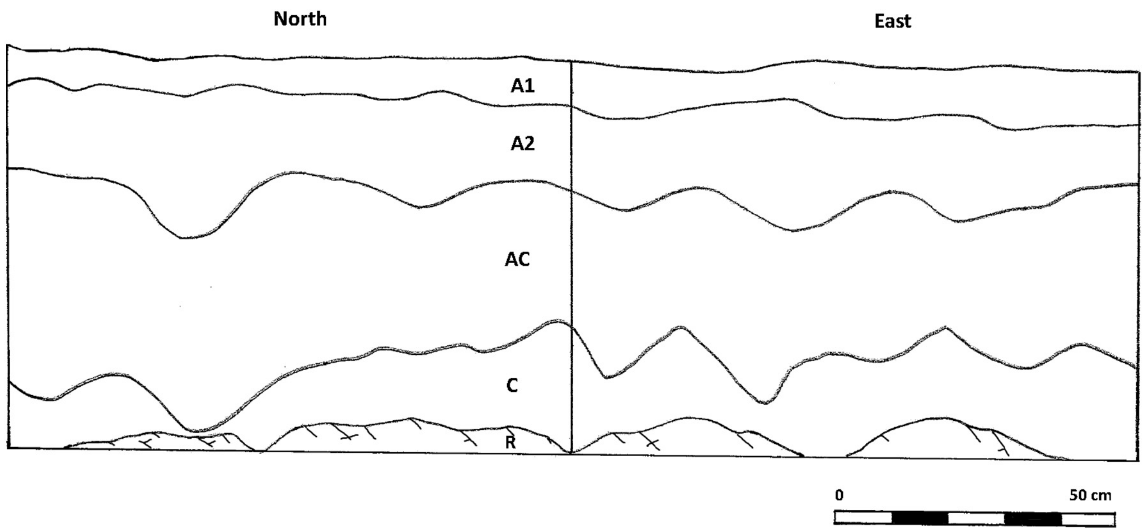

Fig. 17. Yaxnohcah Op. 30C: Excavation at footslope/toeslope juncture.

cohune), a species that thrives in deep, coarser soils, can also be dominant (e.g., in an alluvial fan at the mouth of Drainage 3 in the Far West Bajo at La Milpa; Dunning et al., 2002).

By at least 300 BCE, the Maya began stabilizing sloping land and conserving soil by constructing terraces on slope crests, backslopes, and footslopes (Hansen et al., 2002; Beach et al., 2009; Garrison and Dunning, 2009; Dunning and Beach, 2010). Terracing was used in many hilly areas in the EIR, but not all. The decision to invest in terracing varied widely between sites, ranging from terracing almost all sloping land such as at Caracol (Chase and Chase, 1998; Chase et al., 2011; Chase and Weishample, 2016) to negligible investment such as at Tikal (Dunning et al., 2015b). The populations of neither Tikal nor Yaxnohcah seem to have looked to terracing as a major part of their land management strategies; a few terraces are present at both sites, but most sloping land was not stabilized in this manner. Why terracing was not used in some densely populated areas with abundant sloping terrain (e.g., at Tikal) is an unresolved question, which may relate simply to a lack of remaining soil to protect after severe truncation, the use of other stabilization strategies such as managed tree cover, or perhaps even indifference (Lentz et al., 2014; Dunning et al., 2015b; Beach et al., 2018a). In other places, terracing sometimes does not show up in lidar surveys and ground transects, but has been revealed by excavation such as at La Milpa (Beach et al., 2018b). Hence, terracing cannot always be assumed to be absent even where it has not been mapped.

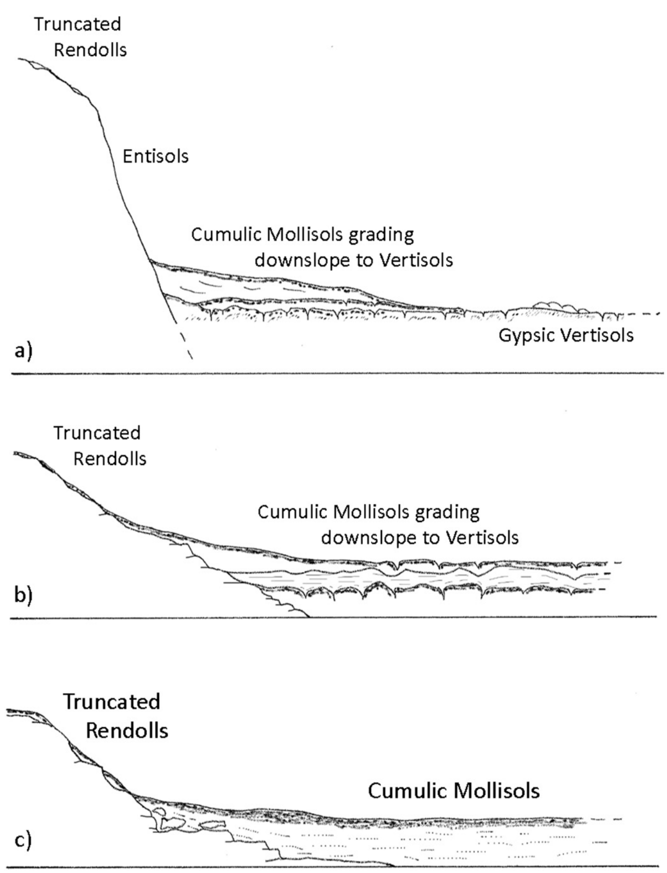

Fig. 18. Three types of bajo-margin soil development.

In addition to procuring a sufficient supply of water, urban and rural ancient Maya populations in the EIR needed to produce a reliable supply of food. Evidence documenting the intensive agricultural exploitation of bajo margins is growing, aided especially by applying airborne lidar to reveal the ground surface in forested areas.

Lidar-derived DEMs of an increasing number of Maya cities in the EIR is revealing extensive systems of field walls, terraces, and ditching, such as at Chactun, Campeche, Mexico (Fig. 19). Terraces and field walls at Chactun often encompass slope crests, shoulders, and backslopes and extend onto footslopes (Šprajc, 2015). In some areas around Chactun, field walls running downslope on footslopes articulate with and transition into ditches on toeslopes, draining further into the bajo. This downslope articulation of field walls and ditches is also evident around La Milpa, Belize (Beach et al., 2002). This transitional land use reflects the downslope transition from well-drained cumulic Rendolls to seasonally inundated Vertisols.

Agricultural intensification along bajo margins also took place outside of urban areas, most notably in the Rio Bec region - a densely populated area with a notable lack of large centers (Lemonnier and Vannière, 2013). Lidar transects created by NASA's G-LiHT biomass assessment program (Cook et al., 2013; Golden et al., 2016) revealed bajo margins in southern Campeche and Quintana Roo states in Mexico with networks of field walls and terraces extending down backslopes and footslopes, a pattern previously noted by Turner and others in the 1970s (Turner, 1983). Toeslopes often show complex ditching that created networks of island fields in the drainage-challenged Vertisols (Fig. 20).

There is some evidence that irrigation was used to increase agricultural production in some bajo margin areas. For example, unlike several other investigated central Tikal reservoirs, investigations revealed that

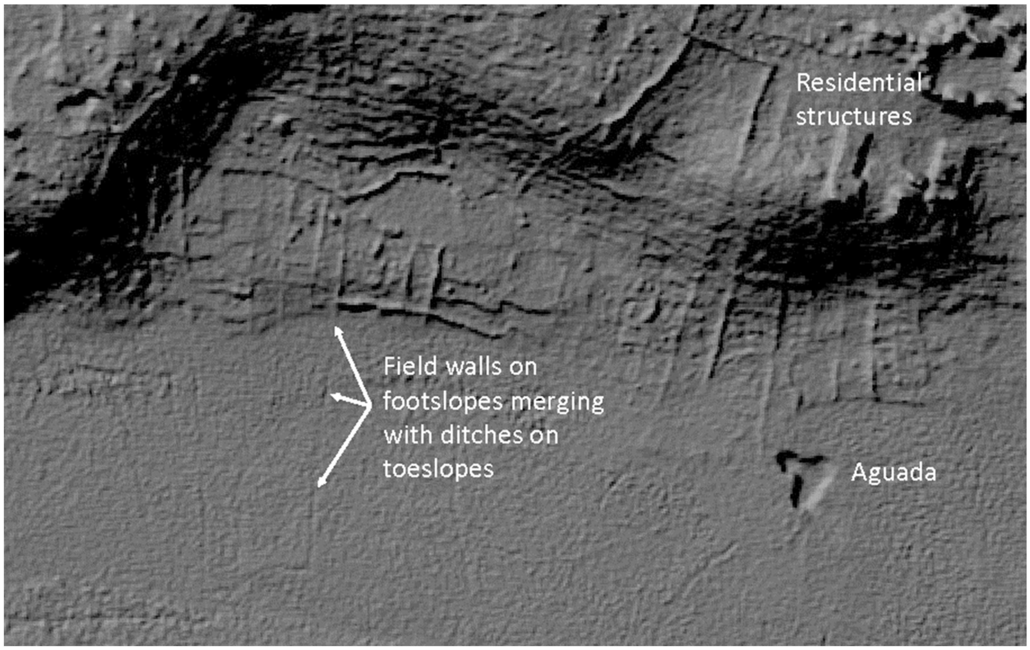

Fig. 19. Lidar image of a part of Chactun, Campeche, Mexico, showing the articulation of slope terraces, field walls, and ditches along a bajo margin.

the ancient Maya made little effort to keep the water in Perdido Reservoir clean, perhaps because it was intended for other purposes (Scarborough et al., 2012). This reservoir is perched on the margin of Perdido Pocket Bajo, and its configuration included a complex gate on its lower side suggesting its use for controlled releases of water into fields that spread across footslopes and toeslopes in the pocket bajo (Dunning et al., 2015b).

The presence of landesque capital investment, including field walls, terraces, ditching, and perhaps irrigation infrastructure along bajo margins, raises the question of what crops were being produced in these areas? Common wisdom held for many years that ancient Maya subsistence depended to a significant degree on the so-called Mesoamerican Triad of maize, beans, and squash, all of which are well-represented in paleoenvironmental proxies such as pollen and carbonized macrobotanical remains, as well as Maya epigraphic and iconographic sources, and early colonial historical and ethnographic sources, though other seed and tree crops were also used (Dunning et al., 2018b). Maize especially was closely linked to Maya cultural identity.

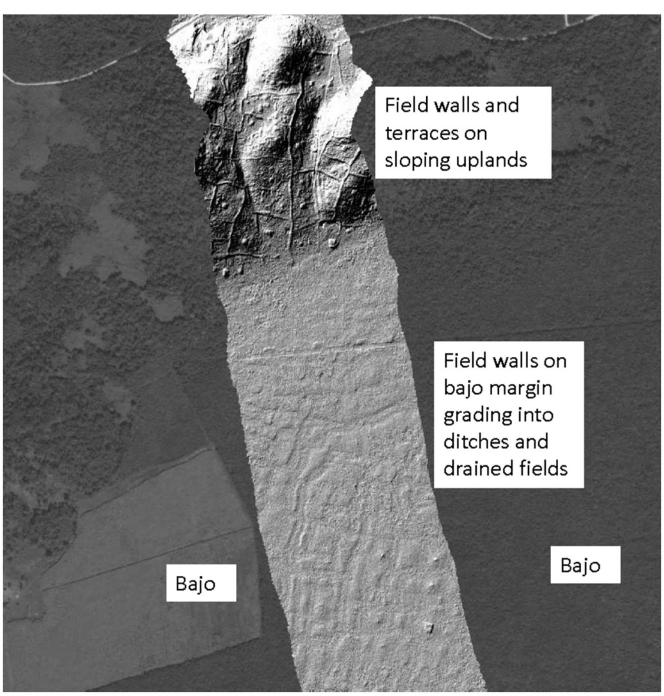

Fig. 20. G-LiHT lidar image of a bajo margin in southern Quintana Roo, Mexico, showing the articulation of slope terraces, field walls, and ditches along a bajo margin.

There is abundant evidence for ancient maize production along bajo margins. Stable carbon isotope ratios in soil organic matter can also be used to document areas of probable ancient maize cultivation (e.g., Webb et al., 2004; Beach et al., 2011). Stable carbon isotopes collected from soil profiles in the Perdido Pocket Bajo are indicative of intensive maize cultivation (Dunning et al., 2015b). Some profiles included multiple isotopic spikes associated with C_4 plant enrichment in soil organic matter as might be expected in an aggrading soil that continued to be used for maize production. Similar stable carbon isotope signatures were found in soil profiles in footslope and toeslope soils in an embayment of the Bajo de Santa Fe east of Aguada de Terminos (Dunning et al., 2015b). Stable carbon isotope investigations of soil profiles in other parts of the greater Tikal urban zone and its hinterlands indicate that this pattern of maize cultivation on bajo footslopes and toeslopes was widespread (Balzotti et al., 2013).

Palynology also offers an important window on land use agriculture on bajo margins. Most pollen studies in the Maya Lowlands have been based on cores from lake sediments which, while providing good proxies for regional vegetation patterns, underrepresent agricultural diversity as many cultigens produce relatively little pollen. Aguadas, the remains of ancient reservoirs, offer the opportunity to capture more local pollen rain (e.g., Akpinar-Ferrand et al., 2012). However, because these reservoirs were periodically cleaned of some of their accumulated sediment while in active use, most aguada sediment/pollen records have sizable gaps - often including some early sediment as well as a record of their final years of use and abandonment (Akpinar-Ferrand et al., 2012; Dunning et al., 2015b). Maize pollen preserves well and is present, sometimes quite abundantly, in pollen records recovered from many bajo-margin reservoirs (Table 3). Importantly, reservoir sediments also include pollen from cultigens not typically present in other records, including root crops.

Because root crops are typically propagated by cuttings, often before flowering, they produce relatively little pollen under cultivation. They

Table 3
Cultivated plants identified by pollen in bajo-margin aguadas in the Elevated Interior Region.

Place	*Zea Mays* (maize)	*Manihot* (manioc)	Cf. *Canna* (achira)	*Gossypium* (cotton)	Economic trees[a]
Aguada Tintal (SB)	Pre	Pre		Pre	Pre
Aguada Los Loros (SB)	Cl			Cl	Cl
Aguada Chintiko (SB)				Cl	Cl
Aguada de Terminos[b] (T)	Pre, Cl, Post		Pre		Pre, Cl, Post
Aguada Vaca del Monte (T)	Cl				Cl
Aguada Pulgada (T)	Cl				Cl
Aguada Lagunita Elusiva (LM)	Cl				Cl
Aguada Fidelia (Y)	Pre			Pre	Pre
Aguada Little Tom (Y)	Pre				Pre
Aguada El Zotz[c] (EZ)	Cl				Cl
Aguada de Olla (LJ)		Cl			Cl
Aguada Zacatal (N)	Cl				Cl

Pre = Preclassic; Cl = Classic; Post = Postclassic. SB = near San Bartolo, Peten, Guatemala (Akpinar-Ferrand et al., 2012; Dunning et al., 2014); T = Tikal area (Dunning, 1999; Dunning et al., 2015b; Lentz et al., 2014); LM = La Milpa area, Belize (Dunning and Beach, 2010); Y = Yaxnohcah (Dunning et al., 2016); EZ = El Zotz, Peten (Beach et al., 2015); LJ = Bajo La Justa, Peten (Dunning, 1999); N = Nakbe (Wahl et al., 2007).

[a] Miscellaneous economic tree species including Arecaceae (palms), Burseraceae (incl. Copal), *Coccoloba sp.*, Moraceae (incl. ramon or breadnut), Myrtaceae (incl. guava and allspice), Sapotaceae (incl. mamey or sapote), and *Spondias sp.* (incl. hogplum). These trees also occur naturally within the forest and are not necessarily indicative or forest management or cultivation.

[b] Preclassic and Classic sediment at Terminos also contained pollen possible from tomatillo (*Physalis*) or peppers (*Capsicum*).

[c] Classic sediment at El Zotz also included phytoliths of *Cucurbita* (squash).

also have pollen grains that are large, fragile and that preserve poorly, therefore these crops are possibly highly underrepresented in ancient Maya pollen records, even in aguadas (Akpinar-Ferrand et al., 2012; Dunning et al., 2015b). Manioc (*Manihot esculenta* Crantz.) pollen has been documented in a few bajo-margin reservoirs (Table 1). While some scholars have speculated for many years that manioc may have been an important ancient Maya cultigen (e.g., Bronson, 1966), data to support this idea were largely lacking until excavations at Joya de Cerén, the *Maya Pompeii*, a village buried rapidly by volcanic ash around 600 CE, provides detailed insights into ancient Maya daily life and agriculture (Sheets, 2002, 2005; Sheets et al., 2011, 2012; Lentz and Ramírez-Sosa, 2002). One important finding from Late Classic Cerén, documented by a combination of carbonized remains and plaster casting of former plant voids, is that the Maya grew at least as much manioc as they did maize. Both crops were grown in extensive fields beyond the village, as well as in household gardens within it. These gardens were clearly carefully planned, well-tended, and included a wide variety of annual seed and tree crops (including various beans, squashes, peppers, agave, avocado, and guava). Malanga (*Xanthosoma sagittifolium* (L.) Schott), another root crop, was also found in the gardens of Cerén.

Malanga is also known from Tikal in carbonized plant remains recovered in middens. Sweet potato (*Ipomoea batatas* [L.] Lam.) has also been identified in carbonized plant remains from a Tikal midden (Lentz et al., 2014, 2015) and is also known from pollen from wetland fields outside of the EIR (Luzzadder-Beach et al., 2012). Pollen from sediments in the Aguada de Terminos at Tikal also indicate that the bajo margin nearby was used for the cultivation of another root crop, probably achira (*Canna indica* L.) (Dunning et al., 2015b). Arrowroot (*Maranta arundinacea*) pollen has been identified in sediments in a bajo wetland at El Palmar, 15 km west of Tikal (Luzzadder-Beach et al., 2017). Taken together, there is mounting evidence that root crops played an important role in ancient Maya agriculture and diet. Ethnobotanical studies also indicate that manioc and sweet potato are traditional Maya crops of great antiquity and cultural significance, and that are also notable for their drought tolerance (Meléndez Guadarrama and Hirose López, 2018).

Notably, the changes in soil cover that took place along bajo margins would have created a habitat more suitable for root crop production than would have existed on a widespread basis in the EIR prior to anthropogenic erosion and aggradation. Manioc and Malanga do best in soils that are at least 30 cm deep, well-drained (or at least not water-logged), pH neutral (though they tolerate a wider range), and with full sun exposure. While they produce best on nutrient-rich soil, both will produce a reasonable crop even on depleted soil (USDA NRCS, 2003; FAO, 2017). Neither would have been good candidates for cultivation on shallow, rocky upland soils or in water-logged bajo soils. Hence, the formation of deep, cumulic, but well-drained soils along bajo margins could have spurred the spread of root crop cultivation. Terracing on uplands and footslopes would have also potentially created planting beds well suited to root crop cultivation, though terraces were also used for other crops, including maize.

In addition to food crops, the Maya cultivated plants for other purposes, most notably cotton. Although cotton (*Gossypium hirsutum* L.) seeds were used as a cooking oil source at Cerén (Lentz and Ramírez-Sosa, 2002), the Maya primarily cultivated cotton as an important source of fiber. Cotton fabric and thread were used for many purposes, and cotton products are known from Classic period Maya sources and early Spanish colonial sources to have been a highly valued trade, tribute, and tax-payment item (Baron, 2018). Cotton produces relatively little pollen that is only dispersed locally via insects and is, therefore, probably grossly underrepresented in pollen-based assessments of ancient agriculture. Cotton pollen does show up in cores taken from a number of bajo-margin reservoirs; for example, the Aguada Tintal near San Bartolo and at the Aguada Fidelia at Yaxnohcah - in both cases found in Late Preclassic sediment (Table 3).

Tree crops also appear in bajo-margin aguada pollen as do many upland and swamp forest species. Propagated fruit trees typically are insect-pollinated and low pollen producers and, hence, generally underrepresented in lacustrine sediment cores. Household garden trees, orchards, and managed forests are all believed to have been important components of the Maya economy, including slope management in the uplands and wood reserves in bajos (e.g., Lentz et al., 2014; Dunning et al., 2018b).

6. Conclusions

The importance of geomorphic change is often neglected in modeling social-ecological systems (Chaffin and Scown, 2018). This neglect is unfortunate because, where available, geomorphic evidence shows that almost all agriculturally used sloping land has been affected by soil erosion in earlier times (Dotterweich, 2013). In many areas, pulses of landscape instability are known and can be tied to changing land use patterns and cultural-historical sequences (e.g., Butzer, 1996).

Within the Elevated Interior Region (EIR), early Maya agriculture induced severe soil loss on sloping upland terrain, generating sedimentation in regional depressions (bajos) and sometimes profound hydrologic changes. Examination of data from Tikal, Yaxnohcah, and elsewhere allowed us to posit three models of bajo-margin soil development

(Fig. 18). Truncation of upland soils occurred at various times, often commencing with the onset of agriculture in the Early Preclassic (c.a., 1500–1000 BCE) and sometimes producing multiple alternating episodes of pedogensis and burial linked to pulses of land cover disturbance and slope instability. The development of relatively stable surfaces on bajo margins encouraged the development of intensive agriculture exploiting those soils. Anthropogenic colluvial and alluvial soils that developed along bajo margins became an important edaphic resource for the ancient Maya. Over time, these soils became a locus for intensive cultivation involving several types of root crops as well as maize. Elsewhere, lidar-based mapping is helping to reveal the ancient investment in durable agricultural infrastructure along bajo margins, including field walls, terracing, and ditching. A multiplicity of paleoenvironmental techniques is revealing the wide range of plants cultivated in these field systems: a testament to ancient Maya adaptation to a changing environment. Maya cities were dependent to a large degree on food that could be produced within the city itself and its close hinterland (e.g., Dunning, 2004; Isendahl, 2012; Dunning et al., 2018b). Hence, the ability to both maximize and sustain food production by fully exploiting highly productive portions of the soilscape was of vital importance.

The landscape created by a combination of anthropogenic slope destabilization and downslope aggradation endures today. Bajo margin footslopes and toeslopes have been colonized by a sufficiently unique suite of tree species characterized by growth patterns reflective of local soil moisture conditions. Consequently, bajo margins typically are clearly visible on multispectral satellite imagery even after a millennium of abandonment. Landesque capital also endures within the landscape. Ancient terraces and ditches continue to affect local hydrology and soil formation. The enduring nature of this heavily modified landscape is a testament to the power of humans, who transformed the surface of the Earth with nothing more than, in practice, Neolithic technology. The slowly fading inheritance of landesque capital also reflects a more ephemeral legacy, namely a system of intensified land use and land tenure that evolved to adapt to the changing landscape. That system unraveled across the EIR after 800 CE as part of a wave of cultural change and regional abandonment (Dunning et al., 2012; Turner and Sabloff, 2012). The intensification of agriculture in the Classic period provided the foundation for extraordinary population growth and urban expansion within the EIR. Decline followed from many years of growth, but growth that contained the seeds of future failure (Isendahl et al., 2014). Population growth and forest removal went hand in hand with political expansions but created a risk spiral leading to increasing vulnerability. Food and wood demands competed for land use - on land that had been pushed to maximum production orchestrated by a rigid political administration unprepared to deal effectively with further perturbations, most notably the droughts that beset the region in the ninth and tenth centuries CE (Lentz et al., 2014). In many parts of the EIR, landscape stability returned post-abandonment and has evolved now with a millennium of minimal human impact. In other parts of the EIR, human colonization has resumed over the past century, and instability is once again evident in forest clearcutting and soil loss - often at the hands of colonists with little incentive for long-term stewardship of the land.

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