



# Agriculture in the Ancient Maya Lowlands (Part 2): Landesque Capital and Long-term Resource Management Strategies

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## Abstract

Pre-Columbian food production in the Maya Lowlands was long characterized as reliant on extensive, slash-and-burn agriculture as the sole cultivation system possible in the region, given environmental limitations, with maize as the dominant crop. While aspects of this “swidden thesis” of Maya agriculture have been chipped away in recent years, there has been an underappreciation of the many forms of long-term capital investments in agriculture made by ancient Maya people. Here, we review the last three decades of research that has overturned the swidden thesis, focusing on long-term strategies. We demonstrate long-lasting agricultural investments by Maya people, in social capital including multigenerational land tenure, in cultivated capital including long-lived trees, and in landesque capital including soil amendments and landscape engineering projects, such as terracing and wetland modification.

**Keywords** Maya · Tropical agriculture · Landesque capital · Terracing · Wetland management · Soils

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## Introduction

Beginning with written descriptions of Maya agriculture dating to the colonial period (e.g., de Landa 1978 [1566]), Maya cultivation practices were described from an outsider perspective as a system of land-extensive, slash-and-burn, shifting cultivation, dependent on maize, supplemented by beans and squash and a few other vegetables and greens. These short-term, shifting, fields of annual cultivars came to be known as the milpa. In the first textbook on the ancient Maya, archaeologist Sylvanus Morley succinctly summed up the long persisting perception of ancient agriculture in the Maya Lowlands: “The modern Maya method of raising maize is the same as it has been for the past three thousand years or more – a simple process of felling the forest, of burning the dried trees and bush, of planting and of changing the location of the cornfields every few years” (Morley 1946, p. 140). This form of milpa cultivation was widely described in the literature, both popular and academic, well into the late 20th century, becoming known as the “swidden thesis.”

The swidden thesis has three primary correlates: maize dominated as the primary cultivar and dietary staple; shifting, slash-and-burn cultivation was the only practice possible or practical in the thin, rocky soil of the region; and cultivation and extensive land use resulted in a lack of investment in land development or improvements and an impermanence in residential location. A companion piece to this review focuses on research conducted since the 1990s that has further dispelled the first two correlates to the swidden thesis as noted above (Morell-Hart et al. 2023). That review focuses on plant cultivation contexts including the milpa (a specific form of swidden cultivation), homegardens, and forest gardens, as well as recovery of ancient plant remains. Here, we focus on the third correlate of the swidden thesis, reviewing a similar span of published research that considers long-term investments in agricultural development that are generally grouped under the heading of agricultural landesque capital (Brookfield 1984; Håkansson and Widgren 2014). As early as 1933, botanist Cyrus Lundell (1933) recognized that terracing in the Maya Lowlands represented long-term or permanent cultivation, a “higher agricultural art” than shifting milpa farming. Lundell’s suggestion went unheeded for decades. Here we expand and build on the notion of long-term investments in agricultural production and further suggest the implications of such frameworks on broader understandings of social processes and ethnoecological dynamics. Critically, we maintain that the evolution of ancient Maya society, as an agriculturally based culture, cannot be understood until the swidden thesis and its three correlates are finally put to rest.

As archaeological research in the Maya Lowlands (Fig. 1) expanded in the 1960s from a near-exclusive focus on temples and palaces to include the study of rural settlement patterns and excavation of household sites, it became clear that swidden cultivation alone could not have supported the growing population estimates for the ancient Maya. Excavation of ancient house sites also provided ample evidence for continuous, long-term, multigenerational occupancy and renovation of residential sites (e.g., Haviland 1970, 1988). By the early 1970s,



Fig. 1 Map of Maya area with locations and areas mentioned in the text. Map compiled by Lydie Dussol.

new evidence was also emerging for ancient agricultural land improvements such as terracing in hilly areas and ditched or raised fields in wetlands (e.g., Turner 1974). The publication in 1978 of the edited volume *Pre-Hispanic Maya Agriculture* (Harrison and Turner 1978), traced “the myth of the milpa” (Hammond 1978) and “the development and demise of the swidden thesis” (Turner 1978b). Several other edited volumes on ancient Maya agriculture and foodways followed, with contributions expanding on themes of local and regional-scale variability in land resources and ecosystems, and the many ways in which the Maya managed

these resources, including agricultural engineering features (e.g., Fedick 1996c; Flannery 1982; White 1999). Recent research summaries of ancient Maya subsistence have also focused on more social aspects of Maya foodways (e.g., Ardren 2020).

In the following sections, we address the relationship between natural capital, social capital, and landesque capital, focusing our attention first on swidden farming and then expanding perspectives on long-term agricultural investments in the Maya Lowlands. Subsequently, we consider various kinds of social investments (or social capital), including maintenance and transmission of specialized knowledge regarding soil classification, land evaluation, and soil microenvironments. We also consider forms of social capital that sometimes translate onto the physical landscape as walls and other features, reflecting land partitioning and land tenure. We then address three kinds of landesque capital, the ways ancient people invested time and energy into developing these types of capital, and how they manifest archaeologically: cultivated capital, soil capital, and feature capital. We pay special attention to feature capital, detailing various landscape engineering investments including soil ridges and rock piles, terraces, agricultural water management, and wetlands management in four different types of zones. These different types of investments, we argue, complicate and even contradict the (persistent) third correlate of the swidden thesis. Our review of studies from the past three decades has implications for modeling the ancient Maya societies that heavily invested in their surrounding landscape, building resilience for times of environmental flux, social strife, and limited natural capital. This review also provides an updated basis for comparison with other recent reevaluations of tropical agriculture, particularly for the Neotropics.

## Swidden Farming and Natural Capital

The basis of swidden agriculture, as traditionally conceived for the ancient Maya, is the use of what is often termed “natural capital,” the background of lands, waters, and biodiversity from which people withdraw elements of subsistence (Börjeson and Ango 2021; Ehrlich et al. 2012). Natural capital is not “fixed” in nature; resources change over time in response to forces such as climate change and human-induced changes such as deforestation and erosion. Each successive generation inherits a potentially altered version of natural capital. In the traditional conception of swidden, no attempt is made to improve the land or prevent degradation, other than pausing use for a number of years to allow vegetation to begin recovery. This is basically the form of swidden described for the Maya in the above quote from Morley (1946, p. 140). Under this perception, swidden cultivation is extractive, providing harvests for a year or two before soil nutrients are depleted or competing vegetation begins to take over as natural succession progresses. Early Maya scholars (e.g., Morley 1946) also believed that the only form of intensification available to the Maya was the progressive shortening of the fallow period as formalized by Boserup (1965). In this model of intensification, from forest fallow, through bush fallow, short fallow, annual cropping, and finally multicropping, the only land “improvements” are

increased time spent weeding fields and the addition of various forms of fertilizers to slow the progress of nutrient depletion.

We recognize that the simplistic notion of swidden cultivation described above would probably be hard to find in actual practice, now as in ancient times. More recent and thorough studies of swidden farming have demonstrated that farmers in many areas of the world practice selective clearing, coppicing, and managed succession of “fallow” fields to promote more rapid regrowth of secondary forest that contains an increased representation of economically useful species (e.g., Balée et al. 2020; Hecht et al. 2014; Pain et al. 2021). Swidden farming, as documented for Maya people in modern times, does present environmental challenges (e.g., decrease of atmospheric phosphorous input; Das et al. 2011), but it is increasingly recognized as a diverse, sophisticated form of sustainable farming that can support significant populations given adequate land resources (e.g., Anderson et al. 2003; Schwartz and Corzo M. 2015) (Fig. 2). It is also recognized as a component or phase of what we have termed “managed succession farming” (Morell-Hart et al. 2023), and in the context of long-term cycles of what is also called “forest gardening” (Ford and Nigh 2016).

Outside observers of lowland Maya agricultural practices, from the colonial period into modern times, rarely include any observations or descriptions of lasting investments intended to increase agricultural production or conservation of land resources. It was long assumed by archaeologists that this held true for ancient Maya societies as well. Although there were scattered reports in the early 20th century of terracing in some hilly regions such as the slopes of the Maya Mountains and



**Fig. 2** A modern milpa in northern Quintana Roo, Mexico. Note the coppicing of trees that will rapidly regrow. This milpa was also planted with manioc in areas of deeper soil. Photograph by Scott Fedick.

Vaca Plateau, these brief notes in the literature did not change interpretations of ancient Maya land use or swidden cultivation. In the same sense, early ethnographic descriptions of Maya orchards, as well as fruit tree cultivation in homegardens, were considered minor supplements to the milpa food base. Again, Morley (1946) represents a “textbook” example of this thinking. But far from a straw man argument, we find strands of swidden models persisting to the present day.

## **Lasting Investments: An Expanded Perspective on Agricultural Landesque Capital**

Many, if not most, forms of traditional agriculture practiced around the world involve some form or forms of labor investment that are intended to improve production and prevent land degradation over years of continuous use (e.g., Doolittle 2000; Whitmore and Turner 2001; Wilken 1987). Since the 1990s, there has been a growing interest in codifying the benefits of increased agricultural production and conservation of land and water resources through landscape modifications, sometimes grouped under the heading of landesque capital. This approach was popularized and refined in anthropology/geography by Brookfield (1984) and has more recently been adapted and expanded by other anthropologists, archaeologists, and geographers (e.g., Håkansson and Widgren 2014; Thurston and Fisher 2007). Blaikie and Brookfield (1987, p. 9) describe landesque capital as “any investment in land with an anticipated life well beyond that of the present crop or crop cycle.” It is also useful to conceptualize landesque capital as “banked labor” (Fisher and Feinman 2005, p. 64) that can be drawn on for many years. Farmers may develop these improvements incrementally during the course of cultivation or may develop them as planned projects prior to initiating cultivation.

The development of landesque capital is considered a distinct form or trajectory of agricultural intensification (Blaikie and Brookfield 1987; Kirch 1994), quite different from the original Boserupian model for intensification of swidden systems (Boserup 1965), although Boserup later modified her thesis to include labor investments in “land-saving” technologies such as terraces and irrigation systems (Boserup 1976, 1981). Boserup’s (1965) swidden intensification leads to diminishing returns on labor investments and sometimes land degradation, while landesque improvements result in reduced labor costs after initial investments and prevention of degradation. Land degradation tends to set in only after landesque features, such as terracing, are no longer maintained or are fully abandoned (e.g., Fisher 2007; Fisher and Feinman 2005; Fisher et al. 2003).

Here, we suggest a modified and expanded definition of landesque capital that recognizes improvements to soils (soil capital), construction of long-lasting features (feature capital), and the cultivation of perennial plants, particularly trees, that may continue to be productive for many years after planting (cultivated capital) (see Börjeson and Ango 2021). We also consider two forms of what might be considered “social capital” that have implications for enduring cultivation systems: land evaluation and land tenure. Knowledge about soil properties and suitability of various soils and microenvironments for specific crops and cultivation techniques is a component

of traditional ecological knowledge (TEK) (Berkes et al. 2000) and of ethnoecology modeling (Barrera-Bassols and Toledo 2005). This attention to the particularities of the landscape, sometimes at a very fine scale of land evaluation, is reflected archaeologically in settlement patterns and the distribution of terraforming features. Land tenure systems are linked to duration of cultivation on established plots of land and are reflected archaeologically in boundary markers such as field/garden walls and long-term or multigenerational occupations of associated residential sites, particularly those established in the best agricultural lands (McAnany 1995). We expand each of these concepts of capital below.

## Social Capital, Shared Knowledge, and Agricultural Strategies

Our use of the term “social capital” borrows from many ideas, some in other disciplines, and represents a specific agricultural interpretation within the broader notion of “social capital,” as most closely articulated by Pretty and Smith (2004), and by McBratney and colleagues (2014) in their characterization of connectivity and codification in the social relationship of soils and humans. Social capital involves family and community bonds, norms, establishment of long-term rights and obligations, and shared knowledge and cooperation. Here we focus on the ways that meaning and practice become imbued in a landscape, in this case agricultural landscapes. Much of what we mean by social capital or investments in agriculture can be linked to the two concepts of the “principle of first occupancy” and “the genealogy of place,” as proposed for the ancient Maya by McAnany (1995). These two concepts are based on the practice of land evaluation as shared knowledge and the establishment of individual or family rights over lands for multigenerational spans of time. These practices assure long-term returns to labor and encourage land conservation strategies. Such concepts are also directly tied to the notion of domestic developmental cycles that can be tracked in the archaeological record (e.g., Haviland 1988; Tourtelot 1988). Landesque and “cultivated” capital also imply stable land tenure—often multigenerational (see Brookfield 1984, p. 36).

The principle of first occupancy states: “Essentially, the best lands are claimed early in the colonization of an area. Families who arrive later or fission from established families must fight for land or cultivate plots of land that yield a harvest with considerably more expenditure of effort and sometimes requires laborious reclamation projects such as ditches, field raising, or terracing” (McAnany 1995, p. 97; see also Hammond 1974, p. 186). This concise and humanized statement about first occupancy has been expanded upon and formalized for the ancient Maya through the perspective of agricultural geography by Fedick (1995b, 2010/1989). More recently, several investigators have offered new insights into ancient Maya land tenure, applying approaches from human behavioral ecology (Fisher 2019; Pruffer et al. 2017; Thompson and Pruffer 2021) and incorporating Maya ethnohistoric concepts (LeCount et al. 2019) and decidedly multidisciplinary perspectives (Fulton and Mixer 2022). These investigators basically begin with the principle of first occupancy and then trace how land tenure develops and evolves, consistently finding that the earliest founded households retain a competitive advantage as reflected in

additive improvements to property or facilities, signaling intergenerational inheritance rights while contributing to increasing inequality between households through time. Newly arriving households must settle on and farm lands of lower quality that require increasing labor investments and improvements such as landesque agricultural features.

Recognizing “the best lands,” as well as the potential for cultivation of less-than-best lands, necessitates a deep, shared knowledge (multigenerational) of soil properties, soil distributions, soil preferences of natural vegetation, and the physiological requirements of differing crops. As Doolittle has noted, the recognition of “best” or “prime” lands by pioneering agriculturalists must be based on the evaluation of pre-cultivation conditions, as farmland does not exist until it is made (Doolittle 2006).

In McAnany’s formulation of a genealogy of place, she recognizes that a common pattern of ancient Maya burial practice was to inter the dead beneath the house floor. As she describes it, “(B)urial places of the ancestors create a genealogy of place that links descendants to that land. In this sense, the creation of ancestors, as a social practice, is an indicator of the enclosure of land into exclusionary tracts with inherited entitlements” (McAnany 1995, p. 65). Following this we find, through post-1960s archaeological investigations, pervasive evidence for multigenerational occupation and rebuilding of residences, sometimes incorporating buried ancestors, along with houselot walls and field walls defining exclusionary tracts and implied land tenure as suggested by McAnany (1995; see also Kwoka et al. 2021). In the following subsections, we elaborate how ancient Maya people may have classified soils, evaluated lands, identified soil microenvironments, and partitioned land. These investments enabled long-term land tenure across the Maya Lowlands, sometimes at the scale of centuries.

## Soil Classification and Land Evaluation

“It is easier to change crops to match the soil, rather than to change the soil to match crops.” Old saying among gardeners.

Archaeologists and geographers have found clear evidence that ancient Maya people developed and applied a deep understanding of soils and the agricultural capabilities of land resources in their tropical homelands. One of the trends in agricultural research in the Maya Lowlands since the mid-1990s has been to recognize environmental heterogeneity and identify how this shaped ancient settlement patterns and agricultural land use practices. There were certainly earlier calls for appreciation of environmental heterogeneity (e.g., Sanders 1977; Wright et al. 1959). More recent work has refined this recognition as new datasets on surface geology, soils, hydrology, and vegetation became available at both regional and local scales (e.g., Bautista et al. 2011). What has emerged is a mosaic of varied and changeable land and water resources that were differentially managed by ancient Maya people across time and space (Chase et al. 2014b; Dunning 1996; Fedick 1996b). At the regional scale within the Maya Lowlands, Dunning and colleagues (1998) defined 27 agricultural adaptive regions with differing habitats and implications for agricultural development. Fedick (1996a) demonstrated how mapping scale could obscure as well as



reveal both perception and reality of land resource variability, moving between the generalized regional scale (e.g., 1:5,000,000) and detailed local scales that could be recognized on the ground by farmers (e.g., 1:10,000). Theoretical models, adapted from agricultural geography, guided analysis of changing settlement and land use patterns at the household scale of decision making (Fedick 1989, 2010).

Land evaluation studies in the Maya Lowlands have generally applied what is referred to as capability analysis — an evaluation based on the summation of various limitations to cultivation without specifying particular crops. An alternative form of land evaluation, known as suitability analysis, considers the soil characteristics as they would relate to the growth of specific crops, such as maize or avocado, which can vary significantly (see Fedick 2010; Wright et al. 1959). To date, nearly all considerations of suitability have dealt exclusively with evaluating lands for maize cultivation. Land suitability analysis holds the potential to provide an understanding of how the ancient Maya might have made best use of varied soil resources to cultivate a wide variety of crops. Land evaluation for agricultural uses and farmstead locations can also include access to other necessary resources, particularly water (e.g., Ford et al. 2009; Thompson and Prufer 2021). Using a land evaluation approach, “prime” agricultural lands, as discussed above, might be defined as those with the fewest limitations to cultivation (high capability), suitability to the greatest range of crop types, and easy access to perennial water sources.

Traditional knowledge in the form of Indigenous Maya soil classification has also proven critical to understanding land use patterns and crop choice in various settings, while demonstrating that Maya classification is not based solely on physical characteristics of the soil, but often incorporates elements of both land capability and suitability analysis (Barrera-Bassols and Toledo 2005; Beach et al. 2017; Culleton 2012; Dunning 1992; Dunning and Beach 2004; Hixson et al. 2017; Isendahl 2002; Jensen et al. 2007; Sweetwood et al. 2009). Studies have also correlated Maya classification systems with current World Reference Base (WRB) soil classification, demonstrating a high level of concordance in the types of soils distinguished by the two systems (Bautista et al. 2005; Bautista and Zinck 2010; Estrada-Medina et al. 2013a; Martínez-Villegas 2007; Palma-López and Bautista 2019; Sedov et al. 2007).

Published soil maps and agricultural land evaluation have enabled detailed analysis of the relationship between settlement and agricultural land use. Examples include the upper Belize River area where analysis has also included predictive modeling (Fedick 1989, 1995b, 1996b, d; Ford and Clarke 2019; Ford et al. 2009; Ford and Nigh 2016; Fulton and Mixter 2022; Lucero et al. 2004; Walden et al. 2023), the New River area of northern Belize (Levi 1996), and the Copan Valley (Wingard 1996). The availability of LiDAR imagery, combined with other data sources, offers the potential of refining soil maps to better match farmers’ perspectives (Fedick et al. 2016). A recent application of LiDAR imagery and GIS modeling for the Puuc region identifies landscape elements characterized by the best agricultural soils while also carefully considering minimum sizes for potential ancient field locations (Ringle et al. 2021).

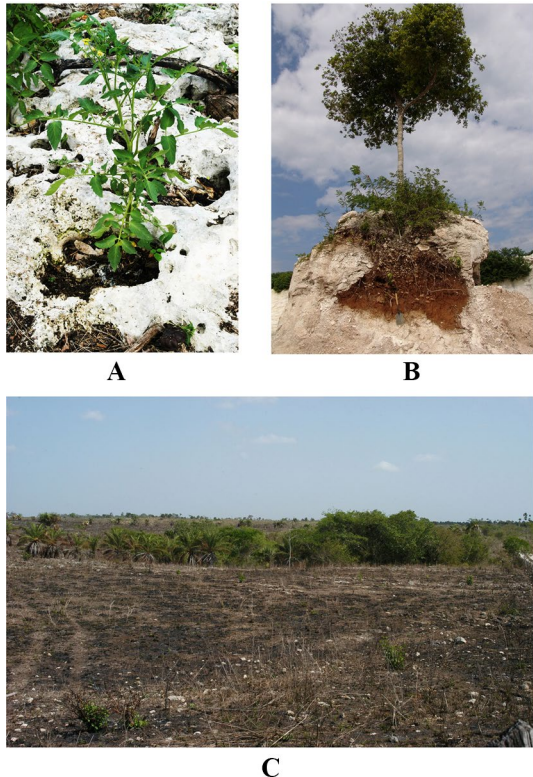
In studies that address land capability, archaeologists approximate ancient knowledge of soils by evaluating overall productive capacity, tracking how different soil resources accord with mapped ancient settlements and agricultural engineering

features. In studies that address land suitability, archaeologists are better able to approximate how ancient farmers matched knowledge of specific soils with particular plants. In both types of studies, archaeologists can track how shared, collective, knowledge-based land evaluation by the Maya guided farming families in identifying the best lands for long-term residence and the establishment of perennial homegardens. Maya families and individuals could mobilize social capital to promote the recognition of long-term rights. This recognition could enable people to maintain use rights over the best agricultural lands, and to maintain control over lands of lesser initial quality to which improvements had been made (following McAnany 1995).

### Soil Microenvironments and Precision Agriculture

Other soil studies have focused on microscale heterogeneity of soil types (Bautista et al. 2005) and how Maya gardeners practice a traditional form of “precision agriculture,” taking advantage of this localized diversity (Flores-Delgadillo et al. 2011). The karstic topography of the Yucatan Peninsula, especially in the north, yields many depressions and cavities that serve as catchments for soils and moisture, some representing highly productive agricultural resources (Fig. 3).

**Fig. 3** Karstic cavities and depressions: (A) tomato growing in a soil-filled cavity, (B) tree growing in a cavity exposed by a modern quarry cut, (C) tree-tops emerging from a *rejollada*. Photographs A and C by Scott Fedick, B courtesy of Elizabeth Solleiro-Rebolledo and Sergey Sedov.



Small soil-filled natural cavities in limestone bedrock (openings ca. 5 cm–2 m in diameter) represent soil microenvironments that modern Maya people use in a manner analogous to container gardening (Fedick et al. 2008; see also Estrada-Medina et al. 2013b); they also may have been locations for ancient tree cultivation (Dahlin et al. 2005). In northwestern Belize, Weiss-Krejci and Sabbas (2002) report on investigations of small karstic depressions, 1 m or less in depth and about 10–15 m in diameter, that apparently served various water storage functions, including one example that they interpret as a garden site, containing a layer of gravel and sherds interpreted as mulch.

Larger and deeper soil-filled karstic sinkholes and depressions (ca. 15–140 m diameter) are generally referred to as *rejolladas*. Both Houck (2006) and Munro-Stasiuk and Manahan (2010) provide useful discussions of these natural features covering both geological terminology and Maya folk classification. Gómez-Pompa and colleagues (1990) first recognized *rejolladas* as locations for cultivation of cacao trees and other crops by the Maya, at least during the Spanish colonial period, and perhaps in prehispanic times based on iconographic evidence. Terry and colleagues (2022) have recently found soil biomarkers of cacao in *rejolladas* of Yucatan and Quintana Roo, including some of those first investigated by Gómez-Pompa and colleagues (1990). Kepecs and Boucher (1996) identified many *rejolladas* in northern Yucatan surrounded by stone walls and presented possible evidence that they were also used for cacao cultivation, specifically the tentative identification of pollen in the Malvaceae family, which includes cacao. Other researchers have examined use of *rejolladas* as local areas favored by modern Maya farmers for cultivation of a variety of tree and vegetable crops, taking advantage of deep soils and proximity to the water table (Dedrick et al. 2020; Dine et al. 2019; Houck 2006; Munro-Stasiuk and Manahan 2010; Munro-Stasiuk et al. 2014). Excavations in *rejolladas* have produced some evidence for ancient use, including ceramics, pollen of economic species, and possible agricultural features (Dedrick et al. 2020). Munro-Stasiuk and Manahan (2010) identified a concentration of *rejolladas* in eastern Yucatan state, and Fedick (2014) used Google Earth imagery to conduct a rapid assessment survey of the northern lowlands to examine the distribution of *rejolladas*, defining a zone in eastern Yucatan state of approximately 11,500 km<sup>2</sup> and containing an estimated 14,430 *rejolladas*. While more common in the northern lowlands, *rejolladas* have also been recorded and studied in the southern lowlands in the Petexbatun area (Dunning et al. 1997) and noted as potential locations for cacao cultivation at Tikal (Lentz et al. 2014). These recent studies of *rejolladas* suggest histories of cultivation that extend well back into ancient times.

Targeted use of the karstic topography, and the many productive soils it contains, is not simply the activity of ancient Maya farmers making the most of difficult and unyielding terrain. Instead, farmers passed along detailed knowledge of the relationship between topography, soils, and particular plant species to realize the full potential of myriad agricultural possibilities. Farmers mobilized social capital—representing bonds between community members and families, long-term land use rights, and cooperation and knowledge—to tailor particular agricultural strategies to specific microenvironments and sometimes even individual plants.

## Land Partitioning and Tenure

McAnany (1995) suggested that long-occupied ancient Maya residential sites represent a genealogy of space that includes exclusionary tracts of land. This phenomenon is physically evident in the ways that people enclosed and demarcated lands by constructing walls, documented most often in the northern lowlands (see Batún Alpuche et al. 2020; Fisher 2014; Guderjan 2016; Kwoka et al. 2018). In modern times interments are no longer situated beneath house floors, but wall systems still commonly define family compounds and express fixed land tenure that can last generations under conditions of social and economic stability. In modern Maya villages of the northern lowlands, household compounds, or houselots (*solares*), are commonly defined by walls. These walls are most often constructed of dry-laid limestone cobbles and are referred to locally as *albarradas* (Fig. 4). Modern houselots can also be bounded by trees or shrubs, or some combination of stone wall and perennial plants. These houselots average about 0.25 to 0.5 ha in area. Killion (1992) examined the spatial structure of various household activities in modern Mesoamerican houselots and provided a widely applied interpretive model for archaeologists, while evidence from historic Maya houselots has helped refine these interpretations (Alexander 1999). Modern houselots generally include a large percentage of space dedicated to gardening, supplying families with a variety of foodstuffs, medicines, and other useful botanical products. The enduring nature of these homegardens, as cultivated capital, is discussed below. Details on the variety of plants cultivated in



**Fig. 4** A Maya houselot and homegarden in northern Quintana Roo surrounded by a stone wall. Photograph by Scott Fedick.

homegardens in both ancient and modern times are presented in our companion article (Morell-Hart et al. 2023).

Like modern Maya villages, ancient Maya communities in northern Yucatan are frequently characterized by *albarradas* that enclose space around residential architecture and are generally interpreted as evidence for homegardens (Fedick 2003b; Fisher 2014; Wyatt 2020). In the northern Maya Lowlands, ancient field walls often define houselot areas surrounding residential units, while other walled areas surround natural features such as *rejolladas* (Batún Alpuche et al. 2020; Dahlin et al. 2005; Kepecs and Boucher 1996). Sometimes walled plots lack visible evidence of enclosed structural remains, while these still tend to be spatially associated with residential areas rather than distant “outfield” agricultural zones. Farther from residences, Gómez-Pompa and colleagues (1987) describe stone walls enclosing stands (up to 2.4 ha) of economically useful trees, known as *pet kot*, used by modern Maya people and possibly extending back to ancient times.

Recent research has documented extensive wall systems at urban sites in the northern lowlands. At Chunchucmil, wall systems have been documented for the later part of the Early Classic period (Hutson and Magnoni 2017; Hutson et al. 2006, 2007) where multigenerational use of houselots is indicated (Fisher 2014). In the Rio Bec area, stone “walls” (described as linear stone ridges) have been documented for the Late/Terminal Classic (Hutson et al. 2021; Lemonnier and Vanni re 2013). Wall systems mapped on Cozumel Island have been assigned to the Postclassic period (Bat n Alpuche 2009). LiDAR has been used for the mapping of Postclassic wall systems and analysis of houselot economic activities at Mayapan, both within and outside of the urban perimeter wall (Hare et al. 2014; Masson et al. 2020). LiDAR survey is revealing walled houselots throughout much of the rural landscape of the northern Yucatan Peninsula (Golden et al. 2016; Kwoka et al. 2018; Schroder et al. 2020).

Houselot wall systems and walls enclosing *rejolladas* are reported for the southern lowlands within the Petexbatun region (Dunning et al. 1997) and within the Pacunam LiDAR survey area in northern Peten (Canuto et al. 2018). But wall systems are generally not in evidence in much of the southern lowlands, where houselots could have been demarcated by trees and shrubs, a common practice in modern times. In the southern lowlands, spacing between residential structure groups and the distribution of artifacts and soil residues surrounding the residential clusters is consistent with maintaining houselots of sizes similar to those found in walled houselots in the north (e.g., Fedick 1995; Isendahl 2012; Robin 1999, 2012). At the Classic period site of Joya de Cer n, El Salvador, the homegardens identified through carbonized remains and voids, preserved beneath volcanic ash, lack any boundary walls or other barriers (Slotten et al. 2020). In other studies of areas where terraces immediately surround residential structures, it has been suggested that some of these adjacent terraced areas functioned as homegardens (e.g., Chase and Chase 1998; Lemonnier and Vanni re 2013; Wyatt 2020).

If agricultural pursuits were limited to shifting swidden cultivation, much more flexibility would be afforded to the selection of residential location (Fedick 1996b) and we would see more mobility on the landscape and shorter-term settlements. Instead, archaeological investigations have revealed long-term land tenure across the

Maya Lowlands. There is widespread evidence for multigenerational occupations of settlements, including renovations to residences, sometimes with buried ancestors, alongside boundary markers of space (McAnany 1995; see also Kwoka et al. 2021). Though not directly contributing to agricultural productive capacity in the same way as terraces, canals, and soil amendments, land partitions nonetheless serve as an index of social capital related to agricultural pursuits and the tenacity of such social investments once manifested on the landscape.

## Cultivated Capital

“The best time to plant a tree was 20 years ago. The second best time is now.” Chinese proverb.

Anthropologists and forest ecologists increasingly recognize forest regeneration strategies and management practices of traditional smallholder tropical farmers as a form of agricultural landesque capital involving long-term cultivation of trees and shrubs (Börjeson and Ango 2021; Pain et al. 2021), what we refer to here as “cultivated capital” (see McBratney et al. 2014). Modern Maya people are reported to make use of 204 indigenous, food-producing species of trees including palms and cycads, 52 species of shrubs, and 61 species of perennials that can grow either as shrubs or trees (Fedick 2020). These productive and drought-resistant trees and shrubs are the dominant components of modern Maya homegardens (Cuanalo de la Cerda and Guerra Mukul 2008) and forest gardens (Ford and Nigh 2009, 2016). Jiménez-Osornio and colleagues (2018) have compiled data from surveys of 2,360 modern homegardens in the Yucatan Peninsula and have assembled a list of the 27 most common indigenous fruiting trees found in the gardens. There is a close correspondence between the most common fruit trees reported for modern Maya homegardens and paleobotanical remains of fruit trees recovered from the village center and homegardens at the ancient site of Joya de Cerén (Jiménez-Osornio et al. 2018; Slotten and Lentz 2021). While there is a large range of variation among species and varieties, most of these trees would require at least five years to begin production of fruit, but could then continue to yield fruit for decades or even several human generations (see Morton 1987). The perennial trees and shrubs of Maya homegardens and forest gardens provide an excellent example of cultivated capital, reflecting long-term investment in place and stable cropping systems (see Batún Alpuche et al. 2020). Of course, trees were also cultivated by the ancient Maya for many other uses besides food; trees were valued for firewood, construction material, and ritual purposes. Further discussion of these plants in the context of Maya cultivation systems and information on recovery of botanical remains from many of these species is provided in our companion article (Morell-Hart et al. 2023).

Pertinent here, and related to the following section, one method of maintaining soil fertility under long-term cultivation is intercropping with plants of the Fabaceae family (legumes), nearly all of which have the ability to fix atmospheric nitrogen and deposit it in the soil (Castro et al. 2016). A small number of plants other than Fabaceae, as well as some microorganisms, have this same ability. Ethnographically, lowland Maya people practiced intercropping and controlled forest regrowth using

nitrogen fixing plants (e.g., Diemont et al. 2006), a practice only occasionally recognized by archaeologists considering ancient soil management practices (e.g., Lentz et al. 2014). Legumes, including tree species, are commonly represented in paleoethnobotanical remains recovered from ancient Maya sites (Morell-Hart et al. 2023). In the following section, we fully review similar strategies of soil capital investment.

## Soil Capital: Amendments and Fertilizers

Investments in soils offer another way to bolster agricultural production and ensure food resilience in times of difficulty, contributing to what has been termed “soil security” (McBratney et al. 2014). Soils of the Maya Lowlands are in general much more fertile and capable for hand cultivation than thought prior to the 1970s (Aubert and Tavernier 1972; Sanchez and Buol 1975). Even when the natural capital of an area includes good soils, maintenance of soil fertility is always an issue under conditions of long-term agricultural use. Ethnographically, Maya farmers used a number of techniques and amendments to maintain soil fertility and workability, including the use of nitrogen fixers as mentioned above, and the spreading of household organic trash. Organic muck from wetlands in the Yalahau region is also transported by modern Maya people for use in homegardens (Fedick 1998; Fedick and Hovey 1995). Archaeologically, dispersal of household trash around infield areas has been interpreted as evidence for fertilization at lowland Maya sites since the 1980s (Dunning 1996).

Soil enhancement practices are largely suggested rather than tested hypotheses. Evidence of ancient practices for maintaining soil fertility has proven elusive in some cases and abundant in others. The site of Chunchucmil, in the northwestern Yucatan Peninsula, is located in an environmental setting that is particularly challenging for agriculture; thin, sparse soils, many of low agricultural capability, located in a region of relatively high aridity. Under these circumstances, it seemed likely to archaeologists that ancient Maya farmers would have used soil amendments to maintain or improve soil fertility in both infield (homegarden/houselot) and outfield (milpa) contexts. Soil testing was conducted at Chunchucmil and surrounding rural areas to identify phosphate enrichment from organic amendments, charcoal amendments (black soil), and stanol biomarkers as an indicator of nightsoil (feces residue) use. Within the urban area of Chunchucmil, the distribution of inorganic artifacts and phosphate enrichment withinouselots suggested that people separated organic and inorganic trash, with the organic component being used as homegarden fertilizer (Hutson and Stanton 2007), but in smaller quantities and distribution than what might be expected (Hutson et al. 2004; Hutson and Stanton 2007). Soil testing to identify ancient use of charcoal or nightsoil as fertilizers has been conducted in both urban and rural areas, but no evidence has been found for fertilization of rural fields (Beach et al. 2017; Dussol et al. 2021; Hutson and Stanton 2007; Sweetwood et al. 2009).

At the site of Marco Gonzalo, on Ambergris Caye, Belize, Graham and colleagues (2017; Macphail et al. 2017) have identified what they call Maya Dark Earth, which they interpret as the product of weathering of carbonate-rich anthropogenic deposits

developed over a long occupation history, including abundant charcoal originating from fires used for Late Classic salt processing. The investigators view this soil as an incidental association with nearby ancient settlement rather than as a resource developed and used for agriculture. Although the Maya Dark Earth is interpreted as an unintentional consequence of long-term human depositional activity, it was noted that in modern times these enriched soils have been collected and transported by locals for gardening (Macphail et al. 2017). The authors do not equate these soils with Amazonian Dark Earth, which is an anthropogenic soil that is recognized and used as an agricultural resource.

At the Preclassic site of Nakbe in the northern Peten of Guatemala, Hansen and colleagues (2002) have identified the transport of wetland muds to nearby upland agricultural terraces as indicated by soil color and texture, and inclusions of durable algae remains, all indicative of perennial wetland environments. In the Yalahau wetland region of the northern lowlands, shells of minute and habitat-specific freshwater snails and bivalves were recovered from infield areas at the Late Preclassic site of Makabil. Given their direct link to specific wetland habitats, these shells were interpreted as evidence for harvest and transport of periphyton, a wetland algal and bacterial mat that produces high levels of nitrogen, phosphorus, and potassium (Fedick 1998, 2003a; Fedick and Morrison 2004; Morrison 2006; Morrison and Cózatl-Manzano 2003). This same periphyton has been demonstrated in controlled experiments to be a highly effective biofertilizer (Palacios-Mayorga et al. 2003) and is the subject of continuing study (Becerra-Absalón et al. 2012).

In terraced fields associated with the Classic period site of Chan, Belize, soil testing identified apparent soil amendments in the form of wood ash and jute snail (*Pachychilus* sp.) shells (Wyatt 2012, 2020). Wood ash is a source of potassium, phosphorus, and magnesium, and its high calcium content is often used to raise the pH of acidic soils. Unlike the minute mollusk shells found in the Yalahau periphyton, jute snails are large enough to be used as food by Maya people, both ancient and modern (Halperin et al. 2003; Healy et al. 1990). The shells recovered from terrace soils at Chan most likely represent an (inadvertent) inorganic component of household rubbish used as fertilizer, or transport of rich alluvial soils with jute shell inclusions (Turner 1978a).

As documented in these studies, ancient Maya farmers paid careful attention to the natural capital offered by existing (and dynamic) soil landscapes, but amplified, enhanced, and managed these soils through a number of amendments and fertilizers. Though archaeologists in the Maya Lowlands document these activities less frequently than other types of capital, the small corpus of studies to date has revealed how Maya farmers—and broader Maya societies—were able to make the most of surrounding environments and negotiate emerging difficulties by mobilizing a broad array of soil investments.

## Feature Capital

The final type of landesque capital is feature capital—by far the type of capital most frequently documented in archaeological scholarship and the most readily visible on the landscape. As we elaborate below, ancient Maya people mobilized themselves



for sometimes monumental labor projects to develop agricultural landscapes at the macroscale, but they also cooperated at the level of the community or between households. We focus on landesque investments including soil ridges, rock piles, terraces, agricultural water management, and wetland management. We discuss how more readily accessible and macroscale technologies (including LIDAR and GIS modeling) have rapidly amplified documentation of surface features and enabled archaeologists to refine and expand models of feature capital. This review of studies from the past three decades suggests that feature capital was a significant labor investment for ancient Maya people, sometimes necessitating ongoing remodeling and upkeep, but yielding significant rewards.

### Field-Surface Management and Rock Piles

Using simple tools to shape soil into mounds, ridges, furrows, and pits is a common element of traditional agriculture, improving edaphic and moisture conditions to promote crop growth (Wilken 1987). While not as durable as features constructed of stone, soil-built features often last multiple years. Rarely, however, is evidence for this form of cultivation found in the archaeological record. An exceptional case is represented at the Classic period site of Joya de Cerén, where volcanic ash deposits preserved soil ridges and furrows in a homegarden planted with a variety of crops and similar features in more distant milpa fields, as well as soil platforms planted with manioc in formal fields located a short distance south of the site. The furrows in these agricultural plots, both infield and outfield, were oriented parallel to slope to facilitate drainage (Sheets et al. 2011, 2012; Sheets and Woodward 2002; Slotten et al. 2020).

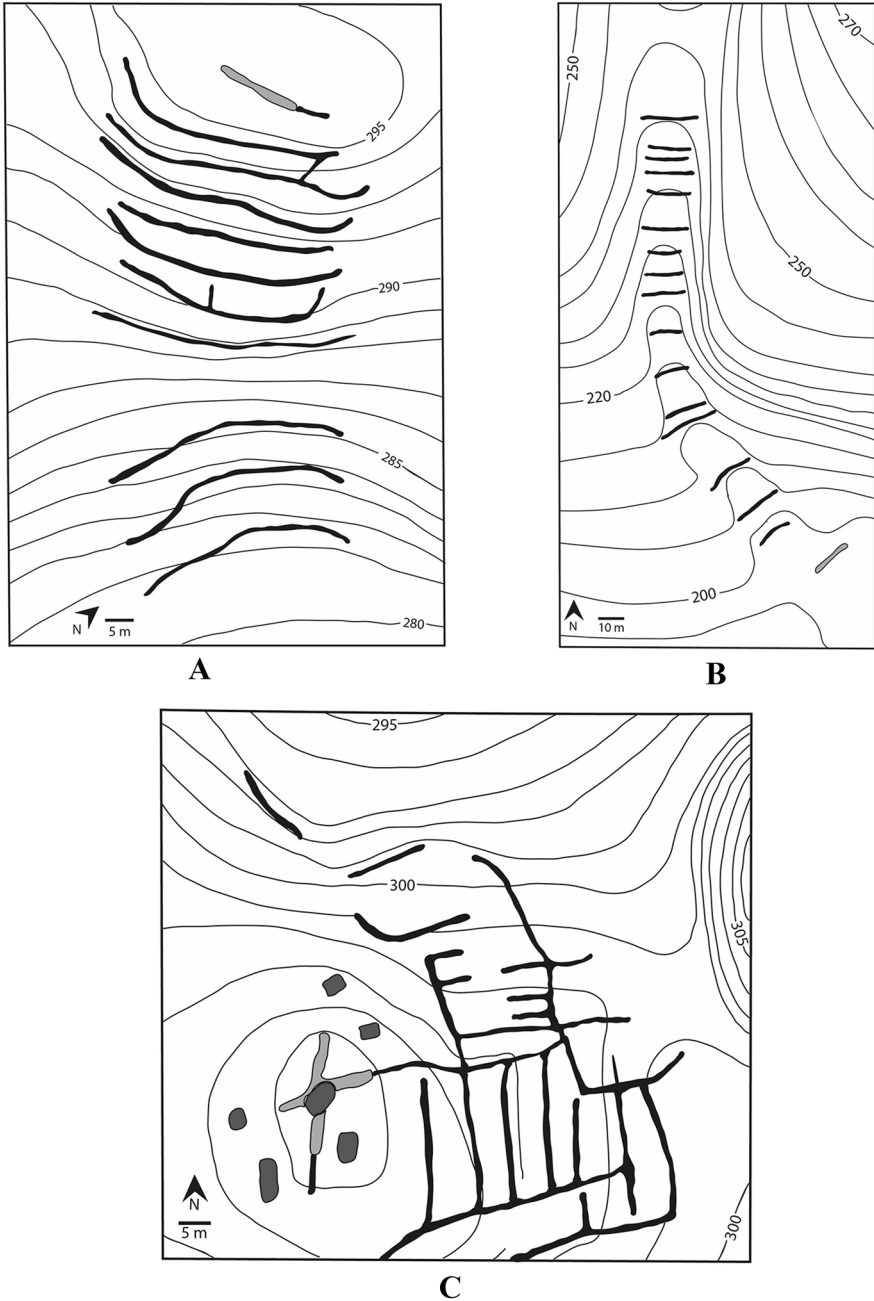
Other, more durable, forms of field surface management are represented by soil-infused rock piles of various configurations. These features may, at least in many cases, represent an ancient and widespread gardening technique known as lithic mulch agriculture (Lightfoot 1994, 1996). In the Maya Lowlands, linear rock berms and circular rock (*chich*) mounds are commonly recorded landscape features, suggesting that ancient farmers shaped their surroundings to accommodate a variety of plant life.

Berms are substantial linear rock piles, most often constructed of chert and limestone cobbles, usually lacking retaining walls, and between 1 and 2 m high and up to 100 m long. Several possible functions have been assigned to berms, including both agricultural and nonagricultural possibilities (Beach et al. 2002; Hughbanks 1998; Kunen 2001; Šprajc et al. 2021). An agricultural function, first proposed by Tourtelot and colleagues (1994), is as raised planting beds or mulch rock piles, an idea supported by research in which berms have been demonstrated to retain moisture (Heindel 2019). Berms do not function as retaining walls to hold soil on slopes as terraces do. In cases where berms are found at angles to slope, they are often interpreted as serving to direct water runoff and eroding soil, or to protect agricultural fields from sheet erosion (Dunning and Beach 2004; Heindel 2019; Hughbanks 1998; Kunen 2001; Lemonnier and Vanni re 2013). These suggestions would not preclude berms

from also functioning as raised planting beds. Berms are also found on level ground, hill tops, and at wetland margins. Berms have been described in spatial association with terrace systems in the Petexbatún region of Guatemala (Dunning et al. 1997), in rolling terrain in the northern part of the Calakmul Biosphere Reserve in Campeche (Šprajc et al. 2021), the Rio Bravo area of northwestern Belize (Beach et al. 2002; Hughbanks 1998, 2006; Kunen 2001), the upper Belize River area (Fedick 1994; Horn et al. 2019; Horn and Ford 2019) (Fig. 5), the Mopan River valley (Heindel 2019), and in the Rio Bec area of southern Campeche and Quintana Roo (Lemonnier and Vannièr 2013; Nondédéo et al. 2013). Most recently, such features have been revealed through the application of G-LiHT imagery analysis (Hutson et al. 2021).

In comparison to berms, smaller rock piles are more often interpreted as likely agricultural features functioning as lithic mulch. These features have often been referred to as *chich* mounds, following the Yucatec Mayan term for limestone gravel. Archaeological reports of ancient settlement often include descriptions of low rock piles, most often round or subrectangular, and sometimes with a border of larger cobbles. These features are generally 2 to 4 m in diameter or widest dimension and less than 25 cm high. The rock piles sometimes have small amounts of ceramic sherds associated with them, but not enough to represent what would be considered residential midden deposits. Prior to the 1990s, these rock piles had been interpreted primarily as foundations for small structures or outbuildings within settlement areas, as field houses in rural areas, as stockpiles of building material, or field clearance piles (see Heindel 2019, p. 111; Killion et al. 1989, pp. 285–286). Kepecs and Boucher (1996) first made the clear argument that *chich* mounds could also be interpreted as ancient agricultural features, following the ethnographic observation that similar rock piles are often found surrounding the base of cultivated trees in homegardens, providing both support for the trees and moisture retention in the shallow soil environment of the northern Yucatan Peninsula. Fedick and Morrison (2004) also note the ethnographic use of low, circular rock piles around cultivated trees in Yucatan and Quintana Roo (Fig. 6), and they have interpreted the 178 *chich* mounds scattered throughout the residential area at the site of T'isil, in northern Quintana Roo, as evidence of tree cultivation (mapping at T'isil has since recorded a total of 301 *chich* mounds).

At the site of Chunchucmil, in the arid and soil-scarce northwestern Yucatan Peninsula, Dahlin and colleagues (2005; Hutson and Magnoni 2017) describe a total of 1,136 *chich* mounds throughout the site area, as “ambiguous” evidence for tree cultivation in the residential area of the site. Isendahl (2002) mapped 60 *chich* mounds at the Puuc site of Xuch and suggests they may represent orchards dating primarily to the Late and Terminal Classic periods, while Lemonnier and Vannièr (2013) interpret similar features at the site of Río Bec as nonagricultural (see Nondédéo et al. 2013). Fedick (personal observation) has also seen soil-infused rock piles in modern Maya homegardens of the northern lowlands used as planting beds for vegetables such as tomato and chile. In such cases, the common presence of household kitchen waste on these rock piles functions as a form of “green compost” that also includes fragments of nonorganic trash like broken ceramics.



**Fig. 5** Ancient terraces (black) and berms (light gray) in the upper Belize River area. Structure remains are dark gray. (A) contour terraces, (B) cross-channel terraces, (C) box terraces. Note the berms at the top of A, bottom of B, and in cross formation around the largest structure in C. Illustrations adapted and redrawn from Fedick 1994.

**Fig. 6** A modern example of a *chich* mound at the base of a tree in northern Quintana Roo, Mexico. Photograph by Scott Fedick, adapted from Fedick and Morrison 2004.



In the southern Maya Lowlands, Kunen (2001) describes rockpile features in both upland settings and along *bajo* margins, interpreting them as possible agricultural features but also suggesting other functions including fieldhouse foundations and lithic stockpiles. In the rolling terrain of the northern Calakmul Biosphere Reserve in Campeche, Šprajc and colleagues (2021) report numerous rock piles located in association with berms and terraces, most often in tight clusters, which suggests to the investigators an agricultural function rather than as foundations for small structures.

### **Slope Management: Agricultural Terracing**

While the Maya Lowlands have often been characterized as a vast, flat, limestone shelf with a few hilly areas, the region actually contains a substantial amount of topographic relief that can be susceptible to erosion when vegetation is cleared. Terracing of hillslopes is widely practiced in traditional agriculture of the New World tropics from ancient into modern times, helping retain and build soil. Terraces also help retain moisture under rain-fed cultivation systems and can be coupled with irrigation (see Wilken 1987 for Mesoamerica and Donkin 1979 for the Americas). The many studies of ancient terracing have defined four distinct types of terraces recognized in the Maya Lowlands (following Beach and Dunning 1995; Fedick 1994). Contour terraces are built like curving steps reflecting the slope like elevation lines on a topographic map. Check-dam terraces, also called cross-channel or weir terraces, are

constructed across narrow drainages or gullies and look like steps on a ladder; these terraces sometimes also function to channel and divert water onto fields. Footslope terraces are substantial retaining walls constructed at the base of a steep slope and are intended to catch slope wash rather than to prevent erosion. Box or gridded terraces are rectangular enclosures in areas of gentle to moderate slope and are often found in close association with residential sites, perhaps functioning as seed beds or door-yard garden plots.

Ancient terraces had sporadically been reported for the hilly flanks of the Maya Mountains of Belize since the early 1900s (Cook 1909; Joyce 1926; Ower 1927) with little or no impact on the traditional perception of Maya swidden agriculture. Terracing was generally interpreted as a response to local population growth, with milpa farming expanding from valley bottoms into surrounding hill sides. It was not until the 1970s, when vast tracts of terracing in the hilly ridges of southern Campeche and Quintana Roo were mapped and reported by Turner (1974), that terracing began to be recognized as a significant agricultural technology in the Maya Lowlands. After this time, reports of terracing throughout much of the Maya Lowlands began to appear.

Beginning in the mid-1990s, studies of ancient terracing began to move beyond correlations between terracing and ancient population levels, placing terraces within geoarchaeological context and local historical ecology. Fedick (1994) examined the distribution of terracing in the upper Belize River area (Fig. 5) through an early application of computerized GIS modeling, taking into consideration not only topographic slope but soil types and parent material from which soils were developed, including the local availability of stone for terrace construction.

Evidence for soil erosion in the southern Maya Lowlands began accumulating in the 1970s through limnological studies of lake sediment cores (see Rice 1993, 1996). Spurred by these studies, investigators began to seek out evidence for how the ancient Maya dealt with, or failed to address, slope management and erosion control for agricultural activities under conditions of changing population levels. Beach, Dunning, and their colleagues (Beach 1998; Beach and Dunning 1995; Dunning et al. 1997; Dunning and Beach 1994) began to approach these questions in the Petexbatún region of Guatemala's Peten through an integrated research program. This program incorporated soil loss predictive models, informed locally through recent forest clearance by modern Maya pioneering agriculturalists; excavation of ancient terraces and downslope deposits and characterization of the depositional history of associated soils; and consideration of the soils and surface geology to help explain the distribution and forms of terracing among edaphic and geological conditions that vary significantly across the Maya Lowlands. Beach, Dunning, and colleagues next undertook studies of ancient landscape management in the Three Rivers region of northwestern Belize (Beach et al. 2002, 2003, 2018a, b; Dunning et al. 1999; Hageman and Lohse 2003; Hughbanks 1998, 2006; Kunen 2001; Kunen and Hughbanks 2003; Lohse 2004; Tourtellot et al. 2003), nearby Blue Creek (Beach et al. 2006; Guderjan et al. 2003), and Cancuén, Guatemala (Beach et al. 2006).

When the geoarchaeological studies mentioned above were coupled with later studies of lake sediment cores (Anselmetti et al. 2007), an interesting, revealing pattern emerged for the chronological pattern of erosion and slope management for a

broad area of the central and southern Maya Lowlands, demonstrating there are no simple correlations between population levels and soil erosion (Beach et al. 2006, 2008, pp. 327–328; Carozza et al. 2007; Fleury et al. 2015). Erosion began and progressed rapidly during the Preclassic period as pioneering settlement expanded across the lowlands and population levels rose. The Early Classic Maya farmers likely recognized the threat of land degradation and began building terraces, in some instances taking advantage of deep, erosion-deposited soils on footslopes and at the margins of scrub-*bajo* wetlands (Garrison and Dunning 2009). During the population peak of the Late Classic, terracing became common, though not ubiquitous, throughout much of the lowlands. During the Late Classic, erosion continued, but often at a slower, controlled rate that can be interpreted, at least in some cases, as more successful, forward-looking slope management than simple response to environmental degradation (Beach et al. 2018a; Dunning et al. 2009). After the abandonments of the Terminal Classic, erosion returned to a slow, natural “background” pace until modern resettlement began a new cycle of rapid erosion under slash-and-burn cultivation and a lack of stable land tenure (Beach 1998).

Following up on early reports of ancient terracing in the Maya Mountains, investigators began in the mid-1980s to focus on the mountainous terrain surrounding the major site of Caracol, Belize, including its widespread settlement and agricultural terracing (Chase and Chase 1987; Healy et al. 1983). Arlen and Diane Chase began a systematic transit-based mapping of settlement and terracing around the site of Caracol in 1985, and by 2009 had documented some 23 km<sup>2</sup> of settlement and approximately 3.5 km<sup>2</sup> of terracing (Chase and Chase 1998; Chase et al. 2011; Murtha 2002, 2009, 2015). With extensive experience of mapping at Caracol, they estimated that “terrace mapping is approximately ten times more time consuming than solely undertaking a transit map of plazuela groups and structures” (Chase and Chase 1998, p. 64). Ancient terraces are notoriously difficult to find during traditional pedestrian survey in forested areas (Fedick 1994). All of that changed in 2009 with the initial testing of LiDAR mapping in the heavily forested terrain around Caracol (Chase et al. 2011, 2012). Flights in 2009 produced LiDAR coverage for a total area of 199.7 km<sup>2</sup>, the vast majority of which was modified with terracing (Chase et al. 2011, 2012; Chase and Chase 2017; Chase and Weishampel 2016). Using the LiDAR data, the Chases were also able to correlate the growth and elaboration of Caracol’s agricultural terrace systems with the areal expansion of the site, as the households were embedded in this landscape (Chase and Chase 2014). In 2013, LiDAR survey was extended east from Caracol and north into the upper Belize River valley (Chase et al. 2014a; Macrae 2017; Macrae and Iannone 2016), expanding earlier studies of terracing within the upper Belize River valley in the hinterlands of Xunantunich and around the nearby site of Chan and associated settlement clusters (L. S. Neff 2002; L. T. Neff 2008, 2010; Robin 2002, 2012; Wyatt 2012, 2020). Another LiDAR study centered on the site of El Pilar in the northern foothills surrounding the upper Belize Valley has revealed numerous terrace systems (Ford 2014; Horn et al. 2019; Horn and Ford 2019).

The site of Copan, Honduras, is situated in a valley surrounded by hilly terrain, approaching the topographic relief of Caracol. Wingard (1996) modeled erosion processes and rates at the site for the Late Preclassic through Postclassic periods,

concluding that erosion, unchecked by terracing, was a major factor in environmental degradation, particularly during the population peak of the Late Classic. This modeling includes the assumption of cultivation limited to maize and beans under differing fallow periods (Wingard 1996, p. 212). Very little evidence for terracing around Copan Valley was reported at the time of the modeling exercise. Some foot-slope terraces had been recorded, apparently intended to capture eroding soil rather than preventing erosion (Wingard 1996, pp. 222–223, 229–230). LiDAR imagery for the Copan region was obtained in 2013, providing new insights into slope management in the Copan Valley (von Schwerin et al. 2016). Ground verification of some terracing at Copan has been completed, while full reevaluation of terracing in the region is pending (von Schwerin et al. 2016). LiDAR-identified terraces at Copan are most commonly check dams or cross-channel terraces, with additional identification of contour terraces with rubble retaining walls, as well as what seems to be bench terraces (Wilken 1987) where slope has been cut away to create stepped contours lacking stone retaining walls (von Schwerin et al. 2016). Similarly, LiDAR imagery from 2017 has revealed for the first time definite terracing in the hilly Puuc region (Ringle et al. 2021). Terracing identified and ground checked in the Puuc hills study area was not extensive, consisting of contour terraces around a small number of hills.

In the Usumacinta Valley, multiple systems of contour terraces have been reported on gentle slopes near the site of Palenque (Liendo Stuardo 2002). Upstream from Palenque, LiDAR imagery, as well as some pedestrian survey, has revealed terrace systems, including contour terracing and check dams, in low hills with slopes of less than 14° (Golden et al. 2021). The researchers report no evidence of agricultural intensification, either terraces or wetland modification, within a 10 km radius of Piedras Negras and the surrounding peri-urban zone, the largest settlement in that study area.

Nearly all the ancient terraces recorded in the Maya Lowlands from the 1970s up to the introduction of LiDAR technology in 2009 had been identified either in cleared agricultural lands (e.g., Turner 1974) or in areas with steep slopes where terraces were constructed with substantial, obtrusive, stone retaining walls, such as at Caracol (e.g., Healy et al. 1983). While LiDAR and further advances in remote sensing technologies (Fernandez-Diaz et al. 2016) will undoubtedly expand our understanding of slope management across the varied and integrated landscapes of the Maya Lowlands (Canuto et al. 2018; Garrison et al. 2019; Golden et al. 2016; Hutson et al. 2021; Schroder et al. 2020; Šprajc et al. 2021), ground verification of these possibly constructed features is still necessary. Beach and colleagues (2002, p. 379) warn that geomorphic features can mimic constructed terracing, particularly in areas with horizontally layered limestone that can erode into natural shelves, and often require excavations to verify human engineering. Disturbed vegetation cover, including that associated with shifting cultivation and secondary regrowth, can also obscure the ability of LiDAR to distinguish topographic features including terracing (Golden et al. 2021; Magnoni et al. 2016; Prufer et al. 2015). In an ongoing program to ground truth all features identified in LiDAR imagery at the site of El Pilar, straddling the Belize–Guatemala border, Horn and colleagues (2019; Horn and Ford 2019) are finding good results for identification of residential mounds and larger

structures, but a fairly low LiDAR visibility of features such as terraces and berms, with many more being identified by on-the-ground survey than those that are visible on LiDAR. At Caracol, where the terrain is generally steeper and terraces more substantial than at El Pilar, Chase and colleagues (2016) still caution that ground verification is necessary.

Evidence from several sites suggests small-scale water storage and irrigation systems were incorporated into terraces (see below). At Caracol, the extensive terracing system is argued to be a result of centralized planning and construction (Chase and Chase 1998; contra Murtha 2002, 2015). Centralized planning is also suggested for the management of some watersheds that included terracing (Beach et al. 2002), while most terracing is thought to have been developed incrementally at the household or interhousehold level (e.g., Hutson et al. 2021; Murtha 2009, 2015; Wyatt 2020).

### Agricultural Water Management

The ancient Maya built extensive and complex systems for water management, primarily intended to collect and store drinking water (e.g., Chase 2016; Dunning et al. 2022; Scarborough et al. 2012; Seefeld 2018; Weiss-Krejci and Sabbas 2002). Currently, there is no archaeological evidence that the ancient Maya diverted water from permanent rivers for agricultural irrigation, practices described as the basis of ancient complex “hydraulic” societies (Wittfogel 1957). Evidence of using intermittent sources of water for irrigation is restricted to the channeling or directing of rainwater runoff into terraced agricultural plots or fields at the base of hillsides (e.g., Chase and Weishampel 2016). Pyburn (2003) has suggested that dams and dikes were constructed to control water flow between Spanish Creek and the wetlands adjacent to the site of Chau Hiix in Belize. Similarly, multiple dams and dikes are reported to have functioned to control the flow of water into channelized wetland fields in the Usumacinta Valley (Golden et al. 2021).

There is also limited evidence for irrigation from impounded water in reservoirs. At the site of Tamarindito in northern Guatemala, a small reservoir, incorporating a dam, is adjacent to agricultural terraces that may have been supplied with water by pot irrigation (Beach and Dunning 1997). At the sites of Caracol and Chan in Belize, terrace systems have small reservoirs interspersed within them that may have been used to water terrace plots by pot irrigation (Chase and Chase 1998). At Chan, evidence of irrigation channels between *aguadas* and downslope terraces has been documented (Wyatt 2012, 2014, 2020). Small reservoirs at Kinal in Guatemala, Yaxnohcah in Campeche, and Xcoch in the Puuc Hills of Yucatan include outlets and sometimes canals that may have been used to release water into downslope agricultural plots (Brewer 2018; Brewer et al. 2017; Scarborough et al. 1994; Smyth et al. 2017). At Tikal, excavations at the Perdido reservoir indicate that impounded water was intended exclusively for crop irrigation in agricultural fields situated on the footslopes of the adjacent pocket *bajo* (Dunning et al. 2015, 2019; Lentz et al. 2018). Three other reservoirs at Tikal (Corriental, Bejucal, and Tikal) may have been used for *bajo*-margin crop irrigation in addition to their primary function of



impounding drinking water (Lentz et al. 2014). Irrigation of *bajo*-margin agricultural fields from a reservoir has also been tentatively suggested for the Classic site of Zacatal, near Nakbe, Guatemala (Wahl et al. 2007).

A unique example of agricultural water management, combining both drainage and water delivery, is documented in northwestern Belize near the site of Dos Hombres (Lohse and Findlay 2000). Studies conducted at a household group that is located near the base of a steep escarpment identified what is hypothesized to be a household-level water management system for small-scale gardening. During heavy rains, drainage would have been an issue as rainwater runoff flowed down the escarpment and through the residential area. Excavations revealed a series of channels linking to natural depressions situated in a possible homegarden. The channel system not only diverted excess water out of the garden area during the rainy season but may have also helped supply and retain moisture over the dry season, aided by limestone gravel added to the depressions and channels, which acted as lithic mulch.

Pot irrigation is another technique for supplying moisture to plants by transporting water in containers such as ceramic pots that is widely practiced in traditional agriculture of Mesoamerica (Wilken 1987). Many archaeologists have suggested that pot irrigation was practiced by the ancient Maya, making use of a variety of water sources. Pot irrigation of homegardens using household wells or natural micro-*cenotes* is often suggested (Dahlin et al. 2005; Fedick 2014; Fisher 2014; Winzler and Fedick 1995). Small reservoirs, often interspaced in terrace systems or located at *bajo* margins, may have been used for pot irrigation (Beach and Dunning 1997; Brewer 2018; Chase and Chase 1998; Gunn et al. 2002; Wyatt 2014). Sunken gardens situated in *rejolladas* and quarries reused for gardening often contain water in low spots or in wells excavated in the base of these features (Dedrick et al. 2020; Kepecs and Boucher 1996; Munro-Stasiuk et al. 2014). Pot irrigation is also suggested for gardens located adjacent to drainage channels that sometimes have wells excavated in their bottoms from which water could be drawn during the dry season (Pyburn 1998). While all these suggestions have merit, it is difficult to demonstrate the practice of pot irrigation through archaeological data, though the presence of particular diatoms may aid such interpretations (Trombold and Israde-Alcantara 2005). Aiding, and perhaps moderating interpretation, Wilken (1987) reports that in modern traditional agricultural practice, carrying water for pot irrigation from source to garden areas is limited to about 15 to 20 m due to the weight of the water and the number of trips that must be made to supply a garden plot.

## Wetland Management

Ever since Siemens and Puleston (1972) first reported patterned ground during aerial reconnaissance over wetlands in southern Campeche, Mexico, there has been debate over the existence, form, chronology, and extent of wetland cultivation in the Maya Lowlands. Early debates centered on natural versus human-engineered origins of patterned ground, raised field versus drained field technologies, the chronology of wetland cultivation in relation to ancient demographic trends, and changes in wetland use due to both human impacts and natural processes. Some of these pioneering

investigations of wetland use include (but are not limited to) those at Bajo Morocoy in southern Quintana Roo (Gliessman et al. 1983), Pulltrouser Swamp (Turner and Harrison 1983), and Albion Island and environs in northern Belize (Bloom et al. 1985; Pohl 1990). Some of the early claims for the ubiquity of wetland use in the southern Maya Lowlands (e.g., Adams 1980, 1982; Adams et al. 1981) were met with critiques based on limitations and potential misinterpretation of remote sensing data, consideration of limited agricultural potential of some wetland soils, and the relative abundance of wetlands versus other land resources in different areas of the southern lowlands (Fedick and Ford 1990; Pope and Dahlin 1989, 1993). While debates about ancient use of wetlands from before the 1990s continue, they are now informed by numerous field investigations in a variety of settings that apply methods of geoarchaeology, pedology, chemistry, hydrology, and paleoethnobotany. Ecological studies have documented that wetlands in the Maya Lowlands are currently highly variable across the region (Bridgewater et al. 2002; Ellison 2004; Olmsted 1993; Rejmánková et al. 1996). Meanwhile, the geomorphological and geoarchaeological studies reviewed here have also demonstrated how these wetlands have changed significantly through time, although not uniformly, in response to water table fluctuations related to sea level changes and climate change, as well as infilling of wetlands caused by both natural processes and human-induced erosion.

The use of wetlands for agricultural production, however, does not necessarily involve human physical modifications in the form of excavated channels or built-up field surfaces. The practice of flood recessional agriculture, taking advantage of natural seasonal cycles of water fluctuations, generally in transitional swamp habitats, is a well-documented form of traditional agriculture often referred to as *marceño* or *matahambre* cultivation in many areas of Mesoamerica (Wilk 1985). Siemens (1996, 1998) has described this as “benign flooding,” suggesting that ancient Maya farmers took advantage of seasonal flooding cycles to plant crops as floodwaters receded. This scheduled exploitation of seasonally shifting microenvironments could also be modified, with minimal effort invested in channelization, to facilitate more rapid drainage as waters receded in the dry season. The practice would also have slowed flooding of planting areas as waters rose in the early wet season.

Earlier classification of wetlands in the Maya Lowlands, posed in the late 1980s and early 1990s, first sought to recognize the diversity of wetlands across the region and how this variability might have influenced ancient Maya use of wetlands for agriculture and other purposes (Fedick and Ford 1990; Pope and Dahlin 1989). Here we use a modified, though still simplified, classification based on geographic setting that holds relevance even as local studies increasingly reveal local diversity and temporal change (see Beach et al. 2009; Dunning et al. 2006; Fedick and Ford 1990; Pope and Dahlin 1989). Wetlands are found at elevations below 80–100 m in the periphery of the Maya Lowlands, where they formed on the margins of slow-moving karstic rivers linked to regional aquifers, as well as in karstic depressions linked to regional aquifers, e.g., the New and Hondo Rivers and Pulltrouser Swamp. In the interior or upland southern Maya Lowlands, wetlands are found above 80–100 m in karstic depressions disconnected from regional aquifers and major rivers, e.g., *bajos* of northern Guatemala. In non-karstic riverine floodplains, wetlands are associated with the margins of faster moving river systems that are subject to strong annual

floods that deposits sediments, including those from upriver, non-karstic settings, e.g., the upper Belize and Usumacinta Rivers. Transitional wetlands between the above types of wetlands are seasonally flooded and often associated with soils and vegetation that are transitional between wetlands and surrounding upland settings.

### Wetlands of the Lowland Periphery

Cobweb Swamp is a karstic depression perennial swamp near Colha in northern Belize. Investigations at Cobweb Swamp by Jones (1991) and Jacob (1992) documented what was at the time the earliest evidence for the use of wetland environments for agricultural production in the Maya Lowlands, dating between 2500 and 1000 BC. This earliest evidence for agriculture consists of a single pollen grain from manioc, while other cultigens, particularly maize, were not present. The earliest use of the wetland was probably based on flood recessional cultivation. While dating channelization along the margins of the perennial wetland is recognized as problematic, it likely began between 1000 and 500 BC (Jacob 1995; Jones 1994). The investigators surmised that natural hummocks and channels within the wetland were modified to facilitate drainage and agriculture, rather than being wholly constructed (Jacob 1995). The buried wetland field surfaces produced abundant pollen from maize, along with single pollen grains from possible chili pepper and cotton (Jones 1994). The research at Cobweb Swamp also provided early evidence for the long evolution of the wetland environment prior to Maya settlement in the region, the continuing influences of sea level fluctuation on wetland hydrology and human use, and the impact of land clearance and subsequent erosion and infilling of the swamp caused by human activity (Jacob and Hallman 1996).

Following the initial investigations at Cobweb Swamp and the evidence for early use of wetlands, excavation and sediment coring were conducted in wetlands along and between the Hondo River and New River in northern Belize (Pohl and Bloom 1996; Pohl et al. 1996; Pope et al. 1996), including both karstic depression perennial swamps and karstic riverine floodplain swamps. These studies concluded that unmodified wetland margins were first used for flood recessional agriculture, pushing back the dates for this activity to about 3000 BC. By 2500 BC, deforestation led to the onset of erosion, and by 1000 BC sea level rise in turn resulted in a rise in the local water table, requiring farmers to excavate drainage channels and to raise the level of natural hummocks to facilitate continued cultivation. Continuing rise in water levels forced the abandonment of the wetland fields during the Late Formative period, at the beginning of the Early Classic (ca. AD 250). This research demonstrated that both natural and anthropogenic processes contributed to the formation of “raised fields” (contra Baker 2003; Harrison 1996; Harrison and Fry 2000), as well as to the changing nature of wetland environments through time. This work set the stage for much subsequent wetland research throughout the Maya Lowlands. More recent research on these perennial wetlands has documented field systems constructed by channelizing and, to varying degrees, building up of planting platforms, as well as the dynamics of changing wetland environments through both natural and human-induced processes in northern Belize (Baker 2003; Beach et al. 2003, 2013, 2015a, b, c; Berry and McAnany 1998, 2007; Guderjan et al. 2003; Guderjan and

Krause 2011; Harrison-Buck 2014; Krause et al. 2019a, b; Luzzadder-Beach and Beach 2008, 2009; Luzzadder-Beach et al. 2012; Pyburn 2003), including recent work incorporating LiDAR imagery to identify patterned ground (Beach et al. 2019; Dunning et al. 2020; Krause 2018; Luzzadder-Beach et al. 2020).

A form of karstic depression perennial swamp, different in both form and ancient use, are the Yalahau wetlands of northern Quintana Roo. These freshwater wetlands (approximately 174) are formed in north-south trending karstic depressions that follow the geological structure of the Holbox fracture zone (Fedick and Hovey 1995; Leonard et al. 2019). The wetlands are directly linked to the water table, and flooding regimes follow both local rainfall runoff and regional water table fluctuations. Unlike the karstic depression perennial swamps of the eastern and western margins of the Yucatan Peninsula, the wetlands of the Yalahau region have generally shallow soils, 10 to 35 cm deep over limestone bedrock, although some of these wetlands contain areas with deeper soils and peat deposits. Most of the shallow wetland soils are leptic calcisols. The shallow soils of the Yalahau wetlands are not suited to management by channelizing or the construction of raised planting beds; instead, the ancient Maya employed networks of rock alignments to control seasonal runoff and soil movement within the depressions (Fig. 7). Early reconnaissance in the Yalahau region documented settlement associated with wetlands and initial evidence for modification by construction of rock alignments (Fedick and Hovey 1995). Complete mapping of rock alignments, limited excavation of wetland features, soil studies, and settlement studies were undertaken in and around the El Edén wetland (Chmilar 2013; Fedick 1998, 2003a; Fedick et al. 2000; Morrison 2000, 2006; Sedov et al. 2007, 2008; Solleiro-Rebolledo et al. 2011), and a regional sample survey recorded rock alignment features in 25 wetlands, coupled with extraction and analysis of numerous sediment cores (Leonard 2013; Leonard et al. 2019). Settlement in the Yalahau region first appeared in the Middle Preclassic, peaked in the Late Preclassic/Early Classic transition, and then decreased sharply until limited reoccupation in the Late Postclassic (Fedick and Mathews 2005). The chronology of wetland use in the region remains uncertain, although it most likely corresponds with the population maximum of the Late Preclassic/Early Classic transition. Although analysis of the wetland sediment cores suggests a complex history of environmental change through time and across individual wetlands, all indicate a gradual rise in water table and increased flooding of the wetlands through time (Leonard et al. 2019).

### Wetlands of the Elevated Interior

Several lines of evidence from multiple *bajos* in northern Guatemala suggest that many were not good for agriculture or as sources of fresh water during early occupation of the upland interior. Lower karstic sinks of *bajos* are often associated with deep clay vertisol soils that are extremely difficult to work, either dry or wet, and have severe limitations on availability of plant nutrients due in part to acidic conditions (Beach et al. 2003; Fedick and Ford 1990; Pope and Dahlin 1989, 1993). More recent work, however, has found exceptions to this characterization, highlighting how soil conditions and hydroperiods vary among these depressions, as well as through time in individual depressions.

**Fig. 7** Mapping and excavation of rock alignment features in the El Edén wetland, Yalahau region, northern Quintana Roo, Mexico. Photographs by Scott Fedick.



In the *bajos* associated with El Mirador in the central karstic uplands of far northern Guatemala and southern Campeche, Mexico, soil profiles and various paleoecological studies suggest that during Preclassic times, the Mirador wetlands were marshes or shallow lakes that eventually infilled, due in large part to human-induced erosion of the surrounding uplands, resulting in the formation of vertisol-dominated *bajos* of today (Hansen et al. 2002). Preclassic use of the Mirador wetlands likely included transport of organic rich wetland soils for use in upland agricultural plots, rather than cultivation within the wetlands (Hansen et al. 2002).

Investigations in other *bajos* reveal a wide range of environmental conditions that were encountered by the Maya when Preclassic settlements were established nearby. Some were the inhospitable seasonal swamps that dominate today, while others were shallow lakes or perennial marshes, or a patchwork of perennial and seasonal swamps with soils of varying agricultural potential (Beach et al. 2003, 2006, 2008, 2009, 2006; Dunning and Beach 2000; Dunning et al. 1999, 2002; Kunen et al. 2000; Nondédéo et al. 2020). There is still no clear evidence for agricultural activities within the main bodies of the *bajos* during the Preclassic, even when accounting for the variable habitats represented by buried Preclassic soil horizons within the wetlands. Preclassic Maya farmers may have found these wetlands as useful sources for water, organic soils as fertilizer for upland gardens, or for exploitation of other resources in the diverse wetland habitats (Dunning et al. 2006). By the middle of the Classic period, environmental changes, driven by some combination of human-induced erosion and climate change, had transformed the variable wetland habitats

of the depressions into the generally inhospitable seasonal *bajos* of modern times (Dunning et al. 2006).

After the mixed reception of early reports of patterned ground in *bajos* based on radar imagery (Adams 1980), more recent satellite imagery identified linear features in Bajo de Azúcar in northern Guatemala, east of El Mirador (Dunning et al. 2017), again suggesting the possibility of agricultural production in the *bajos*. Excavations of several of these linear features revealed them to be partly natural in origin and possibly modified by human engineering. The researchers suggested that these linear features were used in ancient times to facilitate transportation across the *bajos* while providing access for aquaculture and timber harvesting, rather than agricultural pursuits, although ancient cultivation was not ruled out (Dunning et al. 2017). Recently obtained LiDAR imagery of *bajo* areas in northern Guatemala also reveal linear features and hummocks that are thought to have had agricultural functions, although few excavations have been conducted (Canuto et al. 2018; Garrison et al. 2019; Nondédéo et al. 2020). While the main bodies of the *bajos* remain problematic in terms of ancient agricultural production, the margins of these wetlands were used for agriculture during the Classic period (see below).

### Wetlands of Non-Karstic Riverine Floodplains

In an early evaluation of wetlands with satellite imagery, Pope and Dahlin (1989) found no new evidence for wetland cultivation in non-karstic riverine floodplains. They recognized these settings as good locations for agriculture and suggested that sedimentation or modern mechanical cultivation may have obscured evidence of ancient engineering modifications.

Following early reports of possible ditched or channelized fields in areas subject to frequent flooding in the upper Belize River valley (Kirke 1980), LiDAR imagery of 2013 revealed patterned ground in the same area, associated with the site of Baking Pot, which has also been interpreted as drainage ditches, possibly associated with agricultural fields (Ebert et al. 2016a, b).

Minor systems of ditched fields have been documented near Palenque, along the seasonally flooded banks of the Michol River, a tributary of the Usumacinta (Liendo Stuardo 2002). The ditches functioned as drainage features in the rainy season and aided moisture retention in the fields during the dry season. Upstream from Palenque, LiDAR imagery collected in 2019 has revealed patterned ground interpreted as possible canals or ditched fields in floodplain wetlands along tributaries of the Usumacinta River (Schroder et al. 2020). Additional use of this LiDAR imagery (Golden et al. 2021), including extensive ground verification, has revealed clusters of channels within seasonal and perennial wetlands, facilitating drainage into streams and smaller rivers or lakes. Water level in the wetland fields was regulated in some instances with reservoirs, dams, and sluices situated just upstream from the fields. Most of the channelized fields are associated with settlements that date to the Late Classic, with some smaller channel systems associated with Preclassic sites. The researchers report that the wetland channels revealed by LiDAR imagery in the Usumacinta Valley (Golden et al. 2021) are but a fraction of similar features revealed for the same areas that are visible on

Google Earth imagery. As in the case of the upper Belize River valley, it is suspected that much more extensive systems of channelized fields in the Usumacinta Valley may be buried beneath flood-deposited sediments or obscured by modern agricultural activities.

### Transitional Wetlands

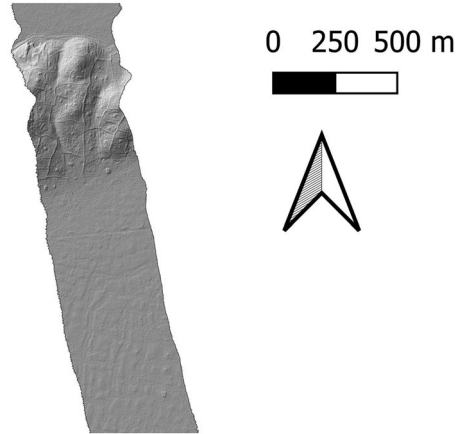
The margins of wetlands have a long history of exploitation for agriculture; perhaps their earliest use was in the lowland periphery where people could take advantage of benign flooding episodes without the need for ditching or raised fields (Pohl and Bloom 1996; Pohl et al. 1996; Pope et al. 1996). In the elevated interior, the margins of *bajos* are characterized by slow-drained transitional soils with generally better agricultural potential than the *bajo* interiors. Ford (1986) reported sparse settlement in slow-drained *bajo* margins and shallow depressions between Tikal and Yaxha; Fedick and Ford (1990) interpret use of these zones as evidence for dry-season water recessional cultivation beginning in the Late Preclassic. In the Bajo La Justa, between Yaxha and Nakum, Kunen and colleagues (2000) also report settlement at the margins of the *bajo*, as well as on “islands” of higher terrain within the main body of the *bajo*. These have varying chronologies of use from the Late Preclassic into the Terminal Classic, and Kunen and colleagues (2000) suggest these settings were used for agricultural production, aided in some cases by the excavation of drainage canals. Similarly, Kunen (2001) describes settlement clustered around the margins of small *bajos* in northwestern Belize, but in this case, the footslopes and transitional soils of *bajo* margins were modified by terraces, berms, and rockpiles, with no ditching reported.

More recent geoarchaeological work has revealed evidence for forest clearance and subsequent erosion of upland soils into the margins of large *bajo* depressions and throughout small “pocket” *bajos* during the Preclassic, creating a soil environment better suited to agriculture. These bands of anthropogenic soils in the large *bajos* vary in width and depth, depending in part on the slope of the adjacent uplands (Beach et al. 2003; Dunning et al. 2002, 2006, 2015; Gunn et al. 2002), whereas the small pocket *bajos* were largely covered with eroded upland sediments (Dunning et al. 2015). Some patterned ground, described as raised fields, has been mapped within the margins of the Laberinto Bajo near Calakmul (Gunn et al. 2002), while more recent LiDAR imagery has identified canals along gently sloping *bajo* margins in the northern area of the Calakmul Biosphere Reserve (Šprajc et al. 2021); G-LiHT imagery has revealed patterned ground within *bajo* margins in southern Quintana Roo and Campeche, which suggests a range of integrated engineering modifications running from field walls on footslopes, grading into ditches and raised fields within *bajo* margins (Dunning et al. 2019) (Fig. 8).

### Summary of Wetland Management

The most striking findings of recent research on ancient Maya wetland cultivation include the great diversity of wetland habitats, how dramatically these habitats

**Fig. 8** G-LiHT/LiDAR image from southern Quintana Roo, Mexico. Upland area in north shows structures and walls, grading to the south into a *bajo* margin with possible ditches and raised fields. Adapted from Dunning et al. 2019, original image downloaded from <https://gliht.gsfc.nasa.gov>, tile Yuc Centro NFI 413.



changed over the course of Maya occupation, and how Maya farmers adapted to these changes. Some environmental changes were the result of natural processes, particularly rising sea levels and the resulting rise in the inland water table in the wetlands of the lowland periphery. The rising water levels not only increased the degree and duration of flooding but also influenced soil formation processes.

In northern Belize and the Yalahau region of northern Quintana Roo, these environmental changes influenced the timing and form of wetland agriculture and may have determined the abandonment of previously productive fields as rising water levels became unmanageable. While human impacts, particularly erosion from land clearance, also contributed to changes in wetland habitats in the lowland periphery, human-induced erosion during the Preclassic, accompanied perhaps by gradually drying climate, apparently had a dramatic impact on *bajos* of the elevated interior. These human activities unintentionally altered the soil environment of *bajo* margins and created new opportunities for intensive cultivation systems during the Classic period.

## Conclusions

The persistence of the swidden thesis and its three correlates has slowed and distorted our understanding of ancient Maya society, biasing our perceptions of, and approaches to, agricultural development in other areas of the tropics, both in ancient times and today. Scholars have been slowly chipping away at the swidden thesis of Maya agriculture since the 1970s, but elements have persisted in academic literature, and even more stubbornly in popular culture. A strong “Western” or European bias shaped early academic and outsider perceptions of the tropics, including the Maya Lowlands, characterizing the agricultural development potential of these vast regions as poor, limited, and unproductive. This assessment was particularly



negative for the ancient Americas due to the lack of iron or steel agricultural tools to aid in clearing and plowing lands.

Technological differences did play a strong role in the evolution of farming practices and crops. In the temperate region of Europe, plow agriculture powered by domestic animals has selected for the cultivation of annual grain crops. Meanwhile, in the Neotropics, hand cultivation has selected for a diversity of perennial crops, particularly root and tree crops (Toensmeier 2007). European colonists disparaged Neotropical agriculture as primitive and limited, applying misguided evaluations of “arable” land (capable of being plowed) and characterizations of “fallow” fields (plowed but left unplanted for a year to reduce weeds) when describing agriculture in the Neotropics (see Ford in press; Morell-Hart et al. 2023).

Reevaluations of Maya agriculture (e.g., Ford and Nigh 2016), including our companion article (Morell-Hart et al. 2023), describe Maya agriculture as a sophisticated, managed successional cropping system in which the swidden/milpa field is recognized as an important early phase of annual crop production within a broader cycle of managed succession dominated by perennial plants. The earlier swidden thesis represented a narrow perception of Maya agriculture, reinforced by the reality of colonial repression, forced relocation of Indigenous people, and demands for increased production of crops (maize and beans) that could be stored and transported in support of Spanish occupation. We maintain that the first two correlates of the swidden thesis, the dominance of maize and exclusivity of swidden cultivation, have now been thoroughly overturned through the recognition of managed succession cropping and the diversity of plants cultivated by the Maya, both in the ethnographic record and through the recovery of ancient plant remains (Morell-Hart et al. 2023).

This new appreciation of Maya agriculture fits well with other reevaluations of Neotropical cultivation systems that stress the fundamentally different trajectories of agricultural development, evolution, and potential for the tropics and temperate/arid regions. As found in lowland South America and elsewhere, elaborate food production strategies in tropical environments involve not only “pure” agriculture but also management of wild resources, agroforestry, horticulture, and growth of domesticated as well as non-domesticated species (Heckenberger et al. 2008; Shepard et al. 2020). The initiation of tropical agricultural practices is not a hard stop for horticultural management, agroforestry, and wild collection practices (Killion 2013). Many tropical agricultural strategies incorporate mixtures of wild and domesticated foods, manifested physically in garden-to-field continuity (Killion 2013) and seasonal variation in practices. Such strategies operate differently from temperate agricultural models in the use of “cultivation without domestication and domestication without agriculture” (Shepard et al. 2020, p. 1). Cropping staple grains intensively in clearly delineated fields are common features that characterize temperate agricultural strategies; tropical agricultural strategies highlight diversity and variability.

Here, we assert that recent investigations have thoroughly overturned the third correlate of the swidden thesis, the supposed lack of investment in land development or improvements and an impermanence in residential location. The development of landesque agricultural capital is now recognized as widespread in the ancient world, found in temperate, arid, and tropical regions (Håkansson and Widgren 2014; Thurston and Fisher 2007). The ancient Maya can now serve as an exemplary case for

the significance of long-term investments in land conservation and improvements. This new appreciation also highlights the problematic use of the direct historical approach to interpret ancient Maya agriculture through application of historic/modern Maya practices. While today there is very little investment in agricultural engineering improvements in the Maya Lowlands, this was certainly not the case in ancient times.

New tools such as LiDAR and other remote sensing technologies, aided by GIS modeling, are providing new datasets and insights we thought impossible only a few years ago. These new visualization technologies are revealing extensive, continuous views of “bare-earth” landscapes, displaying integrated systems of settlement, variable land resources, and landscape modifications. The specific mix of landscape features varies across the lowlands according to the local combination of land resources (differing cultivation capabilities or limiting factors) and population densities (Fedick and Ford 1990), and perhaps specialized agricultural communities (commodity production) and participation in regional marketing/tribute systems (Fedick 2017; King 2021; Scarborough et al. 2003). Landscape engineering was conducted primarily in lands with serious hinderances to cultivation or susceptibility to degradation, including excessive slope or poor drainage. Again, we stress that the best land resources, and those likely first occupied and continuously used, are those with the fewest limitations, where landscape engineering would not have been necessary (see Ford in press). GIS overlays of LiDAR imagery with soil maps and land evaluation maps (capability and suitability) should provide a powerful new approach to interpretation of the managed mosaic (see Horseman 2022; Hutson et al. 2021).

Caution, however, must be exercised in the interpretation of these new means of analysis and visualization. Ground verification, including excavation of landscape features, should still be required before assertions about any agricultural functions of patterned ground are made, to establish both the antiquity of features and the contemporaneity between different features (e.g., Horn and Ford 2019). There has also been a tendency to equate portions of landscapes with many visible landscape features in LiDAR imagery as areas where intensive agriculture took place. While landscape features certainly do indicate intensification, our concern lies in categorizing areas that *lack* such features as areas *without* agricultural intensification. Intensification through managed succession, use of perennial crops, intercropping, and addition of soil amendments are all forms of intensive investments that can be carried out to maintain prime agricultural lands. But these practices are relatively invisible to remote sensing methods and analyses (Ford in press).

Regardless of method, there are several broader implications that can be drawn from the existing scholarship. First, perennial gardening shaped the nature of Maya urbanism. There is a growing trend toward recognizing the phenomenon of low-density urbanism, particularly in the tropics (Fletcher 2009). Classic period Maya urbanism included many examples of “garden cities” or “green cities,” where enough land was maintained around domestic residences to assure continuing “soil connectivity” (Evans et al. 2021); this allowed for intensive, continuous cultivation of homegardens and adjacent terraces using a wide variety of cultigens and methods to maintain soil quality (e.g., Chase and Chase 1998; Dunning 2004; Farrell 1997; Fedick 2003b; Graham 1999; Isendahl 2010, 2012; Lentz et al. 2014; Smyth et al.

1995). The rise of the notion of the garden city (Heckenberger et al. 2008) has challenged earlier social models for the tropics. Furthermore, the program of historical ecology (Balée 2006) has strongly linked environmental dynamics with social modeling by incorporating human practices and agency as active factors in landscape dynamics, rather than framing environmental variables as static impetuses for human activity. Garden cities thus represent dynamic interactions between social, cultivated, and landesque capital (see Evans et al. 2021) and are deserving of more cross-cultural studies, particularly in the tropics, where Western concepts of urban complexity must be overcome (Graham 1999).

Second, while recent research has demonstrated that ancient Maya people were capable of responsible, long-term stewardship of resources in urban and rural landscapes, it is also recognized that they were not consistently successful. Evidence from pioneering phases of settlement, primarily during Preclassic (and modern) times, suggests that deforestation and subsequent erosion was rather common. By Classic times, some areas of the Maya Lowlands appear to have attained carefully managed and relatively stable agricultural landscapes, while other areas experienced increases in degradation. Landesque intensification features, if abandoned or no longer maintained, can rapidly begin to disintegrate and lead to landscape degradation; this process is widely recognized in the recent literature of agricultural landesque capital (e.g., Fisher 2007; Fisher and Feinman 2005; Fisher et al. 2003), but it is not generally recognized for the ancient Maya. Following this observation, examples of Late to Terminal Classic erosion and land degradation may be the *result* of abandonment rather than the *cause* of abandonment. What happened to Maya agriculture and society during the Terminal Classic disruptions is still not fully understood, but there is regional variability in the timing and the impact of these disruptions.

Third, although droughts certainly caused agricultural disruptions and potential shortages of drinking water stored in reservoirs, the mosaic of agricultural systems did have a high degree of resilience, assured in large part by the various forms of landesque capital reviewed here. The diverse assemblage of plants available to the Maya encompasses a wide range of foods resistant to drought, suggesting a previously unrecognized resilience of the subsistence system (Fedick and Santiago 2022). Resilience, however, was not universally shared throughout ancient Maya society. Those families with access and tenure over prime lands had the highest resilience, while less fortunate households faced serious hardships during challenging times, including droughts (see Thompson and Prufer 2021).

In sum, the last three decades of research on ancient Maya agriculture have not only finished off the weakened and vulnerable “swidden thesis” but have provided comprehensive, alternative models for understanding intertwined histories of agricultural strategies and landscape ecology. Ancient Maya people can no longer be viewed as poster children for societies that “choose to fail” through environmental mismanagement (Diamond 2006); rather they provide an example of three millennia of flexible resilience. Recent investigations in the Maya Lowlands now contribute to a robust set of cross-cultural studies that are reevaluating the history and future of sustainable development in the tropics.

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## References Cited

- Adams, R. E. W. (1980). Swamps, canals and the locations of ancient Maya cities. *Antiquity* **54**: 206–214.
- Adams, R. E. W. (1982). Ancient Maya canals: Grids and lattices in the Maya jungle. *Archaeology* **35** (6): 28–35.
- Adams, R. E. W., Brown, W. E., Jr., and Culbert, T. P. (1981). Radar mapping, archeology, and ancient Maya land use. *Science* **213**: 1457–1463.
- Alexander, R. T. (1999). Mesoamerica house lots and archaeological site structure: Problems of inference in Yaxcaba, Yucatan, Mexico. In Allison, P. M. (ed.), *The Archaeology of Household Activities*, Routledge, New York, pp. 78–99.
- Anderson, E. F., Cauich Canul, J., Dzib, A., Flores Guido, S., Islebe, G., Medina Tzuc, F., Sánchez, S., and Valdez Chale, P. (2003). *Those Who Bring the Flowers: Maya Ethnobotany in Quintana Roo, Mexico*, ECOSUR, El Colegio de la Frontera Sur, Chetumal, Quintana Roo, Mexico.
- Anselmetti, F. S., Hodell, D. A., Ariztegui, D., Brenner, M., and Rosenmeier, M. F. (2007). Quantification of soil erosion rates related to ancient Maya deforestation. *Geology* **35**: 915–918.
- Ardren, T. (ed.) (2020). *Her Cup of Sweet Cacao: Food in Ancient Maya Society*, University of Texas Press, Austin.
- Aubert, G., and Tavernier, R. (1972). Soil survey. In: The Committee on Tropical Soils (eds.), *Soils of the Humid Tropics*, National Academy of Sciences, Washington, DC, pp. 17–44.
- Baker, J. L. (2003). *Maya Wetlands: Ecology and Pre-Hispanic Utilization of Wetlands in Northwestern Belize*, Ph.D. dissertation, Department of Anthropology, University of Arizona, Tucson.
- Balée, W. (2006). The research program of historical ecology. *Annual Review of Anthropology* **35**: 75–98.
- Balée, W., Honorato de Oliveira, V., dos Santos, R., Amaral, M., Rocha, B., Guerrero, N., et al. (2020). Ancient transformation, current conservation: Traditional forest management on the Iriri River, Brazilian Amazonia. *Human Ecology* **48**: 1–15.
- Barrera-Bassols, N., and Toledo, V. M. (2005). Ethnoecology of the Yucatec Maya: Symbolism, knowledge and management of natural resources. *Journal of Latin American Geography* **4**: 9–41.
- Batún Alpuche, A. E., McAnany, P. A., and Dedrick, M. (2020). Yucatec land and labor before and after Spanish incursions. In Masson, M. A., Freidel, D. A., and Demarest, A. A. (eds.), *The Real Business of Ancient Maya Economics: From Farmers' Fields to Rulers' Realms*, University Press of Florida, Gainesville, pp. 210–223.
- Batún Alpuche, A. I. (2009). *Agrarian Production and Intensification at a Postclassic Maya Community, Buena Vista, Cozumel, Mexico*, Ph.D. dissertation, Department of Anthropology, University of Florida, Gainesville.

- Bautista, F., Díaz-Garrido, S., Castillo-González, M., and Zinck, A. (2005). Spatial heterogeneity of the soil cover in the Yucatán karst: Comparison of Mayan, WRB, and numerical classifications. *Eurasian Soil Science* **38**: s81–s88.
- Bautista, F., Palacio-Aponte, G., Quintana, P., and Zinck, J. A. (2011). Spatial distribution and development of soils in tropical karst areas from the Peninsula of Yucatan, Mexico. *Geomorphology* **135**: 308–321.
- Bautista, F., and Zinck, J. A. (2010). Construction of an Yucatec Maya soil classification and comparison with the WRB framework. *Journal of Ethnobiology and Ethnomedicine* **6**: 1–11.
- Beach, T. (1998). Soil catenas, tropical deforestation, and ancient and contemporary soil erosion in the Petén, Guatemala. *Physical Geography* **19**: 378–405.
- Beach, T., and Dunning, N. (1997). An ancient Maya reservoir and dam at Tamarindito, Peten, Guatemala. *Latin American Antiquity* **8**: 20–29.
- Beach, T., Dunning, N., Luzzadder-Beach, S., and Scarborough, V. (2003). Depression soils in the lowland tropics of northwestern Belize: Anthropogenic and natural origins. In Gómez-Pompa, A., Allen, M. F., Fedick, S. L., and Jiménez-Osornio, J. J. (eds.), *The Lowland Maya Area: Three Millennia at the Human-Wildland Interface*, Food Products Press, New York, pp. 139–174.
- Beach, T., and Dunning, N. P. (1995). Ancient Maya terracing and modern conservation in the Peten rain forest of Guatemala. *Journal of Soil and Water Conservation* **50**: 138–145.
- Beach, T., Dunning, N. P., Luzzadder-Beach, S., Cook, D. E., and Lohse, J. (2006). Impacts of the ancient Maya on soils and soil erosion in the central Maya Lowlands. *Catena* **65**: 166–178.
- Beach, T., Luzzadder-Beach, S., Cook, D., Krause, S., Doyle, C., Eshleman, S., et al. (2018a). Stability and instability on Maya Lowlands tropical hillslope soils. *Geomorphology* **305**: 185–208.
- Beach, T., Luzzadder-Beach, S., Dunning, N., Jones, H., Lohse, J., Guderjan, T., et al. (2009). A review of human and natural changes in Maya lowland wetlands over the Holocene. *Quaternary Science Reviews* **28**: 1710–1724.
- Beach, T., Luzzadder-Beach, S., Dunning, N. P., and Cook, D. (2008). Human and natural impacts on fluvial and karst depressions of the Maya Lowlands. *Geomorphology* **101**: 308–331.
- Beach, T., Luzzadder-Beach, S., Dunning, N. P., Hageman, J., and Lohse, J. (2002). Upland agriculture in the Maya Lowlands: Ancient Maya soil conservation in northwestern Belize. *The Geographical Review* **92**: 372–397.
- Beach, T., Luzzadder-Beach, S., Guderjan, T., and Krause, S. (2015). The floating gardens of Chan Cahal: Soils, water, and human interactions. *Catena* **132**: 151–164.
- Beach, T., Luzzadder-Beach, S., Krause, S., Guderjan, T., Valdez, F., Fernandez-Diaz, J. C., Eshleman, S., and Doyle, C. (2019). Ancient Maya wetland fields revealed under tropical forest canopy from laser scanning and multiproxy evidence. *Proceedings of the National Academy of Sciences* **116**: 21469–21477.
- Beach, T., Luzzadder-Beach, S., and Lohse, J. C. (2013). Landscape formation and agriculture in the wetlands of northwestern Belize. In Lohse, J. C. (ed.), *Classic Maya Political Ecology: Resource Management, Class Histories, and Political Change in Northwestern Belize*, Costen Institute of Archaeology, University of California, Los Angeles, pp. 43–67.
- Beach, T., Luzzadder-Beach, S., Sweetwood, R. V., Farrell, P., Mazeau, D. E., and Terry, R. E. (2017). Soils and agricultural carrying capacity. In Hutson, S. R. (ed.), *Ancient Maya Commerce: Multidisciplinary Research at Chunchucmil*, University Press of Colorado, Boulder, pp. 197–219.
- Beach, T., Ulmer, A., Cook, D., Brennan, M. L., Luzzadder-Beach, S., Doyle, C., et al. (2018b). Geoarchaeology and tropical forest soil catenas of northwestern Belize. *Quaternary International* **463**: 198–217.
- Becerra-Absalón, I., Buhse, T., Polanco, C., and Tavera, R. (2012). Effect of nitrogen and periphyton extract on the growth of *Nostoc sphaericum* in cultures. *International Scholarly Research Network ISRN Ecology* **2012**: doi:<https://doi.org/10.5402/2012/935476>
- Berkes, F., Colding, J., and Folke, C. (2000). Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications* **10**: 1251–1262.
- Berry, K. A., and McAnany, P. A. (1998). Bugged down in wetland controversy: Current investigations at K'axob, Belize. *Context* **13**: 1–4.
- Berry, K. A., and McAnany, P. A. (2007). Reckoning with the wetlands and their role in ancient Maya society. In Scarborough, V. L., and Clark, J. E. (eds.), *The Political Economy of Ancient Mesoamerica: Transformations during the Formative and Classic Periods*, University of New Mexico Press, Albuquerque, pp. 149–162.
- Blaikie, P., and Brookfield, H. (1987). *Land Degradation and Society*, Routledge, New York.

- Bloom, P. R., Pohl, M., and Stein, J. (1985). Analysis of sedimentation and agriculture along the Rio Hondo, northern Belize. In Pohl, M. (ed.), *Prehistoric Lowland Maya Environment and Subsistence Economy*, Papers of the Peabody Museum of Archaeology and Ethnology Vol. 77, Harvard University Press, Cambridge, MA, pp. 21–33.
- Börjesson, L., and Ango, T. G. (2021). The production and destruction of forests through the lens of landesque capital accumulation. *Human Ecology* **49**: 259–269.
- Boserup, E. (1965). *The Conditions of Agricultural Growth: The Economics of Agrarian Change Under Population Pressure*, Aldine, New York.
- Boserup, E. (1976). Environment, population, and technology in primitive societies. *Population and Development Review* **2**: 21–36.
- Boserup, E. (1981). *Population and Technological Change: A Study of Long-Term Trends*, University of Chicago Press, Chicago.
- Brewer, J. L. (2018). Households as water managers: A comparison of domestic-scale water management practices from two central Maya lowland sites. *Ancient Mesoamerica* **29**: 197–217.
- Brewer, J. L., Carr, C., Dunning, N. P., Walker, D. S., Anaya Hernández, A., Peuramaki-Brown, M., and Reese-Taylor, K. (2017). Employing airborne LiDAR and archaeological testing to determine the role of small depressions in water management at the ancient Maya site of Yaxnohcah, Campeche, Mexico. *Journal of Archaeological Science: Reports* **13**: 291–302.
- Bridgewater, S., Ibáñez, A., Ratter, J. A., and Furley, P. (2002). Vegetation classification and floristics of the savannas and associated wetlands of the Rio Bravo conservation and management area, Belize. *Edinburgh Journal of Botany* **59**: 421–442.
- Brookfield, H. (1984). Intensification revisited. *Pacific Viewpoint* **25**: 15–44.
- Canuto, M. A., Estrada-Belli, F., Garrison, T. G., Houston, S. D., Acuña, M. J., Kováč, M., et al. (2018). Ancient lowland Maya complexity as revealed by airborne laser scanning of northern Guatemala. *Science* **361**: eaau0137.
- Carozza, J.-M., Galop, D., Métaillé, J.-P., Vannièrre, B., Bossuet, G., Monna, F., et al. (2007). Landuse and soil degradation in the Maya Lowlands from the Pre-Classic to Post-Classic period: The case of La Joyanca (Petén, Guatemala). *Geodinamica Acta* **20**: 195–207.
- Castro, I. V. e., Fareleira, P., and Ferreira, E. (2016). Nitrogen fixing symbiosis in a sustainable agriculture In Hakeem, K. R., Akhtar, M. S., and Abdullah, S. N. A. (eds.), *Plant, Soil and Microbes: Volume 1: Implications in Crop Science*, Springer, Cham, Switzerland, pp. 55–91.
- Chase, A. F., and Chase, D. Z. (1987). *Investigations at the Classic Maya City of Caracol, Belize: 1985–1987*, Monograph 3, Pre-Columbian Art Research Institute, San Francisco.
- Chase, A. F., and Chase, D. Z. (1998). Scale and intensity in Classic period Maya agriculture: Terracing and settlement at the "garden city" of Caracol, Belize. *Culture & Agriculture* **20**: 60–77.
- Chase, A. F., Chase, D. Z., Awe, J. J., Weishampel, J. F., Iannone, G., Moyes, H., et al. (2014a). Ancient Maya regional settlement and inter-site analysis: The 2013 west-central Belize LiDAR survey. *Remote Sensing* **6**: 8671–8695.
- Chase, A. F., Chase, D. Z., Fisher, C. T., Leisz, S., and Weishampel, J. F. (2012). Geospatial revolution and remote sensing LiDAR in mesoamerican archaeology. *Proceedings of the National Academy of Sciences* **109**: 12916–12921.
- Chase, A. F., Chase, D. Z., Weishampel, J., Drake, J. B., Shrestha, R., Slatton, K. C., Awe, J. J., and Carter, W. E. (2011). Airborne LiDAR, archaeology, and the ancient Maya landscape at Caracol, Belize. *Journal of Archaeological Science* **38**: 387–398.
- Chase, A. F., Lucero, L. J., Scarborough, V. L., Chase, D. Z., Cobos, R., Dunning, N. P., et al. (2014b). Tropical landscapes and the ancient Maya: Diversity in time and space. *Archeological Papers of the American Anthropological Association* **24**: 11–29.
- Chase, A. F., Reese-Taylor, K., Fernandez-Diaz, J. C., and Chase, D. Z. (2016). Progression and issues in the Mesoamerican geospatial revolution: An introduction. *Advances in Archaeological Practice* **4**: 219–231.
- Chase, A. S. Z. (2016). Beyond elite control: Residential reservoirs at Caracol, Belize. *WIREs Water* **3**: 885–897.
- Chase, A. S. Z., and Weishampel, J. (2016). Using LiDAR and GIS to investigate water and soil management in the agricultural terracing at Caracol, Belize. *Advances in Archaeological Practice* **4**: 357–370.
- Chase, D. Z., and Chase, A. F. (2014). Path dependency in the rise and denouement of a Classic Maya city: The case of Caracol, Belize. *Archeological Papers of the American Anthropological Association* **24**: 142–154.

- Chase, D. Z., and Chase, A. F. (2017). Caracol, Belize, and changing perceptions of ancient Maya society. *Journal of Archaeological Research* **25**: 185–249.
- Chmilar, J. A. (2013). *Ancient Maya Cultivation in a Dynamic Wetland Environment: Insights into the Functions of Anthropogenic Rock Alignments at El Edén Ecological Reserve, Quintana Roo, Mexico*, Ph.D. dissertation, Department of Anthropology, University of California, Riverside.
- Cook, O. F. (1909) *Vegetation Affected by Agriculture in Central America*, U.S. Bureau of Plant Industry Bulletin Vol. 145, Washington, DC.
- Cuanalo de la Cerda, H. E., and Guerra Mukul, R. R. (2008). Homegarden production and productivity in a Mayan community of Yucatan. *Human Ecology* **36**: 423–433.
- Culleton, B. J. (2012). *Human Ecology, Agricultural Intensification and Landscape Transformation at the Ancient Maya Polity of Uxbenká, Southern Belize*, Ph.D. dissertation, Department of Anthropology, University of Oregon, Eugene.
- Dahlin, B. H., Beach, T., Luzzadder-Beach, S., Hixson, D., Hutson, S., Magnoni, A., Mansell, E., and Mazeau, D. E. (2005). Reconstructing agricultural self-sufficiency at Chunchucmil, Yucatan, Mexico. *Ancient Mesoamerica* **16**: 229–247.
- Das, R., Lawrence, D., D'Odorico, P., and DeLonge, M. (2011). Impact of land use change on atmospheric P inputs in a tropical dry forest. *Journal of Geophysical Research* **116**: <http://dx.doi.org/https://doi.org/10.1029/2010JG001403>
- de Landa, D. (1978 [1566]). *Yucatan Before and After the Conquest*, Dover Publications, New York.
- Dedrick, M., Webb, E. A., McAnany, P. A., Kanxo Kumuld, J. M., Jones, J. G., Batún Alpuche, A. I., Pope, C., and Russell, M. (2020). Influential landscapes: Temporal trends in the agricultural use of rejjolladas at Tahcabo, Yucatán, Mexico. *Journal of Anthropological Archaeology* **59**: 101175.
- Diamond, J. (2006). *Collapse: How Societies Choose to Fail or Succeed*, Penguin Group USA, New York.
- Diemont, S. A. W., Martin, J. F., Levy-Tacher, S. I., Nigh, R. B., Ramirez Lopez, P., and Golicher, J. D. (2006). Lacandon Maya forest management: Restoration of soil fertility using native tree species *Ecological Engineering* **28**: 205–212.
- Dine, H., Ardren, T., Bascopé, G., and Báez, C. G. (2019). Famine foods and food security in the northern Maya Lowlands: Modern lessons for ancient reconstructions. *Ancient Mesoamerica* **30**: 517–534.
- Donkin, R. A. (1979). *Agricultural Terracing in the Aboriginal New World*, Viking Fund Publications in Anthropology, Vol. 56, University of Arizona Press, Tucson.
- Doolittle, W. E. (2000). *Cultivated Landscapes of Native North America*, Oxford University Press, Oxford.
- Doolittle, W. E. (2006). Agricultural manipulation of floodplains in the southern Basin and Range Province. *Catena* **65**: 179–199.
- Dunning, N. (2004). Down on the farm: Classic Maya "homesteads" as "farmsteads." In Lohse, J. C., and Valdez Jr., F. (eds.), *Ancient Maya Commoners*, University of Texas Press, Austin, pp. 97–116.
- Dunning, N., Beach, T., and Rue, D. (1997). The paleoecology and ancient settlement of the Petexbatun region, Guatemala. *Ancient Mesoamerica* **8**: 255–266.
- Dunning, N., Brewer, J., Carr, C., Anaya Hernández, A., Beach, T., Chmilar, J., et al. (2022). Harvesting ha: Ancient water collection and storage in the elevated interior region of the Maya Lowlands. In Larmon, J., Lucero, L., and Valdez, F. (eds.), *Sustainability and Water Management in the Maya World and Beyond*, University Press of Colorado, Boulder, pp. 13–52.
- Dunning, N. P. (1992). *Lords of the Hills: Ancient Maya Settlement in the Puuc Region, Yucatán, Mexico*, Monographs in World Archaeology No. 15, Prehistory Press, Madison.
- Dunning, N. P. (1996). A re-examination of regional variability in the prehistoric agricultural landscape. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City, pp. 53–68.
- Dunning, N. P., Anaya Hernández, A., Beach, T., Carr, C., Griffin, R., Jones, J. G., et al. (2019). Margin for error: Anthropogenic geomorphology of bajo edges in the Maya Lowlands. *Geomorphology* **331**: 127–145.
- Dunning, N. P., and Beach, T. (1994). Soil erosion, slope management, and ancient terracing in the Maya Lowlands. *Latin American Antiquity* **5**: 51–69.
- Dunning, N. P., and Beach, T. (2000). Stability and instability in prehispanic Maya landscapes. In Lentz, D. L. (ed.), *Imperfect Balance: Landscape Transformations in the Precolumbian Americas*, Columbia University Press, New York, pp. 179–202.
- Dunning, N. P., and Beach, T. (2004). Fruit of the loom: Lowland Maya soil knowledge and agricultural practices. *Mono y Conejo* **2**: 3–15.

- Dunning, N. P., Beach, T., Farrell, P., and Luzzadder-Beach, S. (1998). Prehispanic agrosystems and adaptive regions in the Maya Lowlands. *Culture & Agriculture* **20**: 87–101.
- Dunning, N. P., Beach, T., and Luzzadder-Beach, S. (2006). Environmental variability among bajos in the southern Maya Lowlands and its implications for ancient Maya civilization and archaeology. In Lucero, L. J., and Fash, B. W. (eds.), *Precolonial Water Management: Ideology, Ritual, and Power*, University of Arizona Press, Tucson, pp. 81–99.
- Dunning, N. P., Beach, T., Luzzadder-Beach, S., and Jones, J. G. (2009). Creating a stable landscape: Soil conservation among the ancient Maya. In Fisher, C. T., Hill, B., and Feinman, G. M. (eds.), *The Archaeology of Environmental Change: Socionatural Legacies of Degradation and Resilience*, University of Arizona Press, Tucson, pp. 85–105.
- Dunning, N. P., Griffin, R. E., Jones, J. G., Terry, R. E., Larsen, Z., and Carr, C. (2015). Life on the edge: Tikal in a bajo landscape. In Lentz, D. L., Dunning, N. P., and Scarborough, V. L. (eds.), *Tikal: Paleocology of an Ancient Maya City*, Cambridge University Press, New York, pp. 95–123.
- Dunning, N. P., Griffin, R. E., Sever, T. L., Saturno, W. A., and Jones, J. G. (2017). The nature and origins of linear features in the Bajo de Azúcar, Guatemala: Implications for ancient Maya adaptation to a changing environment. *Geoarchaeology* **32**: 107–129.
- Dunning, N. P., Luzzadder-Beach, S., Beach, T., Jones, J. G., Scarborough, V., and Culbert, T. P. (2002). Arising from the *bajos*: The evolution of a neotropical landscape and the rise of Maya civilization. *Annals of the Association of American Geographers* **92**: 267–283.
- Dunning, N. P., Ruhl, T., Carr, C., Beach, T., Brown, C., and Luzzadder-Beach, S. (2020). The ancient Maya wetland fields of Acalán. *Mexicon* **42**: 91–105.
- Dunning, N. P., Scarborough, V., Valdez Jr., F., Luzzadder-Beach, S., Beach, T., and Jones, H. G. (1999). Temple mountains, sacred lakes, and fertile fields: Ancient Maya landscapes in northwestern Belize. *Antiquity* **73**: 650–660.
- Dussol, L., Elliott, M., Michelet, D., and Nondédéo, P. (2021). Fuel economy, woodland management and adaptation strategies in a Classic Maya city: Applying anthracology to urban settings in high biodiversity tropical forests. *Vegetation History and Archaeobotany* **30**: 175–192.
- Ebert, C. E., Hoggarth, J. A., and Awe, J. J. (2016a). Classic period Maya water management and ecological adaptation in the Belize River valley. *Research Reports in Belizean Archaeology* **13**: 109–119.
- Ebert, C. E., Hoggarth, J. A., and Awe, J. J. (2016b). Integrating quantitative LiDAR analysis and settlement survey in the Belize River valley. *Advances in Archaeological Practice* **4**: 284–300.
- Ehrlich, P. R., Kareiva, P. M., and Daily, G. C. (2012). Securing natural capital and expanding equity to rescale civilization. *Nature* **486**: 68–73.
- Ellison, A. M. (2004). Wetlands of Central America. *Wetlands Ecology and Management* **12**: 3–55.
- Estrada-Medina, H., Bautista, F., Jiménez-Osornio, J. J. M., González-Iturbe, J. A., and Aguilar Cordero, W. d. J. (2013a). Maya and WRB soil classification in Yucatan, Mexico: Differences and similarities. *ISRN Soil Science* **2013**: 10.
- Estrada-Medina, H., Graham, R. C., Allen, M. F., Jiménez-Osornio, J. J., and Robles-Casolco, S. (2013b). The importance of limestone bedrock and dissolution karst features on tree root distribution in northern Yucatán, México. *Plant Soil* **362**: 37–50.
- Evans, D. L., Vis, B. N., Dunning, N. P., Graham, E., and Isendahl, C. (2021). Buried solutions: How Maya urban life substantiates soil connectivity. *Geoderma* **387**: <https://doi.org/10.1016/j.geoderma.2020.114925>
- Farrell, P. M. (1997). *The Garden City Hypothesis in the Maya Lowlands*, Ph.D. dissertation, Department of Geography, University of Cincinnati, Cincinnati.
- Fedick, S. L. (1989). The economics of agricultural land use and settlement in the upper Belize Valley. In McAnany, P. A., and Isaac, B. L. (eds.), *Prehistoric Maya Economies of Belize*, Research in Economic Anthropology, Supplement 4, JAI Press, Greenwich, CT, pp. 215–253.
- Fedick, S. L. (1994). Ancient Maya agricultural terracing in the upper Belize River area: Computer-aided modeling and the results of initial field investigations. *Ancient Mesoamerica* **5**: 107–127.
- Fedick, S. L. (1995). Land evaluation and ancient Maya land use in the upper Belize River area, Belize, Central America. *Latin American Antiquity* **6**: 16–34.
- Fedick, S. L. (1996a). Conclusion: Landscape approaches to the study of ancient Maya agriculture and resource use. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City, pp. 335–347.
- Fedick, S. L. (1996b). An interpretive kaleidoscope: Alternative perspectives on ancient agricultural landscapes of the Maya Lowlands. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City, pp. 107–131.



- Fedick, S. L. (ed.) (1996c). *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City.
- Fedick, S. L. (1996d). Predicting the past and preserving it for the future: Modeling and management of ancient Maya residential sites. In Phillips, M. D. (ed.), *The Second Interdisciplinary Conference on Belize*, University Press of America, Lanham, MD, pp. 1–22.
- Fedick, S. L. (1998). Ancient Maya use of wetlands in northern Quintana Roo, Mexico. In Bernick, K. (ed.), *Hidden Dimensions: The Cultural Significance of Wetland Archaeology*, University of British Columbia Press, Vancouver, pp. 108–129.
- Fedick, S. L. (2003a). Archaeological evidence for ancient and historic resource use associated with the El Edén wetland, northern Quintana Roo, Mexico. In Gómez-Pompa, A., Allen, M. F., Fedick, S. L., and Jiménez-Osornio, J. J. (eds.), *The Lowland Maya Area: Three Millennia at the Human-Wildland Interface*, Food Products Press, New York, pp. 339–359.
- Fedick, S. L. (2003b). In search of the Maya forest. In Slater, C. (ed.), *In Search of the Rain Forest*, Duke University Press, Durham, pp. 133–164.
- Fedick, S. L. (2010). Theory and method in the analysis of ancient Maya agricultural landscapes: The household model of agricultural production. In Ortiz Díaz, E. (ed.), *Lugar, espacio y paisaje en arqueología: Mesoamérica y otras áreas culturales: VI Coloquio Pedro Bosch Gimpera*, Instituto de Investigaciones Antropológicas, Universidad Nacional Autónoma de México, Mexico City, pp. 47–74.
- Fedick, S. L. (2014). A reassessment of water and soil resources in the flatlands of the northern Maya Lowlands. *Archaeological Papers of the American Anthropological Association* **24**: 72–83.
- Fedick, S. L. (2017). Plant-food commodities of the Maya Lowlands. In Mathews, J. P., and Guderjan, T. H. (eds.), *The Value of Things: Prehistoric to Contemporary Commodities in the Maya Region*, University of Arizona Press, Tucson, pp. 163–173.
- Fedick, S. L. (2020). Maya cornucopia: Indigenous food plants of the Maya Lowlands. In Masson, M. A., Freidel, D. A., and Demarest, A. A. (eds.), *The Real Business of Ancient Maya Economies: From Farmers' Fields to Rulers' Realms*, Oxford University Press, Oxford, pp. 224–237, 488–516.
- Fedick, S. L., Clarke, K. C., and Ford, A. (2016). Refining models of ancient Maya agricultural landscape archaeology in the Belize River area: Initial results making use of LiDAR imagery. *Research Reports in Belizean Archaeology* **13**: 121–128.
- Fedick, S. L., De Lourdes Flores Delgado, M., Sedov, S., Rebolledo, E. S., and Mayorga, S. P. (2008). Adaptation of Maya homegardens by "container gardening" in limestone bedrock cavities. *Journal of Ethnobiology* **28**: 290–304.
- Fedick, S. L., and Ford, A. (1990). The prehistoric agricultural landscape of the central Maya Lowlands: An examination of local variability in a regional context. *World Archaeology* **22**: 19–33.
- Fedick, S. L., and Hovey, K. (1995). Ancient Maya settlement and use of wetlands at naranjal and the surrounding Yalahau region. In Fedick, S. L., and Taube, K. A. (eds.), *The View from Yalahau: 1993 Archaeological Investigations in Northern Quintana Roo, Mexico*, Field Report Series No. 2, Latin American Studies Program, University of California, Riverside, pp. 89–100.
- Fedick, S. L., and Mathews, J. P. (2005). The Yalahau regional human ecology project: An introduction and summary of recent research. In Shaw, J. M., and Mathews, J. P. (eds.), *Quintana Roo Archaeology*, University of Arizona Press, Tucson, pp. 33–50.
- Fedick, S. L., and Morrison, B. A. (2004). Ancient use and manipulation of landscape in the Yalahau region of the northern Maya Lowlands. *Agriculture and Human Values* **21**: 207–219.
- Fedick, S. L., Morrison, B. A., Anderson, B. J., Boucher, S., Ceja Acosta, J., and Mathews, J. P. (2000). Wetland manipulation in the Yalahau region of the northern Maya Lowlands. *Journal of Field Archaeology* **27**: 131–152.
- Fedick, S. L., and Santiago, L. S. (2022). Large variation in availability of Maya food plant sources during ancient droughts. *Proceedings of the National Academy of Sciences* **119**: <https://doi.org/10.1073/pnas.2115657118>
- Fernandez-Diaz, J. C., Carter, W. E., Glennie, G., Shrestha, R. L., Pan, Z., Ekhtari, N., Singhania, A., and Hauser, D. (2016). Capability assessment and performance metrics for the titan multispectral mapping LiDAR. *Remote Sensing* **8**: 936.
- Fisher, C. (2014). The role of infield agriculture in Maya cities. *Journal of Anthropological Archaeology* **36**: 196–210.
- Fisher, C. (2019). *Maya Farming Communities and the Long View of Sustainability at Tzacauil*, Ph.D. dissertation, Department of Anthropology, University of Michigan, Ann Arbor.

- Fisher, C. T. (2007). Agricultural intensification in the Lake Pátzcuaro basin: Landesque capital as statecraft. In Thurston, T. L., and Fisher, C. T. (eds.), *Seeking a Richer Harvest: The Archaeology of Subsistence Intensification, Innovation, and Change*, Springer, New York, pp. 91–106.
- Fisher, C. T., and Feinman, G. M. (2005). Introduction to 'Landscapes over Time'. *American Anthropologist* **107**: 62–69.
- Fisher, C. T., Pollard, H. P., Israde-Alcántara, I., Garduño-Monroy, V. H., and Banerjee, S. K. (2003). A reexamination of human-induced environmental change within the Lake Pátzcuaro basin, Michoacán, Mexico. *Proceedings of the National Academy of Sciences* **100**: 4957–4962.
- Flannery, K. V. (ed.) (1982). *Maya Subsistence: Studies in Memory of Dennis E. Puleston*, Academic Press, New York.
- Fleury, S., Malaizé, B., Giraudeau, J., Galop, D., Bout-Roumazeilles, V., Martinez, P., et al. (2015). Impacts of Maya land use on Laguna Tuspán watershed (Petén, Guatemala) as seen through clay and ostracode analysis. *Journal of Archaeological Science* **49**: 372–382.
- Flores-Delgadillo, L., Fedick, S. L., Solleiro-Rebolledo, E., Palacios-Mayorga, S., Ortega-Larrocea, P., Sedov, S., and Osuna-Ceja, E. (2011). A sustainable system of traditional precision agriculture in a Maya homestead: Soil quality aspects. *Soil & Tillage Research* **113**: 112–120.
- Ford, A. (1986). *Population Growth and Social Complexity: An Examination of Settlement and Environment in the Central Maya Lowlands*, Anthropological Research Papers Vol. 35, Arizona State University, Tempe.
- Ford, A. (2014). Using cutting-edge Lidar technology at El Pilar Belize-Guatemala in discovering ancient Maya sites ~ There is still a need for archaeologists! *Research Reports in Belizean Archaeology* **11**: 271–280.
- Ford, A. (in press). Intensification does not require modification - Tropical swidden and the Maya. In McLeester, M. (ed.), *Finding Fields: Locating and Interpreting Ancient Agricultural Landscapes*, Archeological Papers of the American Anthropological Association.
- Ford, A., and Clarke, K. C. (2019). Linking the past and present of the ancient Maya. In Isendahl, C., and Stump, D. (eds.), *The Oxford Handbook of Historical Ecology and Applied Archaeology*, Oxford University Press, Oxford, pp. 156–183.
- Ford, A., Clarke, K. C., and Raines, G. (2009). Modeling settlement patterns of the Late Classic Maya civilization with Bayesian methods and geographic information systems. *Annals of the Association of American Geographers* **99**: 496–520.
- Ford, A., and Nigh, R. (2009). Origins of the Maya forest garden: Maya resource management. *Journal of Ethnobiology* **29**: 213–236.
- Ford, A., and Nigh, R. (2016). *The Maya Forest Garden: Eight Millennia of Sustainable Cultivation of the Tropical Woodlands*, Routledge, New York.
- Fulton, K. A., and Mixter, D. W. (2022). Maya domestic landscape and household resilience at Actuncan, Belize: A reconstruction and modern implications. In Carson, M. T. (ed.), *Palaeolandscapes in Archaeology: Lessons for the Past and Future*, Routledge, London, pp. 156–191.
- Garrison, T. G., and Dunning, N. P. (2009). Settlement, environment, and politics in the San Bartolom-Xultun territory, El Peten, Guatemala. *Latin American Antiquity* **20**: 525–552.
- Garrison, T. G., Houston, S. D., and Firpi, O., Alcover (2019). Recentring the rural: LiDAR and articulated landscapes among the Maya. *Journal of Anthropological Archaeology* **53**: 133–146.
- Gliessman, S. R., Turner II, B. L., Rosado May, F. J., and Amador, M. F. (1983). Ancient raised field agriculture in the Maya Lowlands of southeastern Mexico. In Darch, J. P. (ed.), *Drained Field Agriculture in Central and South America*, BAR International Series, Vol. 189, British Archaeological Reports, Oxford, pp. 91–110.
- Golden, C., Murtha, T., Cook, B., Shaffer, D. S., Schroder, W., Hermitt, E. J., Firpi, O. A., and Scherer, A. K. (2016). Reanalyzing environmental LiDAR data for archaeology: Mesoamerican applications and implications. *Journal of Archaeological Science: Reports* **9**: 293–308.
- Golden, C., Scherer, A. K., Schroder, W., Murtha, T., Morell-Hart, S., Fernandez Diaz, J. C., et al. (2021). Airborne lidar survey, density-based clustering, and ancient Maya settlement in the Upper Usumacinta River region of Mexico and Guatemala. *Remote Sensing* **13**: <https://doi.org/10.1016/j.geoderma.2020.114925>
- Gómez-Pompa, A., Flores, J. S., and Aliphath Fernandez, M. (1990). The sacred cacao groves of the Maya. *Latin American Antiquity* **1**: 247–257.
- Gómez-Pompa, A., Salvador Flores, J., and Sosa, V. (1987). The "pet kot": A man-made tropical forest of the Maya. *Interciencia* **12**: 10–15.

- Graham, E. (1999). Stone cities, green cities. In Bacus, E. A., and Lucero, L. J. (eds.), *Complex Politics in the Ancient Tropical World*, Vol. 9, Archeological Papers of the American Anthropological Association, Washington, DC, pp. 185–194.
- Graham, E., Macphail, R., Turner, S., Crowther, J., Stegemann, J., Arroyo-Kalin, M., et al. (2017). The Marco Gonzalez Maya site, Ambergris Caye, Belize: Assessing the impact of human activities by examining diachronic processes at the local scale. *Quaternary International* **437**: 115–142.
- Guderjan, T. H. (2016). Did restructuring at the end of Maya Classic period include the beginnings of private land tenure? In Aebersold, L., and Krause, S. M. (eds.), *Changes in Latitudes, Changes in Attitudes: Transitions and Thresholds Throughout Central America and Beyond*, Occasional Paper No. 21, Center for Archaeological and Tropical Studies, University of Texas, Austin, pp. 113–129.
- Guderjan, T. H., Baker, J., and Lichtenstein, R. J. (2003). Environmental and cultural diversity at Blue Creek. In Scarborough, V. L., Valdez Jr., F., and Dunning, N. P. (eds.), *Heterarchy, Political Economy, and the Ancient Maya: The Three Rivers Region of the East-Central Yucatán Peninsula*, University of Arizona Press, Tucson, pp. 77–91.
- Guderjan, T. H., and Krause, S. (2011). Identifying the extent of ancient Maya ditched field systems in the Río Hondo valley of Belize and Mexico: A pilot study and some of its implications. *Research Reports in Belizean Archaeology* **8**: 127–136.
- Gunn, J. D., Foss, J. E., Folan, W. J., Domínguez Carrasco, M. d. R., and Faust, B. B. (2002). Bajo sediments and the hydraulic system of Calakmul, Campeche, Mexico. *Ancient Mesoamerica* **13**: 97–315.
- Hageman, J. B., and Lohse, J. C. (2003). Heterarchy, corporate groups, and Late Classic management in northwestern Belize. In Scarborough, V. L., Valdez Jr., F., and Dunning, N. P. (eds.), *Heterarchy, Political Economy, and the Ancient Maya: The Three Rivers Region of the East-Central Yucatán Peninsula*, University of Arizona Press, Tucson, pp. 109–121.
- Håkansson, N. T., and Widgren, M. (eds.) (2014). *Landesque Capital: The Historical Ecology of Enduring Landscape Modifications*, Left Coast Press, Walnut Creek, CA.
- Halperin, C. T., Garza, S., Prufer, K. M., and Brady, J. E. (2003). Caves and ancient Maya ritual use of jute. *Latin American Antiquity* **14**: 207–219.
- Hammond, N. (1974). Preclassic to Postclassic in northern Belize. *Antiquity* **48**: 177–189.
- Hammond, N. (1978). The myth of the milpa: Agricultural expansion in the Maya Lowlands. In Harrison, P. D., and Turner II, B. L. (eds.), *Pre-Hispanic Maya Agriculture*, University of New Mexico Press, Albuquerque, pp. 23–34.
- Hansen, R. D., Bozarth, S., Jacob, J., Wahl, D., and Schreiner, T. (2002). Climatic and environmental variability in the rise of Maya civilization. *Ancient Mesoamerica* **13**: 273–295.
- Hare, T., Mason, M., and Russel, B. (2014). High-density LiDAR mapping of the ancient city of Mayapán. *Remote Sensing* **6**: 9064–9085.
- Harrison-Buck, E. (2014). Ancient Maya wetland use in the eastern Belize watershed. *Research Reports in Belizean Archaeology* **11**: 245–258.
- Harrison, P. D. (1996). Settlement and land use in the Pulltrouser Swamp archaeological zone, northern Belize. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City, pp. 177–190.
- Harrison, P. D., and Fry, R. E. (2000). *Pulltrouser Swamp: A Lowland Maya Community Cluster in Northern Belize: The Settlement Maps*, University of Utah Press, Salt Lake City.
- Harrison, P. D., and Turner II, B. L. (eds.) (1978). *Pre-Hispanic Maya Agriculture*, University of New Mexico Press, Albuquerque.
- Haviland, W. A. (1970). Tikal, Guatemala and Mesoamerican urbanism. *World Archaeology* **2**: 186–198.
- Haviland, W. A. (1988). Musical hammocks at Tikal: Problems with reconstructing household composition. In Wilk, R. R., and Ashmore, W. (eds.), *Household and Community in the Mesoamerican Past*, University of New Mexico Press, Albuquerque, pp. 121–134.
- Healy, P. F., Emery, K., and Wright, L. E. (1990). Ancient and modern Maya exploitation of the jute snail (*Pachychilus*). *Latin American Antiquity* **1**: 170–183.
- Healy, P. F., Lambert, J. D. H., Arnason, J. T., and Hebda, R. J. (1983). Caracol, Belize: Evidence of ancient Maya agricultural terraces. *Journal of Field Archaeology* **10**: 397–410.
- Hecht, S. B., Morrison, K. D., and Padoch, C. (eds.) (2014). *The Social Lives of Forests: Past, Present, and Future of Woodland Resurgence*, University of Chicago Press, Chicago.
- Heckenberger, M. J., Russell, J. C., Fausto, C., Toney, J. R., Schmidt, M. J., Pereira, E., Franchetto, B., and Kuikuro, A. (2008). Pre-Columbian urbanism, anthropogenic landscapes, and the future of the Amazon. *Science* **321**: 1214–1217.

- Heindel, T. (2019). *Plotting, Planting and Prospering: Ancient Maya Agricultural Production and Water Management at Actuncan, Belize*. Ph.D. dissertation, Department of Anthropology, University of California, Riverside.
- Hixson, D. R., Beach, T., Luzzadder-Beach, S., and Dahlin, B. H. (2017). Environmental heterogeneity in the Chunchucmil economic region. In Hutson, S. R. (ed.), *Ancient Maya Commerce: Multidisciplinary Research at Chunchucmil*, University Press of Colorado, Boulder, pp. 139–155.
- Horn III, S., Ford, A., and Morales, P. (2019). Lasers, lasers, everywhere – and all the trees did shrink: Reliable methods and results from LiDAR-guided survey at El Pilar. *Research Reports in Belizean Archaeology* **16**: 143–155.
- Horn III, S. W., and Ford, A. (2019). Beyond the magic wand: Methodological developments and results from integrated Lidar survey at the ancient Maya center El Pilar. *STAR: Science & Technology of Archaeological Research* **5**: 164–178.
- Horseman, G. (2022). Suitability models of ancient Maya agriculture in the upper Usumacinta River basin of Mexico and Guatemala. Unpublished Bachelor's (B.S.) thesis, School of Interdisciplinary Science, McMaster University, Hamilton, Canada.
- Houck Jr., C. W. (2006). Cenotes, wetlands, and hinterland settlement. In Mathews, J. P., and Morrison, B. A. (eds.), *Lifeways in the Northern Maya Lowlands*, University of Arizona Press, Tucson, pp. 56–75.
- Hughbanks, P. J. (1998). Settlement and land use at Guijarral, northwest Belize. *Culture & Agriculture* **20**: 107–120.
- Hughbanks, P. J. (2006). *Landscape Management at Guijarral, Northwestern Belize*, Ph.D. dissertation, Department of Anthropology, Tulane University, New Orleans.
- Hutson, S. R., Dunning, N. P., Cook, B., Ruhl, T., Barth, N. C., and Conley, D. (2021). Ancient Maya rural settlement patterns, household cooperation, and regional subsistence interdependency in the Río Bec area: Contributions from G-LiHT. *Journal of Anthropological Research* **77**: <https://doi.org/10.1016/j.geoderma.2020.114925>
- Hutson, S. R., and Magnoni, A. (2017). The map of Chunchucmil. In Hutson, S. R. (ed.), *Ancient Maya Commerce: Multidisciplinary Research at Chunchucmil*, University Press of Colorado, Boulder, pp. 27–50.
- Hutson, S. R., Magnoni, A., Mazeau, D. E., and Stanton, T. W. (2006). The archaeology of urban houselots at Chunchucmil, Yucatán. In Mathews, J. P., and Morrison, B. A. (eds.), *Lifeways in the Northern Maya Lowlands: New Approaches to Archaeology in the Yucatán Peninsula*, University of Arizona Press, Tucson, pp. 77–92.
- Hutson, S. R., Magnoni, A., and Stanton, T. W. (2004). House rules? The practice of social organization in Classic-period Chunchucmil, Yucatan, Mexico. *Ancient Mesoamerica* **15**: 75–92.
- Hutson, S. R., and Stanton, T. W. (2007). Cultural logic and practical reason: The structure of discard in ancient Maya houselots. *Cambridge Archaeological Journal* **17**: 123–144.
- Hutson, S. R., Stanton, T. W., Magnoni, A., Terry, R., and Craner, J. (2007). Beyond the buildings: Formation processes of ancient Maya houselots and methods for the study of non-architectural space. *Journal of Anthropological Archaeology* **26**: 442–473.
- Isendahl, C. (2002). *Common Knowledge: Lowland Maya Urban Farming at Xuch*. Studies in Global Archaeology Vol. 1, Uppsala University, Uppsala, Sweden.
- Isendahl, C. (2010). Greening the ancient city: The agro-urban landscapes of the pre-Hispanic Maya. In Sinclair, P. J. J., Nordquist, G., Herschend, F., and Isendahl, C. (eds.), *The Urban Mind: Cultural and Environmental Dynamics*, Studies in Global Archaeology Vol. 15, Uppsala University, Uppsala, Sweden, pp. 527–552.
- Isendahl, C. (2012). Agro-urban landscapes: The example of Maya lowland cities. *Antiquity* **86**: 1112–1125.
- Jacob, J. S. (1992). *Agroecological Evolution of Cobweb Swamp, Belize*. Ph.D. dissertation, Department of Soil and Crop Sciences, Texas A & M University, College Station.
- Jacob, J. S. (1995). Ancient Maya wetland agricultural fields in Cobweb Swamp, Belize: Construction, chronology, and function. *Journal of Field Archaeology* **22**: 175–190.
- Jacob, J. S., and Hallman, C. T. (1996). Holocene stratigraphy of Cobweb Swamp, a Maya wetland in northern Belize. *GSA Bulletin* **108**: 883–891.
- Jensen, C. T., Moriarty, M. D., Johnson, K. D., Terry, R. E., Emery, K. F., and Nelson, S. D. (2007). Soil resources of the Motul de San José Maya: Correlating soil taxonomy and modern Itzá Maya soil classification within a Classic Maya archaeological zone. *Geoarchaeology: An International Journal* **22**: 337–357.

- Jiménez-Osornio, J. J., Pastrana Cervantes, D., Molina Cortez, A., Ruenes Morales, M. d. R., Montañez Escalante, P. I., and Lendecky Grajales, Á. (2018). Sustainable agriculture through resurrection of indigenous fruits. In Scherrer, C., and Verma, S. (eds.), *Decent Work Deficits in Southern Agriculture: Measurements, Drivers and Strategies*, Rainer Hampp Verlag, Augsburg, Germany, pp. 305–322.
- Jones, J. G. (1991). *Pollen Evidence of Prehistoric Forest Manipulation and Maya Cultivation in Belize*, Ph.D. dissertation, Department of Anthropology, Texas A & M University, College Station.
- Jones, J. G. (1994). Pollen evidence for early settlement and agriculture in northern Belize. *Palynology* **18**: 205–211.
- Joyce, T. A. (1926). Report on the investigations at Lubaantun, British Honduras, in 1926. *The Journal of the Royal Anthropological Institute of Great Britain and Ireland* **56**: 207–230.
- Kepecs, S., and Boucher, S. (1996). The pre-Hispanic cultivation of rejoylladas and stone-lands: New evidence from northeast Yucatán. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City, pp. 69–91.
- Killion, T. W. (1992). Residential ethnoarchaeology and ancient site structure: Contemporary farming and prehistoric settlement agriculture at Maticapan, Veracruz, Mexico. In Killion, T. W. (ed.), *Gardens of Prehistory: The Archaeology of Settlement Agriculture in Greater Mesoamerica*, University of Alabama Press, Tuscaloosa, pp. 119–149.
- Killion, T. W. (2013). Nonagricultural cultivation and social complexity: The Olmec, their ancestors, and Mexico's southern Gulf Coast Lowlands. *Current Anthropology* **54**: 569–606.
- Killion, T. W., Sabloff, J. A., Tourtellot, G., and Dunning, N. P. (1989). Intensive surface collection of residential clusters at Terminal Classic Sayil, Yucatán, Mexico. *Journal of Field Archaeology* **18**: 273–294.
- King, E. M. (2021). Modeling Maya markets. In Masson, M. A., Freidel, D. A., and Demarest, A. A. (eds.), *The Real Business of Ancient Maya Economies: From Farmers' Fields to Rulers' Realms*, University Press of Florida, Gainesville, pp. 14–27.
- Kirch, P. V. (1994). *The Wet and the Dry: Irrigation and Agricultural Intensification in Polynesia*, University of Chicago Press, Chicago.
- Kirke, C. M. S. G. (1980). Prehistoric agriculture in the Belize River valley. *World Archaeology* **11**: 281–286.
- Krause, S., Beach, T., Luzzadder-Beach, S., Cook, D., Islebe, G., Palacios-Fest, M. R., et al. (2019a). Wetland geomorphology and paleoecology near Akab Muclil, Rio Bravo floodplain of the Belize coastal plain. *Geomorphology* **331**: 146–159.
- Krause, S., Beach, T., Luzzadder-Beach, S., Guderjan, T. H., Valdez, F. J., Eshleman, S., Doyle, C., and Bozarth, S. R. (2019b). Ancient Maya wetland management in two watersheds in Belize: Soils, water, and paleoenvironmental change. *Quaternary International* **502**: 280–295.
- Krause, S. M. (2018). *Wetland Agroecosystems in the Maya Lowlands of Belize: LiDAR and Multi-Proxy Environmental Change*, Ph.D. dissertation, Department of Anthropology, University of Texas, Austin.
- Kunen, J. L. (2001). Ancient Maya agricultural installations and the development of intensive agriculture in NW Belize. *Journal of Field Archaeology* **28**: 325–346.
- Kunen, J. L., Culbert, T. P., Fialko, V., McKee, B. R., and Grazioso, L. (2000). Bajo communities: A case study from central Peten. *Culture & Agriculture* **22**: 15–31.
- Kunen, J. L., and Hughbanks, P. J. (2003). Bajo communities as resource specialists: A heterarchical approach to Maya socioeconomic organization. In Scarborough, V. L., Valdez Jr., F., and Dunning, N. P. (eds.), *Heterarchy, Political Economy, and the Ancient Maya: The Three Rivers Region of the East-Central Yucatán Peninsula*, University of Arizona Press, Tucson, pp. 92–108.
- Kwoka, J. J., Guderjan, T. H., Eshleman, S., Ruhl, T., Telepak, J., Beach, T., et al. (2021). A multi-method approach to the study of Classic Maya houselots and land tenure: Preliminary results from the Three Rivers region, *Belize Journal of Archaeological Science: Reports* **38**: <https://doi.org/10.1016/j.jasrep.2021.103049>
- Kwoka, J. J., Ruhl, T., and Eshleman, S. (2018). AL17: Investigations of ancient Maya house lots. In Guderjan, T. H., and Hanratty, C. C. (eds.), *The 26th Annual Report of the Blue Creek Archaeological Project*, Research Report 6, Maya Research Program and the Center for Social Science Research, University of Texas, Tyler, pp. 81–92.
- LeCount, L. J., Walker, C. P., Blitz, J. H., and Nelson, T. C. (2019). Land tenure systems at the ancient Maya site of Actuncan, Belize. *Latin American Antiquity* **30**: 245–265.

- Lemonnier, E., and Vanni re, B. (2013). Agrarian features, farmsteads, and homesteads in the R o Bec nuclear zone, Mexico. *Ancient Mesoamerica* **24**: 397–413.
- Lentz, D. L., Dunning, N. P., Scarborough, V. L., and Grazioso, L. (2018). Imperial resource management at the ancient Maya city of Tikal: A resilience model of sustainability and collapse. *Journal of Anthropological Archaeology* **52**: 113–122.
- Lentz, D. L., Dunning, N. P., Scarborough, V. L., Magee, K. S., Thompson, K. M., Weaver, E., et al. (2014). Forests, fields, and the edge of sustainability at the ancient Maya city of Tikal. *Proceedings of the National Academy of Sciences* **111**: 18513–18518.
- Leonard, D. (2013). *A Regional Survey of Ancient Maya Wetland Use in Northern Quintana Roo, Mexico*, Ph.D. dissertation, Department of Anthropology, University of California, Riverside.
- Leonard, D., Sedov, S., Solleiro-Rebolledo, E., Fedick, S. L., and Diaz, J. (2019). Ancient Maya use of hidden soils in the Yalahau wetlands, northern Quintana Roo, Mexico. *Bolet n de la Sociedad Geol gica Mexicana* **71**: 93–119.
- Levi, L. J. (1996). Sustainable production and residential variation: A historical perspective on pre-Hispanic domestic economies in the Maya Lowlands. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource use*, University of Utah Press, Salt Lake City, pp. 92–106.
- Liendo Stuardo, R. (2002). *The Organization of Agricultural Production at a Classic Maya Center: Settlement Patterns in the Palenque Region, Chiapas, Mexico*, Instituto Nacional de Antropolog a e Historia, Mexico, and University of Pittsburgh, Pittsburgh.
- Lightfoot, D. R. (1994). Morphology and ecology of lithic mulch agriculture. *Geographical Review* **84**: 172–185.
- Lightfoot, D. R. (1996). The nature, history, and distribution of lithic mulch agriculture: An ancient technique of dryland agriculture. *The Agricultural History Review* **44**: 206–222.
- Lohse, J. C. (2004). Intra-settlement signatures and implications for Late Classic Maya commoner organization at Dos Hombres, Belize. In Lohse, J. C., and Valdez Jr., F. (eds.), *Ancient Maya Commoners*, University of Texas Press, Austin, pp. 117–145.
- Lohse, J. C., and Findlay, P. N. (2000). A Classic Maya house-lot drainage system in northwestern Belize. *Latin American Antiquity* **11**: 175–185.
- Lucero, L. J., Fedick, S. L., Kinkella, A., and Graebner, S. M. (2004). Ancient Maya settlement in the Valley of Peace area. In Garber, J. F. (ed.), *The Ancient Maya of the Belize Valley: Half a Century of Archaeological Research*, University Press of Florida, Gainesville, pp. 86–102.
- Lundell, C. L. (1933). The agriculture of the Maya. *Southwest Review* **19**: 65–77.
- Luzzadder-Beach, S., and Beach, T. P. (2008). Water chemistry constraints and possibilities for ancient and contemporary Maya wetlands. *Journal of Ethnobiology* **28**: 211–230.
- Luzzadder-Beach, S., and Beach, T. P. (2009). Arising from the wetlands: Mechanisms and chronology of landscape aggradation in the northern coastal plain of Belize. *Annals of the Association of American Geographers* **99**: 1–26.
- Luzzadder-Beach, S., Beach, T. P., and Dunning, N. P. (2012). Wetland fields as mirrors of drought and the Maya abandonment. *Proceedings of the National Academy of Sciences* **109**: 3646–3651.
- Luzzadder-Beach, S., Beach, T. P., and Dunning, N. P. (2020). Wetland farming and the early anthropocene: Globally upscaling from the Maya Lowlands with LiDAR and multiproxy verification. *Annals of the American Association of Geographers* **111**: 795–807.
- Macphail, R. I., Graham, E., Crowther, J., and Turner, S. (2017). Marco Gonzalez, Ambergris Caye, Belize: A geoarchaeological record of ground raising associated with surface soil formation and the presence of a dark earth. *Journal of Archaeological Science* **77**: 35–51.
- Macrae, S. A. (2017). *Terracing, Agricultural Strategies, and Resilience at the Ancient Maya Minor Center of Waybil*, Ph.D. dissertation, Department of Anthropology, University of Florida, Gainesville.
- Macrae, S. A., and Iannone, G. (2016). Understanding ancient Maya agricultural terrace systems through LiDAR and hydrological mapping. *Advances in Archaeological Practice* **4**: 371–392.
- Magnoni, A., Stanton, T. W., Barth, N., Fernandez-Diaz, J. C., Osorio Le n, J. F., P rez Ru z, F., and Wheeler, J. A. (2016). Detection thresholds of archaeological features in airborne LiDAR data from central Yucat n. *Advances in Archaeological Practice* **4**: 232–248.
- Mart nez-Villegas, N. (2007). An overview of different soil classification systems used in Mexico. *Terra Latinoamericana* **25**: 357–362.
- Masson, M. A., Peraza Lope, C., Hare, T. S., Russell, B. W., Delgado K , P., Escamilla Ojeda, B., and Flores Cob , L. (2020). Rural economies of agrarian houselots before and after the rise of urban Mayap n. In Mason, M. A., Freidel, D. A., and Demarest, A. A. (eds.), *The Real Business of*

- Ancient Maya Economies: From Farmers' Fields to Rulers' Realms*, University Press of Florida, Gainesville, pp. 79–97.
- McAnany, P. A. (1995). *Living with the Ancestors: Kinship and Kingship in Ancient Maya Society*, University of Texas Press, Austin.
- McBratney, A., Field, D. J., and Koch, A. (2014). The dimensions of soil security. *Geoderma* **213**: 203–213.
- Morell-Hart, S., Fedick, S. L., and Dussol, L. (2023). Agriculture in the ancient Maya Lowlands (Part 1): Paleoethnobotanical residues and new perspectives on plant management. *Journal of Archaeological Research* **31**: in press.
- Morley, S. G. (1946). *The Ancient Maya*, Stanford University Press, Stanford.
- Morrison, B. A. (2000). *Ancient Maya Settlement of the Yalahau Region: An Example from the El Edén Wetland*, Ph.D. dissertation, Department of Anthropology, University of California, Riverside.
- Morrison, B. A. (2006). From swidden to swamp: The study of ancient Maya agriculture. In Mathews, J. P., and Morrison, B. A. (eds.), *Lifeways in the Northern Maya Lowlands: New Approaches to Archaeology in the Yucatán Peninsula*, University of Arizona Press, Tucson, pp. 41–55.
- Morrison, B. A., and Cózatl-Manzano, R. (2003). Initial evidence for use of periphyton as an agricultural fertilizer by the ancient Maya associated with the El Edén wetland, northern Quintana Roo, Mexico. In Gómez-Pompa, A., Allen, M. F., Fedick, S. L., and Jiménez-Osornio, J. J. (eds.), *The Lowland Maya Area: Three Millennia at the Human-Wildland Interface*, Food Products Press, New York, pp. 401–413.
- Morton, J. F. (1987). *Fruits of Warm Climates*, Julia F. Morton, Miami, FL.
- Munro-Stasiuk, M. J., and Manahan, T. K. (2010). Investigating ancient Maya agricultural adaptation through ground penetrating radar (GPR) analysis of karst terrain, northern Yucatán, Mexico. *Acta Carsologica* **39**: 123–135.
- Munro-Stasiuk, M. J., Manahan, T. K., Stockton, T., and Ardren, T. (2014). Spatial and physical characteristics of rejlolladas in northern Yucatan, Mexico: Implications for ancient Maya agriculture and settlement patterns. *Geoarchaeology: An International Journal* **29**: 156–172.
- Murtha, T. (2015). Negotiated landscapes: Comparative regional spatial organization of Tikal and Caracol. In Marken, D. B., and Fitzsimmons, J. L. (eds.), *Classic Maya Polities of the Southern Lowlands: Integration, Interaction, Dissolution*, University Press of Colorado, Boulder, pp. 75–98.
- Murtha Jr., T. M. (2002). *Land and Labor: Classic Maya Terraced Agriculture at Caracol, Belize*, Ph.D. dissertation, Department of Anthropology, Pennsylvania State University, University Park.
- Murtha Jr., T. M. (2009). *Land and Labor: Maya Terraced Agriculture: An Investigation of the Settlement Economy and Intensive Agricultural Landscape of Caracol, Belize*, DM Verlag Dr. Muller, Saarbrücken, Germany.
- Neff, L. S. (2002). Gender divisions of labor and lowland terrace agriculture. In Ardren, T. (ed.), *Ancient Maya Women*, AltaMira Press, Walnut Creek, CA, pp. 31–51.
- Neff, L. T. (2008). *A Study of Agricultural Intensification: Ancient Maya Agricultural Terracing in the Xunantunich Hinterland, Belize, Central America*, Ph.D. dissertation, Department of Anthropology, University of Pennsylvania, Philadelphia.
- Neff, L. T. (2010). Population, intensive agriculture, and elite-commoner political power relations in the Xunantunich hinterlands. In LeCount, L. J., and Yaeger, J. (eds.), *Classic Maya Provincial Politics: Xunantunich and Its Hinterlands*, University of Arizona Press, Tucson, pp. 250–271.
- Nondédéo, P., Arnauld, M. C., and Michelet, D. (2013). Río Bec settlement patterns and local sociopolitical organization. *Ancient Mesoamerica* **24**: 373–396.
- Nondédéo, P., Castanet, C., Purdue, L., Lemonnier, E., Dussol, L., Hiquet, J., Garnier, A., and Testé, M. (2020). Archaeological and paleoenvironmental reconstructions in the tropical Maya area: The case of Naachtun (Guatemala). In Tsirtoni, Z., Kuzucuoglu, C., Nondédéo, P., and Weller, O. (eds.), *Different Times? Archaeological and Environmental Data from Intra-site and Off-site Sequences: Papers Presented in a Session Organised in the 18th UISSP International Congress Paris, June 8, 2018*, Vol. 4, Archaeopress, Oxford, pp. 94–110.
- Olmsted, I. (1993). Wetlands of Mexico. In Whigham, D. E., Dykyjova, D., and Hwny, S. (eds.), *Wetlands of the World. I: Inventory, Ecology and Management*, Kluwer, Dordrecht, Netherlands, pp. 637–677.
- Ower, L. H. (1927). Features of British Honduras. *The Geographical Journal* **70**: 372–386.
- Pain, A., Marquardt, K., Lindh, A., and Hasselquist, N. J. (2021). What is secondary about secondary tropical forest? Rethinking forest landscapes. *Human Ecology* **49**: 239–247.

- Palacios-Mayorga, S., Anaya, A. L., González-Velázquez, E., Huerta-Arcos, L., and Gómez-Pompa, A. (2003). Periphyton as a potential biofertilizer in intensive agriculture of the ancient Maya. In Gómez-Pompa, A., Allen, M. F., Fedick, S. L., and Jiménez-Osornio, J. J. (eds.), *The Lowland Maya Area: Three Millennia at the Human-Wildland Interface*, Food Products Press, New York, pp. 389–400.
- Palma-López, D. J., and Bautista, F. (2019). Technology and local wisdom: The Maya soil classification app. *Boletín de la Sociedad Geológica Mexicana* **71**: 249–260.
- Pohl, M. D. (ed.) (1990). *Ancient Maya Wetland Agriculture: Excavations on Albion Island, Northern Belize*, Westview Press, Boulder, CO.
- Pohl, M. D., and Bloom, P. (1996). Prehistoric Maya farming in the wetlands of northern Belize: More data from Albion Island and beyond. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City, pp. 145–164.
- Pohl, M. D., Josserand, K., Pope, K. O., Jones, H. G., Jacob, J. S., Piperno, D. R., et al. (1996). Early agriculture in the Maya Lowlands. *Latin American Antiquity* **7**: 355–372.
- Pope, K. O., and Dahlin, B. H. (1989). Ancient Maya wetland agriculture: New insights from ecological and remote sensing research. *Journal of Field Archaeology* **16**: 87–106.
- Pope, K. O., and Dahlin, B. H. (1993). Radar detection and ecology of ancient Maya canal systems - Reply to Adams et al. *Journal of Field Archaeology* **20**: 379–383.
- Pope, K. O., Pohl, M. D., and Jacob, J. S. (1996). Formation of ancient Maya wetland fields: Natural and anthropogenic processes. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City, pp. 165–176.
- Pretty, J., and Smith, D. (2004). Social capital in biodiversity conservation and management. *Conservation Biology* **18**: 631–638.
- Prufer, K. M., Thompson, A. E., and Kennett, D. J. (2015). Evaluating airborne LiDAR for detecting settlements and modified landscapes in disturbed tropical environments at Uxbenká, Belize. *Journal of Archaeological Science* **57**: 1–13.
- Prufer, K. M., Thompson, A. E., Meredith, C. R., Culleton, B. J., Jordan, J. M., Ebert, C. E., Winterhalder, B., and Kennett, D. J. (2017). The Classic period Maya transition from an ideal free to an ideal despotic settlement system at the polity of Uxbenká. *Journal of Anthropological Archaeology* **45**: 53–68.
- Pyburn, K. A. (1998). Smallholders in the Maya Lowlands: Homage to a garden variety ethnographer. *Human Ecology* **26**: 267–286.
- Pyburn, K. A. (2003). The hydrology of Chau Hux. *Ancient Mesoamerica* **14**: 123–129.
- Rejmánková, E., Pope, K. O., Post, R., and Maltry, E. (1996). Herbaceous wetlands of the Yucatan Peninsula: Communities at extreme ends of environmental gradients. *Internationale Revue der gesamten Hydrobiologie und Hydrographie* **81**: 223–252.
- Rice, D. S. (1993). Eighth-century physical geography, environment, and natural resources in the Maya Lowlands. In Sabloff, J. A., and Henderson, J. A. (eds.), *Lowland Maya Civilization in the Eighth Century AD*, Dumbarton Oaks, Washington, DC, pp. 11–63.
- Rice, D. S. (1996). Paleolimnological analysis in the central Petén, Guatemala. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City, pp. 193–206.
- Ringle, W. M., Gallareta Negrón, T., May Ciau, R., Seligson, K. E., Fernandez-Diaz, J. C., and Ortegón Zapata, D. (2021). Lidar survey of ancient Maya settlement in the Puuc region of Yucatan, Mexico. *PLoS ONE* **16**: <https://doi.org/10.1371/journal.pone.0249314>
- Robin, C. (1999). *Towards an Archaeology of Everyday Life: Maya Farmers of Chan Nòohol and Dos Chombitos Cik'in, Belize*, Ph.D. dissertation, Department of Anthropology, University of Pennsylvania, Philadelphia.
- Robin, C. (2002). Gender and Maya farming: Chan, Nòohol, Belize. In Ardren, T. (ed.), *Ancient Maya Women*, AltaMira Press, Walnut Creek, CA, pp. 12–30.
- Robin, C. (ed.) (2012). *Chan: An Ancient Maya Farming Community*, University Press of Florida, Gainesville.
- Sanchez, P. A., and Buol, S. W. (1975). Soils of the tropics and the world food crisis. *Science* **188**: 598–603.
- Sanders, W. T. (1977). Environmental heterogeneity and the evolution of lowland Maya civilization. In Adams, R. E. W. (ed.), *The Origins of Maya Civilization*, University of New Mexico Press, Albuquerque, pp. 287–297.



- Scarborough, V. L., Connolly, R. P., and Ross, S. P. (1994). The pre-Hispanic Maya reservoir system at Kinal, Peten, Guatemala. *Ancient Mesoamerica* **5**: 97–106.
- Scarborough, V. L., Dunning, N. P., Tankersley, K. B., Carr, C., Weaver, E., Grazioso, L., et al. (2012). Water and sustainable land use at the ancient tropical city of Tikal, Guatemala. *Proceedings of the National Academy of Sciences* **109**: 12408–12413.
- Scarborough, V. L., Valdez Jr., F., and Dunning, N. (eds.) (2003). *Heterarchy, Political Economy, and the Ancient Maya: The Three Rivers Region of the East-Central Yucatán Peninsula*, University of Arizona Press, Tucson.
- Schroder, W., Murtha, T., Golden, C., Hernández, A. A., Scherer, A., Morell-Hart, S., et al. (2020). The lowland Maya settlement landscape: Environmental LiDAR and ecology. *Journal of Archaeological Science: Reports* **33**: <https://doi.org/10.1016/j.jasrep.2020.102543>
- Schwartz, N. B., and Corzo M., A. R. (2015). Swidden counts: A Petén, Guatemala, milpa system: Production, carrying capacity, and sustainability in the southern Maya Lowlands. *Journal of Anthropological Research* **71**: <http://dx.doi.org/https://doi.org/10.3998/jar.0521004.0071.104>
- Sedov, S., Solleiro-Rebolledo, E., Fedick, S. L., Gama-Castro, J., Palacios-Mayorga, S., and Vallejo-Gómez, E. (2007). Soil genesis in relation to landscape evolution and ancient sustainable land use in the northeastern Yucatan Peninsula, Mexico. *Atti della Società Toscana di Scienze Naturali, Memorie Serie A* **112**: 115–126.
- Sedov, S., Solleiro-Rebolledo, E., Fedick, S. L., Pi-Puig, T., Vallejo-Gómez, E., and Flores-Delgado, M. d. L. (2008). Micromorphology of a soil catena in Yucatán: Pedogenesis and geomorphological processes in a tropical karst landscape. In Kapur, S., A.R., M., and Stoops, G. (eds.), *New Trends in Micromorphology*, Springer-Verlag, Berlin, pp. 19–37.
- Seefeld, N. (2018). *The Hydraulic System of Uxul: Origins, Functions, and Social Setting*, Archaeopress, Oxford.
- Sheets, P. D., Dixon, C., Guerra, M., and Blanford, A. (2011). Manioc cultivation at Ceren, El Salvador: Occasional kitchen garden plant or staple crop? *Ancient Mesoamerica* **22**: 1–11.
- Sheets, P. D., Lentz, D. L., Piperno, D. R., Jones, J., Dixon, C. C., Maloof, G., and Hood, A. (2012). Ancient manioc agriculture south of the Cerén village, El Salvador. *Latin American Antiquity* **23**: 259–281.
- Sheets, P. D., and Woodward, M. (2002). Cultivating biodiversity: Milpas, gardens, and the Classic period landscape. In Sheets, P. D. (ed.), *Before the Volcano Erupted: The Ancient Cerén Village in Central America*, University of Texas Press, Austin, pp. 184–191.
- Shepard Jr., G. H., Neves, E., Clement, C. R., Lima, H., Moraes, C., and dos Santos, G. M. (2020). Ancient and traditional agriculture in South America: Tropical lowlands. In *Oxford Research Encyclopedia of Environmental Science*, Oxford University Press, Oxford, pp. 1–48.
- Siemens, A. H. (1996). Benign flooding on tropical lowland floodplains. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City, pp. 132–144.
- Siemens, A. H. (1998). *A Favored Place: San Juan River Wetlands, Central Veracruz, AD 500 to Present*, University of Texas Press, Austin.
- Siemens, A. H., and Puleston, D. E. (1972). Ridged fields and associated features in southern Campeche: New perspectives on the lowland Maya. *American Antiquity* **37**: 228–239.
- Slotten, V., and Lentz, D. L. (2021). Trees, shrubs, and forests at Joya de Cerén, a Late Classic Mesoamerican village. *Quaternary International* **593–594**: 270–283.
- Slotten, V. M., Lentz, D. L., and Sheets, P. D. (2020). Landscape management and polyculture in the ancient gardens and fields at Joya de Cerén, El Salvador. *Journal of Anthropological Archaeology* **59**: 1–12.
- Smyth, M. P., Dore, C. D., and Dunning, N. P. (1995). Interpreting prehistoric settlement patterns: Lessons from the Maya center of Sayil, Yucatan. *Journal of Field Archaeology* **22**: 321–347.
- Smyth, M. P., Dunning, N. P., Weaver, E. M., Beynen, P. V., and Ortegón Zapata, D. (2017). An enigmatic Maya center: Climate change, settlement systems, and water adaptations at Xcoch, Puuc region, Yucatán. In Rubenstein, M. (ed.), *Recent Investigations in the Puuc Region of Yucatán*, Archaeopress Oxford, pp. 3–23.
- Solleiro-Rebolledo, E., Cabadas-Báez, H. V., Pi, P. T., González, A., Fedick, S. L., Chmilar, J. A., and Leonard, D. (2011). Genesis of hydromorphic calcisols in wetlands of the northern Yucatan Peninsula, Mexico. *Geomorphology* **135**: 322–331.
- Šprajc, I., Dunning, N. P., Štajdohar, J., Hernández Gómez, Q., Chato López, I., Marsetič, A., et al. (2021). Ancient Maya water management, agriculture, and society in the area of Chactún,

- Campeche, Mexico *Journal of Anthropological Archaeology* **61**: <https://doi.org/10.1016/j.jaa.2020.101261>
- Sweetwood, R. V., Terry, R. E., Beach, T., Dahlin, B. H., and Hixson, D. (2009). The Maya footprint: Soil resources of Chunchucmil, Yucatán, Mexico. *Soil Science Society of America Journal* **73**: 1209–1220.
- Terry, R. E., Brown, B. M., Stanton, T. W., Ardren, T., Anaya, T. C., Lowry, J., et al. (2022). Soil biomarkers of cacao tree cultivation in the sacred cacao groves of the northern Maya Lowlands *Journal of Archaeological Science: Reports* **41**: <https://doi.org/10.1016/j.jasrep.2021.103331>
- Thompson, A. E., and Prufer, K. M. (2021). Household inequality, community formation, and land tenure in Classic period lowland Maya society. *Journal of Archaeological Method and Theory* **28**: 1276–1313.
- Thurston, T. L., and Fisher, C. T. (eds.) (2007). *Seeking a Richer Harvest: The Archaeology of Subsistence Intensification, Innovation, and Change*, Springer, New York.
- Toensmeier, E. (2007). *Perennial Vegetables: From Artichokes to "Zuiki" Taro, a Gardener's Guide to Over 100 Delicious, Easy-to-Grow Edibles*, Chelsea Green, White Water Junction, VT.
- Tourtellot, G. (1988). Developmental cycles of households and houses at Seibal. In Wilk, R. R., and Ashmore, W. (eds.), *Household and Community in the Mesoamerican Past*, University of New Mexico Press, Albuquerque, pp. 97–120.
- Tourtellot III, G., Estrada Belli, F., Rose, J. J., and Hammond, N. (2003). Late Classic Maya heterarchy, hierarchy, and landscape at La Milpa, Belize. In Scarborough, V. L., Valdez Jr., F., and Dunning, N. P. (eds.), *Heterarchy, Political Economy, and the Ancient Maya: The Three Rivers Region of the East-Central Yucatán Peninsula*, University of Arizona Press, Tucson, pp. 37–51.
- Tourtellot III, G., Rose, J. J., Grube, N., Donaghey, S., and Hammond, N. (1994). More light on La Milpa: Maya settlement archaeology in northwestern Belize. *Mexicon* **16**: 119–124.
- Trombold, C. D., and Israde-Alcantara, I. (2005). Paleoenvironment and plant cultivation on terraces at La Quemada, Zacatecas, Mexico: The pollen, phytolith and diatom evidence. *Journal of Archaeological Science* **32**: 341–353.
- Turner II, B. L. (1974). Prehistoric intensive agriculture in the Maya Lowlands. *Science* **185**: 118–124.
- Turner II, B. L. (1978a). Ancient agricultural land use in the central lowlands. In Harrison, P. D., and Turner II, B. L. (eds.), *Pre-Hispanic Maya Agriculture*, University of New Mexico Press, Albuquerque, pp. 163–183.
- Turner II, B. L. (1978b). The development and demise of the swidden thesis of Maya agriculture. In Harrison, P. D., and Turner II, B. L. (eds.), *Pre-Hispanic Maya Agriculture*, University of New Mexico Press, Albuquerque, pp. 13–22.
- Turner II, B. L., and Harrison, P. D. (1983). *Pulltrouser Swamp: Ancient Maya Habitat, Agriculture, and Settlement in Northern Belize*, University of Texas Press, Austin.
- von Schwerin, J., Richards-Rissetto, H., Remondino, F., Spera, M. G., and Auer, M. (2016). Airborne LiDAR acquisition, post-processing and accuracy - Checking for 3D webGIS of Copan, Honduras. *Journal of Archaeological Science: Reports* **5**: 885–904.
- Wahl, D., Schreiner, T., Byrne, R., and Hansen, R. (2007). A paleoecological record from a Late Classic Maya reservoir in the north Petén. *Latin American Antiquity* **18**: 212–222.
- Walden, J. P., Hoggarth, J. A., Ebert, C. E., Fedick, S. L., Biggie, M., Meyer, B., et al. (2023). Classic Maya settlement systems reveal differential land use patterns in the upper Belize River valley. *Land* **18**: 483. <https://doi.org/10.3390/land12020483>.
- Weiss-Krejci, E., and Sabbas, T. (2002). The potential role of small depressions as water storage features in the central Maya Lowlands *Latin American Antiquity* **13**: 343–367.
- White, C. D. (ed.) (1999). *Reconstructing Ancient Maya Diet*, University of Utah Press, Salt Lake City.
- Whitmore, T. M., and Turner II, B. L. (2001). *Cultivated Landscapes of Middle America on the Eve of the Conquest*, Oxford University Press, Oxford.
- Wilk, R. R. (1985). Dry season agriculture among the Kekchi Maya and its implications for prehistory. In Pohl, M. (ed.), *Prehistoric Lowland Maya Environment and Subsistence Economy*, Papers of the Peabody Museum of Archaeology and Ethnology Vol. 77, Harvard University Press, Cambridge, pp. 47–57.
- Wilken, G. C. (1987). *Good Farmers: Traditional Agricultural Management in Mexico and Central America*, University of California Press, Berkeley.

- Wingard, J. D. (1996). Interactions between demographic processes and soil resources in the Copan Valley, Honduras. In Fedick, S. L. (ed.), *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, University of Utah Press, Salt Lake City, pp. 207–235.
- Winzler, S., and Fedick, S. L. (1995). Ancient wells and water resources of Naranjal and the Yalahau region. In Fedick, S. L., and Taube, K. A. (eds.), *The View from Yalahau: 1993 Archaeological Investigations in Northern Quintana Roo, Mexico*, Field Report Series No. 2, Latin American Studies Program, University of California, Riverside, pp. 101–113.
- Wittfogel, K. A. (1957). *Oriental Despotism: A Comparative Study of Total Power*, Yale University Press, New Haven.
- Wright, A. C. S., Romney, D. H., Arbuckle, R. H., and Vial, E. (1959). *Land in British Honduras: Report of the British Honduras Land Use Survey Team*, Her Majesty's Stationery Office, London.
- Wyatt, A. (2020). Gardens of the Maya. In Masson, M. A., Freidel, D. A., and Demarest, A. A. (eds.), *The Real Business of Ancient Maya Economies: From Farmers' Fields to Rulers' Realms*, University Press of Florida, Gainesville, pp. 187–209.
- Wyatt, A. R. (2012). Agricultural practices at Chan: Farming and political economy in an ancient Maya community. In Robin, C. (ed.), *Chan: An Ancient Maya Farming Community*, University Press of Florida, Gainesville, pp. 71–88.
- Wyatt, A. R. (2014). The scale and organization of ancient Maya water management. *WIREs Water* **1**: 449–467.

## Bibliography of Recent Literature

- Beach, T., Luzzadder-Beach, S., Cook, D., Dunning, N., Kennett, D. J., Krause, S., et al. (2015). Ancient Maya impacts on the earth's surface: An early Anthropocene analog? *Quaternary Science Reviews* **124**: 1–30.
- Beach, T., Luzzadder-Beach, S., Krause, S., Walling, S., Dunning, N., Flood, J., Guderjan, T., and Valdez, F. (2015). 'Mayacene' floodplain and wetland formation in the Rio Bravo watershed of northwestern Belize. *The Holocene* **25**: 1612–1626.
- Chase, A. S. Z., Chase, D. Z., and Chase, A. F. (2017). LiDAR for archaeological research and the study of historical landscapes. In Masini, N., and Soldovieri, F. (eds.), *Sensing the Past: From Artifact to Historical Site*, Springer, Cham, Switzerland, pp. 89–100.
- Dunning, N., Wahl, D., Beach, T., Jones, J., Luzzadder-Beach, S., and McCane, C. (2014). The end of the beginning: Drought, environmental change, and the Preclassic to Classic transition in the east-central Maya Lowlands. In Innone, G. (ed.), *The Great Maya Droughts in Cultural Context: Case Studies in Resilience and Vulnerability*, University Press of Colorado, Boulder, pp. 107–126.
- Dunning, N. P., Beach, T. P., and Luzzadder-Beach, S. (2012). Kax and kol: Collapse and resilience in lowland Maya civilization. *Proceedings of the National Academy of Sciences* **109**: 3652–3657.
- Dunning, N. P., Weaver, E., Smyth, M. P., and Ortegón Zapata, D. (2014). Xoch: Home of ancient Maya rain gods and water managers. In Stanton, T. W. (ed.), *The Archaeology of Yucatán*, Archaeopress, Oxford, pp. 65–78.
- Graham, E., MacPhail, R., Crowther, J., Turner, S., Stegemann, J., Arroyo-Kalin, M., et al. (2016). Past and future earth: Archaeology and soil studies on Ambergris Caye, Belize. *Archaeology International* **19**: 97–108.
- Isendahl, C., Scarborough, V. L., Gunn, J. D., Dunning, N. P., Fedick, S. L., Iannone, G., and Lucero, L. J. (2019). Applied perspectives on pre-Columbian Maya water management systems: What are the insights for water security? In Isendahl, C., and Stump, D. (eds.), *The Oxford Handbook of Historical Ecology and Applied Archaeology*, Oxford University Press, Oxford, pp. 506–523.
- Kunen, J. L. (2004). *Ancient Maya Life in the Far West Bajo: Social and Environmental Change in the Wetlands of Belize*, Anthropological Papers Vol. 69, University of Arizona Press, Tucson.
- Liendo, R., Solleiro-Rebolledo, E., Solis-Castillo, B., Sedov, S., and Ortiz-Pérez, A. (2014). Population dynamics and its relation to ancient landscapes in the northwestern Maya Lowlands: Evaluating resilience and vulnerability. *Archeological Papers of the American Anthropological Association* **24**: 84–100.

- Lucero, L. J. (2006). *Water and Ritual: The Rise and Fall of Classic Maya Rulers*, University of Texas Press, Austin.
- Lucero, L. J., Fedick, S. L., Dunning, N. P., Lentz, D. L., and Scarborough, V. L. (2014). Water and landscape: Ancient Maya settlement decisions. *Archeological Papers of the American Anthropological Association* **24**: 30–42.
- McAnany, P. A. (2014). *Living with the Ancestors: Kinship and Kingship in Ancient Maya Society*, rev. ed., Cambridge University Press, New York.
- Turner II, B. L., and Sabloff, J. A. (2012). Classic period collapse of the central Maya Lowlands: Insights about human–environment relationships for sustainability. *Proceedings of the National Academy of Sciences* **109**: 13908–13914.

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