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Agriculture in the Ancient Maya Lowlands (Part 1): Paleoethnobotanical Residues and New Perspectives on Plant Management

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Abstract

We focus on pre-Columbian agricultural regimes in the Maya Lowlands, using new datasets of archaeological wood charcoal, seeds, phytoliths, and starch grains; biological properties of plants; and contemporary Indigenous practices. We address inherited models of agriculture in the lowlands: the limitations of the environment (finding more affordances than anticipated by earlier models); the homogeneity of agricultural strategies (finding more heterogeneity of strategies across the lowlands than a single rigid template); the centrality of maize in agriculture (finding more reliance on root crops and tree crops than historically documented); the focus on the milpa system as food base (finding more agroforestry, homegardening, horticulture, and wild resource management than previously documented); the dominance of swidden strategies in agricultural practices (finding more diverse practices than accounted for in most models); and the foregrounding of maize crop failure in collapse models (finding more evidence of resilience and sustainable agricultural practices than predicted).

Keywords Maya Lowlands · Agriculture · Milpa · Homegarden · Managed successional cropping system · Paleoethnobotany

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Introduction

Agriculture in tropical environments takes many forms, as agricultural practices are diverse and even definitions of "tropical environment" vary widely. In this article, we focus on agricultural regimes in the Maya Lowlands, synthesizing investigations from the past several decades, indicating new research directions, and revealing complications in old models. Two of the most persistent debates in Maya history are the relative importance of swidden cultivation of the milpa (maize field cropping system) and the relative centrality of maize in subsistence regimes. Regardless of the specific agricultural model they use, however, scholars rarely debate the role maize-focused milpa subsistence would have played directly or indirectly in the abandonment of Maya cities. Here, we address cultivation of other plants besides maize—particularly root crops, legumes, and tree fruits – and techniques besides swidden cultivation—particularly homegarden horticulture, agroforestry, and the management of wild areas and milpas undergoing managed succession. In this reframing, ongoing labor regimes, daily subsistence practices, movement of foodstuffs in tax and trade, responses to environmental challenges, social strife related to crop failure, and abandonment of communities are all implicated.

In the following passages, we offer general context for the Maya Lowlands, an area encompassing a number of vegetation communities and environmental conditions, from evergreen rainforests, to seasonally dry forests, to semi-dry savannahs. We present traditional understandings of agricultural practice in the Maya Lowlands, understandings grounded frequently in ethnohistoric and ethnographic research from the Spanish colonial era through the 1980s. We then synthesize contemporary approaches to revisit old questions, drawing on new datasets from analyses of archaeological wood charcoal, seeds, phytoliths, and starch grains; biological properties of plants including pollination regimes; and contemporary Indigenous uses of food plants. We integrate these approaches to develop an updated picture of lowland Maya agriculture, revisiting Fedick's (1996c) description of the "managed mosaic."

Agricultural strategies across the Maya area, as in other tropical environments, require water management (to supplement or reduce), dampness management (especially of grains), frequent need for clearing of vegetation (given rapid growth), frequent need for weeding (given rapid growth), constant management of insect pests (given lack of freezing temperatures), and management of soil fertility (to control for acidity, nutrient content, organic matter, and salinity). Here we focus primarily on plants and cultivation systems, leaving detailed examination of landscape engineering and soil management (e.g., terraces and raised/drained wetland fields, fertilization, use of soil microenvironments) to a separate treatment (Fedick et al. in press). We present an in-depth review of literature published since the 1990s, when ancient agricultural research in the Maya area saw a turning point in approaches and datasets. We focus on published data from the Formative through the Classic periods, sourced from across the Maya Lowlands (Fig. 1), although studies from larger city centers, Classic period occupations,

Fig. 1 Map of Maya area archaeological sites mentioned in the text. Two circles indicate Rio Bravo study area (N) and upper Belize River valley study area (S) (Map by Lydie Dussol)

and the southern lowlands are much more robustly represented in the available literature.

This review of over 120 studies with paleoethnobotanical data allows us to develop new perspectives on agricultural techniques of the Formative and Classic periods, and to discuss the implications of revised agricultural modeling on current collapse models. Comparing this new synthesis with earlier understandings of agricultural practice, we illuminate the general heterogeneity of strategies that Maya people used in the lowlands as they negotiated dynamic socio-environmental contexts. However, we do not address specific spatial-temporal patterns of plant cultivation, domestication, or diffusion. These are different research questions that require extensive datasets for each plant to be addressed, dating back to at least the Archaic period, and such datasets are not yet available.

Comparing this new synthesis with earlier understandings of pre-Columbian agricultural practice, we illuminate the general heterogeneity of strategies that Maya people used in the lowlands as they negotiated social contexts. Despite this overall heterogeneity, we see a few general trends in recent datasets that raise new questions and methodological challenges for future research, regarding 1) characterizations of lowland Maya environments (affordances and limitations); 2) homogeneity of agricultural strategies (milpa, etc. vs. managed mosaic); 3) centrality of maize in subsistence and agriculture (vs. root crops, tree crops, and non-domesticates); 4) centrality of the milpa system as food base (vs. incorporation of agroforestry, homegarden horticulture, wild collection); 5) preponderance of swidden strategies in agricultural practices (vs. high diversity in agricultural practices); and 6) dominance of maize crop failure in societal collapse models. We ground our understandings in traditional knowledge of sustainable agricultural practices and forest management and consider the application of such approaches elsewhere in the global tropics.

This synthesis contributes to broader understandings of tropical agriculture by providing refinements to collapse models and insights into modes of resilience. Discussions of the Terminal Classic "collapse," both academic and popular, invoke agricultural collapse under conditions of extended or repeated droughts and, in some cases, overpopulation. These scenarios imply that the ancient Maya system of agriculture was inherently unstable and inflexible, leading to the wholesale abandonment of communities and widespread social collapse. Through the synthesis of new evidence, we challenge persistent assumptions regarding agricultural strategies and products, given that new research reveals overall diversity of subsistence strategies and new insights into resilience and sustainability.

Agriculture in the Tropical Maya Lowlands: Historical Models and Approaches through the 1980s

To understand the history of the "outsider" perspective on Maya agriculture that has dominated the literature since Spanish colonial times, it is helpful to first consider agriculture as practiced in Spain during the early 16th century. At that time, agricultural practices in Spain were heavily dominated by annual species cultivated by plow tillage. The author of *Perennial Vegetables* (Toensmeier 2007) notes that agriculture in Spain, at the time of contact with peoples of the Americas, was heavily dependent on annual crops of grains (wheat, barley, rye, oats, millet) and pulses (chickpeas, broad beans, lentils), supplemented with a small number of perennial fruits, nuts, and vegetables. Plow cultivation in Europe selected for annual crops, while hand cultivation selected for perennial crops in the American tropics (Toensmeier 2007, p. 7). For comparative purposes, fairly complete lists of crops cultivated in Spain before 1492 are provided by Hernández-Bermejo and León (1994) and Dunmire (2004). *Obra de Agricultura*, an agricultural "handbook" first assembled in 1513, details the crops most widely grown in Spain at the time and stresses the domination of the plow for cultivation (see Arellano 2006 for a partial English translation).

In the Maya area, Spanish soldiers and religious clerics who arrived to conquer and settle the Yucatan Peninsula brought with them clear expectations of good agricultural land and the types of crops that represented proper foods. What they found, from their perspective, was a land distinctly lacking in both. The vast limestone shelf that makes up the Yucatan Peninsula was characterized, with a few localized exceptions, as having shallow soils with common patches of exposed bedrock, ill-suited for plow cultivation and, thus, lacking in true arable land.

Later archaeologists attended to these historic accounts, and agricultural practices held particular importance in initial studies in the Maya area. In the mid-20th century, archaeologists developed a rich set of analogies to apply to ancient Maya practices by using ethnographic and historical literature. Unfortunately, such analogies were often applied wholesale in studies of ancient Maya agriculture. For many years, early ethnographic and ethnohistoric descriptions of agriculture served as the starting point for discussion, whether or not such frameworks were then critically reassessed using updated datasets.

Many early works began with Friar Diego de Landa's 16th century account of *The Things of Yucatan*. De Landa described Yucatan as "... the country with least earth that I have seen, since all of it is one living rock ..." (Tozzer 1941, p. 186). Similarly, Francisco de Montejo, the eventual conqueror of Yucatan, reported in 1534 to the Spanish crown that there was "not a single square foot of soil" in Yucatán (Chamberlain 1948, p. 164). While these early Spanish chroniclers engaged in a bit of negative exaggeration, most lands of the Yucatan Peninsula are in fact poorly suited to tillage by plow and, therefore, were very limited for "proper" agricultural production from the perspective of European farmers. Furthermore, when the Spanish first encountered the Maya, they were exposed to food plants that were novel and difficult to accept as proper food (Schwartz 1990, pp. 54–55). Although early Spaniards did come to recognize maize and beans as closest to the European staples that they were used to (Farriss 1984, p. 33), much early writing shoehorns these crops into European agricultural models.

Other oft-cited works in early archaeological studies include early ethnographic accounts, like the work of Redfield and Villa Rojas in 1934 (Redfield et al. 1962), who wrote about Maya lifeways in northern Yucatan during the earlier part of the 20th century. Benedict and Steggerda (1936) also attempted to quantify relative contributions of different foods to Maya diets, relating these in a more limited way to agricultural activities. Such early accounts coalesced several key expectations for crops and agricultural activities in the ancient past.

First, domesticated species did not stray far from maize, beans, and various squashes. In discussions of agriculture, this "triad" of taxa was presumed to provide the primary source of sustenance, with maize as an outsized cornerstone (e.g., de Landa 1978 [1566]; Redfield et al. 1962; Tozzer 1907, 1941). Iconographic and epigraphic representations of agricultural products, dating to before Spanish contact, emphasize the maize and cacao prized by royalty and rulers (e.g., Beliaev et al.

2010; Stuart 2006; Taube 1989), and much less frequently reference other identifiable economic species (e.g., Schele and Mathews 1999; see also Santini 2016, pp. 262–271). Across ethnohistoric and early ethnographic sources, maize, beans, and squashes were framed as ubiquitous and dominant in cuisine, in spite of the variety of ingredients and cooked dishes also referenced by these early authors, including wild and managed species (de Landa 1978 [1566]), pp. 101–107) and roots and tubers (de Landa 1978 [1566], pp. 101–107; Redfield et al. 1962; Tozzer 1907, 1941). Even in the sacred *Chilam Balam of Chumayel*, the sweet potato is identified specifically as an element among the four sets of objects belonging to the "Four Quarters of the World" (Roys 1967, p.63). Such attention to the sweet potato implicates its importance in the cosmological as well as the quotidian.

Second, although we glimpse nuance in early descriptions of agricultural practices and crops, including management of wild resources, homegarden horticulture, and foraging activities (de Landa 1978 [1566], pp. 101–107), consistently the presumed mode of food production was the outfield milpa system. Scholars perceived a dichotomy between forests and fields, as deduced from Postclassic and Spanish colonial period cosmogonies in which the world was represented as a quadrangular maize field and reflected antagonism between the domesticated human world and the wild forest occupied by feral animals (see Taube 2003). In this system, fields are modeled at a remove—and sometimes at great distance—from settlements.

Third, and related to this premise, the default agricultural practice modeled in outfield milpas was a particular form of swidden. In this swidden model, initial extensive clearing takes place using a slash-and-burn method. Cleared fields then pass through cycles of high production, then fallowing, then clearing and burning of fallow vegetation to prepare plots anew (Dumond 1961; Reina 1967). Scholars have more recently documented variation in types of swidden (e.g., Ford and Nigh 2016) and its ecological effects (Ferguson et al. 2003), suggesting that swidden practices may sometimes be optimal for tropical environments. But in the dominant model used by archaeologists, swidden practices have been characterized primarily as destructive (Abrams and Rue 1988; Sanders 1973; Turner II and Sabloff 2012). The destructive capacity of swidden agriculture was pervasive and amplified once population densities exceeded the presumed low carrying capacity of such an agricultural system (cf. Russell 1988). In these models, exceeding the carrying capacity resulted in radical deforestation, soil exhaustion, soil erosion, elimination of biodiversity, and even anthropogenic transformations to local climates.

Fourth, Classic period social organization around agricultural production and foraging of wild resources was assumed to be mainly reactive, local, family centered, and subsistence based, instead of proactive and mapped across varying sociopolitical contexts. This model did not include the centralization and/or specialization of production and redistribution, as is documented for the Postclassic and Spanish colonial periods (Masson and Freidel 2012). As a consequence, few strategies of risk management were anticipated in earlier frameworks, particularly water management in times of drought, as the dominant model was of exclusively rainfed agriculture.

Archaeologists through the 1980s built models of social dynamics on the scaffolding of these limited cultivated species, agricultural practices, and perspectives of the environment. Social models for the ancient Maya emphasized land ownership, tax and tribute, and trade, where maize served as impetus for labor, product for tribute, and common marketplace foodstuff. In these hierarchical social models, ubiquitous swidden milpa agriculture resulted in a host of environmental issues that in turn led to a host of societal problems. These troubles were linked to the large-scale abandonment of city centers in the southern Maya Lowlands and collapse of political systems, if not entire regional populations (see Aimers 2007).

Scholars working in the latter half of the 20th century initially focused on similar themes, by foregrounding maize and extensive swidden agricultural practices. But new techniques and hypotheses also began to expand knowledge in other directions. Some early scholars signaled caution in using the direct-historic approach to construct usable analogies, and models began to emerge that were experimental (e.g., Puleston 1971) and cross-culturally comparative (e.g., Drucker and Fox 1982). Types of archaeological evidence began to include palynological profiles (e.g., Turner II and Harrison 1981), isotopic signatures (e.g., White and Schwarcz 1989), and chemical residues (e.g., Hurst et al. 1989), as well as amplified datasets from paleoethnobotanical research and settlement studies (e.g., McClung de Tapia 1985; Sheets 1982; Zier 1980). Types of archaeological queries began to shift from description toward systems approaches (e.g., Sharer 1977), cultural ecology (e.g., Sanders 1962), and political economy (e.g., Culbert 1977). Labor estimates, caloric counts, crop yields, and carrying capacities began to be calculated, and the origins of domesticated crops began to be carefully tracked (e.g., Cowgill 1962; Dumond 1961; Wiseman 1978). In social modeling, debates arose surrounding the classification of Maya states versus Maya chiefdoms, the movement of grain in tax and tribute, and the particular forms of social hierarchy in the Maya area (e.g., Culbert 1977; Hosler et al. 1977; Sharer 1977). As in other tropical environments (Shepard et al. 2020), however, scholars increasingly found that resources were richer and more varied than earlier models anticipated (Harrison and Turner II 1978; Wilken 1971), that societies were more densely populated and socially diverse (Drucker and Fox 1982; Hellmuth 1977), and that long-distance exchange factored more heavily in subsistence strategies (Voorhies 1982).

In the later part of the 20th century, scholars began to explore the role of root crop cultivation (Bronson 1966; Hellmuth 1977; Sheets 1982), silviculture (Gómez-Pompa 1987; Hellmuth 1977; Sheets 1982), raised fields, terraces, and similar agricultural strategies (Harrison 1977; Puleston 1977; Wilken 1971). Many of their approaches were rooted in earlier ethnographic and historic paradigms. But the turn toward global perspectives on tropical agriculture amplified the potential range of activities that could be investigated in the Maya area, especially regarding complex agricultural intensification strategies that were used in combination with extensification strategies.

The suite of key cultivated species was also amplified in the latter part of the 20th century. Bronson (1966), using data on modern root crop distribution, information from early conquest times, and lexical and nutritional data, made a relevant argument for the use of root crops in pre-Columbian times. Models of domesticated species began to shift in response to paleoethnobotanical work across the Maya Lowlands. Hammond and Miksicek (1981) identified fragments of manioc stems at the site of Cuello, Belize. From macrobotanical residues, Sheets (1982) in El Salvador, Beltrán Frías (1987) in Quintana Roo, and Turner and Miksicek (1984) in Belize identified a wide spectrum of seed, root, and tree crops cultivated, as well as their integration with noncultigens. Hellmuth (1977) identified a wide variety of wild, managed, and cultivated resources from historic documents, highlighting root crops and tree crops.

In response to changing understandings of food procurement and production, political and economic models of Maya society also began to shift in latter 20th century studies. One classic approach taken by Coe and Diehl (1980) modeled agrarian surpluses that undergirded increasing sociopolitical complexity (in Killion 2013). This model—described for the Olmec—was mirrored in the Maya area. The movement of goods through social and settlement hierarchies relied on extensive cultivation (through swidden practices) of grain crops that were resistant to rot (as opposed to root crops) and produced at a surplus (not simply for subsistence). By the 1980s, however, interdisciplinary studies began to produce more nuanced models (Hammond and Miksicek 1981). Subsequently, in the 1990s, we see continued and sometimes dramatic shifts in conceptualizations of ancient Maya agriculture.

Ancient Problems and New Approaches: Agricultural Publications since the 1990s

Since 1990, archaeological studies, especially those employing paleoethnobotanical methods, have begun to further complicate a direct-historical picture of the past. Scholars have critically reappraised earlier agricultural models in response to investigations of land management (e.g., Dunning et al. 1998; Fedick 1996b, c), water management (e.g., Scarborough 1993), ethnographic understandings of indigenous food plants (e.g., Fedick 2020) and cultivation systems (e.g., Ford and Nigh 2016), and recovered botanical residues (e.g., Crane 1996; Lentz 1999; Lentz et al. 2005; McNeil 2002). Some of these studies have been produced with models of social dynamics already in mind, while other studies have been used as the means to generate models of social dynamics.

New social questions have emerged over the past few decades, in the same way that theoretical trends in social sciences have impacted the questions asked about agricultural practices generally (see Morehart and Morell-Hart 2015; Morell-Hart 2014, 2020; Venegas Durán 2019). Such paradigm shifts have turned attention to the semiotics of agricultural landscapes (e.g., as multivalent places of growing, sacred offering, disposal, food collection, and fallowing for hunting and herb collection), basic understandings of edibility and food preferences (e.g., maize vs. root crops), varied perspectives on agricultural production (e.g., indebted farmer vs. attached kitchen specialist vs. local ruler), relationships between agricultural practice and broader ecological activities (e.g., cultivation vs. management vs. collection), political control and tribute (e.g., preservation and transport of commodities like cacao beans vs. local use of plants like fleshy cacao fruits), gendered aspects of agricultural and horticultural or gardening practices (e.g., proxemics and meanings of infield practices vs. outfield practices), and relationships between agricultural structuration and *habitus* (e.g., the persistence of digging stick use over time, as related to assumptions about the value of using a digging stick, as related to the persistence of digging stick use over time, and so on).

Interpretive frameworks—linked directly to the types of queries described above—have drawn from amplified ethnographic information and attention to traditional ecological knowledge (TEK). Studies since the 1990s have recognized traditional knowledge of indigenous food plants in the Maya Lowlands, sustainable agricultural practices, forest management, and understandings of agricultural spaces and places (e.g., Anderson 1995; Atran 1993; Hanks 1990). Social models, broadly, have shifted from cultural ecological models and environmental determinism toward historical ecological and ethnoecological models that consider relationships to be dynamic and human actions to have impact on surrounding landscapes as much as the reverse. As Alexander (2006, p. 450) has noted, "it is erroneous to explain Maya settlement as a 'cultural survival' because it misconstrues the long-term and historically contingent processes by which anthropogenic landscapes are created." The emergence of anthropogenic landscapes is a dynamic process of co-creation, impacted and contextualized by long- and short-term processes.

Apart from shifts in types of social questions and interpretive frameworks, shifts in basic types of data and their collection have also expanded our views of tropical agriculture at the empirical level. Shifts in data collection have included where and how we sample (see D'Alpoim Guedes et al. 2015), with scholars targeting more households and smaller sites (vs. large city centers), engaging in more blanket sampling (vs. simply targeting hearths and tombs), and exploring more rural areas (for agricultural features and soil chemistry studies). Some traditional methods in data collection, including GIS and spatial archaeology, soil studies, isotopic analysis, usewear studies, ecology modeling, and ethnographic data, have undergone a sharp uptick and more refinement, as methods have improved. Other datasets have also seen significant shifts, as analyses of phytoliths, starch grains, wood remains, paleofire signals, plant genetics, and plant biology have been initiated or augmented with advancements in sister fields. Meanwhile, the use of LiDAR has thrown agricultural features literally into high relief (Golden et al. 2021; Schroder et al. 2020).

We next outline the results of these methodological and theoretical developments, demonstrating how new types of questions and refinements in data collection since 1990 have led to broad challenges to several inherited models related to the characterization of lowland Maya environments (affordances and limitations), the homogeneity of agricultural strategies (milpa, etc. vs. managed mosaic), the centrality of maize in agriculture (vs. root crops and tree crops, etc.), the centrality of the milpa system as food base (vs. agroforestry, homegarden horticulture, wild collection), the preponderance of swidden strategies in agricultural practices (vs. other diverse agricultural strategies), and the dominance of crop failure in collapse models (vs. drought resilience of crops, social issues, trade route shifts, ceremonial warfare). We review the results of these new methods and models in detail, synthesizing published literature from 1990 to 2020.

Maya Agriculture: A Managed Successional Cropping System

We begin with broad characterizations of lowland Maya environments and the diverse agricultural strategies used by ancient Maya farmers to negotiate these environments, expanding beyond swidden strategies as the sole practice and the milpa system (and specifically maize) as the sole food base. One emerging perspective on Maya agriculture represents a distinct break with the traditional milpa/fallow model described above and replaces it with a broader ecological model of a managed successional cropping system (Ford and Nigh 2016; Gómez-Pompa 1987; Hart 1980; Vieira et al. 2009). This perspective characterizes succession without the need for naming specific species. Modeling a managed successional cropping system instead identifies shifting proportions of physiological categories of encouraged plants, from pioneering sun-loving annuals, to fast-growing herbaceous perennials, to fast-growing woody perennials, to shade-tolerant perennials, climax tree species, and multistrata structure (similarly to landscape management described by Doolittle 2000). In contemporary practice, Maya cultivation takes place in spatial and temporal units that effectively "freeze" plant succession at various stages and in locations that provide a wide range of managed habitats and species mixes. As Gómez-Pompa noted (1987, p. 9), "each abandoned milpa is an empirical experiment in directed succession." The various managed habitats—including milpas, milpas undergoing managed succession, homegardens, managed wetlands, and forest gardens—differ in form, setting, and content.

Furthermore, contemporary Maya people have an available cornucopia of at least 497 species of indigenous food plants (Fedick 2020), and it is likely that an equally high number of plants was available in the past. Pollen analysis (e.g., Beach et al. 2019; McNeil et al. 2010; Rushton et al. 2020), isotopic analysis (e.g., Scherer et al. 2007; Somerville et al. 2013; Tykot 2002), relict forest studies (e.g., Benz et al. 1997; Campbell et al. 2006; Ross 2008; Thompson et al. 2015b), and chemical residue analyses of aDNA (e.g., Lentz et al. 2021), isotopes (e.g., Coyston 2002), lipids and other biomarkers (e.g., Hall et al. 1990; King et al. 2022; Mirón Marván 2014; Powis et al. 2002; Prufer and Hurst 2007; Spenard et al. 2020) have all factored heavily into understandings of ancient food consumption in the Maya Lowlands. Given space limitations, we focus here on archaeological food residues including seeds, fruits, phytoliths, and starch grains, as well as residues from wood charcoal (some food related), reviewing over 120 sources published since 1990. We have compiled these citations for recovered botanical remains of key cultivated species in a supplemental table (Supplemental Table 1), arranged by taxonomic identification.

Below, we consider evidence for traditional maize milpa agriculture, cultivation of root crops, cultivation and management of food taxa outside the milpa (e.g., homegardens and agroforestry), and other food taxa that complement cultivation (e.g., foods from milpas undergoing managed succession). We highlight consistencies with earlier understandings and challenges to earlier assumptions, based on new evidence and approaches.

We arrange the following sections according to increasing distance from the home (similar to Anderson 1995; Hanks 1990; Killion 1990) as well as the plants generally found within each stage of succession, moving from homegardening, to milpa cycling, to forest gardening. In these sections, we focus on the plants corresponding with each type of location and note the high redundancy in species between some locations, a redundancy that also indexes some overlap in practice. Homegardens were generally closest to the home, milpas further afield, and forests and formal orchards generally most distant from the home, including areas that held managed as well as cultivated plants. We highlight the general diversity of food plants, finding that food plants and food residues partially overlap with forest management and wood residues in terms of recovered taxa.

Different forms of agricultural practice could also overlap in a single locale, as horticulture and homegardening, milpa cropping, and agroforestry and forest management could all unfold over time a single location. A “forest” or “wetland” could shift into a milpa location, and vice versa. In the next three sections, we emphasize that each type of location is a stage temporarily frozen in a continuum of temporal cycling and spatial organization. This dynamic successional system, thus, encompasses ideas of place, notions of time, categories of plants, and types of practices. Overall, the system has a fluidity that may characterize tropical agriculture strategies more than temperate agriculture strategies. In later sections, we address the management practices that sometimes crosscut these locations.

Homegardening

Ancient Maya farmers, like other farmers across Mesoamerica and North America (Doolittle 2000, 2004; Whitmore and Turner 1992, 2001), did not constrain plant cultivation to the field, nor limit crop plants to only a few annual species. As documented ethnographically in the contemporary Maya Lowlands, homegardens are established in the immediate vicinity of a residence, and the houselot (*solar*) are often bounded by stone walls (Fisher 2014) and living fences (Figs. 2–3). The spatially segregated multistrata homegarden effectively “freezes” several spatially partitioned stages of plant succession, providing the household with a wide range of plant products (De Clerck and Negreros-Castillo 2000; Herrera Castro 1994). Some areas of the homegarden are reserved for sun-loving early successional crops, while other areas are allowed to develop sun-loving, fast-growing woody perennials like chaya and papaya. Other areas come to be dominated, after several years, by shade-tolerant species and fruit trees. Homegardens also contain nonfood plants such as medicinals, pollinator species, and commonly used plants such as indigo (*Indigofera suffruticosa*) that have other economic uses (Herrera Castro 1994).

Tree and Shrub Crops in Homegardens

Fedick (2020) has found 204 species of trees (including 26 palms and two cycads), 52 species of shrubs, and 61 species that can grow as either trees or shrubs, all indigenous to the Maya Lowlands and reported in the ethnographic literature as being used by Maya people as food sources. These findings are consistent with

Fig. 2 Traditional arboriculture in the Maya area: **a** photomicrograph of *Cordia* cf. *dodecandra* (Boraginaceae) archaeological charcoal, photographed in transverse section at 50x (from Dussol et al. 2021a, appendix 2); **b** a *siricote* tree (*Cordia dodecandra*) cultivated for its fruits and beautiful flowers, **c** in a homegarden in the town of Uaxactún, Petén, Guatemala (All photos by Lydie Dussol)

ethnographic findings by Anderson (1995), Atran (1993), Hanks (1990), and Herrera Castro (1994), who indicate that wild and managed stands of forest provide a variety of foodstuffs, and wild trees may be managed within houselots, milpas, and reserves. Jiménez-Osornio and colleagues (2004, 2018) have documented both the diversity and the core set of trees found in Maya homegardens. The many economic tree and shrub species planted and/or tended in contemporary Maya communities include fruit trees such as avocado (*Persea americana)* and guava (*Psidium guajava*), leafy shrubs such as chaya (*Cnidoscolus* spp.), nut trees such as ramón (*Brosimum alicastrum*), and legume trees such as guanacaste (*Enterolobium cyclocarpum)*.

There is abundant archaeological evidence supporting the antiquity of such tree crops across the Maya Lowlands (Figs. 2–4; Supplemental Table 1), whether cultivated in houselots and orchards or managed in forests and "fallow" milpas as they diversify through succession. Thanks to genetic and biological studies of living tree populations, we now know that many fruit-bearing trees have a long history of cultivation and domestication in the pre-Columbian Neotropics (e.g., Clement et al. 2017; Croft 2012; Fuentes and Santamaría 2014; Zarrillo et al. 2018; see also Piperno and Pearsall 1998). Although the status of the Maya Lowlands as an actual center of plant domestication remains unclear (Piperno 2011), local domestication or semi-domestication of certain tree species may have occurred independently thanks to human selection and agricultural manipulation, perhaps as early as the Archaic period (Colunga-García Marín and Zizumbo-Villarreal 2004; see also Doolittle 2000, 2004).

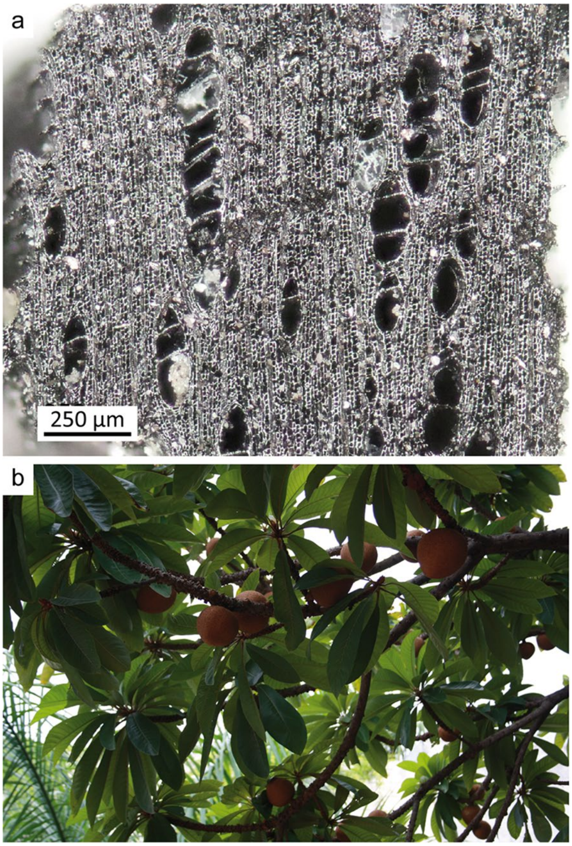

Fig. 3 Traditional arboriculture in the Maya area: **a** Photomicrograph of *Pouteria* type (Sapotaceae) archaeological charcoal, photographed in transverse section at 50x (from Dussol et al. 2021a, appendix 2); **b** a sapote mamey tree (*Pouteria sapota*) cultivated for its fruits and shade in a homegarden in the town of Mérida, Yucatán, Mexico (All photos by Lydie Dussol)

Scholars have primarily identified key tree and shrub crops through macrobotanical, pollen, and phytolith evidence. This evidence serves as an index of ancient Maya consumption of a number of succulent fruits (Supplemental Table 1). Pungent nance *(Byrsonima crassifolia;* Fig. 4a–b), with an extraordinarily durable endocarp, is the succulent fruit taxon most frequently found at sites across the Maya Lowlands. Wood charcoal of *Byrsonima* sp. is also frequently identified in Maya sites. Tart hogplums (*Spondias* spp.) were almost equally beloved across the Maya area. Buttery avocado (*Persea* spp.) was also highly ubiquitous and was clearly a mainstay across Maya communities. Cacao *(Theobroma cacao)*, enjoyed for its fruit but prized for its seeds, is more rarely recovered as macroremains but has been found as a chemical residue. Mealy ramón or breadnut (*Brosimum alicastrum)* has had higher recovery rates as wood but lower recovery rates as fruit or seed. Various sapote and mamey fruits (Sapotaceae spp.) are also quite common across the Maya Lowlands (McKillop 1994; Morehart 2011; Reed 1999), primarily the intensely sweet sapote or mamey *(Pouteria sapota;* Fig. 5) and chicozapote or sapodilla *(Manilkara zapota)*. Wood charcoal identified as Sapotaceae is also very common in Maya sites in the central lowlands.

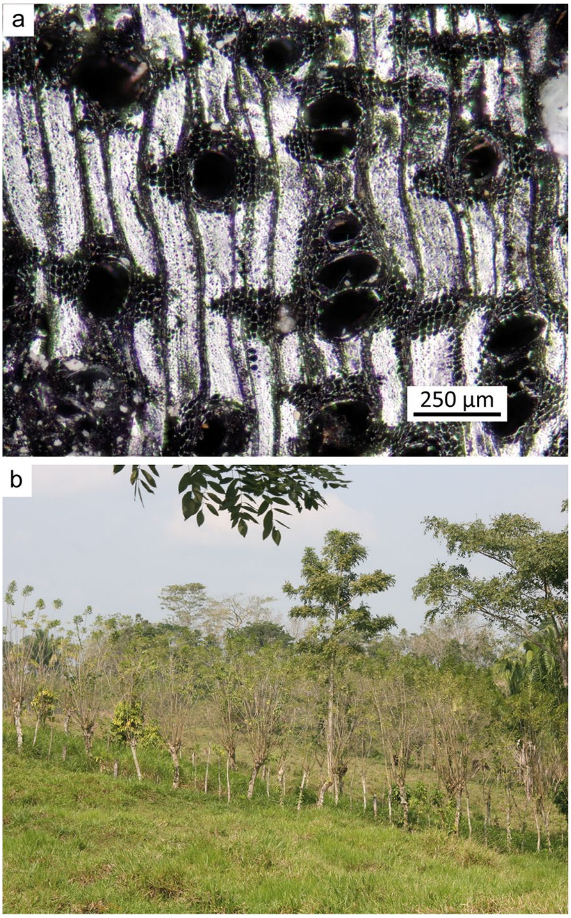

Fig. 4 Traditional arboriculture in the Maya area: **a** Photomicrograph of *Gliricidia sepium* (Fabaceae) archaeological charcoal, photographed in transverse section at 50x (from Dussol et al. 2021a, appendix 2); **b** a typical living fence made of *madre cacao* trees (*Gliricidia sepium*) in a rural area in Alta Verapaz, Guatemala (All photos by Lydie Dussol)

Ancient Maya people also enjoyed numerous other sweet and succulent arboreal fruits, albeit less frequently. These include sweet and tart guaya fruits (*Talisia olivaeformis)*, small hackberries (*Celtis* spp.), siricotes (*Cordia* sp.; Fig. 2), floral guavas (*Psidium guajava)*, and inga or paterno fruits (*Inga* spp.), consumed for the sweet pulpy mass surrounding the inedible seeds. Seeds of tart custard apple, soursop, and annona fruits (*Annona* spp.) have also been recovered at several sites.

Seeds of floral-tasting papaya fruits *(Carica papaya)*—a ubiquitous tree in contemporary times—have only been recovered from a few ancient sites. The guapinol or stinking toe tree (*Hymenaea coubaril*), similar to paterno, was only consumed for the dry mass surrounding the seeds, though in this case, the flavor is savory and yeast like. Guapinol has been recovered in only a few locations. Intensely sugary capulín (*Muntingia calabura)* was likely enjoyed across the southern lowlands, but it has miniscule and difficult-to-find seeds that make it more challenging to recover. Cashew or marañón *(Anacardium occidentale)*,

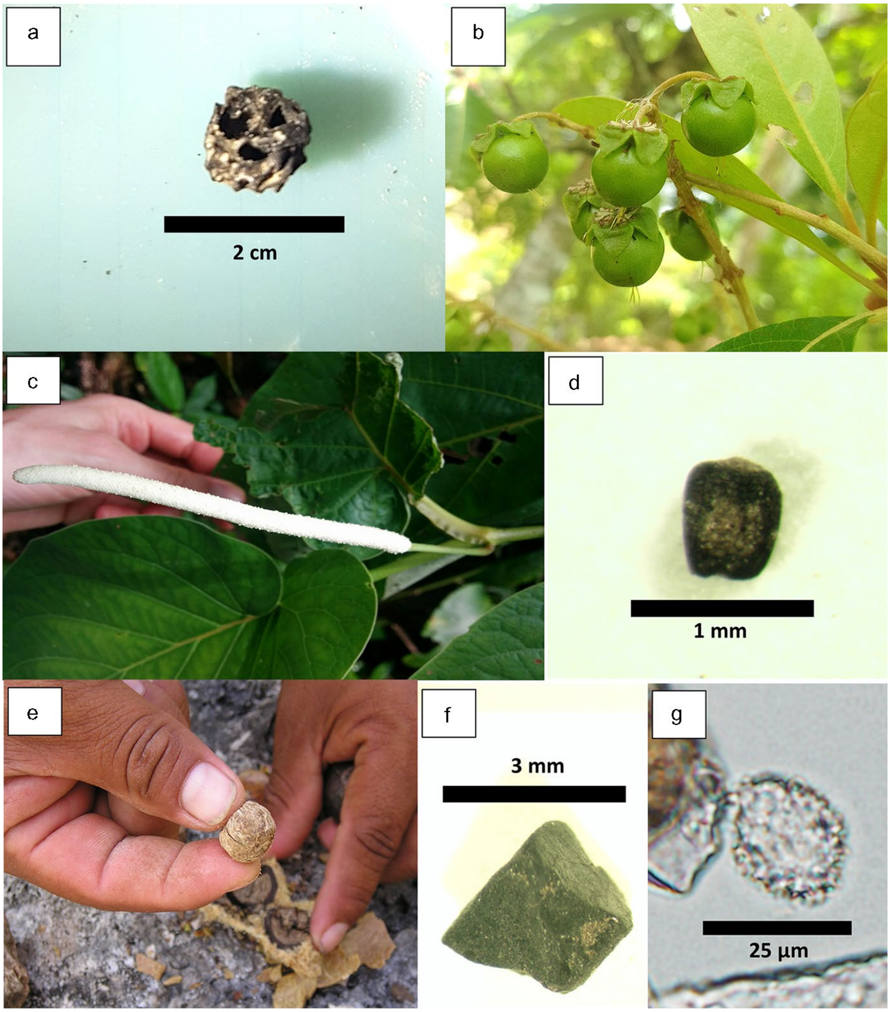

Fig. 5 Several key cultivated fruit taxa identified in carpological and microbotanical analyses in the Maya area: **a** nance (*Byrsonima crassifolia)* seed recovered from Piedras Negras heavy fraction of flotation sample; **b** nance fruits (immature) growing in a homegarden, Budsilha, Chiapas; **c** Hoja Santa *(Piper auritum)* growing in a homegarden, Piedras Negras, Guatemala; **d** *Piper* sp. seed recovered from Piedras Negras light fraction of flotation sample (photo by Sarah Watson); **e** modern cocoyol palm *(Acrocomia mexicana)* endocarp and endosperm, Naranjal, Quintana Roo; **f** fragment of *Acrocomia* endocarp recovered from Piedras Negras heavy fraction of flotation sample; **g** *Acrocomia* endocarp phytolith from Northwestern Honduras sediment sample (All photos by Shanti Morell-Hart except where noted)

consumed for seeds and fruit alike, has only been found as wood charcoal in the central and southern Maya Lowlands, and not thus far in the northern Maya Lowlands.

Popular shrubs with edible leaves include chaya (*Cnidoscolus* spp.), pungent verbenas (Verbenaceae), and fragrant pepperleaf (*Piper* spp.; Fig. 4c–d). All these genera, though common in contemporary homegardens, are found in wild stands of forest, as well.

Nut and seed crops from trees include the musty achiote or annatto (*Bixa orellana)* and pungent allspice (*Pimenta dioica*). Guanacaste (*Enterolobium cyclocarpum*), used primarily for shade and dyes, also has an edible seed once the thick, hard testa is removed—perhaps through toasting. Residues from Guanacaste have been recovered from multiple sites (Supplemental Table 1).

Maya people in the lowlands also favored a number of food palms (Arecaceae). Palms have high visibility in the archaeological record thanks to durable endocarps, distinctive anatomy of the woody stem, and high productivity of diagnostic phytoliths. The most common of these are peach palm (*Bactris* spp.), coyol or cocoyol (*Acrocomia* spp.; Fig. 4e–g), and cohune or corozo (*Attalea spp.* or *Orbignya cohune)*. There is also circumstantial evidence for the use of chapay *(Astrocaryum mexicanum)* and pacay *(Chamaedorea tepejilote)* for their edible inflorescences. Palm family phytoliths have been recovered virtually everywhere that microbotanical analysis has been carried out, with some from dental calculus (Cummings and Magennis 1997).

Another key economic species was cotton (*Gossypium hirsutum*), with seeds used perhaps to produce edible oil and fibers used in textile production. However, despite the fact that the Maya Lowlands have been indicated as the probable center of cotton domestication in the Neotropics (Piperno 2011), our knowledge of the pre-Columbian Maya cotton-textile industry is limited by the remarkable scarcity of both archaeobotanical remains and archaeological textiles (Morehart 2011; Morehart et al. 2004). The visibility of textiles and fibers is diminished in semitropical settings, where they rapidly deteriorate. Rare cotton seeds and pollen grains have been identified at only a few Maya sites, and exceptional occurrences of textile fragments made of cotton fibers are known from a few others, such as Barton Creek Cave, Chichén Itzá, and Aguateca (Lentz et al. 2014a, b; Morehart et al. 2004; Supplemental Table 1).

In sum, fruit-bearing tree and shrub crops were important components of the ancient Maya agro-urban landscape, a model discussed in greater detail in our companion article on engineered landscapes (Fedick et al. in press). The richness of the archaeobotanical record mimics the richness of traditional homegardens in which avocado, annonas, papaya, guava, sapotes, palms, ramón, siricote, nance, achiote, allspice, and other valued trees are planted together (Atran 1993; Fedick 2020; Herrera Castro 1994; Jiménez-Osornio et al. 2004, 2018; Supplemental Table 1). Tree crops, once established, are more stable than annual crops, though annual yields may vary. Optimization of cultivated landscapes by tending multipurpose trees was certainly a critical strategy of subsistence for Maya people (Dussol et al. 2017a, 2021a; Gómez-Pompa 1987; Puleston 1982), as these practices continued through Spanish colonial times (Atran 1993).

Horticulture and Non-Domesticates

Non-domesticated plants were not characterized as prominent in foodways or daily practice in studies prior to 1990. In their 1934 ethnographic study, Redfield and Villa Rojas (Redfield et al. 1962) noted the use of some of these plants, marking them primarily as "condiments." But non-domesticates and plants considered to be "wild" or "weeds" were likely important components of daily and ritual life (Doolittle 2000; Herrera Castro 1994), given their presence in the archaeological record (Supplemental Table 1). Even contemporary formal milpa areas contain *pachpakal* areas that are the parts of the fields where "a wide variety of crops and medicinal herbs is planted" (Anderson 1995, p. 142). Here, we include non-domesticated plants in our discussion of homegardening and horticulture, though we acknowledge that "gardening," "agroforestry," and "field cultivation" overlap in significant ways across Mesoamerica and North America (Doolittle 2000, 2004; Whitmore and Turner 1992, 2001).

Smaller amaranth family (Amaranthaceae) species are frequent components of archaeological assemblages. These include pungent epazote or goosefoot (*Chenopodium* spp.), amaranth (*Amaranthus* spp.), and unclassified Chenopodiaceae family taxa listed as "Cheno-Am." Apart from chile peppers and tobacco, the nightshade family (Solanaceae) also contributes frequently to archaeological assemblages as sour and flavorful tomatillos (*Physalis* spp.), alongside various *Solanum* spp. that may have been incidental or economic. Pungent chinchín or chipilín (*Crotalaria* spp.) is present but rare across the Maya Lowlands.

Tannin-heavy wild grape (*Vitis* sp.) is relatively frequent in lowland Maya assemblages. Juicy cactus fruits such as pitahaya (*Hylocereus* spp.) are more rarely found. Pungent aster family (Asteraceae) species are almost universal, but the macroremains are often difficult to distinguish into genera and the phytoliths are thus far impossible to distinguish below the family level. Grass family (Poaceae) species are also frequently recovered, likely indicating their use in *bajareque* (daub) clays, cord, tinder, matting, thatch, brooms, and basketry (Lentz et al. 1996; Sheets 1998). Vanilla (*Vanilla planifolia*) is documented, thus far only in a few instances as relict stands (Fedick et al. 2012) and as chemical residues (Spenard et al. 2020).

The broad use of various non-domesticates across the Maya Lowlands and the visibility of horticulture in places such as Joya de Cerén present a complementary narrative to the management of domesticated and non-domesticated tree species, root crops, and annual milpa domesticates. The relative contribution of such plants to ancient diets is harder to assess. It is also difficult to determine the original growing context of many such species: deliberate planting or adventitious growth, in wild or managed reserves, in milpa fields undergoing managed succession, or homegardens. These taxa are still worthy of attention, however, as Montero López and colleagues (2016) and Goldstein and Hageman (2010) have revealed in their studies of politically charged feasting practices. The use of non-domesticated plants was not simply related to daily subsistence but was related to ritualized practice, as well, where Maya rulers incorporated a suite of wild species into their performative repertoire for highly symbolic purposes.

Milpa Cycling

Milpa crop areas contain early successional crops: both annuals and herbaceous perennials. In recent studies, scholars have demonstrated that ancient Maya farmers relied on many more crops than maize, beans, and squash to prepare elaborate recipes (Faust 1998; Terán et al. 1998). The traditional milpa triumvirate was supplemented with other annuals such as tomato and amaranth, alongside full-sun, fast-growing herbaceous perennials that could be harvested in the first year, including makal, sweet potato, and chile peppers, as well as manioc, a fast-growing woody perennial. Furthermore, "fallowing" milpas were likely a rich source of food, medicinal plants, pollinator species, and commonly used plants with other economic uses.

Annual Crops

Paleoethnobotanical studies since 1990 have revealed abundant evidence of classic milpa annual cultivars: maize *(Zea mays)*, beans *(Phaseolus* spp.), and squash *(Cucurbita* spp.), which, alongside chiles *(Capsicum* spp.) form a sort of "triumvirate plus." All four of these food plants have been documented across the Maya area, with maize, in particular, found at almost every site (Supplemental Table 1) and most visible overall (Fig. 6). Most of these studies draw data from large city centers dating to the Classic period, with only a few exceptions from Archaic and Postclassic sites, and cave and wetland field sites.

The high recovery rate of these domesticated taxa is partially dependent on their high visibility in the archaeological record. All four cultivars have recoverable diagnostic starch grains (Fig. 6), with some distinction even possible between varietals of maize. Squashes and maize alike feature diagnostic phytoliths, with different squash species even distinguishable from each other. Maize cob phytoliths and maize leaf phytoliths even offer distinct and diagnostic forms. Common macrobotanical remains of these four domesticated taxa include seeds and caryopses, rinds and peduncles of squashes, maize cupules, and maize cobs. The regular findings and general high ubiquity of these domesticated taxa support classic milpa cultivation models. However, these four taxa are not as highly ubiquitous, relative to other taxa, as anticipated in traditional models (Hageman and Goldstein 2009). Nor are these domesticated taxa as ubiquitous as expected given their high visibility relative to other taxa, due to possible identification through both diagnostic macroremains and microremains (Fig. 6). Furthermore, where Maya people grew these taxa—milpa and/or homegarden?—and with which sort of techniques—swidden and/or terracing?—are questions that have been addressed with direct botanical evidence in only a handful of studies (e.g., Hather and Hammond 1994; Miksicek 1990; Sheets et al. 2012). At these sites, annual milpa crop remains were directly recovered in situ where ancient Maya people had originally cultivated them.

Geophyte Crops

Contemporary Maya people make use of 30 indigenous plant species with edible geophytes—roots, rhizomes, tubers, or bulbs (Fedick 2020). Twenty-seven of these species are herbaceous perennials. With few exceptions, the importance of edible geophyte crops was not well reflected in archaeological literature prior to 1990. This earlier absence was due to the traditional focus on ethnographic sources and the sparse collection of macrobotanical remains in archaeological

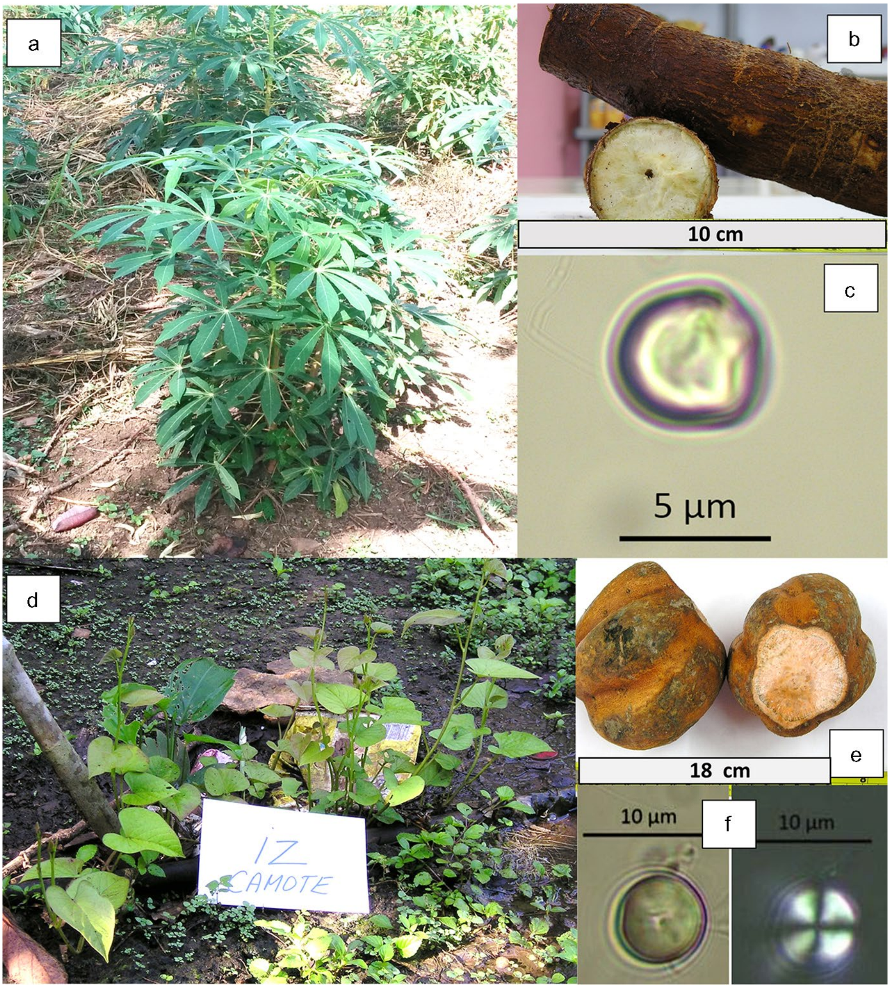

Fig. 6 Two key cultivated geophyte taxa identified in microbotanical analyses in the Maya area: **a** manioc *(Manihot esculenta)* field near San Pedro Sula, Honduras; **b** manioc purchased from central market of Mérida, Yucatán; **c** slightly damaged cf. *Manihot* starch grain recovered from human tooth residue at Piedras Negras; **d** camote *(Ipomoea batatas)* growing in homegarden in Naranjal, Quintana Roo (photo by Lucia Gudiel); **e** camotes purchased at central market in Mérida, Yucatán; **f** cf. *Ipomoea* starch grain recovered from obsidian blade residue, Río Amarillo area, Honduras (All photos by Shanti Morell-Hart except where noted)

studies. Hather's pioneering work (1988, 1991) on identification of charred parenchymous tissue made inroads to the identification of geophytes in the archaeological record of the Maya area (Hather and Hammond 1994). As paleoethnobotanical studies have increased across the Maya Lowlands, particularly studies focused on starch grains and phytoliths, so too has archaeological evidence related to cultivated geophytes. All the key cultivated taxa have high visibility in the microbotanical record, as all have diagnostic starch grains (Fig. 6). Several taxa also have

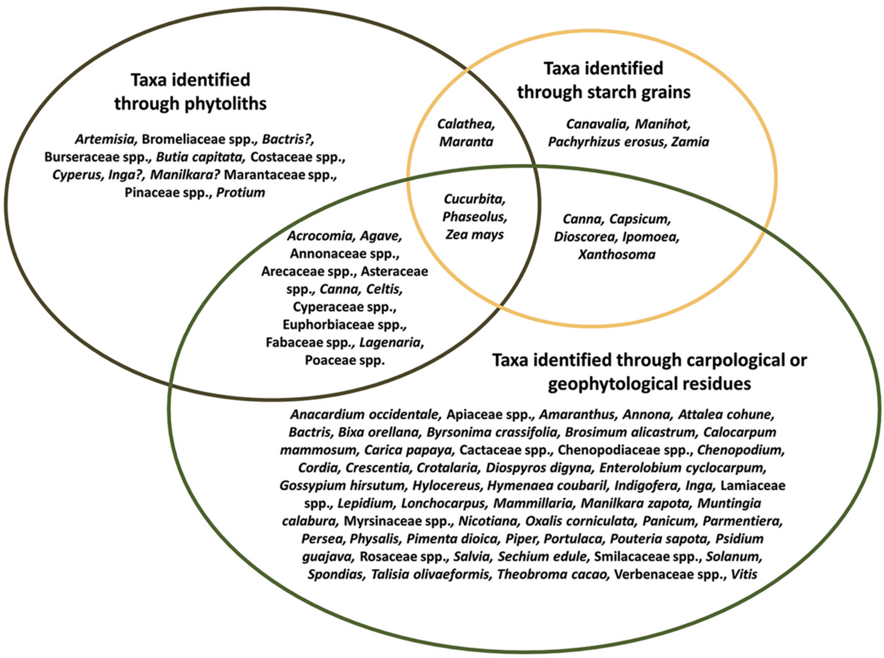

Fig. 7 Complementarity and overlap between types of analysis in the Maya Lowlands, as reflected in key taxa residues recovered from artifacts (starch grain and phytolith residues), small sediment samples (phytolith residues), and bulk flotation samples (carpological and geophytological residues) (Redrawn and modified by Shanti Morell-Hart from Morell-Hart 2019, fig. 2; see Supplemental Table 1 for full list of common names)

diagnostic phytoliths (e.g., arrowroot [*Maranta*] and lerén [*Calathea*]). Over the past few decades, studies of microbotanical remains have yielded a rich array of these starchy underground food resources (Supplemental Table 1), complementing macrobotanical datasets and revealing the prominence of other types of crops in past Maya foodways.

Far from famine food, manioc (*Manihot esculenta;* Fig. 7a–c), a woody perennial, appears to have a key role in ancient Maya cuisine. Found at archaeological sites across southeastern Mesoamerica, the Caribbean, and through southern Central America (Hather and Hammond 1994; Lentz et al. 1996; Morell-Hart 2014; Piperno and Holst 1998), manioc appears to have varied regionally in importance as a food resource among Maya communities. At sites across the Maya Lowlands, this tuber crop has been identified via a number of proxies including pollen (Jones 1994; Pohl et al. 1996; Pope et al. 2001; Santini 2016), carbonized stems (Miksicek 1991), starch grains on artifacts (Cagnato 2016, 2019; Cagnato and Ponce 2017; Devio 2016; Novelo-Pérez et al. 2019; Simms 2014; cf. in Bérubé 2018), starch grains in dental calculus (cf. Cummings and Magennis 1997), starch grains in sediments (Zimmermann 2019), carbonized tubers (Santini 2016; potentially in Hather and Hammond 1994; Miksicek 1991; Morehart 2002), and excavated plaster casts from fields at Joya de Cerén (e.g., Sheets et al. 2012; Slotten et al. 2020), where it was monocropped and likely was a staple. The apparent ubiquity of manioc comes as no surprise—the plant is drought-resistant, has high caloric content, and can grow even in poor soils.

Sweet potato *(Ipomoea batatas;* Fig. 7d–f) has also been frequently recovered across the Maya Lowlands, as pollen (Rushton et al. 2020), starch grains on artifacts (Cagnato 2016; Fernández Souza et al. 2020; Lentz et al. 2015; Novelo-Pérez et al. 2019; Trabanino García and Meléndez Guadarrama 2016; Venegas Durán 2019; Venegas Durán et al. 2020; Zimmermann 2019; cf. in Bérubé 2018), and as seeds and other diagnostic parts (Beltrán Frías 1987; Cagnato 2016). Cocolmeca and ñame (*Dioscorea* spp.) have been recovered as starch grains from artifact residues in both the northern Yucatan Peninsula and the Petén region (Devio 2016; Novelo-Pérez et al. 2019; Trabanino García 2012; Trabanino García and Liendo Stuardo 2012). Yam family species have also been recovered from Belizean sites as macroremains (Miksicek 1990). Similarly, arrowroot *(Maranta arundinacea)* has a fairly robust presence in Maya sites, found through extractions of phytoliths (Abramiuk et al. 2011; Morgan 2010; Simms 2014) and starch grains (Novelo-Pérez et al. 2019; cf. in Cagnato 2016; Morell-Hart et al. 2018a, b; Simms 2014; Zimmermann 2019).

Other taxa are less frequently recovered but nonetheless augment the already high ubiquity of geophyte crops at Lowland Maya sites. Ancient Maya farmers grew jícama (*Pachyrhizus erosus)* in both northern and southern lowland communities, as evidenced by starch grains and macroremains (Novelo-Pérez et al. 2019; cf. in Cagnato 2016). Juicy achira rhizomes (*Canna* sp.) have distinctive starches documented in several locations (Cagnato 2016; Dunham et al. 2009; Lentz et al. 2015; Santini 2016; cf. in Abramiuk et al. 2011; Morell-Hart et al. 2021), as well as the occasional seed (Morell-Hart and González Córdova 2017). Starchy corms of malanga or macal (*Xanthosoma* spp.) have been recovered as starch grains and charred macrobotanical fragments (Bronson 1966; Hather and Hammond 1994; Lentz et al. 2015; Novelo-Pérez et al. 2019), and as plaster-filled cavities in fields at Joya de Cerén (Heindel 2012; Lentz and Ramírez-Sosa 2002). Cycad (*Zamia* sp.) starch grains (from the root-like stem) have only been recovered in the northern part of the Maya Lowlands (Simms 2014), while lerén or llerén (*Calathea*; Cagnato 2016; Craig 2010) has only been found in the southern part of the Maya Lowlands.

These combined data indicate that geophyte crops, far from a rarity, are found almost everywhere that microbotanical studies have yielded diagnostic remains, in addition to several places that have yielded more fragile macrobotanical remains. The high ubiquity of geophyte crops in microbotanical studies—where they preserve well for identification—indicates the likely high reliance placed on them by Maya farmers in the lowlands (Dunning et al. 2018, 2020; Fedick 2017, 2020; Hather and Hammond 1994). In some cases, geophyte crops dominate assemblages while maize is secondary (e.g., Sheets et al. 2012; Slotten et al. 2020). Critical future work could address spatial-temporal patterns of geophyte crop diffusion and intensity of use, as paleoethnobotanical datasets become more robust and microbotanical studies become more common.

Forest Gardening: Silviculture and Arboriculture

Alongside a diverse portfolio of planted annual and geophyte crops, Maya farmers drew on various perennial managed resources, as scholars have shown through new evidence that challenges traditional models in which swidden strategies, dominance of milpa system provisions, and generally homogeneous agricultural strategies are taken as granted. We use the term silviculture, literally meaning the cultivation of forests, to refer to all practices intended to manage, enhance, and use woodlands, whereas we use the term arboriculture to refer to the cultivation of trees. Both are intertwined in traditional systems since trees can be planted in managed forests and, conversely, spontaneous species can be integrated in arboricultural systems if they provide ecological or economic benefits. As documented in ethnographic studies, forest management represents a long-term cycle of managed succession and eventual recutting that begins with pioneering herbaceous annuals and reaches maturity with shade-loving woody perennials (Ford and Nigh 2009, 2016; Gómez-Pompa 1987). Managed forests include permanent stands or orchards dominated by single or few species, as well as bounded areas of mature forest developed to contain a mixture of particularly valued late-succession species. Nonfood species are an integral part of these systems, and people manage a variety of species used for building materials, firewood, medicine, and other products used in craft such as bark, resin, latex, dyes, and fibers, as well as for ecological activities (nutrient cycle, pollination, shade, food supply for wildlife, etc.).

Since the 1990s, we have seen a growing interest in archaeological documentation of ancient Maya forest management as anthracological and wood studies become more popular in the Maya area (e.g., Dussol et al. 2017a; Lentz and Hockaday 2009; Miksicek 1990; Morehart et al. 2005; Thompson 2013; Supplemental Table 1). Regardless of time period, a general pattern of fuel wood diversification has emerged in several lowland Maya sites (Dussol et al. 2021a; Miksicek 1991; Robinson and McKillop 2014; Thompson et al. 2015b). Although they vary from one site to another, these fuel woods include early successional shrubs and trees such as nightshade (*Solanum*), redhead (*Hamelia*), cockspur (*Acacia*), cordoncillo (*Piper*), trumpet tree (*Cecropia*), hackberry (*Celtis*), star apple (*Chrysophyllum*), and pixoy (*Guazuma*); latter successional trees such as gumbo limbo (*Bursera*), guanacaste (*Enterolobium*), bribri or paterno (*Inga*), turtlebone (*Pithecellobium*) and pine (*Pinus*); and slow-growing forest members such as sapodilla (*Manilkara*), sapote trees (Sapotaceae spp.), wild fig (*Ficus*), avocado (*Persea*), manax (*Pseudolmedia*), siricote (*Cordia*), nance (*Byrsonima*), allspice (*Pimenta*), soursop (*Annona*), Spanish cedar (*Cedrela*), and guapinol (*Hymenaea*). Since these diverse taxa characterize different forest successions, we can view them as an index of the way that ancient Maya people regularly cleared significant parts of land around their settlements while also preserving patches of mature forests. Contemporary agroforestry systems that have been well documented since the 1990s (e.g., Atran 1993; Ford and Nigh 2016; Remmers and De Koeijer 1992) provide models of forest succession management that can be used to interpret past practices.

Shifting slash-and-burn agriculture typically leads to the development of a mosaic of forest successions, which represent a main reserve of firewood (Sanabria 1986). Another silvicultural system called *t'olche'* in Yucatan consists of the preservation of forest belts around milpas, thus, providing large amounts of dead wood from mature trees that serve as fuel (Remmers and De Koeijer 1992). Maya people could have used similar silvicultural systems at least since the Preclassic and Classic periods, as seen in the anthracological data, and these practices might have helped preserve direct availability of diverse forest resources.

Maya people actively favored tree species of high economic value, as seen through the frequency with which scholars identify macroremains from avocado (*Persea*), allspice (*Pimienta*), ramón (*Brosimum*), guava (*Psidium*), nance (*Byrsonima;* Fig. 4a, b), siricote (*Cordia;* Fig. 2), cashew (*Anacardium*), sapotes (Sapotaceae; Fig. 5), and several palm (Arecaceae) species (Fig. 4e–g). All these species were important sources of fruits, nuts, spices, or timber. In diachronic studies, scholars have further shown that some of these species were intensively used during long periods of time, perhaps indicating intentional long-term management. Lentz and Hockaday (2009) showed that sapodilla (*Manilkara zapota*) was probably tended by Tikal elite for the use of its very durable hard wood in buildings. Scholars have also used charcoal analysis to demonstrate that reliance on Sapotaceae species and other fruit-bearing trees for fuel consumption increased during the Late and Terminal Classic period at Naachtun, perhaps as a result of intensification of arboricultural practices (Dussol et al. 2021a).

Other scholars have tracked the selection of various species for particular traits as possible evidence of arboriculture intensification. Thompson and colleagues (2015a) addressed the pre-Columbian arboriculture of sapodilla (*Manilkara zapota*) through analysis of the genetic diversity in current populations, as did Dvorak and colleagues (2005) regarding Caribbean pine (*Pinus caribaea*). An argument for pre-Columbian tree species enhancement was made by Peters (2000). He compared phenotypic and phenological differences between modern populations of ramón (*Brosimum alicastrum*) in the Tikal National Park and in other Central American forests (i.e., number of fruitings per year) and hypothesized that the greater productivity of the Tikal trees reflects relict genotypes deliberately selected by ancient Maya people.

Other trees might have been favored for ecological purposes. Legumes (Fabaceae) are very frequently found in archaeological charcoal in Maya sites, including *Acacia*, *Gliricidia* (Fig. 3), *Enterolobium*, *Inga*, *Lysiloma*, *Lonchocarpus*, *Piscidia*, *Dalbergia*, *Caesalpinia*, *Haematoxylon*, *Swartzia,* and *Diphysa*. Legumes are nitrogen-fixing plants particularly valued in modern agroecology. They have been planted in combination with cereals (Poaceae) and other vegetable crops to balance soil nutrients in traditional farming systems worldwide. In Central America, madre cacao (*Gliricidia sepium*) (Fig. 3) and guanacaste (*Enterolobium cyclocarpum*) are usually tended as living fence around fields as well as in milpas undergoing managed succession, pastures, and tree plantations for ecosystem management. Furthermore, 29 species of tree and shrub legumes are used as food by the contemporary Maya (Fedick 2020). More careful attention to the evolution of these taxa in archaeological charcoal records should reveal relevant insights into ancient agroforestry strategies.

Boosting valued tree species or discouraging the less preferred ones is a long-lasting practice of forest management that has been documented in contemporary communities like the Itza in northern Petén and the Lakantun in Chiapas (Atran 1993; Ford and Nigh 2016). Although it would be premature to generalize, we nevertheless suggest that the trends highlighted here show that ancient Maya people implemented sustainable silvicultural practices, though these practices probably varied greatly over time and across space. When did this forest management begin, and did it lead to the development of extant "forest gardens" (Campbell et al. 2006; Ford and Nigh 2016; Gómez-Pompa 1987)? These are questions that require systematic examination of anthracological datasets covering long periods of time in multiple sites.

Vegetation Growth Management

From early successional crops to mature forest gardens, vegetation growth management would have involved (along a timeline): clearing, weeding, culling of non-economic species, and pruning of trees to improve fruit production as well as for firewood management, a vital resource for food preparation. Many of the specific trees and "weedy" plants are mentioned in preceding sections, but we focus here on the set of practices that shifted one type of place to another and one type of succession stage to another. As we elaborate below, ancient Maya farmers made use of more strategies than milpa cropping, tailoring their activities to particular needs and ecological contexts in disparate ways. These practices include slashing-and-burning, weeding, trimming, pruning, and coppicing, although our evidence for many critical vegetation management strategies is severely limited by their relative invisibility in the archaeological record.

Undoubtedly, fire was a major tool of vegetation modification used by Paleoindian hunter-gatherers and Mesoamerican farmers since at least the early Holocene, as scholars have demonstrated using multiple sediment cores studied since the 1990s. Scholars have associated decreasing arboreal pollen, higher erosion rates, and abundant microscopic charcoal, since 2500 BC in northern Belize, with pollen of maize and disturbance taxa in wetland sediments (Jones 1994; Pohl et al. 1996). Similar phenomena were observed for the Preclassic and Classic periods near several lowland sites (e.g., Dunning et al. 1998; Wahl et al. 2007). Such data indicate the spread of slash-and-burn agriculturalists in the lowlands as early as the Late Archaic period (Piperno 2006).

Temporal trends are broadly concordant between sites. Higher levels of fire activity often correlate with higher human occupation, indicating that growing population pressure generally led to the reduction of length of time between cultivar plantings. However, discrepancies arise at the more local scale, with lower levels of fire activity observed during periods of intense human activity (e.g., Anderson and Wahl 2016), indicating changes toward more intensive farming practices that took place differently in certain areas and at certain times. However, inferences of agrarian practices based on the fire signal are complicated by the lack of knowledge regarding the relationship between the vegetation burned and the resulting micro-charcoal concentration in lakes and soils (Dussol et al. 2021b). Moreover, in research carried out since the 1990s in contemporary Maya communities, scholars have demonstrated that slash-and-burn agriculture probably played a significant part in soil restoration and biodiversity conservation, thus, contradicting the traditional view that this system necessarily leads to deforestation (Atran 1993; Ford and Nigh 2010; Remmers and De Koeijer 1992). Other uses of fire intended to manage soil fertility have been documented, such as the ignition of low-intensity fires to produce biochar, or the spread of ash refuse in fields (Nigh 2008; Nigh and Diemont 2013; Wyatt 2008).

Besides vegetation burning, other potential practices of vegetation growth management are equally complicated to identify and sometimes more so. Weeding would have been required to remove choking vegetation and nurture desired plants across growing zones. Evidence of weeding may be presented by "weedy" ruderal plants—such as many of those in the amaranth family—that may have been thrown into fires after removal. But we face an equifinality problem in the presence of many of these adventitious or self-propagating plants: were some used as tinder and deliberately plucked for this purpose? Were some picked for medicinal or condiment use, with scraps and remains then tossed into the fire? Equally, evidence for trimming, pruning, and coppicing are scarce and mostly indirect. Dussol and colleagues (2021a) hypothesize that the heavy use of wood from fruit-bearing trees in Naachtun resulted from regular pruning in fruit tree plantations. Late Classic samples from Río Bec also yielded higher proportions of some of those fruit trees, particularly sapotes and siricote (Dussol et al. 2016), leading scholars to suggest that it was not an isolated practice. Charcoal concentrations containing pieces of branches of the same taxon with similar calibers are also relatively frequent in Maya sites. In such cases, tree coppicing, a common practice of fuel management, may be implicated, especially when tree taxa have a high regeneration capacity.

Landscape Engineering and Soil Management

Ancient farmers, pursuing diverse strategies for promoting and maintaining (and sometimes removing) plant species, also included a number of other practices in their repertoire. Though outside the scope of this paper, and instead a topic for a separate forthcoming paper (Fedick et al. in press), here we briefly summarize and provide examples of some key archaeological findings to date.

Ancient Maya farmers drew on a deep knowledge of varying soils and landscapes across a patchwork of lowland environments and developed sophisticated strategies for soil and landscape management. Initially, farmers would classify and evaluate soils and assess soil microenvironments, then focus cultivation on lands with the fewest limitations, while taking advantage of soils suited to particular crops and cultivation systems (Dunning et al. 1998; Fedick 1989). The degree of recognized land resource variability depended on the scale farmers were operating, which may differ from the scale at which contemporary soil maps distinguish such variability (Fedick 1996a). Microenvironments were used to squeeze the most out of moisture levels and soil productivity for particular plants, as farmers made the most of localized patches of specific soils, small bedrock cavities, and larger limestone depressions *(rejolladas)* to engage in "precision agriculture" (Fedick et al. 2008; Flores-Delgadillo et al. 2011; Munro-Stasiuk et al. 2014). Maya farmers engaged several techniques to increase and maintain soil fertility, scattering household organic trash and wood ash, targeting zones for nightsoil deposits, and transporting muck from wetlands (Dunning 1996; Wyatt 2012).

Farmers also modified field surfaces, sometimes in dramatic ways. These modifications range from the soil ridges at the Classic period site of Joya de Cerén, El Salvador (Sheets et al. 2012), to soil-infused rock piles such as *chich* mounds (Fedick and Morrison 2004), to linear rock piles that may have functioned as planting platforms and berms to direct rainwater runoff. Such built features concentrated soils, increased drainage, and prevented erosion. Farmers also managed erosion on sloped surfaces through terracing, documented across hilly zones in the Maya Lowlands (Beach et al. 2006, 2018; Chase and Chase 1998; Dunning and Beach 1994). The use of LiDAR has augmented the record of terrace use considerably (Chase et al. 2011; Chase and Weishampel 2016; Macrae and Iannone 2016), though this method requires ground truthing for scholars to establish the antiquity of features and demonstrate contemporaneity with other features and structures.

Similarly, water management required large-scale transformations to the landscape, including channels (Wyatt 2020), the berms mentioned previously, dams and dikes (Pyburn 2003), and perhaps pot irrigation from water stored in reservoirs (Beach and Dunning 1997). Farmers also managed wetlands for agriculture, from the lowland periphery (Leonard et al. 2019), to the elevated interior (Dunning et al. 2017), to the riverine floodplains (Ebert et al. 2016; Golden et al. 2021), including transitional wetlands along *bajo* margins (Dunning et al. 2015; Kunen et al. 2000). In such cases, farmers took advantage of natural seasonal cycles of increased moisture, sometimes leaving a light footprint and in other areas cutting channels and forming raised fields. Scholars in a range of studies have documented the high diversity of wetland zones, dramatic environmental shifts in these zones over time, and adaptations of Maya farmers to these changing conditions (see Chase et al. 2014; Lucero et al. 2014). Through such research, scholars have documented modes of resilience already embedded in Maya societies.

Small-scale landscape engineering and minor soil amendments are usually attributed to local farmers, who constructed incrementally at the household level (Wyatt 2020). Larger canal and terrace projects, however, may have been the result of centralized planning (Beach et al. 2002; Chase and Chase 1998) or were more local projects (Murtha 2002). Regardless at which scale such terraforming took place—local or regional, initiated by farmers or elites—the lowland Maya landscape bears evidence of a wide array of strategies and transformations.

Maya Agriculture: Corroborations, Contradictions, Complementarities, Caveats

The additions and refinements in data collection described in previous passages lead us to view anew the inherited models we outlined in earlier sections. We apply our data syntheses to prior understandings of limitations of lowland Maya environments, homogeneity of agricultural strategies across the lowlands, centrality of one crop (maize), centrality of the milpa system as food base, dominance of swidden strategies in agricultural practices, and emphasis on crop failure in collapse models.

In our review of literature from 1990 to 2020, we see corroboration between some archaeological datasets, including evidence of wild and managed taxa in assemblages of both food plants and wood; diverse agricultural strategies in botanical residues as well as landscape features; and specific strategies such as arboriculture, identified through features as well as wood charcoal assemblages. Complementarity between datasets is evident in, for example, the visibility of root crops uniquely offered by starch grains and phytoliths (Fig. 6), the visibility of fuel harvesting and deforestation uniquely identified through wood residues and pollen, and the heightened visibility of water management presented by canal features. We also see a few contradictions between datasets, including differing tempos in correlations between agricultural strategies and "crisis" periods, and differing understandings of swidden practices in terms of ancient types used and their environmental effects. These latter contradictions, however, are likely related to the relationships of ancient farming practices to particular topographies, moisture regimes, and other factors at different points in time.

We now consider how models prior to the 1990s stand in regard to analyses carried out over the past three decades. Models inherited from earlier scholarly studies have faced several serious challenges over the past 30 years, while other models have held up under scrutiny and new datasets. Following our synthesis of research of the past 30 years, we reevaluate six key themes in agricultural modeling: characterizations of lowland Maya environments (affordances and limitations), homogeneity of agricultural strategies (milpa, etc. vs. managed mosaic), centrality of maize in subsistence and agriculture (vs. root crops, tree crops, and non-domesticates), centrality of the milpa system as food base (vs. incorporation of agroforestry, homegarden horticulture, wild collection), preponderance of swidden strategies in agricultural practices (vs. terraforming terraces and canals, enhancing soils), and dominance of maize crop failure in societal collapse models.

Many of these themes are closely related, as they respond to early approaches that placed maize milpa, extensification of farmland, and abandoned fallow as central to subsistence models. In subsequent years, scholars incorporated terraforming and water management but continued to rely on models that foregrounded maize dominance. In research of the past three decades, scholars have equated the milpa with the primary stage of a managed succession cycle, highlighted the diversity of crops and gathered plants in agriculture, and incorporated other cultivation locations and agricultural strategies including homegardens, forest gardens, and wetland and terrace fields.

Recharacterizing Lowland Maya Environments

The Maya Lowlands encompass various wet and dry tropical environments, characterized by high vegetation density and biodiversity, abundant though seasonally variable rainfall, high sensitivity of soils to erosion, and high ecological dynamism.

Although the 1970s saw some appreciation for environmental heterogeneity, new datasets of vegetation, soils, hydrology, and surface geology have since revealed an even busier assortment of dynamic land and water resources. Although these variable habitats had implications for agricultural development, they were not as highly limiting as was first assumed. Research since the 1990s has revealed more affordances in the landscape and fewer limitations than previously thought. As in other tropical agricultural zones (Fausto and Neves 2018; Heckenberger et al. 2008), we find evidence of dense populations in environments once thought to be marginal.

Soils, especially in the northern Yucatan where bedrock is frequently exposed, appeared scarce or unworkable in the eyes of early Spaniards. As previously discussed, Spanish models and terminology become incorporated into colonial period records that were then mined for analogs by Maya archaeologists. The term “arable” originated in the context of European agriculture and was based on plow technology: “arable” specifically means plowable, or land that can be plowed, according to the Oxford English Dictionary. Over time, use of the word has been expanded to sometimes mean land suitable for agriculture. But the use of the word in cultural or historical contexts that exclude the use of plows is inappropriate for ancient Maya agriculture. Maya farmers, instead, saw opportunities in the diverse microclimates on the landscape, practicing forms of “precision agriculture” to take advantage of this variability (Fedick 2014; Flores-Delgadillo et al. 2011). Microenvironments with diverse soil and water resources are found throughout the Maya Lowlands, including soil-filled karstic sinkholes, depressions of varying sizes, and even small bedrock cavities. The potential of these diverse landscapes is recognized in contemporary ecological knowledge, and almost every type of landscape was used in the ancient past, as evidenced in settlement locations and engineering features.

Furthermore, food residue research has revealed not simply the use of infield gardens and outfield milpas but rather a range of diverse places. The various food plant residues from these places indicate nuanced perceptions of local ecologies and degrees of domesticity (Goldstein and Hageman 2010; Slotten et al. 2020), where “agricultural land, both irrigated and rain fed, lies in an intermediate position between fully social and fully natural space” (Hanks 1990, p. 306). Engineering and management of wetland areas are reflected in botanical assemblages containing taxa of wetland plants (Goldstein and Hageman 2010) and the movement of periphyton from wetland areas into dryland fields (Fedick and Morrison 2004). Maya lowland environments were quite diverse, perceived as such, and accounted for in traditional ecological knowledge, agricultural strategies, and landscape management.

Emphasizing Heterogeneity of Agricultural Strategies

In older models, scholars argued that increasing populations from the Preclassic through Classic periods led to increasing deforestation and environmental degradation. Using many new lines of evidence, however, we suggest a more complicated narrative. We find increasing evidence for the slowing of deforestation and erosion at several sites during the Classic period, and even some faunal studies (Emery and Thornton 2008) show no loss of species diversity as would be expected with deforestation and habitat loss. In some cases, it appears that ancient Maya farmers slowed soil erosion through carefully tailored engineering strategies, indicating forward-looking slope management (Beach et al. 2018; Dunning et al. 2009). Furthermore, in some cases, the effects of Preclassic erosion actually created new favorable conditions for agriculture at footslopes and *bajo* margins.

Ancient Maya people recognized and took advantage of natural features and microclimates (e.g., *rejolladas* and bedrock cavities), adapting agricultural strategies to these diverse micro-habitats. Overall, landscape engineering for agricultural production has proven to be widespread and varied, from terracing of slopes to modification of wetlands, with adaptations fine-tuned to local conditions and responding to environmental changes, both natural and human induced.

Complementary techniques of artifact residue analysis, microbotanical analysis of sediments, and macrobotanical analysis of charred remains have yielded multiple sorts of foodstuffs, indicating a wide range of growing and managing practices. These various data points—phytoliths, starch grains, and macrobotanical remains—have helped widen the spectrum of economic plants and broaden the "vocabulary" of agricultural practices in the Maya area. The diversity of plants recovered is a good index of the broad range of plants, practices, and ethnoecological relationships described in the ethnographic literature (e.g., Anderson 1995; Atran 1993; Hanks 1990; Killion 1990). This ethnographic literature also illuminates the seamless blending of agroforestry, horticulture, and annual cultivation strategies represented in the archaeobotanical record (Goldstein and Hageman 2010; Rushton et al. 2020). Furthermore, plant assemblages from site to site, and over time, reveal the diverse strategies that different communities employed across the Maya Lowlands.

Combining the botanical evidence and features marking the landscape, we see evidence of polycultural strategies, the use of the managed successional cropping system as described above, and rich mosaics of agricultural and forest management strategies. Arboriculture offers one particularly rich area of complementary study, with the combined available evidence of archaeological *chich* mounds, the use of *rejolladas*, fruit tree residues in the form of wood, fruit, and seeds, microbotanical remains, and genetics research on modern tree populations. Further research is needed, however, into how ancient Maya people matched the specific needs of certain plants to the suitability of specific microenvironments.

Reconsidering Centrality of Maize in Subsistence and Agriculture

How to evaluate the relative contribution of different foodstuffs (cereals, geophytes, vegetables, fruits) in the diet of ancient Maya, people is a key question in the debate over the centrality of maize prior to Spanish contact. In our review, we have noted that some taxa such as maize, nance, and palms are well represented in the archaeological record (Fig. 6; Supplemental Table 1), while other taxa such as papaya and allspice are rather uncommon in botanical residues, despite their wide distribution in forests, managed farmlands, and homegardens today. Determining whether this ubiquity reflects actual differences in the use of these plants is complicated by our limited knowledge regarding the taphonomy of plant remains in the tropics. Variation in taphonomic processes depends on preservation conditions and taxa physiologies. In temperate regions, cereals and pulses are more frequently preserved by carbonization, while waterlogged features such as wells usually yield more diverse assemblages including more fruits and oil seeds (e.g., Marinval 1999; Ruas and Bouby 2010). In the Maya area, the fact that macrobotanical remains are predominantly preserved by carbonization may imply similar biases in the representation of taxa, just as combustion differently impacts tropical wood taxa (Dussol et al. 2017b).

In spite of these complications, paleoethnobotanical studies offer a few hints as to how our perceptions of maize might be shifted. Given the botanical evidence, some Maya subsistence regimes relied heavily on orchard cultivation and forest management practices (Goldstein and Hageman 2010; McKillop 1994; Morell-Hart 2020). In some cases, tree crops were indispensable elements of ritualized practice (Morehart and Butler 2010) and indices of local, specialized ecological knowledge (Morehart and Helmke 2008; Morell-Hart 2020; Thompson et al. 2015b). Ubiquities of taxa indicate some tree fruits were consumed in as many locations as maize in feasting deposits (Cagnato 2016, p.183), though maize was dominant in overall quantity. We find ample evidence of arboriculture not simply through these food residues but also through features as we previously described.

Furthermore, researchers have recovered residues of geophytes from almost as many locations as maize, in every case where microbotanical studies have been carried out (see tables of Cagnato 2016, pp. 102, 183, 215, 264; Cagnato 2017, p. 82; Cavallaro 2013, , pp. 55, 59; Craig 2010, pp. 168, 179; Cummings and Magennis 1997, p. 215; Dedrick 2014, p. 74; Devio 2016, pp. 106, 111; Lentz 1999, p. 9; Morell-Hart et al. 2021; Novelo-Pérez et al. 2019; Rosenswig et al. 2014; Santini 2016, p. 190; Simms 2014, p. 291; Slotten 2015, p. 173; all broadly summarized in Supplemental Table 1). Maize quantity may be equivalent to achira, manioc, and sweet potato on some artifacts (e.g., Cagnato 2016, p. 215), while manioc field space may be equivalent to that of maize in thus-far excavated areas at Joya de Cerén (Sheets et al. 2012). The high ubiquity of geophyte crops, particularly where microbotanical analysis is used, reveals their high value to Maya farmers in antiquity. We would, thus, characterize maize as sometimes more dominant in agricultural strategies, but sometimes less dominant, instead operating as a "peer" member of an assemblage that included many other types of foodstuffs including geophytes and tree crops.

Displacing Centrality of Milpa System as Food Base

In addition to the high number of geophyte crops incorporated into Maya agricultural systems, there is an extended and rich history of the use of non-domesticates by various peoples throughout Mesoamerica, from the deep past into the present. Whether foodstuffs are used in some other way, a variety of plants was involved in a wide array of practices. The dynamic and polycultural successional cropping system seems the best model for millennia of Maya agricultural practices, as this model folds in milpa strategies yet also accounts for horticulture, homegardens, agroforestry, and the management of wild commons. The array of food plant remains, combined with the variety of food-productive features, reveals the range of options taken by Maya farmers to broaden their food base.

We see some fixity over centuries, at least in the legacy of silvicultural practices, as documented at Tikal (Thompson et al. 2015b). Crane (1996) utilized pollen and carbonized botanical remains from the Late Formative site of Cerros to reveal changes and continuities of subsistence and, by implication, agricultural practices. She indicated that the cultivation of staple crops like squash and maize maintained prominence over time, whereas utilization of alternate resources increased at about 100 BC. Crane (1996) claims the use of non-staple crops, such as tree fruits, also corresponded with an increase in social stratification. Dussol and colleagues (2021a) also detected an intensification of arboriculture of fruit trees in Naachtun at the time of the city apogee. Miksicek (1990) reviewed taxa and likely agricultural practices in wetland areas of Belize. In this ecological context, he found evidence for change over time from occasional and intermittent planting to regular flood-recessional cropping, and then later difficulties with increased sedimentation and a decrease in the fallow cycle. Similar to Miksicek (1990), McNeil (2002) and Johnston and colleagues (2001) have revealed data that support a model of increased deforestation over time, which Miksicek associated with swidden agricultural practices.

Evidence of shifts toward arboricultural intensification is correlated in some cases with evidence of increasing political authority. Elite control of forest resources through the management of high-value orchards is suggested in Classic period imagery (see Santini 2016). Nevertheless, the nature and location of such tree groves are difficult to trace, except when exceptional preservation conditions allow precise spatial reconstructions as at Joya de Cerén (Lentz et al. 2015; Slotten et al. 2020), or through concentrations of *chich* mound features or potentially *rejolladas*. Scholars have suggested that *rejolladas* were valued microenvironments for cultivation of plants such as cacao, outside of their natural range (Gómez-Pompa et al. 1990; Kepecs and Boucher 1996).

Changing trends in resource use could also reflect an intensification of trade of plant products that may have been distributed in markets without elite control (Cliff and Crane 1989; Dahlin et al. 2005). Despite not easy for scholars to demonstrate through standard paleoethnobotanical methods, interregional trade of plant products has been considered as a probable component of pre-Columbian Maya economies (Fedick 2017; Lentz 2000). However, apart from luxury goods such as cacao seeds, incense resin, rubber, and perhaps pine wood (Coggins and Ladd 1992; Lentz et al. 2005), interregional trade of agricultural products has not been addressed. Both the perishable nature of plants and the burden of transporting large quantities of staple food have been considered critical limits to such long-distance trade (Arnauld and Michelet 2004; Voorhies 1982).

Similar to the place of maize in broader subsistence strategies, we would, thus, characterize the milpa system as sometimes more dominant in agricultural strategies, but sometimes less dominant, instead operating as a "peer" strategy within a suite that included many other types of agricultural practice, including homegardening, arboriculture, and forest management.

Rethinking Swidden Strategies in Agricultural Practices

As discussed previously, agricultural features and botanical residues reveal a wide suite of ancient agricultural strategies, within which swidden held a role. But there is disagreement over the impetus, extent, and impact of swidden practices in the deep past, as well as their indices in the archaeological record. From estimations of wood needs based on ethnographic data, scholars have highlighted the likely competing interest between expanding cultivated areas and maintaining forests for wood supply, particularly for fuel (Abrams and Rue 1988; Hansen et al. 2002; Wiseman 1978). If extensive slashing-and-burning was the main agricultural strategy used by the ancient Maya, then expanding fields and reducing periods between cultivar plantings to meet the staple food needs of growing populations would have indeed dramatically accelerated deforestation.

However, Alexander (2006, p. 453), addressing shifts in the Spanish colonial and historic periods, noted: "Research in archaeology, ethnohistory, and ethnography overwhelmingly demonstrates that the swidden hypothesis mischaracterizes the complexity and intensity of Maya subsistence over the long term… Practice of extensive slash-and-burn agriculture is linked to the political and technological changes instituted after Independence, when settlement nucleation was enforced by the state and metal tools became increasingly available."

Moreover, swidden practices appear quite diverse, in timing, intensity, and scale. The study of paleoethnobotanical remains, interwoven with paleofire studies, has shed new light on arboricultural practices, forest management, and more broadly economic systems for pre-Columbian Maya people. Evaluating the historical time depth of human practices such as swidden is indeed a key prerequisite to understanding the long-term ecological impact of human activities. In this view, Thompson and colleagues (2015b) confronted the charcoal record of Tikal with the current composition of forests. They demonstrated that the order of taxa importance is correlated in both records with what they interpret as evidence of the low impact, which the Maya of Tikal had on the forest composition over the long term. In the same vein, the remote sensing study by Hightower and colleagues (2014) in Caracol shows that pre-Columbian terraces have durably impacted the structure of the canopy by modifying the topography and soil chemistry. Both studies are in line with ecological data that show prehistoric human settlements had long-lasting, indirect repercussions on ecosystems, for example, by creating optimal growing conditions for certain species (e.g., Graham et al. 2017; Ross and Rangel 2011). On the contrary, the ecological dynamism of tropical environments implies that even intensively cultivated tree species may be rapidly replaced by more competitive species after human activities cease (Peters 2000). All these factors point toward slashing-and-burning as a complicated part of lowland Maya agriculture, but by no means, the sole part or universally destructive.

We also wish to call attention specifically to the "fallowing" practices that form a part of the swidden cycle. The term "fallow" has a historical specificity that may render it a poor choice for Maya agricultural practices. "Fallow" specifically refers to fields that have been plowed but left unplanted for a year or more to reduce weeds, according to the Oxford English Dictionary. But in the Maya area, specialized, nonfood crops referred to as "fallow crops" are sometimes cultivated in fallow fields. These crops are also grown primarily to suppress weeds and pathogens and to increase soil organic matter, then cut and mulched before a regular cropping cycle. This practice is very different than the function and management of the traditional "fallow" field. In our findings, the "fallow" milpa is either left unmanaged to allow natural succession (while still exploited for useful plants) or is actively managed to encourage a controlled and productive succession. For these reasons, we instead suggest "periods between cultivar plantings," and "milpas undergoing managed succession," to describe lowland Maya time periods and places currently delineated as "fallow."

Reevaluating Dominance of Maize Crop Failure in Social Models

The widespread abandonment of large Maya centers during the Terminal Classic period in the southern Maya Lowlands implicates both broad shifts in demographics and radical disruptions in rulership. What is often termed the Maya "collapse" instead represents a complex convergence of observations related to meteorological droughts, warfare, fewer representations of divine rulership, disruptions to supply chains (staple and sumptuous), shifts in trade routes, and reduction of actively occupied settlements (Aimers 2007; Aimers and Hodell 2011; Yaeger 2020). Furthermore, it is difficult to resolve the tempo of the southern collapse with sufficient temporal granularity, and this core problem of collation, as Yaeger has noted (2020), is compounded by issues of correlation between transformations and, moreover, establishing causality between them.

One key issue with many traditional models of the relationship between food production and society, especially regarding resilience and collapse, is that these models generally presume wholesale agricultural societies. Malthusian perspectives define limits to land and, thus, population and food supply. Boserupian models address limits to land, adjusted by innovation in agriculture (Boserup 1976). Burbankian models address the potential of genetic selection to increase agricultural output (Burbank 2004). Geertzian models present involution as a problem of increased outputs (though not per person) (Geertz 1963). Brookfieldian perspectives incorporate the importance of social production and social returns, beyond simple caloric returns (Brookfield 1972). All these calculations of limitations and affordances, and their impacts on populations and environments, are based on agricultural production and the cultivation of key staple crops (usually grain) as the primary mode of food acquisition.

For decades, scholarly literature has documented how the extensive cultivation of maize spurred increasing population density and social complexity throughout the Maya area. In these narratives the triad of maize, beans, and squash was considered the cornerstone of society and its survival, with most social and ritual practice oriented toward ensuring high agricultural yields. In this model, the primary locus of food production is the milpa, a field where the triad of cultivars is produced. The milpa is prepared by slashing-and-burning "virgin" areas, then planting occurs in the cleared field. Periodically, as the soil nutrients are depleted and weed competition increases, these milpas are left “fallow” until used again several crop cycles later. The organization of society is based on the organization of this agricultural production. Active landscape management is, thus, oriented toward maize agriculture, with a slight nod toward the use of forest products and fallow fields.

Fedick and Santiago (2022) have conducted an analysis of the drought resistance of all 497 documented indigenous food plants of the Maya Lowlands. The milpa triad of maize, beans, and squash is composed of annual plants that are highly susceptible to drought. The impact of meteorological droughts on agriculture is not certain or clear. Depending on the seasonality of rainfall during drought, there could have been a disruption of plant food availability, but the diversity of plants and their edible parts could have averted famine.

While maize has mild drought resistance due to the C4 photosynthetic pathway, none of the triad would produce any food during moderate or extreme droughts (Fedick and Santiago 2022). In contrast, physiological attributes of other available food plants (such as manioc and chaya) render over 70% of them highly drought resistant, potentially providing a wide variety of foodstuffs under all but the most extreme drought conditions (Fedick and Santiago 2022). The failure of annual domesticates during drought conditions highlights the lack of resilience in cases where reliance on milpa cultivation is the sole subsistence strategy. During times of drought (as well as excess rain), the Maya could have turned to the perennial crops of the homegarden and forest garden, as well as the rich diversity of non-domesticated plants of the forest. We prefer to think of these non-milpa crops as resilient foods rather than famine foods, as most were used on a regular basis, as reflected in recovered paleoethnobotanical remains. The diversity of food plants cultivated in Maya agriculture and horticulture, and gathered from differing ecosystems, provides a great deal of flexibility and resilience when challenged with natural events such as drought or excessive rainfall. The decrease in available food sources under increasing climatic stress represents a slow chipping away of resources with ample opportunity for adjusting agricultural strategies rather than sudden or unavoidable agricultural collapse.

For these reasons, we argue for the need to shift from using maize production, or potential maize production, as the single measure of “carrying capacity” or productiveness of land resources. Different agricultural products—abundant in the paleoethnobotanical record—also have different soil and moisture preferences. Future models need to recognize variation in land suitability for these different agricultural products and incorporate the variety of food plants and cropping systems into food production and carrying capacity estimates. No archaeological study thus far accounts for the food production capability of homegardens or geophytes, as most address potential maize production in milpa fields.

Furthermore, our review of the literature over the past several decades also reveals much more evidence of intensive cultivation systems than solely extensification systems. As Alexander (2006, p. 454) noted: “Smallholders are likely to adopt ‘non-Boserupian’ patterns of intensification. Such factors include social production for prestation, ceremony, or ritual; market incentives; risk minimization; the availability and cost of agricultural technology; and the degree to which the state ‘meddles’ in land ownership, labor organization, disposal of produce, and availability of capital and credit." Combining various food production strategies (including terraforming/land engineering features) and diversifying cultivated taxa would have helped ancient Maya farmers, artisans, and royalty mitigate ecological risk (Montero López et al. 2016) as well as maximize culinary elaborations (Slotten et al. 2020).

Caveats and Comments

We acknowledge that our survey of the literature reflects several biases, not simply in the perspectives and skill domains of the authors. The data are biased toward visibility of remains (subject to taphonomic processes) and analytical foci of research programs (variable across the Maya Lowlands). There are temporal biases, as well, with more attention paid to the Classic and (secondarily) Formative/Preclassic periods, while less direct evidence of agricultural strategies has emerged in the Maya area from the Archaic (where agriculture is incipient), Postclassic, and Spanish colonial periods. The colonial period, in particular, has been subject to general reliance on historic documents, while understandings of the Late Postclassic period, given proximity to the colonial period, borrow much from this same literature.

Integrating botanical datasets is also a complex endeavor (Morell-Hart 2019), especially given the complexity and tempo of different kinds of investigations and the paucity of scholars to carry out certain types of analyses. Analyses of botanical remains are time consuming. Results of these analyses often make their way into appendices instead of the main text when they arrive long past analyses of other types of data. Promisingly, however, scholars are revisiting old studies and folding them into new interpretations by robustly integrating datasets using GIS, among other techniques (e.g., Farahani et al. 2017a, b). One area that is particularly ripe for such integration is the pairing of soil enrichment studies and paleoethnobotanical analysis. This includes the interpretation of stable carbon isotope enrichment studies of soils that equate C4 signatures with maize cultivation. Besides maize, the Maya made use of 14 other food plant species that use the C4 photosynthetic pathway (Fedick and Santiago 2022). Furthermore, many of the early succession "weeds" that would grow in milpas, terraced fields, and similarly disturbed locations are also C4 plants.

Finally, many other agricultural strategies used by Maya farmers are known from the ethnographic record but have much less visibility in the archaeological record, or they have simply been much less explored. Although we know these strategies to be critical to agricultural success, archaeologists have amassed little evidence to date of these strategies. Areas ripe for further research include insect pest and beneficial pollinator management, timing and seasonality of crops in the short arc of successional management, and crop and food storage and preservation techniques.

Although we are unable to control for specific taphonomic processes across the Maya Lowlands, we offer a few brief suggestions to build a more robust dataset for the region and to help answer agricultural questions specific to particular locations and time periods. We suggest the systematic collection of at least one liter of unscreened sediments for processing to retrieve floral and faunal remains; regular screen collection and curation of botanical items; early consultation with botanists, ecologists, and paleoethnobotanists to maximize sampling strategies and recovery; and leaving artifacts and human teeth unwashed where possible or selecting a subset for future microbotanical or chemical analyses.

We recommend that all such efforts be undertaken with prior knowledge of which sorts of analyses will best reveal targeted taxa (Fig. 6). Here, we highlight the high potential visibility of residues from maize *(Zea mays)*, squashes (*Cucurbita),* and beans *(Phaseolus)* across various types of paleoethnobotanical analyses, as compared to all other taxa; amplified visibility of geophytes such as achira *(Canna)*, sweet potato *(Ipomoea),* arrowroot *(Maranta)*, and manioc *(Manihot)* through starch grain and phytolith analyses; and exclusive visibility of many non-domesticated taxa and fruit trees such as papaya *(Carica papaya)*, cacti (Cactaceae spp.), sapotes (Sapotaceae spp.), nance *(Byrsonima crassifolia)*, ramón *(Brosiumum alicastrum),* and allspice *(Pimienta dioica)* through seed, fruit, and wood analyses.

Conclusions

In this review, we have documented challenges to several inherited models of agriculture in the Maya Lowlands: the limitations of the environment (more affordances), the homogeneity of agricultural strategies (more heterogeneity), the centrality of maize in agriculture (more reliance on root crops and tree crops), the focus on the milpa system as food base (more agroforestry, homegardening, horticulture, and wild resource management), the dominance of swidden strategies in agricultural practices (more evidence of landscape and soil modification), and the foregrounding of maize crop failure in collapse models (more evidence of resilience and sustainable agricultural practices). New methods and models since 1990 have shifted understandings in three key areas: agricultural engineering and landscape modifications (the focus of our companion article), forest management and wood residues, and food plants and food residues. The old models have been found wanting under the scrutiny of new datasets.

If we take the documentary evidence at face value, then we inherit the dominant perspective from de Landa. De Landa's documentation was written in 16th century Spain and organized according to core principles of Spanish cuisine: based on staple grains, pulses, and domesticated animals, the use of plow agriculture, and with the occasional inclusion of key fruits and nuts. In writing about Maya lifeways, "Their principal sustenance is maize," de Landa noted in his 1566 document (Tozzer 1941, p. 34). When scholars mine historic accounts, such as those of de Landa, in search of analogs for ancient lifeways, maize is modeled as the cornerstone of subsistence for over 2000 years, and maize-cropping practices are seen as relatively homogeneous across time and space. Using this analogy for Maya agricultural practices, we would, thus, expect maize to be highly ubiquitous across sites and within sites, and for maize to be the relatively dominant species in all botanical assemblages. The ethnoecological implications would include deforestation, soil erosion, and other maladies linked to high maize production and frequent cropping cycles. Meanwhile, sociocultural factors (warfare) and climatological factors (drought) would be expected to exacerbate lower crop production resulting from such troubles. Ultimately, in this model, maize crop failure of some form could result in the collapse of society (e.g., Brewbaker 1979).

For the past several decades, however, scholars have turned greater attention to actual remains of foodstuffs and evidence of activities in the landscape. They have also formulated more queries regarding sustainable agricultural strategies and resilience. As outlined in our review, early challenges to the model of maize/milpa/swidden primacy emerged from settlement studies that revealed such features as channeled fields (e.g., Siemens and Puleston 1972) and from archaeobotanical studies that revealed such cultivars as geophyte crops (e.g., Hammond and Miksicek 1981). Such studies have intensified over the past several decades, revealing sustainable agricultural practices (e.g., Lentz et al. 2015 at Tikal), disputing deforestation for milpa fields as a cause of collapse (e.g., McNeil et al. 2010 at Copan), expanding techniques of soil enrichment (e.g., Fedick and Morrison 2004 in the Yalahau region), expanding the potential importance of geophyte crop cultivation (e.g., Sheets et al. 2012 in El Salvador), and illuminating the role of long-term forest management in ancient communities (e.g., Ford and Nigh 2016 in Belize).

As with other types of economies, the development and movement of agricultural strategies had to do with logics and cosmologies of the ruling class (Beliaev et al. 2010; McNeil 2010; Morehart et al. 2005; Stuart 2006), local socio-environmental dynamics (Fedick 2017; Lentz et al. 2015; Simms 2014), and quotidian household activities (Farahani et al. 2017b; Sheets 2000; Simms 2014). Agricultural practices were, thus, directly linked to social factors as well as environmental conditions, even implicating models of rulership. In a footnote in *Against the Grain: A Deep History of the Earliest States*, Scott (2017, pp. 268–269) notes that he has made a distinction between "'state' crops like rice" and "'state-evading' crops like cassava and potatoes," arguing that states depend on grain crops that are grown in fixed fields and that "populations wishing to evade taxation and state control adopted subsistence strategies such as root crops, swidden, shifting cultivation, hunting, and foraging to place themselves outside of state control."

However, in a push against the grain in *Against the Grain*, a number of scholars now highlight the role of root crops and agroforestry practices in broader political systems. As Cyphers et al. (2013, p. 594) note in their response to Killion (2013), "staggered, vegetative propagation may be considered a form of 'in-ground' storage, and, as well, the sundried fibrous roots, once ground into flour, may be stored for consumption during the midsummer drought and high flood season." Atran (1993) makes the claim that the decline of Late Classic populations in the southern lowlands may even be attributable to a turn from the multicropping and tree-tending systems of earlier time periods toward a more intensive and parasitic agro-engineering system that pivoted around fewer cultivated species and crop cycles.

It is undeniable that radical demographic shifts unfolded across the Maya Lowlands at several points in time and over several centuries. But the impetus and impacts of these shifts are worthy of critical reappraisal. Regardless of which segments of society or which systems "collapsed," the timing of this "collapse" across the Maya Lowlands, or the different manifestations of "collapse" in Maya society, new data increasingly lead scholars to model resilience, sustainability, and survivance alongside more dire models of social upheaval in response to crop failure

(Fedick and Santiago 2022; Lentz et al. 2018; Macrae 2017; McAnany and Negrón 2010; Zimmermann 2019). As we have documented in this article, mounting evidence over the past 30 years reveals more resilience built into ancient Maya communities, in terms of available food options and environmental management strategies.

Such studies have led to new trajectories of research: approaches to polyculture, successional system management, and "managed mosaics" (Fedick 1996c) of landscape. In this lowland Maya mosaic, mixed plant practices appear relatively heterogeneous across time and space. Maize, though relatively common across Classic period sites for certain segments of population, was not the only cultivar. We find abundant evidence of multiple strategies that incorporated non-domesticates, tree crops, and geophyte crops across time and space. We see landscape engineering manifested in various ways: soil management, slope management, field-surface management, and wetland management. The ethnoecological implications of this evidence are that some locations in the Maya Lowlands had low resilience, while many other locations had high resilience potential through the multiple sustainable practices already in play. In terms of societal impacts, we find the disappearance of one set of lifeways in some locations for some segments of the population, but the resilience of Maya populations as a whole through a blend of migrations, maintenance of sustainable practices, and the development of new strategies in response to crisis.

Past to Future

Archaeological research on ancient agricultural systems has contributed greatly to understandings of ancient societies, where researchers have taken an ethnoecological perspective and considered the longue durée. We hope this broad review of new evidence provides scaffolding for the next step: spatio-temporal analysis of the arrival and development of key cultigens and practices at the regional level. But beyond documenting the particulars of ancient societies, what might be some contributions of archaeological studies to contemporary agricultural practices and governmental policy directives, both in the Maya Lowlands and elsewhere in the global tropics? Archaeological datasets have been interpreted for contemporary narratives in three primary ways: preserving "timeless values," revealing cautionary tales, and actively strategizing for the future. More simply, modern narratives about current anthropogenic impacts already draw from archaeology to restore, to revitalize, to sustain, and to warn (e.g., Diekmann et al. 2007; Montagnini 2006; Renard et al. 2012; Stannard et al. 2004; Tainter 2014). Public policies and governmental initiatives have drawn from archaeological research to address traditional cultivation techniques, revitalization of crops and practices, health issues, dietary concerns, food security, and the curation of biodiversity. Such initiatives have taken the form of heirloom seed distribution, plant curation, ancient cuisine workshops, and even the expulsion of GMO crops from farmlands.

Building big picture views of the landscape has real-world impacts. Echoing Alexander's comments on Maya settlement (2006, p. 450), we could argue that forms of contemporary Maya agriculture were not cemented in the ancient past but are instead "a sensitive indicator of the ecological, political economic, and social changes that reshaped the cultural landscape of the nineteenth and twentieth centuries." Rather than "cultural survival," Alexander (2006, p. 465) writes, "extensive shifting cultivation and down-the-line settlement expansion should be viewed as a short-term adjustment by smallholders for coping with demographic collapse, political turmoil, and local violence."

Positioning ancient Maya people as attentive and careful stewards of the environment has implications for modern Maya people (Ardren 2006; Fedick 2003), who did not "choose to fail" in the sense of Diamond (2006). Generally, forest conservation and restoration efforts are aided by a deep-time understanding of ecological dynamics (Ford and Clarke 2002). In several cases, such archaeological research has been incorporated directly into public action. Scholars are engaged in ongoing work to connect farmers and researchers (Allen et al. 2003; Jiménez-Osornio 2003), adjust to global and local food crises (Doolittle et al. 2002; Zarger 2009), understand contemporary soil erosion (Beach 1998), enhance sustainability (Kennett and Beach 2013; Tainter 2014), and reduce farmer vulnerability (Fisher 2020; Vallejo Nieto et al. 2011).

For these reasons, it is critical to reappraise old models of agriculture in the tropics, not only to more accurately represent people in the past but to more meaningfully contribute to resolving issues in the present, including environmental justice, deforestation, neoliberal agrarian reform, and other critical issues (Abramiuk et al. 2011; Briggs et al. 2006; Dine et al. 2019; Eusebio 2020; Fisher 2020; Guttmann-Bond 2010, 2014; Hayward and Kuwahara 2012; Logan 2013; Mann 2004; Montagnini 2006; Renard et al. 2012; Zimmermann 2019). Our synthesis of recent findings has indicated an extensive use of geophyte crops as well as wild plants (vs. maize as exclusive staple); wide spectra of procurement and production strategies from forests, swamps, and uncultivated areas (vs. exclusive cultivation practices); the maintenance of wild stands and careful management of forest resources; heavy reliance on horticultural and homegarden products; and a wide array of agro-engineering strategies tailored to varying and dynamic conditions. These findings have led us and other researchers to reconsider environmental relationships, societal collapse, and societal resilience.

How might we negotiate productivity and sustainability (through many cultural and natural definitions)? The record of ancient tropical agricultural strategies in the Maya area reveals several pathways to natural and cultural sustainability: striving for agricultural productivity with and without surplus; using local ingredients and those adapted from similar ecological regimes; growing various types of crops—grain, root, and tree; incorporating various types of ingredients—domesticated, managed, and collected; and molding landscapes and sediments to encourage sustainable agriculture.

Which alternate farming solutions might we offer, based on archaeological research and understandings of traditional ecological knowledge in the Maya area? Ancient tropical agricultural strategies offer contemporary pathways here as well: modeling community-based agriculture, using ancient techniques and techniques passed down over generations, approaching agriculture holistically as part of living ecosystems and living cultures, recentering horticulture and plant management, and incorporating alternatives to swidden practices. We see great potential in future work that is more deeply collaborative, where farmers and archaeologists closely align research strategies, interpretations, and outcomes through frameworks offered by contemporary Indigenous archaeology and community-engaged archaeology (see Schneider and Panich 2021).

Finally, which new agricultural strategies could be inspired—or discouraged—by ancient practices? Here the archaeological record yields several ideas: avoiding overreliance on monocrops and grain crops, maintaining seed banks and diverse genetic portfolios, approaching radical terraforming cautiously, creatively using extant topography, using alternate fertilizing agents, and accounting for greater climatological variability than represented in a 100-yr timespan.

The final question we pose instead to readers: which additional agricultural strategies might we consider in an era of radical environmental change?

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