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ARTICLE

Suitability Models of Ancient Maya Agriculture in the Upper Usumacinta River Basin of Mexico and Guatemala

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Abstract

Recent archaeological and remote sensing research in the Maya Lowlands has demonstrated evidence for extensive modification of the landscape in the forms of channeled fields and upland terraces. Scholars often assume these measures were taken primarily to intensify maize production; however, paleoethnobotany highlights a greater diversity of crops grown by the precolonial Maya. This study combines the growth requirements of 18 crops cultivated by ancient Maya farmers with lidar and other geospatial data in a suitability model that maps optimal areas for growth. These 18 crops cluster into five groups of crops with similar growth requirements. Across the study region, different groupings of crops had different suitability in and around different ancient Maya centers and agricultural features. This spatial variation in suitability reflects the heterogeneity of land resources and adaptations and contributes to existing conversations about economic and settlement organization in the study area. The results of this study serve as a foundation for future field studies and more complex spatial models.

Resumen

Recientes investigaciones arqueológicas y de teledetección en el área maya han demostrado evidencia de modificaciones del paisaje en forma de campos canalizados y terrazas en zonas altas. Aunque frecuentemente se supone que estas modificaciones eran usadas para la intensificación de la producción de maíz, investigaciones paleoetnobotánicas resaltan la diversidad de productos cultivados por los antiguos mayas. Para evaluar la relación entre tipos de cultivos y la ubicación de las terrazas agrícolas y campos canalizados en la zona alta del rio Usumacinta, este estudio combina los requisitos de crecimiento de 18 cultivos de los antiguos agricultores mayas, con lidar y otros datos geoespaciales en un modelo de idoneidad que mapea las áreas óptimas de crecimiento. Estos 18 cultivos fueron reunidos en cinco grupos con requisitos de crecimiento similares. En la región de estudio, diferentes grupos de cultivos tuvieron idoneidades diferentes en y alrededor de los distintos sitios y rasgos agrícolas. Esta variación espacial en idoneidad refleja la heterogeneidad de recursos y adaptaciones de la tierra, y contribuye a discusiones sobre la organización económica y de los asentamientos dentro de la zona de estudio. Los resultados de este estudio funcionan como la base de futuros estudios en campo y modelos espaciales más complejos.

Keywords: ancient Maya agriculture; lidar; landscape engineering; crop suitability; GIS modeling

Palabras clave: agricultura maya; lidar; capital paisajista; idoneidad agrícola; SIG

Prior to the mid-twentieth century, the dense forest and karst, wetland terrain of the Lowland Maya landscape was believed to limit agricultural potential and, by extension, cultural and political development (e.g., Meggers 1954). Even as archaeological research revealed complex cityscapes across the region, this general understanding persisted. Precolonial Maya subsistence was seen to be based on swidden—or milpa—agriculture and on a few staple crops, primarily maize (Turner 1978). This "swidden thesis" dominated the literature through at least the 1960s, and heavily influenced arguments about ancient Maya economy, population density, urbanism, decline, and environmental degradation (Morell-Hart et al. 2023; Rathje 1971; Russell 1988; Turner 1978).

In the late twentieth century this maize-swidden agriculture paradigm was challenged by scholars exploring the importance of root crops (Bronson 1966) and the growing evidence for intensive agriculture strategies, including terracing and wetland field cultivation (Bloom et al. 1983; Healy et al. 1983; Siemens and Puleston 1972; Turner 1974; Turner and Harrison 1983; Wilken 1971). This shift broadened perspectives on food production systems of ancient Maya people and led scholars to reimagine the possibilities for sociopolitical, economic, and demographic models in the area (Fedick 1989, 1996; Fedick and Ford 1990; Flannery 1982; Gómez-Pompa 1987; Hather and Hammond 1994; Turner and Miksicek 1984).

As the dominant models of ancient Maya agriculture evolved, remote sensing and other geospatial technologies and methods became important tools for gathering and analyzing evidence of intensive cultivation across the Lowlands, offering the promise of reduced time and costs for extensive landscape surveys in densely forested environments (e.g., Adams et al. 1981; Garrison et al. 2008; Pope and Dahlin 1989; Saturno et al. 2007; Sever and Irwin 2003). Over the past decade, lidar (light detection and ranging) remote sensing has received particular attention in Maya archaeology for its unique ability to "penetrate" the jungle canopy (Chase and Chase 2001; Saturno et al. 2007). Lidar has been instrumental in revealing the expansiveness of agricultural activity of many other regions across the Maya Lowlands (e.g., Beach et al. 2019; Canuto et al. 2018) and in revealing new possibilities for the organization of and relationships between agricultural activity and settlement at various sites (Garrison et al. 2019; Schroder et al. 2020).

This research builds on that geospatial revolution and contributes to new understandings of the complexity of ancient Maya landscapes and agricultural system dynamics. By considering the growth requirements of a multitude of crops cultivated by ancient Maya farmers, as well as nonswidden agricultural practices, this research reconsiders agricultural modeling that has largely focused on maize, swidden agriculture, and non-crop-specific capability modeling (for examples of capability vs. suitability modeling, see Fedick 1995). Capability modeling, a basic type of land evaluation, involves describing, quantifying, and classifying the features necessary for plant growth and assesses limitations on cultivation without specifying any crop. Suitability modeling, in contrast, is crop specific (Fedick 2010). Often, capability modeling is simply maize suitability modeling in disguise, potentially obscuring a range of important crops grown for subsistence (such as manioc) and trade (such as cotton).

Here, we make use of lidar data collected in 2019 by the National Center for Airborne Laser Mapping (NCALM) in collaboration with the Proyecto Arqueológico Busiljá-Chocoljá (PABC) (Golden et al. 2021) and plant and soils information gathered from key resources to assess the suitability of the Upper Usumacinta region of the Maya Lowlands for 18 key crops (see Supplemental Text 1) cultivated by ancient Maya farmers. Using GIS modeling, we also investigate the spatial relationships between the suitability of the land for different crops and the placement of agricultural features and settlement in the Upper Usumacinta River region. We take into account the heterogeneity of settlement and agricultural patterns across the Lowlands and build off the general relationships between the physical landscape and agricultural and settlement features established in literature. Such an approach also addresses the economic (Fedick 2017) and sociopolitical context (Freidel and Shaw 2000) of ancient Maya communities, as they influenced and were influenced by crop selection and agricultural intensification.

Tracking Agriculture in the Maya Area

Esther Boserup's (1965) model of agricultural intensification was particularly important in the evolution of thought regarding ancient Maya agriculture. In this model, population growth is an independent variable that drives the intensification of agricultural production, understood in terms of cropping frequency. Though influential, population and its relationship to intensification as described in

Boserup's field agriculture-focused model do not account for the variety of causes and trajectories of agricultural intensification (Johnston 2003; Morrison 1994).

In another approach, Brookfield (1972) highlights the use of increased capital, labor, and skill to intensify agricultural production from an area, which grounds agricultural intensification in landesque capital improvements. Such landesque improvements include permanent alterations to the landscape maintained with relatively little labor after an initial investment in construction (Brookfield 1972; Fedick et al. 2024). The nature of our data encourages us to focus on terraces and channelized fields as evidence of intensification; however, we also recognize landesque capital investments that are less readily visible, such as soil amendments and managed succession.

Agricultural intensification was a key part of complex Maya socioeconomic and sociopolitical systems involving decision-making and land evaluation, beyond simply the need for greater agricultural production. McAnany (1992) discusses evidence of "marginal" lands (e.g., hillslopes and wetland areas) reclaimed for agriculture. She hypothesizes that, with population growth, after production on optimal lands is maximized or taxation demands and participation of sites in exchange networks increase, communities may have pursued agricultural intensification in such marginal areas. Risk reduction is also cited as a potential cause of agricultural intensification. In regions with high environmental variability, such as the Maya Lowlands, farmers may intensify production to mitigate the risk of crop failure. The intensification of agriculture may also be a response to social risks, such as warfare (Batún Alpuche 2009).

Terrace and channelized field construction have been associated with varying degrees of centralized planning and management, from local or household-level, small-scale projects that did not require high levels of social organization (Dunning and Beach 1994; Guderjan et al. 2017; Lemonnier and Vannière 2013; Turner 1983), to large-scale alterations of the landscape requiring administrative control that is implicated in broader systems of trade (Beach et al. 2019; Canuto et al. 2018). Ancient Maya texts are silent on such engineering efforts and the specifics of landownership or control over labor (Houston and Inomata 2009:242). It is important to note that the relationships between intensive agricultural production and organization and economic and political organization varied temporally as well as spatially (Liendo Stuardo 2002:191).

Such alterations to the landscape demonstrate an intimate knowledge of available environmental resources and their sustainable management. Practices corresponded with local environments rather than reflecting a singular template repeated on the landscape, as we might expect from direct mandates of elites who were managing a number of areas. Similar to investments in landesque capital, investments in cultivated capital (cultivation of and reliance on a variety of plants for subsistence; see Fedick et al. 2024) have implications for the mediation of ecological risk to ancient Maya populations in the variable and changing Lowland environment. Developing cultivated capital requires in-depth knowledge of the biological characteristics of varying plants, the physical landscape of the Lowlands, and the skills to best utilize these natural resources. Paleoethnobotanical research has been particularly important in identifying the wide variety of domesticated food sources utilized by ancient Maya people and in reconsidering the absolute centrality of the Mesoamerican triad of squash (*Cucurbita* spp.), beans (*Phaseolus* spp.), and especially maize (*Zea mays*) in ancient Maya agricultural systems (Cagnato 2016; Cagnato and Ponce 2017; Ebert et al. 2019; Hather and Hammond 1994; Lentz 1999; McKillop 1994; Morehart 2011; Morell-Hart et al. 2023; Sheets et al. 2011).

Fedick (2020) reports 497 species of autochthonous plants used as food by contemporary Maya people, a variety likely available to ancient Maya people as well. Maize, squash, and beans are well established as dietary mainstays that also played important roles in the social and economic lives of ancient Maya people. Cacao (*Theobroma cacao*) is another food plant of importance, particularly in spiritual and political matters, similar to maize (Fedick 2017; McNeil 2020). In addition to cacao, there is evidence for the consumption of numerous fruits, seeds, and nuts from trees and shrubs including nance (*Byrsonima crassifolia*), hogplum (*Spondias* spp.), avocado (*Persea* spp.), ramón (*Brosimum alicastrum*), and mamey, especially *Pouteria sapota* (Morell-Hart et al. 2023). Tree crops were cultivated in home gardens, orchards, and forest gardens and are an example of cultivated capital, as they reflect long-term investments in place (Fedick et al. 2024). The use of crops was not limited to food. Cotton (*Gossypium hirsutum*), for example, is known foremost for its use in textiles, though its seeds may have also been ground and used for oil (Lentz et al. 1996; Morehart et al. 2004). Many palms and trees used by the ancient Maya were similarly multipurpose and used as food, as medicine, in ritual, and for construction (McKillop 1996; McNeil 2020).

Along with tree crops, edible geophytes, especially manioc (*Manihot esculenta*), were likely a major part of the ancient agricultural landscape. Research at Joya de Cerén in the highlands of El Salvador provides evidence for root-crop-based subsistence (Bronson 1966). Manioc was cultivated as a monocrop over a large area outside the village, suggesting it was a dietary staple (Sheets et al. 2011; Slotten et al. 2020). Other notable geophyte crops recovered from this site include sweet potato (*Ipomoea batatas*), malanga (*Xanthosoma* spp.), and arrowroot (*Maranta arundinacea*). Studies at Cerén also revealed tree/shrub cultivation in home gardens along with other key crops, especially chile peppers (*Capsicum* spp.) (Lentz et al. 1996).

Modeling Agricultural Suitability

Frameworks for land evaluation developed by the Food and Agriculture Organization of the United Nations are widely referenced for modern suitability assessments (e.g., Food and Agriculture Organization of the United Nations 1976). We generally follow these guidelines. However, such frameworks for land evaluation often assume the use of modern cultivation technologies, presume at least some participation in globalized markets and are not specific to a single land unit or crop plant. For these reasons, inputs and outputs of such frameworks may not be appropriate for understanding agricultural suitability in archaeological contexts (Fedick 2010).

Although suitability models have been applied to archaeological research across the globe, their potential is underexplored in the Maya area. In the Maya Lowlands, the focus in land evaluation studies has largely been on milpa agriculture, using general capability modeling and suitability modeling of maize (Fedick et al. 2024). Existing studies approach general capability and maize suitability through traditional soil classifications (e.g., Barrera-Bassols et al. 2006; Jensen et al. 2007), while others focus more heavily on soil mapping and GIS to assess agricultural productivity for re-creating, validating, and estimating population levels and agricultural surplus, as well as analyzing relationships between agriculture land use and settlement (Fedick 1995; Ford and Nigh 2016; Walden et al. 2023). However, here we recall the limitations of Boserup's (1965) model in (1) considering only field agriculture and (2) population as a driver in agricultural intensification.

In this study we follow Hanselka and King (2017), who used weighted overlay analysis in northern Mexico to produce a suitability raster for maize growth, isolating optimal areas for maize farming to identify areas of high to moderate suitability for maize and predict areas with high potential for archaeological sites defined by agricultural activity and dependence. We apply a multi-criteria evaluation weighted overlay (MCE-WO) suitability model to identify the most and least optimal areas of growth for the 18 crops investigated in this study (first developed by Horseman [2022]). We compare the results of this suitability analysis with known settlement locations and relict agricultural features.

The Study Area

Since 2010, the PABC has undertaken research in the Upper Usumacinta River region of the western Maya Lowlands that includes the major centers of Piedras Negras and Yaxchilán, as well as smaller royal and nonroyal centers, such as Lacanja Tzeltal, La Mar, El Cayo, and Budsilha (Figure 1; Scherer and Golden 2012).

During the Classic period (AD 250–900) the economic and political power of royal courts at Piedras Negras and Yaxchilan and their smaller neighbors exerted a significant influence on regional trade. The most obvious material indicators of such trade include ceramics, obsidian, jade, and similar durable goods (Golden et al. 2012, 2020a; Roche Recinos 2021). Although less immediately evident archaeologically, such trade surely included agricultural commodities—agricultural goods that are storable and transportable—as well (Fedick 2017; Morell-Hart et al. 2023).

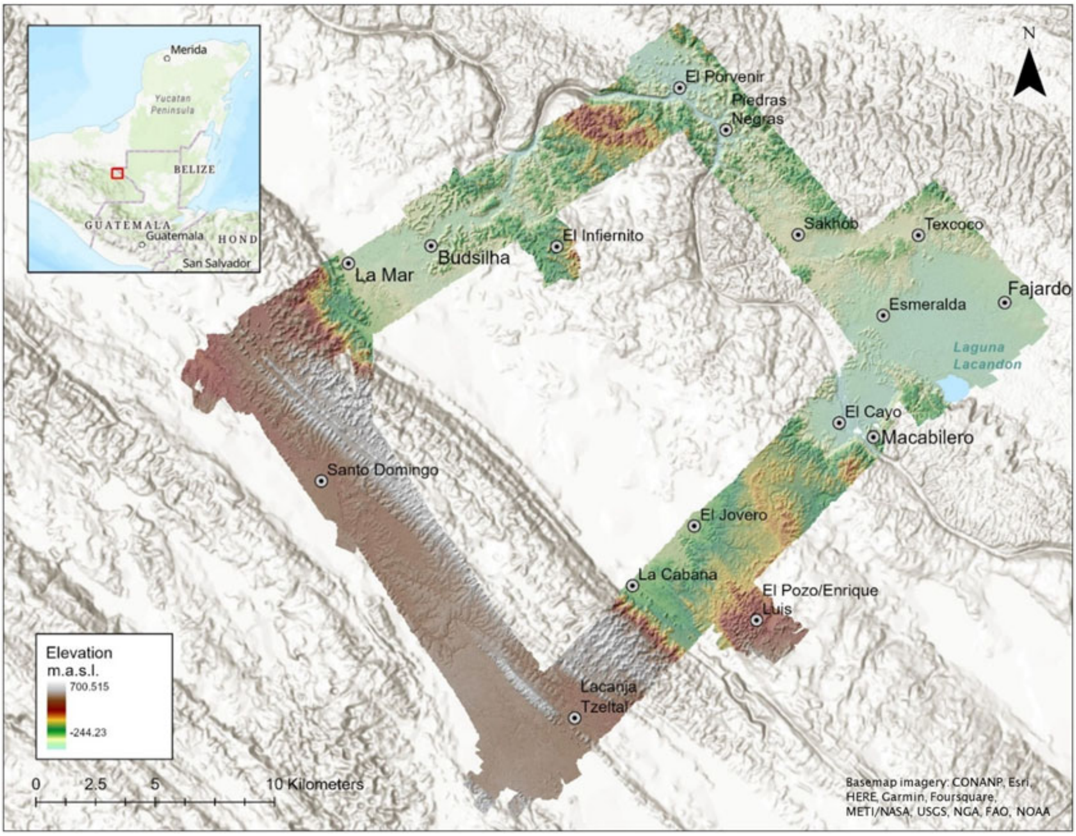

Figure 1. Map of the study region, including key sites. Lidar data from the 2019 NCALM-PABC survey. Created in Esri ArcGIS Pro 2.9.

Agriculture in the Study Area

Patterns of agricultural production and agricultural strategies in the Upper Usumacinta River region are not well understood. Dietary stable isotopic analysis on human skeletons from Piedras Negras firmly establishes the importance of maize in the diets of those living at that polity capital (Scherer et al. 2007), while paleoethnobotanical analyses reveal a wide suite of cultivated crops (Morell-Hart et al. 2023). At Piedras Negras, the soils largely fall into the soil order Mollisols, which are appropriate for agriculture because they are generally deep, well-drained, and fertile (Fernández et al. 2005; Johnson et al. 2007). The deep, toe slope soils near Piedras Negras may have been particularly suitable for agriculture compared to the thinner, more easily erodible hillslopes. On these toe slopes, high $\delta^{13}C$ in soil organic matter, a signature of C_4 plant (such as maize) growth, provides evidence for ancient agriculture in and around the ancient city. The $\delta^{13}C$ enrichment of the toe slopes decreases as distance from Piedras Negras increases (Fernández et al. 2005).

The lack of terracing immediately around Piedras Negras and its surrounding peri-urban sites led Zachary Nelson (2005) to suggest that Piedras Negras was reliant on a medium-fallow swidden agriculture system to support a maximum population of 2,600 individuals (see also Golden et al. 2021). Extensive terracing and channelized fields, however, have been observed in and around the Laguna Lacandon some 14 km southeast of Piedras Negras (Golden et al. 2021; Scherer and Golden 2014). Like Piedras Negras, the soils in this area also fall into the soil order Mollisols, and isotopic analysis of those sediments has confirmed evidence of the cultivation of C_4 plants, which suggested to Johnson and colleagues (2007) that this area was a maize "breadbasket" for Piedras Negras (unpublished data in Fernández et al. 2005). Another proposed "breadbasket" is located between the centers of

La Mar and Budsilha, an area characterized by deep soils and relatively flat topography. In contrast to Piedras Negras, the terrain around La Mar and Budsilha was extensively modified by terraces and channeled fields (Golden et al. 2021; Scherer and Golden 2012). The production of maize by households in these regions of high maize production likely exceeded local needs and surpluses could have moved through nonmarket and market exchange systems in the wider region. While some maize may have been paid locally as tax and tribute, gifted, or bartered, the surplus may have also supported the maize-rich diets of the people at Piedras Negras and other major centers through taxed trade at central markets (Golden et al. 2020a).

The diversity of low-density urban land uses and intriguing distribution of agricultural fields have many consequences for our understandings of subsistence, the relationships between the different sites in the study region, as well as the economic and social systems in place in the Classic period kingdoms. Golden and colleagues (2021) have elsewhere put forward four hypotheses. First, settlements like Piedras Negras that were engaged in local crop production without investments in terraces and wetland fields engaged in agroforestry or the production of nonagricultural goods. Second, the areas near La Mar, with expansive durable evidence of agricultural intensification, reflect an increase in taxation and tribute from royal courts and nobles throughout the Classic period. Third, agricultural intensification in this region provided goods for marketing and long-distance trade, such as cacao. Fourth, the visible agricultural infrastructure represents an investment in risk reduction against crop loss due to war and climate variability. Another means to hedge against climate variability would be to maintain a diverse crop portfolio, including plants that might have grown during periods of unusually high or low precipitation, or when the timing of the rainy season fell outside of the expected parameters. This study provides a first attempt at testing several of these hypotheses by modeling the region's suitability for supporting diverse species of crops.

Methods—Multi-Criteria Evaluation Weighted Overlay Modeling

MCE-WO analysis was performed in ESRI's ArcGIS Pro 2.9 using the Weighted Overlay tool. This analysis consists of overlaying multiple integer rasters that have a common scale to produce one output suitability raster, where higher cell values indicate more suitable areas. Each raster has a weight assigned to it based on its importance to the problem or decision being evaluated; in this case, suitability of the land for each crop. This weight, or its percent influence on the outcome compared to the other criteria, combined with the individual cell values of the input rasters produces the output suitability surface for each crop. All weights were determined using a ratio estimation weighting scheme. Using this method, the most important criteria, or layer, is assigned a value of 100. Proportionally lower values were then assigned to criteria of less importance. Finally, the ratio of each criterion was taken relative to the least important criteria and the final weight was derived by dividing each ratio by the sum of all ratios (see Supplemental Figure 1 for more detail).

The growth preferences considered in this model are slope, soil texture, and soil moisture. As model inputs, these factors take the form of slope, % clay, and plant available water capacity rasters. Preprocessing of the input layers included projection into a common coordinate system of WGS 1984 UTM Zone 15N and, if necessary, clipping to the study area extent and resampling to a common 250 m resolution. A total of 250 m was chosen based on the lowest resolution dataset being used.

Due to the low specificity of the data, many different crops appear to have very similar growth preferences and would have the same model inputs. Thus, given the nearly identical habitat preferences for several species in this model, five crop groupings emerged from the 18 plants considered in this study (Supplemental Table 1), each of which formed the basis of one output suitability map. The input rasters were then reclassified into nine classes using the Reclassify tool, where the most suitable values for a given crop group are coded as 9 and the least suitable as 1. The rescaled rasters were then combined with their relative weights applied (Supplemental Figure 2).

Data collection, classification, and preparation are further described in Supplemental Text 1 and Supplemental Tables 1, 2, and 3. Although a more sophisticated modeling strategy than general capability assessments, the land suitability output for each crop grouping should be viewed as a starting point for further work, and not a final product (see Supplemental Table 3 and Supplemental Text 2 for details on model limitations).

Results

We present the suitability maps for each of five groups of plants (detailed in Supplemental Text 1). We then use the output for each grouping to consider relationships with anthropogenic features: terraces and channels. In each case, we select only a subset of the broader region documented with lidar. The area around the archaeological sites of La Mar and Budsilha and the region near the Laguna Lacandon were chosen for their abundance of terraces and channelized fields, respectively.

Group A

Much of the study region is moderately to highly suitable (ranks 4–9) for the cultivation of Group A crops—malanga and beans (*X. sagittifolium* and *P. vulgaris*). The mean value of suitability across the map is 6.2, which is the highest average across all suitability maps. That is, these three plants should thrive best in the region. Approximately 112.5 km^2 of the 308.40 km^2 suitability map is predicted to be highly suitable (ranks 7–9) for the cultivation of Group A plants (see Supplemental Table 4 for full tables of descriptive statistics for each crop group). The areas of highest suitability appear in the regions between Santo Domingo and Lacanja Tzeltal as well as between El Torreon and Macabilero. However, in the region between Santo Domingo and Lacanja Tzeltal, there is also a stretch of land with low suitability on the interior of the study area.

Terraces and channeled fields (Figure 2) generally fall within zones of moderate to high suitability for Group A plants (ranks 4–8), though the areas with channeled fields are located in areas of higher suitability than those with terraces.

Group B

The suitability map for Group B plants—cohune and coyol palms, sweet potato, manioc, and arrowroot (*A. cohune*, *A. aculeata*, *I. batatas*, *M. esculenta*, and *M. arundinacea*)—ranges from 2–9. The region is for the most part moderately suitable for this group of plants. Suitability ranks 4–6 for approximately 73% of the study region and the average suitability value across the map is 5.2. That is, this group of five plants should do moderately well in the region overall. Like the map of suitability for Group A plants, the largest areas with high suitability are located between Santo Domingo and Lacanja Tzeltal and between El Torreon and Macabilero.

The mapped terraces generally fall within areas of low to moderate suitability for Group B plants, whereas the areas where channelized fields have been observed are in areas of moderate and high suitability (Figure 3).

Group C

The suitability map for Group C, consisting of only (*P. copal*), is different than the maps produced for Group A and Group B plants. The regions between Santo Domingo and Lacanja Tzeltal and between El Torreon and Macabilero, that are highly suitable for Group A and Group B plants are instead areas of lower suitability for copal. The terraced regions and area between La Mar and Budsilha display the highest suitability for copal. The region between Veinte de Noviembre and El Cayo and Macabilero is also highly suitable for the growth of copal. Overall, the region is mostly moderately suitable for copal, the mean suitability across the study region being 5.2.

The area with the highest density of channelized fields near the Laguna Lacandon falls within an area of low to moderate suitability for copal. The channelized fields near La Mar and Budsilha are in areas of high suitability (Figure 4b). Areas with terraces, by contrast, largely fall into areas of moderate-high suitability.

Group D

Suitability of the study area for achiote, squash, cacao, allspice, maize, and chile peppers (*B. orellana*, *C. pepo*, *G. hirsutum*, *T. cacao*, *P. dioica*, the three *Z. mays* varietals, and *C. annuum*) ranges from 4–9.

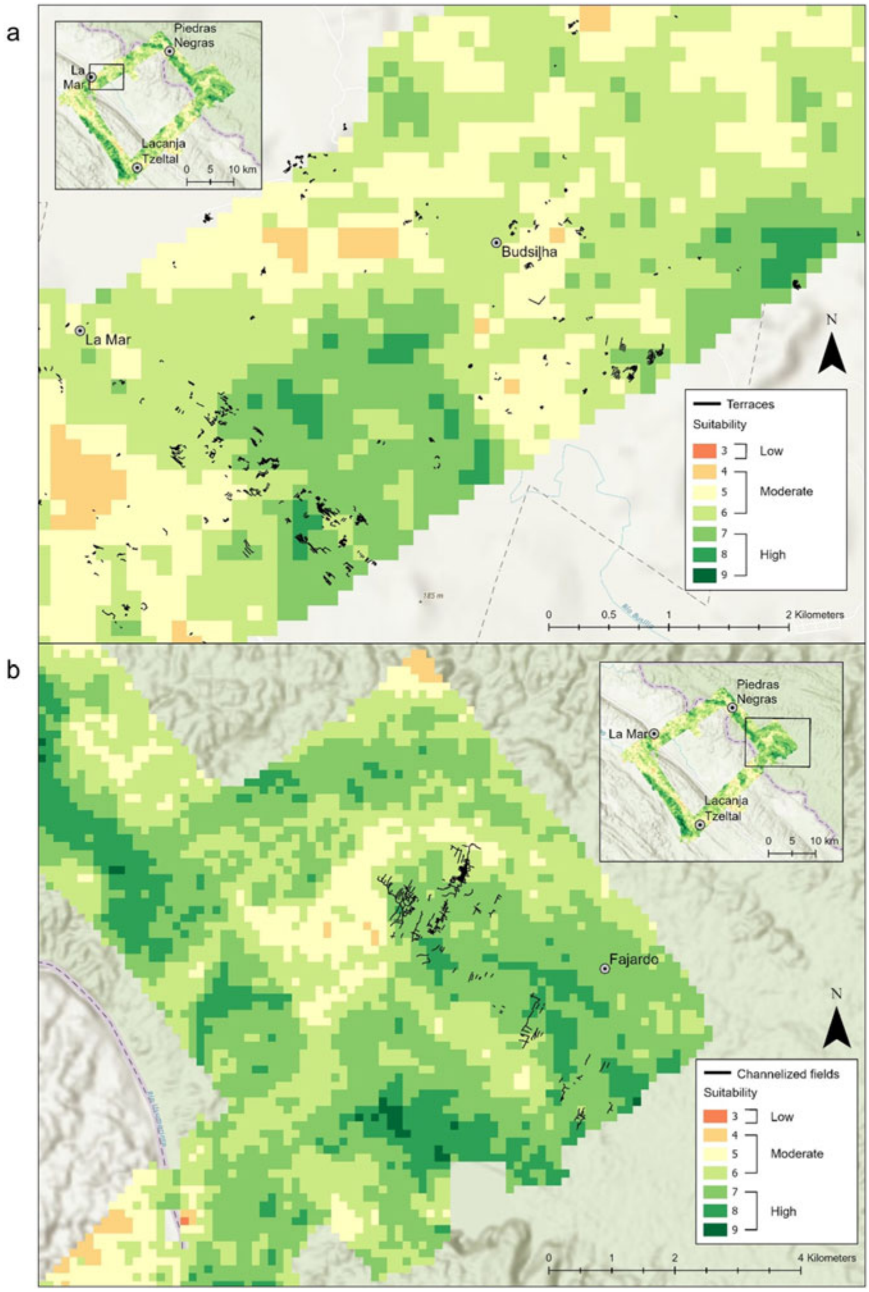

Figure 2. (a) Suitability surface produced from Group A crops including *X. sagittifolium* and *P. vulgaris* near the sites of La Mar and Budsilha. Mapped terrace areas overlaid onto the suitability surface. (b) Suitability surface produced for Group A crops including *X. sagittifolium* and *P. vulgaris* near the Laguna Lacandon. Mapped channelized field areas are overlaid onto the suitability surface.

No regions in the study area are of low suitability for this group of plants. The region is largely moderately suitable for Group D plants (approximately 70% of the study region) and the average suitability of the region is 6.1. That is, all eight of these plants should grow moderately well across the region.

Terraces and channelized fields both fall into areas that are for the most part moderately suitable for Group D plants across the study area. However, channelized fields mapped near Lacanja Tzeltal are

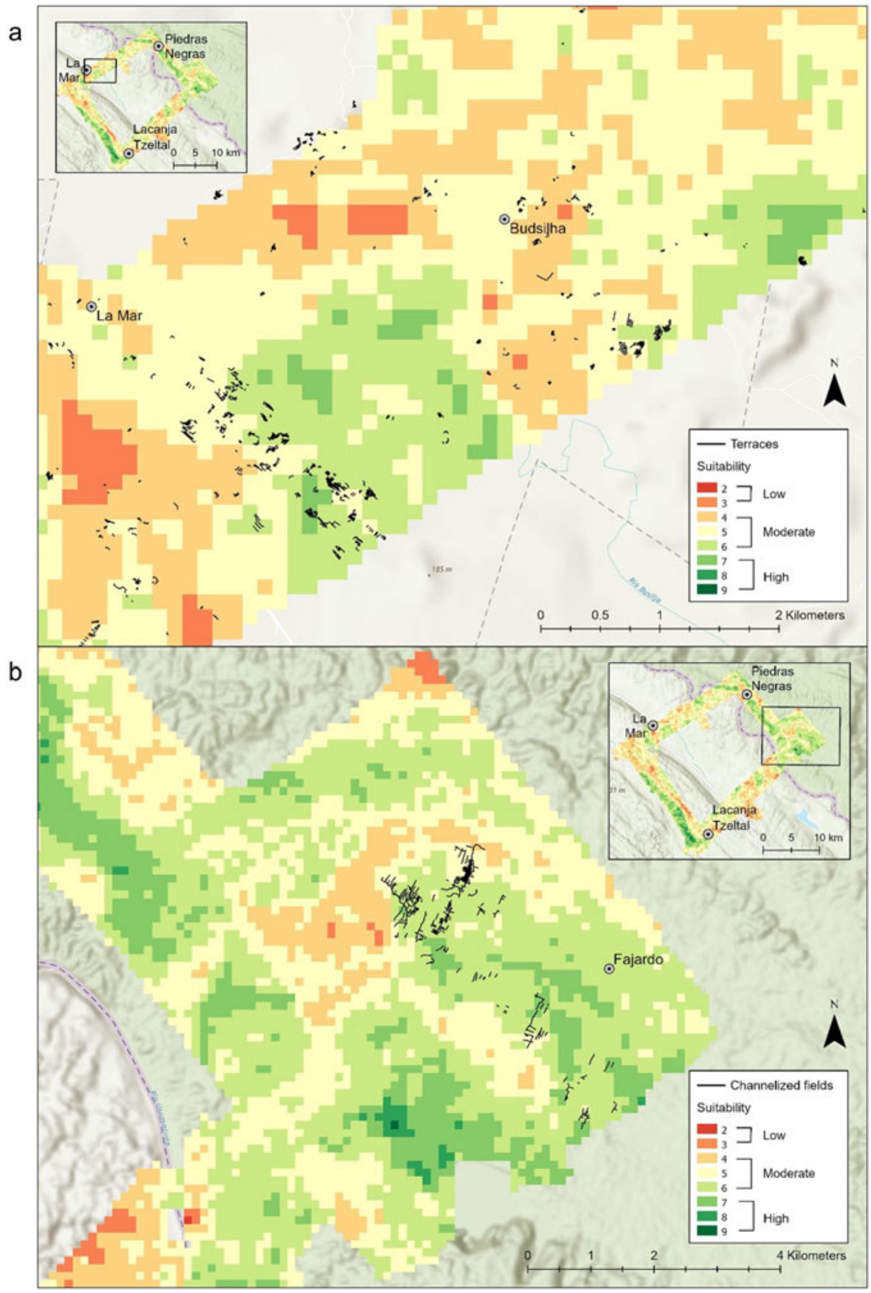

Figure 3. (a) Suitability surface produced for Group B crops including *A. cohune*, *I. batatas*, *M. esculenta*, *M. arundinacea*, and *A. aculeata* near the sites of Lar Mar and Budsilha. Mapped terrace areas are overlaid onto the suitability surface. (b) Suitability surface produced for Group B crops, including *A. cohune*, *I. batatas*, *M. esculenta*, *M. arundinacea*, and *A. aculeata* near the Laguna Lacandon. Mapped channelized field areas are overlaid onto the suitability surface.

positioned in areas of high suitability and do not cross into areas of moderate suitability as other field systems do (Figure 5).

Group E

The suitability of the study region for Group E, mamey sapote (*P. sapota*), ranges from 1–9 and the average suitability of the region is 5.1. The study region is for the most part moderately suitable for

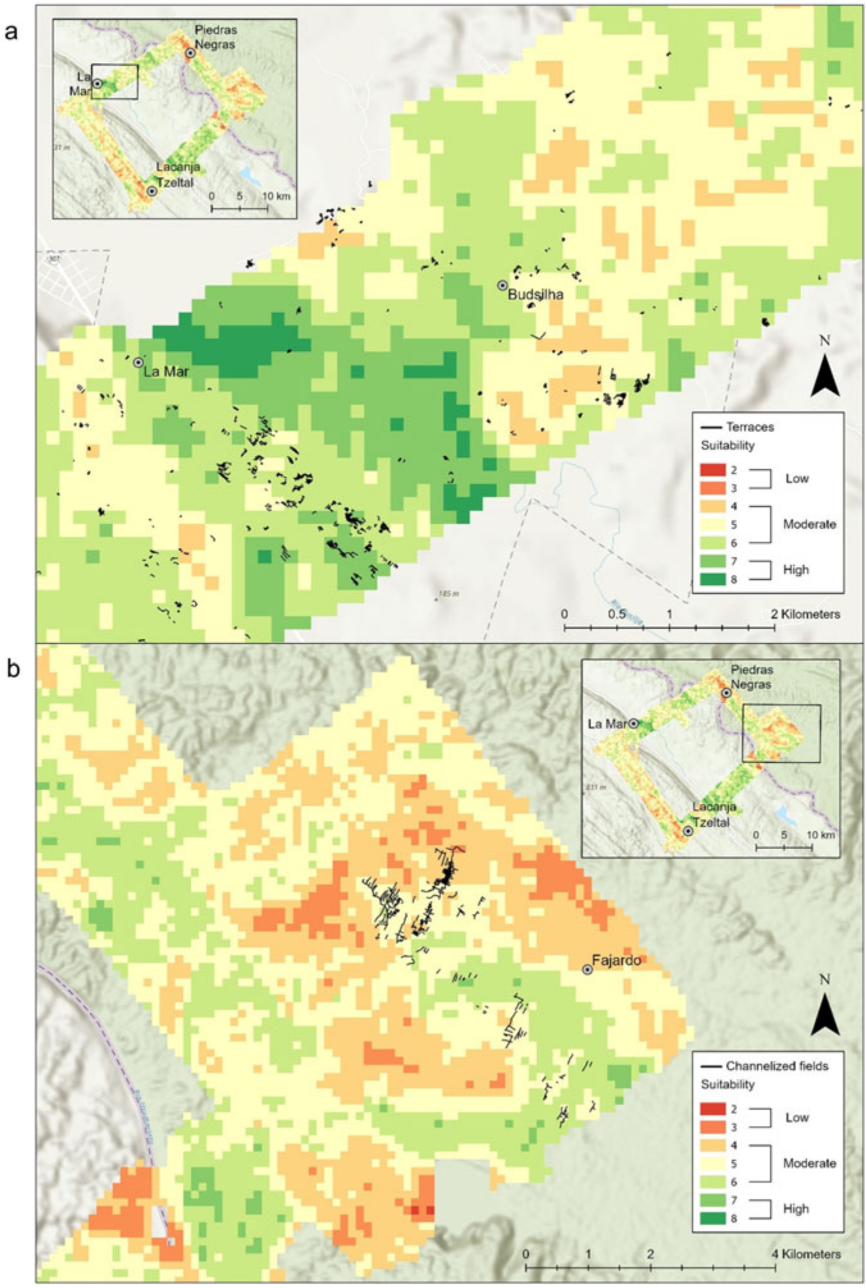

Figure 4. (a) Suitability surface produced for Group C, *P. copal* near the sites of La Mar and Budsilha. Mapped terrace areas are overlaid onto the suitability surface. (b) Suitability surface produced for Group C, *P. copal* near the Laguna Lacandon. Mapped channelized field are overlaid onto the suitability surface.

the growth of *P. sapota* (approximately 58% of the study region). The areas of high suitability are smaller in size in this map compared to the maps for other groups. Where large areas, for example between Lacanja Tzeltal and Santo Domingo, tend to be of one suitability category (e.g., moderate, see Figure 3), the same region in the suitability map for mamey has smaller areas of low, moderate, and high suitability interspersed between each other. Terraces and channelized fields lie with areas of moderate and high suitability for mamey across the study region (Figure 6).

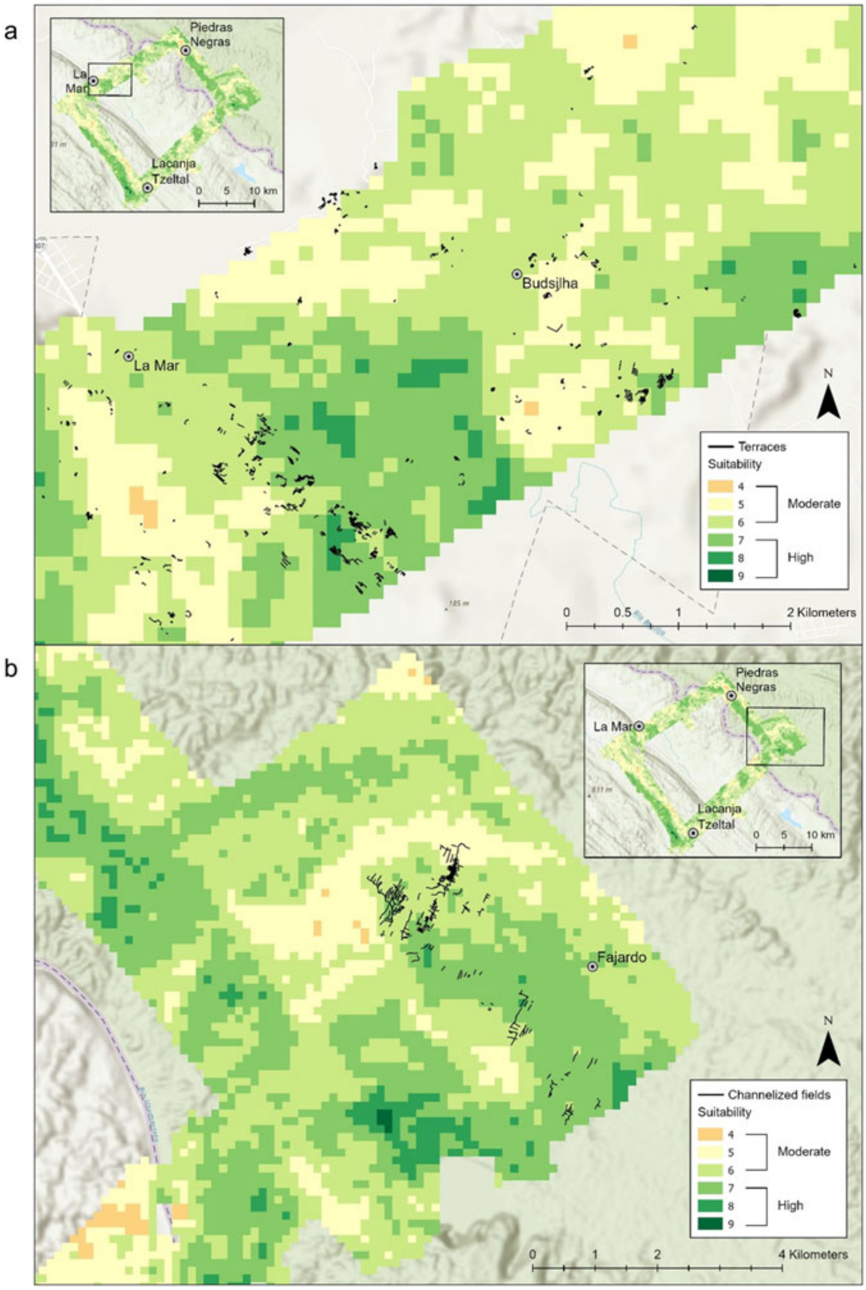

Figure 5. (a) Suitability surface produced for Group D crops, including *B. orellana*, *C. pepo*, *G. hirsutum, T. cacao*, *P. dioica*, *Z. mays*, and *C. annuum* near the sites of La Mar and Budsilha. Mapped terrace areas are overlaid onto the suitability surface. (b) Suitability surface produced for Group D crops, *B. orellana*, *C. pepo*, *G. hirsutum, T. cacao*, *Z. mays*, and *C. annuum* near the Laguna Lacandon. Mapped channelized field areas are overlaid onto the suitability surface.

Terraces and Channelized Fields: All Groups

Directly comparing the region between La Mar and Budsilha for all groups (Figure 7), there is one zone of high suitability for numerous crops, while there are two areas of generally low crop suitability. The area of highest suitability for all groups is located immediately to the east of the large terrace system at La Mar, though the suitability values in these zones vary across groups. The highest suitability value in this potentially productive region is 9, and this occurs for Group E, *P. sapota*, while the lowest

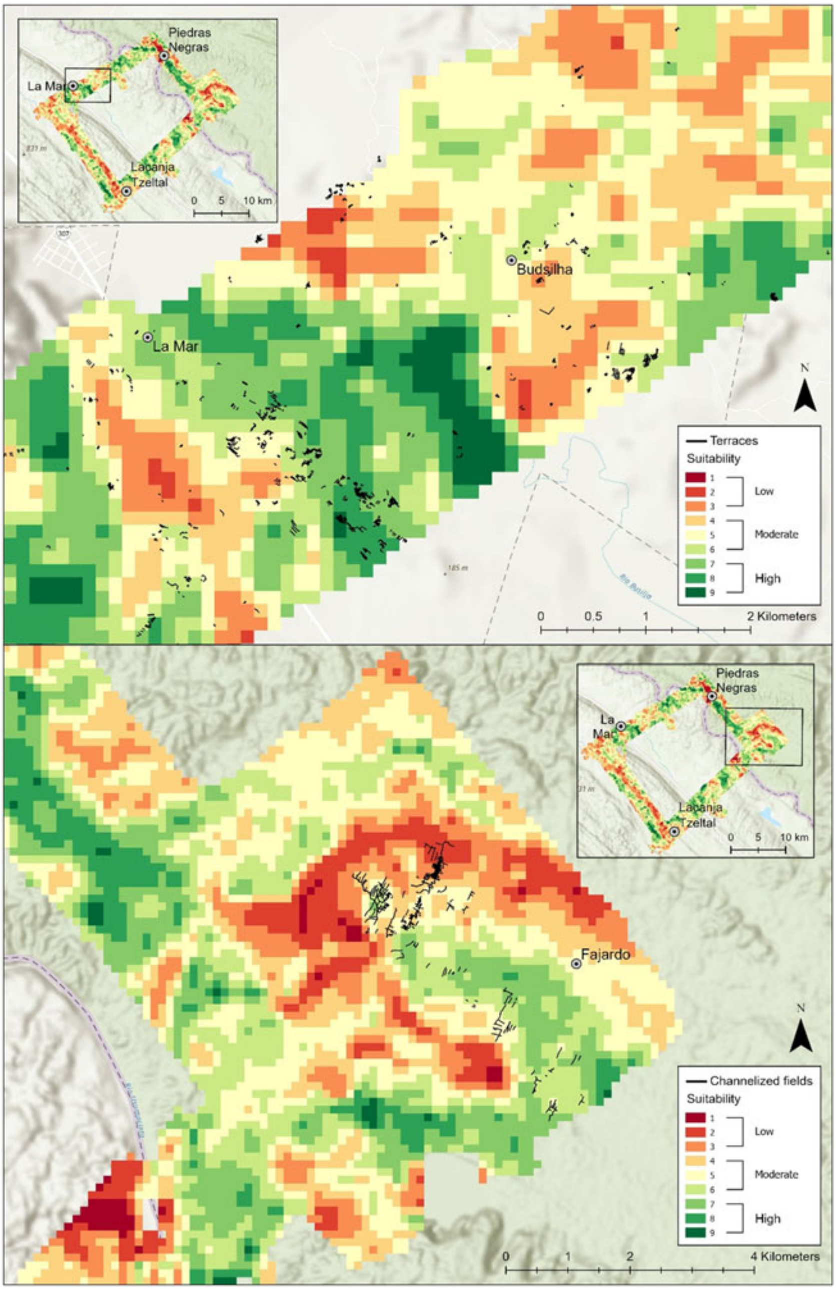

Figure 6. (a) Suitability surface produced for Group E, *P. sapota* near the sites of La Mar and Budsilha. Mapped terrace areas are overlaid onto the suitability surface. (b) Suitability surface produced for Group E, *P. sapota* near the Laguna Lacandon. Mapped channelized field areas are overlaid onto the suitability surface.

suitability value is 5 (for Groups B, C, and E). Group A, Group C, and Group D crops are similarly suitable for this area (values generally ranging from 6 to 8). Group B is the least suitable for this area, as it primarily has a suitability value of 6 and few high suitability pixels. Apart from Group C, the size and shape of this high suitability region are fairly consistent across groups. By contrast, an area of generally low suitability is located to the east of the potentially productive zone near Budsilha. A second area of generally low suitability is located to the west of the productive zone, nearer to the settlement of La Mar. In both instances, there are comparatively higher numbers of low (1–3) and moderate suitability

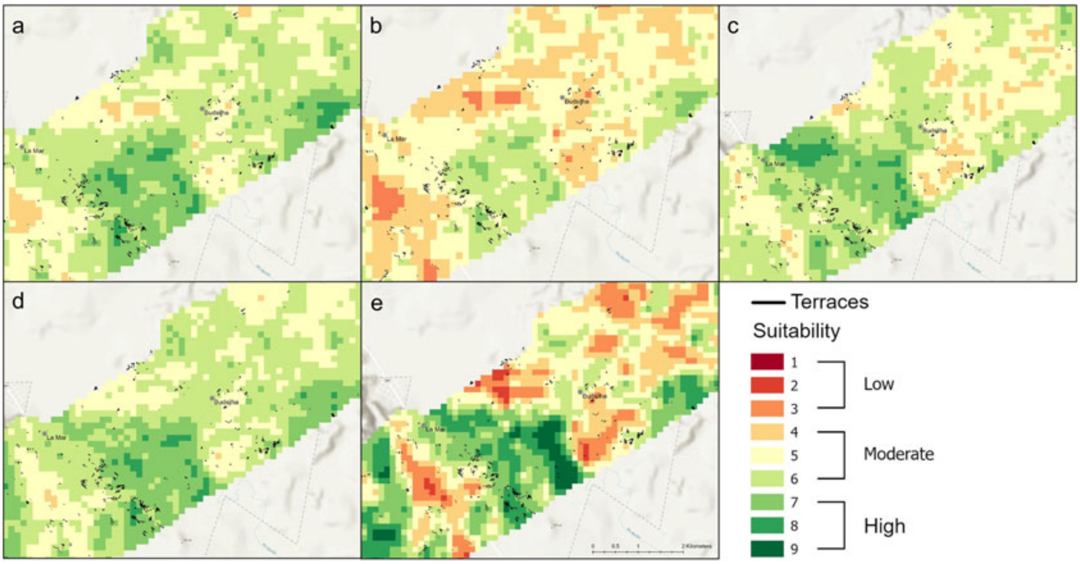

Figure 7. Direct comparison of the suitability of the terraced regions near La Mar and Budsilha for the groupings of crops A–E (a–e). The small black lines indicated terraces, many of them contour terraces and check dams previously mapped by Golden and colleagues (2021).

value pixels (4–6). Suitability for Group B and Group E crops in these regions span more and lower suitability values than the other groups.

The region of dense channelized fields near the Laguna Lacandon demonstrates a mix of crop suitability. Immediately to the west of the most extensive mapped channelized fields (near Texcoco), the region generally has low to moderate suitability for all crops (Figure 8). Here, the lowest suitability is 1 and occurs for Group E, *P. sapota*. Elsewhere in the area around the Laguna Lacandon, Group A and Group D crops are highly suitable, and there are some very highly suitable pixels (9) for not only

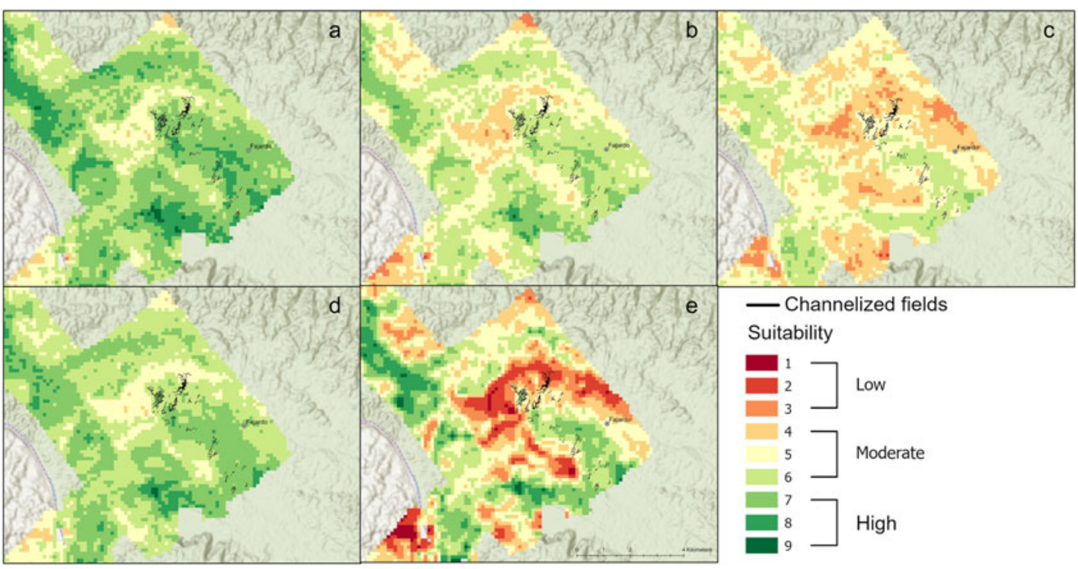

Figure 8. Direct comparison of the suitability of the channelized field network near Macabilero for the groupings of crops A–E (a–e). The small black lines indicate the groupings of orthogonal channels and shorter channels previously mapped by Golden and colleagues (2021).

Group A and D but also B and E. Moving toward Piedras Negras, between Esmeralda and Sakhob, the area is largely suitable for all crop groups. The region immediately adjacent to the Laguna Lacandon is also for the most part highly suitable for the growth of all groups, except Group C crops, where the land is largely moderately suitable.

Although Figures 7 and 8 contain different agricultural features and are not at the same scale, a comparison of the two images underscores that while both provide clear evidence for agricultural intensification and are modeled to have been productive crop zones, there are fundamental differences between the two regions. Overall, the region near La Mar and Budsilha is more homogeneous—consistently moderately to highly suitable for agriculture—relative to the region near the Laguna Lacandon. In both regions, the suitability for Group E spans the greatest number of suitability values, though only reaches the lowest suitability value, 1, in the region near Macabilero and Fajardo (Figure 8). Both regions are generally highly suitable for Group A and Group B crops. Further, while Group B crops display the largest areas of continuous moderate suitability for the region near La Mar and Budsilha, Group C crops display the largest area of continuous moderate suitability for the region near Macabilero and Fajardo.

Discussion

Maize in the Upper Usumacinta River Region

The study area is widely suitable for maize cultivation (mean suitability 6.1), though from the results of the model, the dominance of maize agriculture at any one location on the landscape is difficult to assess without confirmation from field data. Nevertheless, the findings here support prior results (Golden et al. 2021; Johnson et al. 2007), indicating the area around the Laguna Lacandon as highly suited to maize agriculture. Johnson and colleagues (2007) identified soils with stable carbon isotope signatures consistent with maize agriculture within the zone of channelized fields near the Laguna Lacandon that were otherwise unnoticed until identified by Golden and colleagues (2021) through analysis of lidar data. Here, that same area produced a suitability of 6 and 7 for maize (Figure 5). Similarly, the regions sampled by Fernández and colleagues (2005) that also showed evidence of maize cultivation south of Piedras Negras align with areas of moderate to high suitability for maize (Figure 5).

While suitable for the cultivation of maize, these regions also show high potential for the cultivation of the other Group D crops, whose production in the area has not yet been identified archaeologically. Among these, it has been suggested that cacao was grown in the region near the Laguna Lacandon (Golden et al. 2008), while others also suggest that cacao was cultivated in channelized fields (Dahlin 1976). Further, Group A crops have a slightly higher mean suitability for the study region overall (6.2) and appear to be even better suited to the area covered by the channelized field network than maize, cacao, and the other Group D crops (Figure 8). Similarly, while there is no supporting evidence from soil studies, the extensively modified land near La Mar and Budsilha—the second proposed "breadbasket" for Piedras Negras—is moderate to highly suitable for Group D crop cultivation. It is also of note that at Macabilero manioc was found to be highly ubiquitous in the paleoethnobotanical record, equal in ubiquity to maize (Watson 2022). While Macabilero shows only moderate potential for Group B crops, including manioc, the nearby Laguna Lacandon is highly suitable for their growth (Figure 3).

Piedras Negras lacks durable evidence for significant agricultural intensification and its population may have been supported by crops imported from these regions. While there is evidence for some maize agriculture near Piedras Negras as noted earlier, the residents may otherwise have invested in agroforestry as suggested by Golden et alia (2021). The area around Piedras Negras is moderately suitable for the growth of coyol and cohune palm (Figure 3) but has lower suitability for the growth of copal and mamey (Figures 4a and 6a). Cultivation of tree crops would have been a sensible adaptation to the sloped land around Piedras Negras and may also have been an adaptation annual climate variability. For example, the palms predicted to have grown in the vicinity of Piedras Negras would have been reliable food sources in times of extreme drought (Fedick and Santiago 2022).

Without the additional field data needed to validate predictions of the model, it is not possible to comment on the level of production or spatial extent of the cultivation of any of these groupings of crops or individual crops. However, the results of this study point toward the multitude of crops that may have also been grown alongside or alternating with maize across the study region. These results will inform further studies of crop diversity in the study region. Overall, these findings highlight the potential for crop diversity in the Maya Lowlands where ongoing modeling continues to focus almost exclusively on maize.

Additionally, the suitability maps produced by the model provide insufficient evidence to comment on the use of maize as an object of tax, tribute, trade, or as a commodity more broadly, particularly in relation to the economic dynamics of the Piedras Negras polity. The proposed "breadbaskets" for Piedras Negras near La Mar and the Laguna Lacandon have moderate to high suitability for maize cultivation. Thus, while the results of the model appear to agree with the proposition that this region was agriculturally suitable for the cultivation of maize, it does not model the productivity or the potential for surplus production that could have supported the high maize consumption at Piedras Negras.

While the model does not provide clear evidence for the production and distribution of maize, it nevertheless raises questions pertaining to how other crops with moderate to high suitability might have shaped the local economy. That is, while maize was likely traded in the markets of Piedras Negras, and given as tribute to the ruling elite, other commodities would also likely have been traded. Cacao, for example, may have been equally integrated with and important to regional and long-distance exchange networks (see Caso Barrera and Aliphat Fernández 2006). Throughout the study area, local variation in the suitability of the land for different crops would have impacted local agricultural systems and the spatial and social dynamics of the region overall.

Relationships between Settlement, Landesque Investment, and Agricultural Activity

Golden and colleagues (2021) remark that settlement in the study area and its patterns and relationships with agricultural intensification form a variety of "low-density urbanisms," particularly between the three kingdoms of Piedras Negras, La Mar, and Lacanja Tzeltal. While there is no evidence that royal courts had significant or direct role in food production during the Classic period (Golden et al. 2020a), at La Mar the proximity of the expansive terrace network to royal architecture has suggested some royal involvement in the organization and management of agricultural production (Golden et al. 2021). The land near La Mar where the terraces are located is generally of moderate to high suitability across all plant groups (Figure 7). This area may have been important for the subsistence of people in the region, as well as the relationship of La Mar with Piedras Negras. The *ajaw* of La Mar was identified as a *baahkab*, "head earth." As Simon Martin (2020:85) observes, the significance of the title remains poorly understood but might allude to control over land and its resources. Here, the authority of the La Mar lord may have been tied directly to the oversight of the surrounding agricultural terrain that demonstrates a high level of landesque investment. The land around Piedras Negras has low to moderate suitability for most plant groups. Over time, royal courts were increasingly concerned with control of the physical terrain, particularly areas for food and nonfood production (Golden and Scherer 2013), and thus may have sought greater control over production in areas like La Mar where more types of plants thrived. Meanwhile, the area around Lacanja Tzeltal, like La Mar, had moderate to high suitability across all plant groups. However, unlike La Mar, both the scale of settlement and extent of agricultural intensification in the form of feature capital on the landscape was limited at Lacanja Tzeltal. For reasons that remain unknown, Lacanja Tzeltal, one of the seats of the Sak Tz'i' dynasty during the Late Classic period, never had Classic period population levels equivalent to those near La Mar and Piedras Negras and thus perhaps never needed to intensify agricultural production (Golden et al. 2020b).

Broadly, in examining these three political centers, we do not see a strong relationship between settlement density and high general agricultural capability (Fedick 1995), which may highlight the influences of other factors, political and social, in decision-making on the landscape. While perhaps complicated by these additional factors, across the study area most archaeological sites fall within regions of moderate to high suitability for at least several groupings of crops, which supports the very general model that most agricultural activity took place in and around settlements.

In areas with durable evidence of agricultural intensification, terraces and channelized fields crosscut suitability regions. Where terraces and channelized fields fall within regions of moderate or low suitability for different crops, this may reflect the use of these agricultural systems to improve the land for agriculture. However, where these features occur in regions of overall high suitability for diverse crops, it may be that positioning terraces on already optimal land improved production levels beyond that of swidden agriculture, as suggested previously by Canuto and colleagues (2018:6).

Interestingly, in the areas of most extensive terracing (Figure 7) and channelized field networks (Figure 8) we find that these features crosscut suitability values for all groups of plants. This strategic intensification of terrain widely suitable for a variety of crops may have had consequences for the political and economic systems of the region. In terms of the intensification of agricultural production, these features enhance land suitability for a wide range of crops, potentially indicating their use for the high-level production of a suite of commodities, as opposed to optimization for one particular crop, such as maize. This finding may be particularly relevant for a number of regions of dense agricultural features, including those that fall within the outlying "breadbaskets" of Piedras Negras.

Conclusions and Future Research

To briefly summarize, this research intervenes in three key areas with new findings: (1) from 18 key crops grown by ancient Maya farmers, five groups of crops with similar growth requirements emerged; (2) the suitability of the study region for all five groups shows different spatial variation; and (3) this spatial variation in suitability of each group of plants contributes to existing literature on economic organization and settlement organization in the study area. While more research is needed to understand the patterns of agricultural production as they relate to suitability in the Upper Usumacinta River Basin and elsewhere across the Lowlands, this research highlights the importance of knowing the landscape, to bring nuance to our understandings of agricultural, political, and economic systems of ancient Maya communities.

Ultimately, this study points toward the extensive knowledge and skill of Maya farmers to maximize the landscape—not only for maize but also for a number of economically valuable crops. However, many questions remain: Were terraces and channels used to improve the suitability of the land or *maintain* the suitability for certain plants? And did Maya farmers grow only the plants *most* suitable for each of these areas, or did they simply improve the land enough to yield some agricultural products from plants that were only moderately suitable for these areas? Despite these questions, the results of this study underscore the promise of spatial perspectives and suitability analysis for understanding how ancient Maya farmers used and adapted to variable land resources in the region to cultivate a variety of different crops.

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Data Availability Statement. The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request. The following datasets are used in this study:

Hengl, Tomislav. 2018. Clay Content in % (Kg / Kg) at 6 Standard Depths (0, 10, 30, 60, 100 and 200 Cm) at 250 m Resolution (v0.2). Zenodo. https://doi.org/10.5281/zenodo.1476855, accessed March 22, 2022.

Hengl, Tomislav, and Surya Gupta. 2019. Soil Available Water Capacity in Mm Derived for 5 Standard Layers (0–10, 10–30, 3–60, 60–100 and 100–-200 Cm) at 250 m Resolution. Zenodo. https://doi.org/10.5281/zenodo.2784001, accessed October 18, 2021.

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Supplemental Figure 1. Weighted overlay example.
Supplemental Figure 2. Model schematic.
Supplemental Text 1. Crop plant data collection and model inputs.
Supplemental Text 2. Model limitations.
Supplemental Table 1. Crop plant preferences.
Supplemental Table 2. Crop plant table variable descriptions.
Supplemental Table 3. Model input layer descriptions.
Supplemental Table 4. Results tables.

References Cited

Adams, Richard E. W., Walter E. Brown, and T. Patrick Culbert. 1981. Radar Mapping, Archeology, and Ancient Maya Land Use. *Science* 213(4515):1457–1463.

Barrera-Bassols, N., J. A. Zinck, and E. Van Ranst. 2006. Local Soil Classification and Comparison of Indigenous and Technical Soil Maps in a Mesoamerican Community Using Spatial Analysis. *Geoderma* 135:140–162.

Batún Alpuche, Adolfo Iván. 2009. Agrarian Production and Intensification at a Postclassic Maya Community, Buena Vista, Cozumel, Mexico. PhD dissertation, Department of Anthropology, University of Florida, Gainesville.

Beach, Timothy, Sheryl Luzzadder-Beach, Samantha Krause, Tom Guderjan, Fred Valdez, Juan Carlos Fernandez-Diaz, Sara Eshleman, and Colin Doyle. 2019. Ancient Maya Wetland Fields Revealed under Tropical Forest Canopy from Laser Scanning and Multiproxy Evidence. *PNAS* 116(43):21469–21477.

Bloom, Paul R., Mary Pohl, Cynthia Buttleman, Frederick Wiseman, Alan Covich, Charles Miksicek, Joseph Ball, and Julie Stein. 1983. Prehistoric Maya Wetland Agriculture and the Alluvial Soils Near San Antonio Rio Hondo, Belize. *Nature* 301(5899): 417–419.

Boserup, Ester. 1965. *Conditions of Agricultural Growth*. Routledge, London.

Bronson, Bennet. 1966. Roots and the Subsistence of the Ancient Maya. *Southwestern Journal of Anthropology* 22(3):251–279.

Brookfield, H. C. 1972. Intensification and Disintensification in Pacific Agriculture. *Pacific Viewpoint* 13(1):30–48.

Cagnato, Clarissa. 2016. A Paleoethnobotanical Study of Two Classic Maya Sites, El Peru-Waka and La Corona. PhD dissertation, Department of Anthropology, Washington University, St. Louis, Missouri.

Cagnato, Clarissa, and Jocelyne M. Ponce. 2017. Ancient Maya Manioc (Manihot Esculenta Crantz) Consumption: Starch Grain Evidence from Late to Terminal Classic (8th–9th Century CE) Occupation at La Corona, Northwestern Petén, Guatemala. *Journal of Archaeological Science: Reports* 16:276–286.

Canuto, Marcello A., Francisco Estrada-Belli, Thomas G. Garrison, Stephen D. Houston, Mary Jane Acuña, Milan Kováč, Damien Marken, et al. 2018. Ancient Lowland Maya Complexity as Revealed by Airborne Laser Scanning of Northern Guatemala. *Science* 361(6409):eaau0137.

Caso Barrera, Laura, and Mario Aliphat Fernández. 2006. Cacao, Vanilla and Annatto: Three Production and Exchange Systems in the Southern Maya Lowlands, XVI–XVII Centuries. *Journal of Latin American Geography* 5(2):29–52.

Chase, Arlen F., and Diane Z. Chase. 2001. Ancient Maya Causeways and Site Organization at Caracol, Belize. *Ancient Mesoamerica* 12(2):273–281.

Dahlin, Bruce H. 1976. Cash Croppping in the Protoclassic: A Cultural Impact Statement. In *Maya Archaeology and Ethnohistory*, edited by Norman Hammond and Gordon R Willey, pp. 21–37. University of Texas Press, Austin.

Dunning, Nicholas P., and Timothy Beach. 1994. Soil Erosion, Slope Management, and Ancient Terracing in the Maya Lowlands. *Latin American Antiquity* 5(1):51–69.

Ebert, Claire E., Julie A. Hoggarth, Jaime J. Awe, Brendan J. Culleton, and Douglas J. Kennett. 2019. The Role of Diet in Resilience and Vulnerability to Climate Change among Early Agricultural Communities in the Maya Lowlands. *Current Anthropology* 60(4):589–601.

Fedick, Scott L. 1989. The Economics of Agricultural Land Use and Settlement in the Upper Belize Valley. In *Prehistoric Maya Economies of Belize*, Research in Economic Anthropology Supplement No. 4, edited by Patricia McAnany and Barry Isaac, pp. 215–253. JAI Press, Greenwich, Connecticut.

Fedick, Scott L. 1995. Land Evaluation and Ancient Maya Land Use in the Upper Belize River Area, Belize, Central America. *Latin American Antiquity* 6(1):16–34.

Fedick, Scott L, ed. 1996. *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*. University of Utah Press, Salt Lake City.

Fedick, Scott L. 2010. Theory and Method in the Analysis of Ancient Maya Agricultural Landscapes: The Household Model of Agricultural Production. In *Lugar, espacio y paisaje en arqueología: Mesoamérica y otras áreas culturales: VI Coloquio Pedro Bosch Gimpera*, edited by Edith Ortiz Díaz, pp. 47–76. Instituto de Investigationes Antropológicas, UNAM, Mexico City.

Fedick, Scott L. 2017. Plant-Food Commodities of the Maya Lowlands. In *The Value of Things: Prehistoric to Contemporary Commodities in the Maya Region*, edited by Jennifer P. Mathews and Thomas H. Guderjan, pp. 163–172. University of Arizona Press, Tucson.

Fedick, Scott L. 2020. Maya Cornucopia: Indigenous Food Plants of the Maya Lowlands. In *The Real Business of Ancient Maya Economies: From Farmers' Fields to Rulers' Realms*, edited by Marilyn A. Masson, David A. Freidel, and Arthur A. Demarest, pp. 224–237. University Press of Florida, Gainesville.

Fedick, Scott L., and Anabel Ford. 1990. The Prehistoric Agricultural Landscape of the Central Maya Lowlands: An Examination of Local Variability in a Regional Context. *World Archaeology* 22(1):18–33.

Fedick, Scott L., and Louis S. Santiago. 2022. Large Variation in Availability of Maya Food Plant Sources during Ancient Droughts. *PNAS* 119(1):e2115657118.

Fedick, Scott L., Shanti Morell-Hart, and Lydie Dussol 2024. Agriculture in the Ancient Maya Lowlands (Part 2): Landesque Capital and Long-Term Resource Management Strategies. *Journal of Archaeological Research* 32:103–154.

Fernández, Fabián G., Kristofer D. Johnson, Richard E. Terry, Sheldon Nelson, and David Webster. 2005. Soil Resources of the Ancient Maya at Piedras Negras, Guatemala. *Soil Science Society of America Journal* 69(6):2020–2032.

Flannery, Kent V. 1982. *Maya Subsistence: Studies in Memory of Dennis E. Puleston*. Academic Press, New York.

Food and Agriculture Organization of the United Nations. 1976. *A Framework for Land Evaluation*. Soils Bulletin 32. Food and Agriculture Organization of the United Nations, Rome.

Ford, Anabel, and Ronald Nigh. 2016. *The Maya Forest Garden: Eight Millennia of Sustainable Cultivation of the Tropical Woodlands*. Routledge, New York.

Freidel, David A., and Justine Shaw. 2000. The Lowland Maya Civilization: Historical Consciousness and Environment. In *The Way the Wind Blows: Climate, History, and Human Action*, edited by Roderick J McIntosh, Joseph A. Tainter, and Susan Keech McIntosh, pp. 271–300. Columbia University Press, New York.

Garrison, Thomas G., Stephen D. Houston, Charles Golden, Takeshi Inomata, Zachary Nelson, and Jessica Munson. 2008. Evaluating the Use of IKONOS Satellite Imagery in Lowland Maya Settlement Archaeology. *Journal of Archaeological Science* 35(10):2770–2777.

Garrison, Thomas G., Stephen Houston, and Omar Alcover Firpi. 2019. Recentering the Rural: Lidar and Articulated Landscapes among the Maya. *Journal of Anthropological Archaeology* 53:133–146.

Golden, Charles, and Andrew K. Scherer. 2013. Territory, Trust, Growth, and Collapse in Classic Period Maya Kingdoms. *Current Anthropology* 54(4):397–435.

Golden, Charles, Andrew K. Scherer, A. René Muñoz, and Rosaura Vasquez. 2008. Piedras Negras and Yaxchilan: Divergent Political Trajectories in Adjacent Maya Polities. *Latin American Antiquity* 19(3):249.

Golden, Charles, Andrew Scherer, A. René Muñoz, and Zachary Hruby. 2012. Polities, Boundaries, and Trade in the Classic Period Usumacinta River Basin. *Mexicon* 34(1):11–19.

Golden, Charles, Andrew K. Scherer, Whittaker Schroder, Clive Vella, and Alejandra Roche Recinos. 2020a. Decentralizing the Economies of the Maya West. In *The Real Business of Ancient Maya Economies: From Farmers' Fields to Rulers' Realms*. University Press of Florida, Gainesville.

Golden, Charles, Andrew K. Scherer, Stephen Houston, Whittaker Schroder, Shanti Morell-Hart, Socorro del Pilar Jiménez Álvarez, George Van Kollias, et al. 2020b. Centering the Classic Maya Kingdom of Sak Tz'i'. *Journal of Field Archaeology* 45(2):67–85.

Golden, Charles, Andrew K. Scherer, Whittaker Schroder, Timothy Murtha, Shanti Morell-Hart, Juan Carlos Fernandez Diaz, Socorro del Pilar Jiménez Álvarez, et al. 2021. Airborne Lidar Survey, Density-Based Clustering, and Ancient Maya Settlement in the Upper Usumacinta River Region of Mexico and Guatemala. *Remote Sensing* 13(20):4109.

Gómez-Pompa, Arturo. 1987. On Maya Silviculture. *Mexican Studies/Estudios Mexicanos* 3(1):1–17.

Guderjan, Thomas H., Sheryl Luzzadder-Beach, Timothy Beach, Steven Bozarth, and Samantha Krause. 2017. Production of Ancient Wetland Agricultural Commodities in the Maya Lowlands. In *The Value of Things: Prehistoric to Contemporary Commodities in the Maya Region*, edited by Jennifer P. Mathews and Thomas H. Guderjan, pp. 20–48. University of Arizona Press, Tucson.

Hanselka, J. Kevin, and Brian King. 2017. Modeling Agricultural Potential Near the Ocampo Caves, Tamaulipas: Integrating Archaeological and Geospatial Applications. *Journal of Ethnobiology* 37(2):260–281.

Hather, Jon G., and Norman Hammond. 1994. Ancient Maya Subsistence Diversity: Root and Tuber Remains from Cuello, Belize. *Antiquity* 68(259):330–335.

Healy, Paul F., John D. H. Lambert, J. T. Arnason, and Richard J. Hebda. 1983. Caracol, Belize: Evidence of Ancient Maya Agricultural Terraces. *Journal of Field Archaeology* 10(4):397–410.

Horseman, Grace. 2022. Suitability Models of Ancient Maya Agriculture in the Upper Usumacinta River Basin of Mexico and Guatemala. Bachelor's thesis, School of Interdisciplinary Science, McMaster University, Hamilton, Ontario, Canada.

Houston, Stephen D., and Takeshi Inomata. 2009. *The Classic Maya*. Cambridge University Press, Cambridge.

Jensen, Christopher T., Matthew D. Moriarty, Kristofer D. Johnson, Richard E. Terry, Kitty F. Emery, and Sheldon D. Nelson. 2007. Soil Resources of the Motul de San José Maya: Correlating Soil Taxonomy and Modern Itzá Maya Soil Classification within a Classic Maya Archaeological Zone. *Geoarchaeology* 22(3):337–357.

Johnson, Kristofer D., Richard E. Terry, Mark W. Jackson, and Charles Golden. 2007. Ancient Soil Resources of the Usumacinta River Region, Guatemala. *Journal of Archaeological Science* 34(7):1117–1129.

Johnston, Kevin J. 2003. The Intensification of Pre-Industrial Cereal Agriculture in the Tropics: Boserup, Cultivation Lengthening, and the Classic Maya. *Journal of Anthropological Archaeology* 22(2):126–161.

Lemonnier, Eva, and Boris Vannière. 2013. Agrarian Features, Farmsteads, and Homesteads in the Río Bec Nuclear Zone, Mexico. *Ancient Mesoamerica* 24(2):397–413.

Lentz, David. L. 1999. Plant Resources of the Ancient Maya: The Paleoethnobotanical Evidence. In *Reconstructing the Ancient Maya Diet*, edited by Christine D. White, pp. 3–18. University of Utah Press, Salt Lake City.

Lentz, David L., Marilyn P. Beaudry-Corbett, Maria Luisa Reyna de Aguilar, and Lawrence Kaplan. 1996. Foodstuffs, Forests, Fields, and Shelter: A Paleoethnobotanical Analysis of Vessel Contents from the Ceren Site, El Salvador. *Latin American Antiquity* 7(3):247–262.

Liendo Stuardo, Rodrigo. 2002. *The Organization of Agricultural Production at a Classic Maya Center: Settlement Patterns in the Palenque Region, Chiapas, Mexico*. Instituto Nacional de Antropología e Historia, Mexico City; University of Pittsburgh, Pittsburgh, Pennsylvania.

Martin, Simon. 2020. *Ancient Maya Politics: A Political Anthropology of the Classic Period 150–900 CE*. Cambridge University Press, Cambridge.

McAnany, Patricia. 1992. Agricultural Tasks and Tools: Patterns of Stone Tool Discard Near Prehistoric Maya Residences Bordering Pulltrouser Swamp, Belize. In *Gardens of Prehistory: The Archaeology of Settlement Agriculture in Greater Mesoamerica*, edited by Thomas W. Killion, pp. 184–214. University of Alabama Press, Tuscaloosa.

McKillop, Heather. 1994. Ancient Maya Tree Cropping: A Viable Subsistence Adaptation for the Island Maya. *Ancient Mesoamerica* 5(1):129–140.

McKillop, Heather. 1996. Prehistoric Maya Use of Native Palms: Archaeobotanical and Ethnobotanical Evidence. In *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*, edited by Scott L. Fedick, pp. 278–294. University of Utah Press, Salt Lake City.

McNeil, Cameron L. 2020. Favored Plants of the Maya. In *The Maya World*, edited by Scott R. Hutson and Traci Ardren, pp. 183–202. Routledge, London.

Meggers, Betty J. 1954. Environmental Limitation on the Development of Culture. *American Anthropologist* 56(5):801–824.

Morehart, Christopher T. 2011. *Food, Fire and Fragrance: A Paleoethnobotanical Perspective on Classic Maya Cave Rituals*. BAR International Series 2186. Archaeopress, Oxford.

Morehart, Christopher T., Jaime J. Awe, Michael J. Mirro, Vanessa A. Owen, and Christophe G. Helmke. 2004. Ancient Textile Remains from Barton Creek Cave, Cayo District, Belize. *Mexicon* 26(3):50–56.

Morell-Hart, Shanti, Lydie Dussol, and Scott L. Fedick. 2023. Agriculture in the Ancient Maya Lowlands (Part 1): Paleoethnobotanical Residues and New Perspectives on Plant Management. *Journal of Archaeological Research* 31:561–615.

Morrison, Kathleen D. 1994. The Intensification of Production: Archaeological Approaches. *Journal of Archaeological Method and Theory* 1(2):111–159.

Nelson, Zachary. 2005. Settlement and Population at Piedras Negras, Guatemala. PhD dissertation, Department of Anthropology, Pennsylvania State University, University Park.

Pope, Kevin O., and Bruce H. Dahlin. 1989. Ancient Maya Wetland Agriculture: New Insights from Ecological and Remote Sensing Research. *Journal of Field Archaeology* 161(1):87–106.

Rathje, William L. 1971. The Origin and Development of Lowland Classic Maya Civilization. *American Antiquity* 36(3):275–285.

Roche Recinos, Alejandra. 2021. Regional Production and Exchange of Stone Tools in the Maya Polity of Piedras Negras. PhD dissertation, Department of Anthropology, Brown University, Providence, Rhode Island.

Russell, W. M. S. 1988. Population, Swidden Farming and the Tropical Environment. *Population and Environment* 10(2):77–94.

Saturno, William, Thomas L. Sever, Daniel E. Irwin, Burgess F. Howell, and Thomas G. Garrison. 2007. Putting Us on the Map: Remote Sensing Investigation of the Ancient Maya Landscape. In *Remote Sensing in Archaeology*, edited by James Wiseman and Farouk El-Baz, pp. 137–160. Springer, New York.

Scherer, Andrew K., and Charles Golden (editors) 2012. *Revisiting Maler's Usumacinta: Recent Archaeological Investigations in Chiapas, Mexico*. Precolumbia Mesoweb Press, San Francisco.

Scherer, Andrew K., and Charles Golden. 2014. Water in the West. In *The Great Maya Droughts in Cultural Context*, edited by Gyles Iannone, pp. 207–230. University Press of Colorado, Denver.

Scherer, Andrew K., Lori E. Wright, and Cassady J. Yoder. 2007. Bioarchaeological Evidence for Social and Temporal Differences in Diet at Piedras Negras, Guatemala. *Latin American Antiquity* 18(1):85–104.

Schroder, Whittaker, Timothy Murtha, Charles Golden, Armando Anaya Hernández, Andrew Scherer, Shanti Morell-Hart, Angélica Almeyda Zambrano, Eben Broadbent, and Madeline Brown. 2020. The Lowland Maya Settlement Landscape: Environmental LiDAR and Ecology. *Journal of Archaeological Science: Reports* 33:102543.

Sever, Thomas L., and Daniel E. Irwin. 2003. Landscape Archaeology: Remote-Sensing Investigation of the Ancient Maya in the Peten Rainforest of Northern Guatemala. *Ancient Mesoamerica* 14(1):113–122.

Sheets, Payson, Christine Dixon, Monica Guerra, and Adam Blanford. 2011. Manioc Cultivation at Ceren, El Salvador: Occasional Kitchen Garden Plant or Staple Crop? *Ancient Mesoamerica* 22(1):1–11.

Siemens, Alfred H., and Dennis E. Puleston. 1972. Ridged Fields and Associated Features in Southern Campeche: New Perspectives on the Lowland Maya. *American Antiquity* 37(2):228–239.

Slotten, Venicia, David Lentz, and Payson Sheets. 2020. Landscape Management and Polyculture in the Ancient Gardens and Fields at Joya de Cerén, El Salvador. *Journal of Anthropological Archaeology* 59:101191.

Turner, Billie L., II. 1974. Prehistoric Intensive Agriculture in the Mayan Lowlands. *Science* 185(4146):118–124.

Turner, Billie L., II. 1978. The Development and Demise of the Swidden Thesis of Maya Agriculture. In *Pre-Hispanic Maya Agriculture*, edited by Peter D. Harrison and Billie L. Turner II, pp. 13–22. University of New Mexico Press, Albuquerque.

Turner Billie L., II. 1983. The Excavations of Raised and Channelized Fields at Pulltrouser Swamp. In *4. The Excavations of Raised and Channelized Fields at Pulltrouser Swamp*, edited by Billie L. Turner II and Peter D. Harrison, pp. 30–51. University of Texas Press, Austin.

Turner, Billie L., II, and Peter D. Harrison (editors). 1983. *Pulltrouser Swamp: Ancient Maya Habitat, Agriculture, and Settlement in Northern Belize*. University of Texas Press, Austin.

Turner, Billie L., II, and Charles H. Miksicek. 1984. Economic Plant Species Associated with Prehistoric Agriculture in the Maya Lowlands. *Economic Botany* 38(2):179–193.

Walden, John P., Julie A. Hoggarth, Claire E. Ebert, Scott L. Fedick, Michael Biggie, Brett Meyer, Kyle Shaw-Müller, et al. 2023. Classic Maya Settlement Systems Reveal Differential Land Use Patterns in the Upper Belize River Valley. *Land* 12(2):483.

Watson, Sarah E. 2022. Maya Food Strategies at Macabilero: A Paleoethnobotanical Study of Ancient Maya Agriculture and Ethnoecology during the Formative and Classic Periods. Master's thesis, Department of Anthropology, McMaster University, Hamilton, Ontario, Canada.

Wilken, Gene C. 1971. Food-Producing Systems Available to the Ancient Maya. *American Antiquity* 36(4):432–448.

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