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Ancient Agriculture on Lava Flows: Using LiDAR and Soil Science to Reassess Pre-Hispanic Farming on *Malpaís* Landforms in West Mexico

Antoine Dorison[1]

Abstract. *The Mexican Central Highlands have been a major cluster for human settlement since pre-Hispanic times and its soils provide much of the food for modern Mexico. Rainfed cultivation yielded and still yields most of the agricultural products. However, pre-Hispanic rainfed cultivation has been less documented than other practices. Moreover, textual and ethnographic records, mostly post-dating the deep modifications made by the Spanish conquerors, have long been prevalent in studies on pre-Hispanic farming and have tended to bias our conception of the latter. Archaeology provides new key information but struggles to address rainfed techniques, which leave few remains behind in some landscapes. To that regard, spatial approaches considering geoecological parameters are helpful. Furthermore, remote sensing techniques and airborne laser scanning (LiDAR), above all, offer increasing potential for feature detection and provides new ways to address fossilized landscapes at both archaeological and environmental levels. This paper offers new insights on pre-Hispanic rainfed cultivation through an interdisciplinary approach. It focuses on archaeological settlements on* malpaís *landforms (young and rugged lava flows) in the Malpaís de Zacapu, in western Mexico. There, a method combining fieldwork and remote sensing in archaeology and soil science was developed to reassess pre-Hispanic farming. After presenting the method and this study's main results, I discuss the latter in light of examples of ethnohistorical and ethnographical uses of* malpaís *landforms. They suggest that widespread conceptions about agricultural soils of the Mexican Central Highlands held by external observers differ from Indigenous and local farmers' notions, which seem partly inherited from pre-Hispanic times.*

Keywords: *Mesoamerica, pre-Hispanic agriculture, geoarchaeology, LiDAR,* Malpaís

Introduction

The major part of the Mexican population has been concentrated since pre-Hispanic times in the fertile lake basins of the Central Highlands (Borah and Cook 1963; SEDATU et al. 2018). This long-lasting appeal is explained by the presence of permanent bodies of water and good farmlands, whose soils have formed from volcanic ash deposits along the still-active Trans-Mexican Volcanic Belt (TMVB) (Ferrari et al. 2012). Despite these favorable pedological conditions, the subtropical climate, with its marked seasonality (dry/humid) (García 2004), constrains the growing season to a six-month window (May–October). Consequently, water management has been the main agronomic challenge in the Mexican Central Highlands since the emergence of subsistence agriculture by 8000 BC (Flannery 1986). Research on pre-Hispanic practices shows that farmers developed various cultivation techniques to overcome this constraint (Sluyter 1994; Whitmore and Turner 2001).

Nevertheless, most current models of pre-Hispanic farming are based primarily on post-Conquest sixteenth century texts and ethnographic extrapolation (Rojas Rabiela and Sanders 1985), though archaeological works thoroughly addressing agriculture are multiplying (Dunning et al. 2015; Pickersgill 2016). One subsequent issue is that

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ethnohistorical texts tend to focus on farming techniques seen as remarkable by the observer, such as those involving irrigation or drainage systems. The best examples are the raised fields built by the Aztecs in the fifteenth century and known as *chinampas*, which have fascinated both Spanish settlers and scientists until today (Armillas 1971; Coe 1964; Morehart and Frederick 2014). Another issue rising from ethnohistorical and ethnographic approaches is that post-Conquest Mexican agriculture was deeply modified by the introduction of European technologies and perspectives, such as beasts of burden or the plough, notably leading farmers to colonize new lands. The best illustration in this case is the fact that colonial and modern planners frequently chose to drain millennial lake basins to cultivate lacustrine soils (e.g., Guzmán Ávila 2002; Musset 1989). To some extent, the prevalence of textual and ethnographic perspectives tends to bias our conception of pre-Hispanic agriculture and can even lead to misunderstandings. Raised fields and similar systems have somewhat monopolized our attention, while modern agricultural practices corroborate the preconceived idea that wetland and alluvial soils have always been preferred by farmers (e.g., Logan and Sanders 1976; Pollard and Gorenstein 1980).

As a result, pre-Hispanic rainfed cultivation—including the ubiquitous terrace networks of Mesoamerica (Donkin 1979)—has been less thoroughly documented by textual sources, even though it constituted the principal and most widespread means of production in subsistence farming (Palerm 1955, 1962; Whitmore and Turner 2001), just as it does today (Sanders et al. 1979; Wilken 1987). In this perspective, archaeology has helped fill in some of the blanks, but excavations are still roughly limited to a rather small number of terraces (Borejsza 2006; Borejsza et al. 2008; Dorison 2019; Evans 1985, 1990; Peréz Peréz 2007; Smith and Price 1994; Smith et al. 2013; Wusher 2003). In fact, studying rainfed cultivation is challenging for archaeologists, because it does not always leave behind perennial agrarian features (e.g., walls, terraces, dikes, etc.) (Boissinot and Brochier 1997; Killion 1992). Nevertheless, geographic information systems (GIS) and new remote sensing techniques, with airborne laser scanning (or LiDAR-derived) digital elevation models (DEM) at the top of these, are allowing scientists to detect agrarian features associated with rainfed cultivation by the thousands (Beach et al. 2019; Canuto et al. 2018; Chase and Weishampel 2016; Dorison 2020; Hightower et al. 2014; Prufer et al. 2015). LiDAR is reshaping archaeologists' understanding of the cultivated landscapes of Mesoamerica.

However, interpreting LiDAR-derived data is also quite challenging (Banaszek et al. 2018; Fernandez-Diaz et al. 2014; Forest et al. 2020; Kokalj and Somrak 2019). In addition to the methodological constraints inherent to the technology and its processing, archaeological features are not always easy to visualize, and established archaeological morpho-typologies do not always provide undisputable answers when it comes to identifying what is seen on the screen. In that regard, geosciences, such as geomorphology, soil science, or geology, whose relevance to interpreting archaeological data is well-established (Goldberg and Macphail 2006; Holliday 2004; Nicosia and Stoops 2017), can prove very helpful to unraveling the anthropogenic from the "natural" in LiDAR-derived images (Golden et al. 2016). Approaches combining LiDAR, archaeology, and geosciences are especially beneficial for studying agriculture in its spatial aspects and offer new perspectives to better understand rainfed cultivation, whose material traces are difficult to detect in the field (Dorison 2020; Dorison and Siebe 2021).

The present paper discusses the results of such an interdisciplinary approach. Combining fieldwork and remote sensing in archaeology and soil science, it constitutes part of a doctoral dissertation undertaken to reassess pre-Hispanic farming in the Malpaís de Zacapu lava flows complex (MZC), located in northern Michoacán, in west Mexico (Dorison 2019; Figure 1). Early archaeological research (Arnauld and Faugère 1998; Michelet 1992) established that the people inhabiting this region had agricultural societies; however, no substantive investigation had been undertaken to document ancient agriculture before this research. Besides the analysis of internal organization at some selected sites (Forest 2014; Michelet 2008), regional scale survey did not push spatial archaeology much further than the establishment of basic distribution patterns. Residential settlements were simply seen as clusters surrounded by poorly understood gaps in between them (Migeon 2016). Attention to agricultural activities was limited to the occasional mention of terraces.

After presenting the methods and principal results of the interdisciplinary study, I discuss the latter in light of ethnohistorical and ethnographic examples from northern Michoacán. They suggest that widespread conceptions about agricultural soils of the Mexican Central Highlands held by external observers differ from Indigenous notions, which seem at least partly inherited from pre-Hispanic times.

Materials and Methods

Study Area

At 19° 50′ N and 300 km west of Mexico City, in the heart of the TMVB, the Malpaís de Zacapu or "Zacapu's badland" lies north of the eponymous city, on the western hilly fringe of a lacustrine plain drained in 1903 (Arnauld et al. 1993; Figure 1). *Malpaís* is a generic term given by the Spaniards upon their arrival in Mexico to young lava flows, where shallowness or absence of soil and the omnipresence of rock outcrops impeded cultivation with the horse-pulled plough. The MZC thus constitutes a 50 km² complex of superposed blocky lava flows less than 100,000 years old (Reyes-Guzmán et al. 2018). Two of the youngest edifices are dated to the last two millennia BC—1340–940 BC and 200–80 BC, respectively—while the latest eruption occurred at the beginning of the tenth century AD (Mahgoub et al. 2017). Rocks are mostly porous andesites (Reyes-Guzmán et al. 2018). Soil cover, mainly formed from volcanic ash deposits, is scarce and intermittent within the MZC, contrasting with the smooth hills of the surrounding highlands and the flat lake basin. The sub-tropical temperate climate, consistent with other parts of the TMVB, brings 800 mm of precipitation from May to October (Garcia 2004). Paleoclimatic studies indicate relatively constant conditions

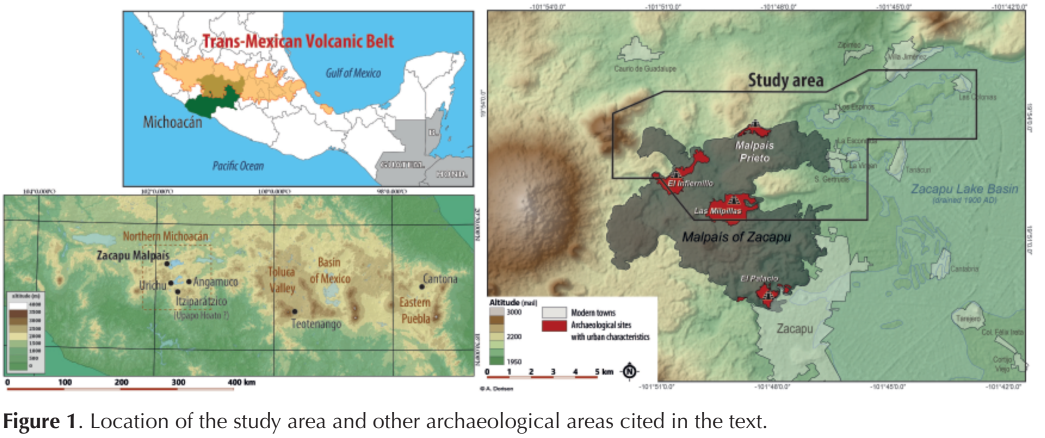

Figure 1. Location of the study area and other archaeological areas cited in the text.

over the last millennia (Metcalfe et al. 2000; Pétrequin 1994).

A sharp dichotomy exists between the lowlands, rather humid because of a high water table (i.e., the lacustrine plain) and the western highlands, where the lack of humidity is increased by the permeability of geological formations. Today, villages concentrate in the former, where semi-mechanized and extensive cultivation is conducted. The highlands are instead characterized by a piecemeal of smaller parcels, interrupted by forests and pastures. The MZC is almost exclusively occupied by the two latter.

At the archaeological level, the MZC is best known for the four urban settlements built in the mid-thirteenth century upon three of its most rugged lava flows and that were later abandoned after a 200-year occupation (Michelet et al. 2005). These sites constituted the founding settlements of the Tarascan culture (Pereira and Padilla Gutiérrez 2018), whose core shifted subsequently to the adjacent Pátzcuaro Basin (LPB), dominating west Mexico and rivaling the Aztec state until the Spanish conquest (Pollard 1993, 2008). Modern Purhépecha groups in northern Michoacán descend from this pre-Hispanic culture (West 1948). Beyond the Tarascan occupation, archaeological works conducted in the 1980s and 1990s showed that the Zacapu Basin has been inhabited since the first century BC (Arnauld and Faugère 1998). In addition, recent research shed light on a substantial human occupation in and around the MZC, beginning in the sixth century (Pereira et al. 2021).

The present work focuses on an 81 km^2 area encompassing the northern MZC, the surrounding highlands and the northwestern part of the lacustrine plain. Both the lowlands and highlands were taken into account to assess agricultural potential and pre-Hispanic land-use. Among the 17 archaeological settlements known in the area before the study, most were residential clusters—from 1 to 100 hectares, approximately—with 20 to over 100 houses (Dorison 2019). However, the area also included the three northernmost Tarascan urban centers of the MZC, which contain more than 1000 houses each (Forest 2014). The raw LiDAR data used in this study were collected and pre-processed in 2015 by the National Center for Airborne Laser Mapping (NCALM) at Houston and cover around 60% of the area. LiDAR-derived DEMs have a 50 cm mean resolution.

Archaeological Approach

My principal archaeological objective was to identify agrarian features: the human-made works built for cultivation. In the preliminary phase, prior to fieldwork, I identified anomalies on satellite images and conducted a digital survey based on various LiDAR-derived visualizations (Dorison 2020), mostly implemented with RVT software (Kokalj and Somrak 2019) and SagaGis (Figure 2). Fieldwork (2013–2015) included semi-systematized and systematized pedestrian surveys with GPS. Focus was first put on areas of interest that had been highlighted by previous archaeological works and local informants' knowledge. These areas were broadened by remotely detected features, especially after LiDAR acquisition (2015). The survey was followed by the excavation of 30 test pits (2 x 2 m) down to the bedrock or, if not possible, to a depth of ~1.5 m on selected features. The laboratory phase consisted of the classification of over 14,000 potsherds—issued from excavations and systematic surface collections—into the established typochronology of the area (Jadot 2016; Michelet 2013). All ground-truthed features were added to the preliminary LiDAR-based digitalization in QGIS v.2.8 to update the archaeological map and perform spatial analyses.

Geopedologic Approach

To complement the archaeological data, I also tried to identify and characterize the arable soils worked by humans to cultivate. A preliminary mapping and classification of landforms was carried out using available maps, satellite images, and LiDAR-derived visualizations (see above and Figure 2), following a geopedologic approach (Zinck 2012); the main geoforms (e.g., lava flows, cinder cones) were subdivided into the smallest landforms detectable based on our remote sensing dataset (e.g., summits, shoulders, footslopes). Fieldwork consisted of observations and auger test pits (over 100) to verify the preliminary mapping and 23 descriptions of pedological pits (1.5 x 1.5 m) to characterize the soils within the main geoforms. Sixty soil samples were collected from 15 of the most relevant test pits and analyzed at the Laboratorio de Edafología Ambiental at the University of Mexico (UNAM) to assess the soil's main characteristics (see Table 1). These data led to the establishment of an original geopedologic map for the survey area.

Results

Soils: Humid Lowlands and Dry Highlands

The study confirmed the sharp dichotomy that exists between the highlands and the lowlands in terms of soil characteristics and fertility (Figure 3). However, intermediate to basic parent materials (volcanic ash) in the whole study area induce a naturally good soil chemistry in terms of plant nutrients (i.e., medium to elevated rates of Ca, Mg, and K). Table 1 presents the main characteristics for soil profiles considered as typical of the main geopedologic units of the lowlands (P22) and highlands (P4, 5, 8, and 23).

The lowlands display two main geopedologic units: the former pre-Hispanic lake bottom and the emerging part of mid-Pleistocene lava flows, which constituted

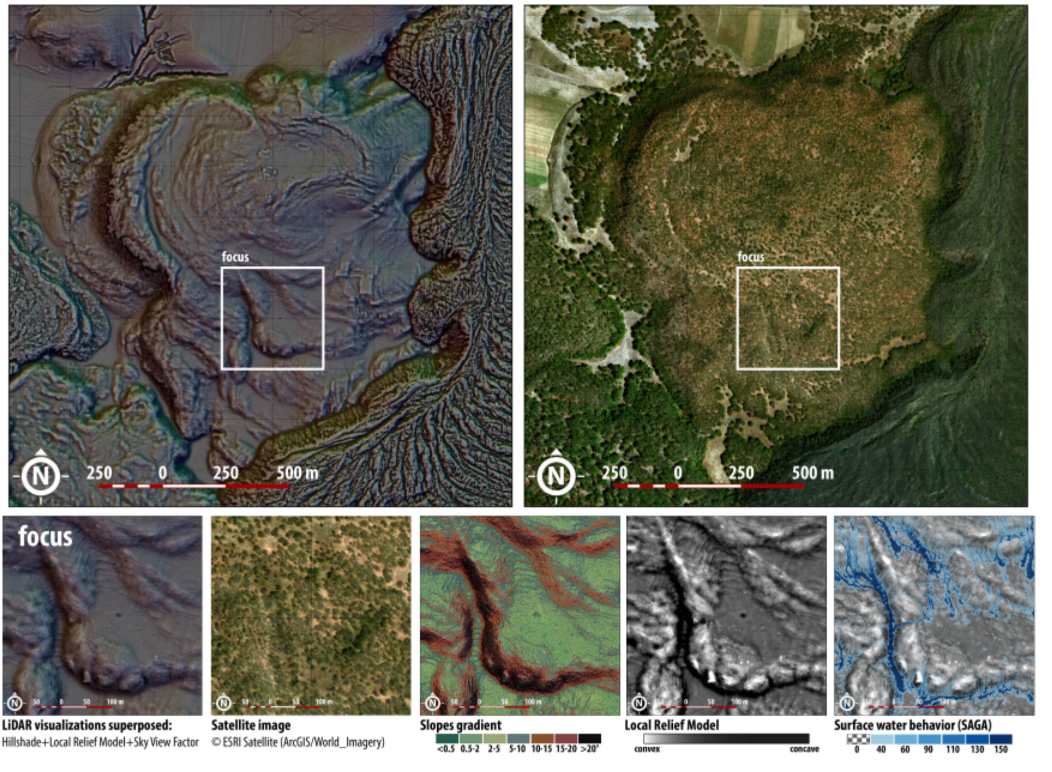

Figure 2. Examples of LiDAR visualizations, modeling, and satellite images used to detect anthropogenic and geopedologic features on a late Pleistocene lava flow. Note the focus on the terrace networks located in between linear outcrops.

Table 1. Main characteristics for soil profiles typical of the main geopedologic units of the area.

Soil profile code	**P8**	**P23**	**P5**	**P4**	**P22**
Location	late Pleistocene lava flow (*malpaís*)	late Pleistocene lava flow (*malpaís*)	Cinder cone footslope	early to mid-Pleistocene lavic plateau	Lacustrine plain
Texture (mean)[2]	silt loam	silt loam	silt loam	silt clay-loam [clay]	silt clay-loam
Structure (mean)[1]	weak to moderate granular	weak to moderate granular	weak to moderate granular	moderate granular [blocky]	weak to moderate granular
Munsell color (mean)[1]	7.5YR4/4	7.5YR4/4	10YR3/3	7.5YR3/2	7.5YR3/1
Physiological depth (reachable for roots) [cm][1]	140	140	160	76	65
Aeration capacity [%][1]	7	8.8	8.75	7.3 [4]	6 [3]
Field capacity (moisture) [L·m-2][1]	377	325.7	425	359	254
Available water capacity (for plants) [L·m-2][1]	171.7	223.2	269.2	118.8	waterlogged
Natural drainage[1]	moderate	moderate	rapid	moderate	very slow
Total carbon (C) in surficial horizon Ah [%][5]	6.65	4.5[1]	> 3[1]	5.2	> 6[1]
Total nitrogen (N) [%][5]	0.61	-	0.49	0.75	-
Available phosphorous (P) [mg·kg-1][4]	1.2	-	5.3	1.9	-
Base saturation (Ca, Mg, K, Na) [%][6]	50–70	75[1]	50–60	35–65	70[1]
pH[3]	6.4	6	6.6	6.1	5.5

[1] estimated in the field based on Siebe et al. (2006)
[2] measured with a pipette
[3] potentiometer (1: 2.5 soil/solution)
[4] Bray's method (Van Reeuwijk 2002)
[5] Elemental analysis with a Perkin Elmer 2400
[6] Ammonium acetate extract and Atomic Absorption Spectroscopy (AAS)
Ecological evaluation: good, moderate, low, very low
[ ] conditions at over 50 cm depth

former islands. The lacustrine soils are well textured for cultivation—not too coarse (sand) nor too fine (clay). In these soils, ancient volcanic ash deposits and continuous colluvium bring the aforementioned nutrients. Meanwhile, depositional processes of at least 25,000 years in the former lake (Siebe et al. 2012) result in high rates of organic matter. However, plants are often unable to access the nutrients contained within the

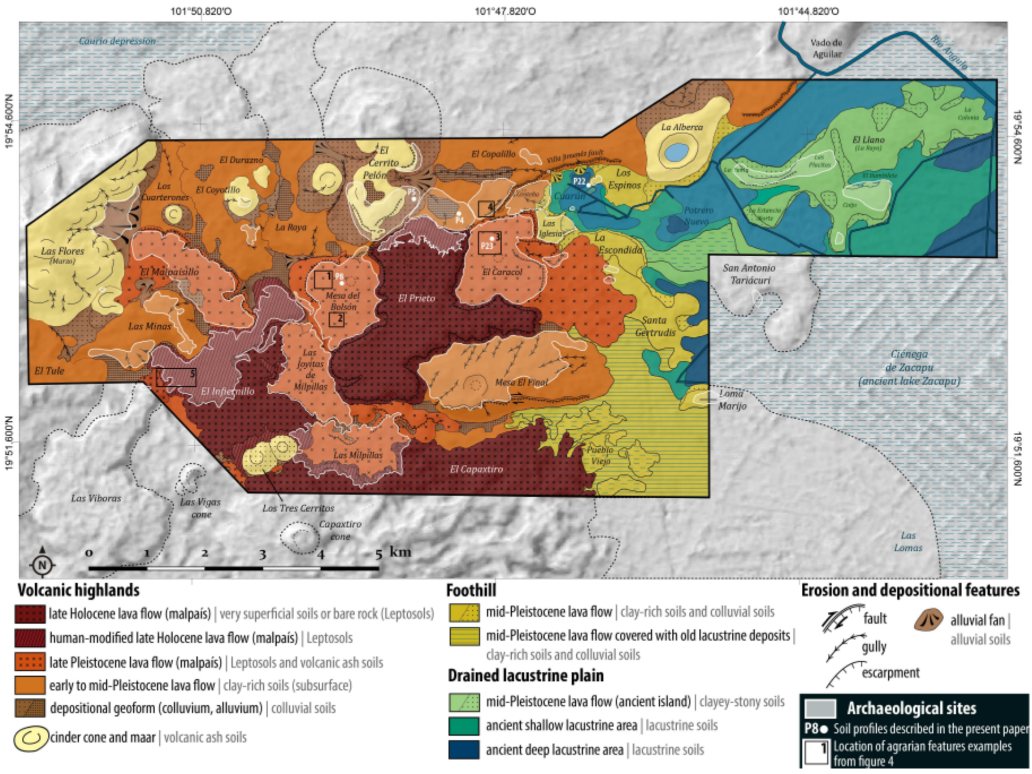

Figure 3. Simplified geopedologic map of the survey area.

organic-rich layers because decomposition and humification are slowed by continuous humid conditions. Indeed, waterlogging is the principal problem for agriculture in lowland soils, as the water table is shallow. Even modern canals often constitute inefficient surface drainage. The former islands are less impacted by these humid conditions. They display medium-age soils with high clay rates and important near-surface stoniness. As regards agronomic potential, both lowlands soil units display rather strong constraints on agricultural use despite their chemical fertility: slow internal drainage in lacustrine soils; clay and stoniness in islands soils.

The highlands display three main units: the mid-Pleistocene plateaus and hills, the late Pleistocene lava flows (< 30,000 yrs BP), and the late Holocene lava flows (< 3000 yrs BP). The two latter are considered as *malpaís* landforms and constitute the MZC. The plateaus and hills show rather old soils, between one hundred thousand and one million years old. Pedogenesis is ongoing and induces high clay rates and structuration in the subsoil. These processes are mainly influenced by topographic-dependent internal drainage. Well-drained contexts with moderate slope display loam to clay-loam soils—a well-balanced soil texture for cultivation—while subsurface clays hold humidity. Rapidly drained sloping terrains are characterized by thin soils that are more clayey and stony. Finally, closed depressions have higher clay rates, which may create localized areas with subsurface stagnant water and gley soils. In contrast, younger lava flows of the MZC are characterized by the omnipresence of continuous volcanic rocks. Its late-Holocene lava flows have almost no soil cover. However, in the pre-Hispanic urban settlements, humans crushed in situ stones to create thin layers of sediment and moved earth from surrounding locations in order to level residential areas (Forest 2014).

Thus, they created thin and stony artificial soils rarely suited for agricultural practices (Dorison 2019). Within the late Pleistocene lava flows of the MZC, although exposed volcanics are omnipresent too, the terrain presents patches where sediment has accumulated between outcrops. This sediment accumulation originates partially from the mechanical erosion of the lava flow itself but a greater part derives from subsequent volcanic ash deposits issued by surrounding volcanoes. Soils formed from the alteration of these materials are rather coarse textured (clay rates below 20%). They show high degrees of porosity and turn powdery once dehydrated. Their internal drainage is rapid.

In sum, regarding agronomic potential and except for areas with continuous rock, the highlands soils are overall fertile (nutrients from volcanic ash), well-textured (loam to clay-loam in surface horizons), and well-aerated in general. However, rapid internal drainage and the omnipresence of permeable bedrock limits soil water retention in many areas, which constitutes the principal constraint of the zone. This lack of humidity is slightly counterbalanced by subsurface clays in medium-age soils and high porosity in younger ones.

Human Occupation: Appropriating the Highlands

The present study—and subsequent archaeological works (see Pereira et al. 2021)—raised the number of archaeological settlements observed in the area from 17 to 31. It also revealed that the majority of archaeological features (residential, civic, artisanal, and agrarian) are concentrated in the highlands and MZC (Figure 3). Very few features were detected on the ancient lakeshores and islands. Although this lack of evidence in the lowlands partly results from conservation-related problems—higher sedimentation rate, modern cultivation, and villages—this difference in proportion cannot be explained by taphonomy alone.

Agrarian features are by far the most abundant detected (Figure 4). Based on a sample of nearly 5000 features digitized in GIS, over 70% (3744) are agrarian features. Among these, terraces are the most widespread. They display various types depending on slope gradient, soil type, and sediment transport and water flow within the landform where they are built (Figure 5). In parallel, contiguous parcel systems extending over large areas (several hectares) were identified on flattish parts of rugged lava flows, including on a Holocene *malpaís* dated to the second millennium BC. Their construction probably results from systematic stone removal/accumulation having generated thousands of subangular and decametric plots (Dorison 2019). Although they most likely served agricultural functions, these parcels still lack field verification. Possible dikes were also detected on older volcanic plateaus but their use and age remain unclear. All of these agrarian features display morphologies adapted to the specific geopedologic contexts in which they were constructed. A detailed typology has been published elsewhere (Dorison 2020; Dorison and Siebe 2021).

Finally, an important point regarding agrarian features is their chronology. Spatial analyses with GIS allowed us to identify recurrent patterns of agrarian features associated with residential and civic elements. Correlation with chronological data from the fieldwork made it possible to propose a relative dating for these patterns. This archaeogeographical approach (see Chouquer 2008) enabled us to reconstruct the evolution of the farming system in its physical aspect. Thereby, from the sixth to the ninth century, pre-Hispanic farmers seem to have favored the late Pleistocene *malpaís* landforms, with their patches of light and porous soils, to cultivate. From the tenth to the twelfth century, this trend seems to have remained broadly unchanged, but this point remains unclear because the area was largely abandoned at the time (see Pereira et al. 2021). A switch seems to have taken place with the arrival of Tarascan farmers recolonizing and urbanizing the area in the

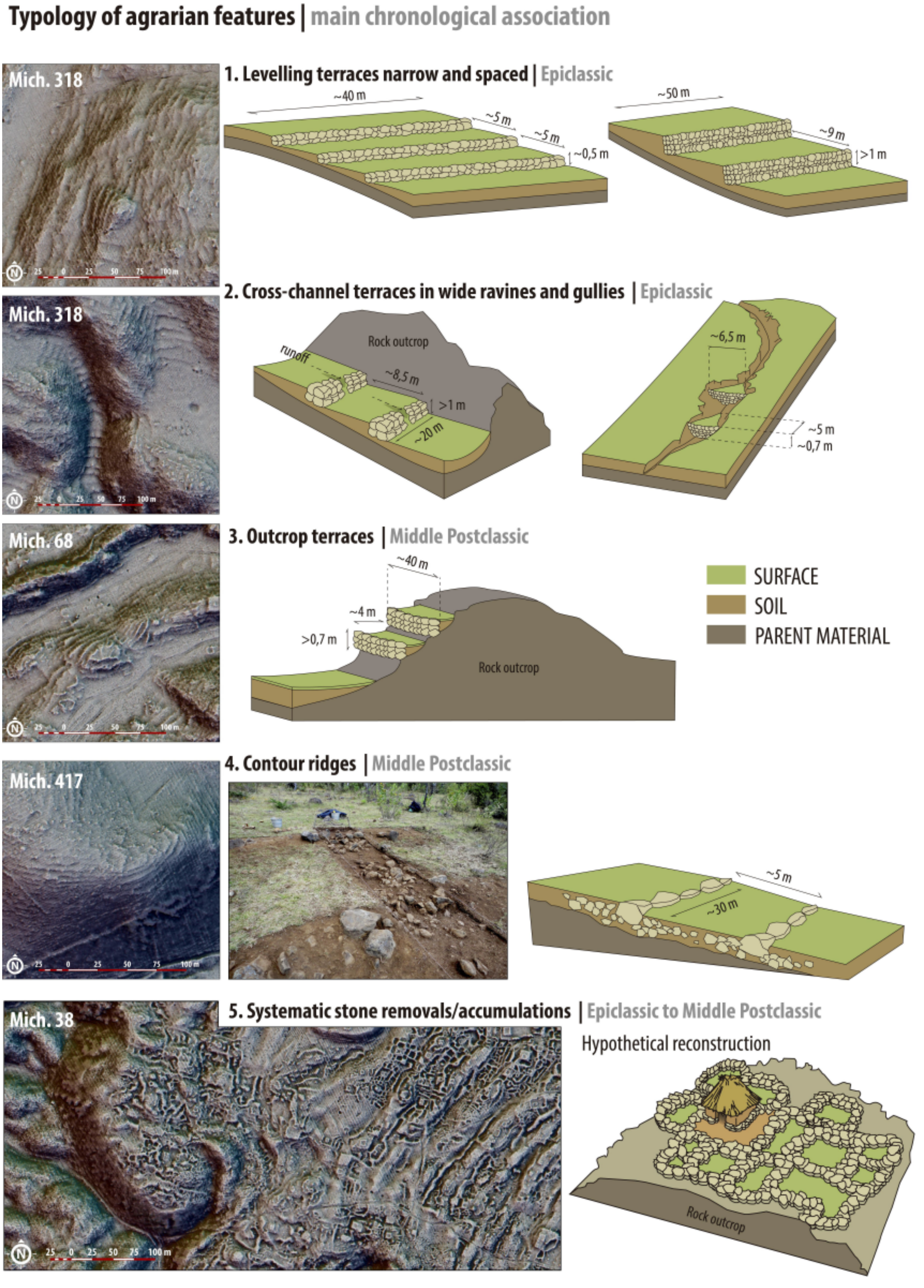

Figure 4. Typology of the main agrarian features with examples from the LiDAR image (see location on Figure 3)

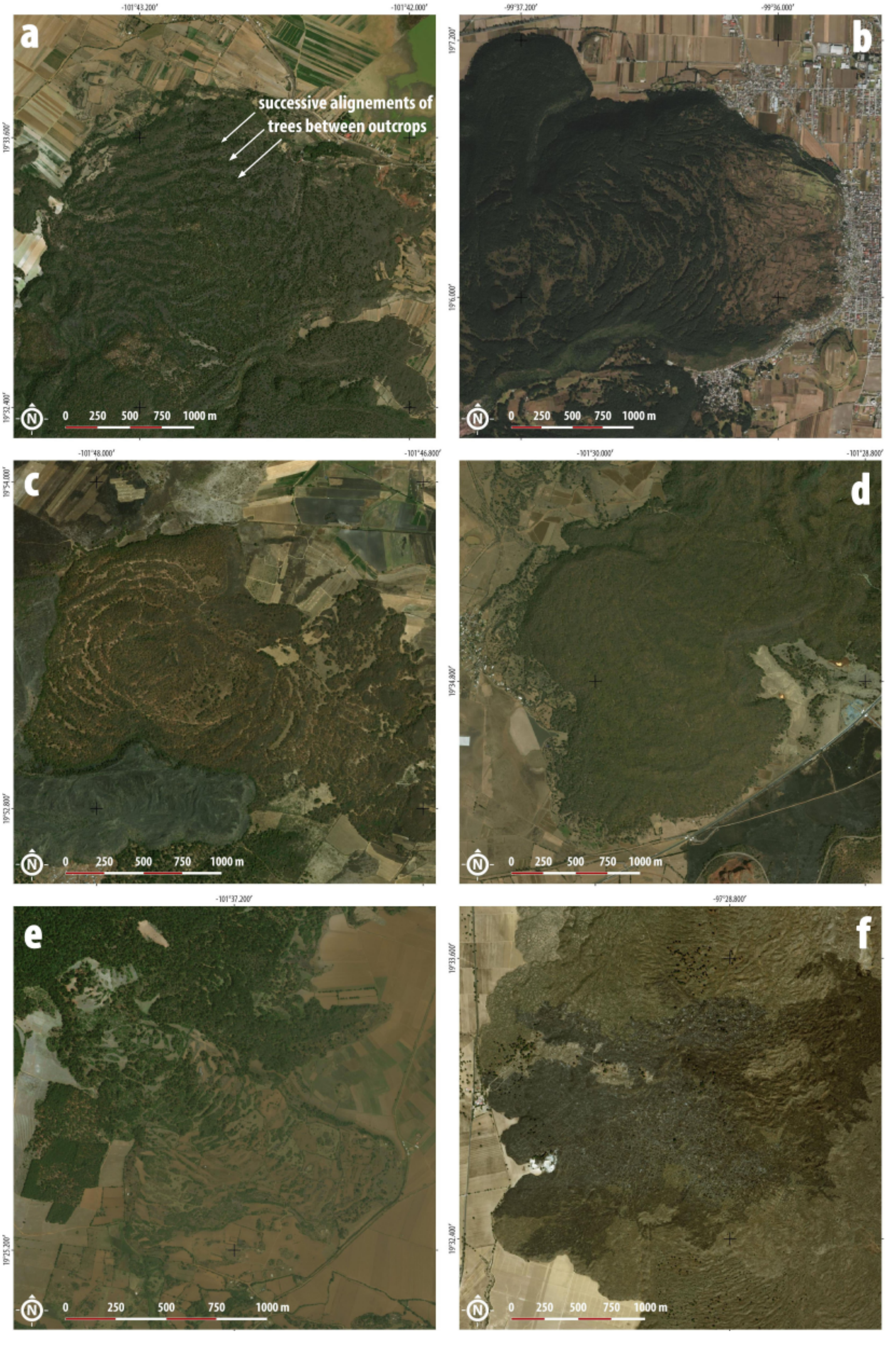

Figure 5. Examples of *malpaís* landforms of different ages along the TMVB. a. Arócutin (LBP); b. Tenango (Toluca Valley); c. Caracol (MZC); d. Angamuco (LPB); e. *malpaís* NW of Opopeo; f. Tepeyahualco (Eastern Puebla).

mid-thirteenth century. Although not wholly abandoned, some late Pleistocene *malpaís* landforms seem to have been left unexploited, while farmlands were extended towards older soil covers of the plateaus and hills of the highlands.

Discussion: A Reassessment of *Malpaís* Landforms

In this last section of the paper, I would like to discuss the pre-Hispanic agricultural perceptions of *malpaís* landforms by correlating my results with comparable contexts of the TMVB and ethnohistorical and ethnographical examples. The need to reassess *malpaís* landforms arises from the paradox observed in Zacapu. Modern farmers live and cultivate in the lacustrine plain, while a significant part of the highlands and the entire MZC are dedicated to grazing. In contrast, the study showed that pre-Hispanic farmers lived and cultivated in the highlands. Furthermore, although the mid-thirteenth century colonization of the most recent and roughest lava flows of the MZC remains typical of the Tarascan period, all *malpaís* landforms have been intensively inhabited by pre-Hispanic groups since the sixth century AD and their surfaces substantially modified by farmers for cultivation. In fact, the omnipresence of volcanic rock outcrops would not have constituted a problem for the latter, as they did not use the plough. Therefore, I pose the question of whether this situation corresponded to a cultural trajectory specific to Zacapu or if such pre-Hispanic use of *malpaís* landforms was more widespread and why.

The roughness of *malpaís* landforms surface is undeniable. Nevertheless, two points should be stressed regarding their agronomic potential. The first is that *malpaís* is a generic term that does not distinguish between very young lava flows with no soil cover and older formations with soil and vegetation. The second point is that, until now, the perception of *malpaís* agronomic potential was based on the points of view of observers of European tradition. It was Spanish settlers who invented this pejorative name. The first mention that I found is in the 1570s in *Relaciones Geográficas* (Acuña 1987:104). It is also modern farmers who relegate most *malpaises* to secondary use (e.g., grazing, timber harvesting). Finally, it is also archaeologists themselves who, in the MZC at least, documented the prevalence of very thin profile soils.

Malpaises Geoecological Characteristics and Pre-Hispanic Settlement Strategies

Regarding the generic nature of the term *malpaís*, our study asserted that the MZC, often seen as a single entity, is actually an accumulation of multiple lava flows with different agronomic characteristics. The latter are related to both the age of the flow and the rate of volcanic ash deposition, which contributes to the upbuilding of soil profiles (Peña Ramirez et al. 2015). This chronological diversity of *malpa*ís landforms should most likely be extrapolated to the whole TMVB. To support this assertion, I emphasize the homogeneity of geoecological conditions across this geological province, which produces a similar geopedologic evolution for lava flows today designated as *malpaises*. Altitude (~2,000 masl), climate (Cw type [temperate with dry winter]; García 2004), and mean annual precipitation (600–1200 mm; Douglas et al. 1993) are rather consistent across the zone. Geochemistry is more varied (Ferrari et al. 2012) and produces chemical diversity among volcanic ash deposits, but the chaotic morphology of *malpaises* results predominantly from intermediate to basic lavas (Bardintzeff 2011). All these conditions, in accordance with soil formation principles (Jenny 1941), control pedogenesis and associated plant communities along the TMVB (Rzedowski 1978).

Noteworthy examples of such *malpaís* diversity and evolutions are widespread in northern Michoacán and beyond (Figure 5). One is the Malpaís de Arócutin (La Taza scoria cone), southwest of the Lake Pátzcuaro basin, which is dated to 9300–8400 yrs BP

(Osorio-Ocampo et al. 2018; Figure 5a). On satellite imagery, we see successive alignments of forested areas. These alignments are actually distributed along the linear depressions that have formed between the pressure ridges of the lava flow where the sediments have accumulated. The lines of trees are evidence of localized pedogenesis. A similar morphology is visible on the Tenango lava flow (Figure 5b) south of the Toluca Valley, dated to 8510 ± 160 yrs BP. (Bloomfield and Valastro 1974), although, with time and more advanced pedogenesis, the distribution tends to be reversed: trees grow on the outcrops and the depressions between them become clearings (probably linked to human action in many cases). East of the LPB, the 29,000-year-old Malpaís de Angamuco (Rancho Seco volcano) (Figure 5d; Ramírez-Uribe et al. 2019) is entirely covered by oak trees and shows great similarity with late Pleistocene *malpaises* of Zacapu (Figure 5c). One final example from the far eastern part of the TMVB is the Tepeyahualco lava flow (Los Humeros) (Figure 5f), dated to 2200–1100 BC (Juárez-Arriaga et al. 2018), whose smoother but younger surface in a drier area only allowed for the development of herbaceous vegetation, shrubs, and xerophyte trees.

All these examples were given because they share one other common factor: they were all inhabited in pre-Hispanic times. Settlements on *malpaís* landforms are actually quite frequent along the TMVB. In the LPB, core of the Tarascan state, Urichu lies on the Arócutin (Pollard 2008), while Angamuco occupies the eponymous flow (Fisher and Leisz 2013). Teotenango is an important center located on top of the Tenango (Piña Chan 1975), just like the city of Cantona, which lies on top of the Tepeyahualco lava flow (García Cook 2003). Archaeologists generally consider that settlement upon *malpaís* is the result of a need for defense (García Cook 2003; Michelet et al. 2005; Piña Chan 1975; Pollard 2008). Indeed, various *malpaís* sites seem to emerge during the Epiclassic and Early Postclassic periods (AD 600–1200), which are marked by movements of population in the Mexican Central Highlands, political reorganization, and possibly increasing competitions between human groups (Beekman and Christensen 2003; Cowgill 2013; Pollard 2008). However, although I do not deny that *malpaís* landforms constitute natural strategic positions, I argue that defense was not the sole reason for their choice as settlement locations. Returning to the second point mentioned, I suggest (1) that pre-Hispanic perceptions of *malpaís* landforms were different from colonial and current views and (2) that their agronomic potential was well-known by pre-Hispanic groups and decisive in the selection of such places to live. With regard to the case of northern Michoacán, these assertions are supported by examples from ethnohistory and ethnography.

Ethnohistorical Evidence of the Pre-Hispanic Perception of *Malpa*ís Landforms

Concerning ethnohistory, I present here two textual sources indicating that at least some *malpaís* landforms were seen as good cultivation places by pre-Hispanic farmers.

The first one is the 1579 *Relation of Chichota*, a town located about 30 km west of the MZC, where reference is made explicitly to ancient terrace cultivation within the *malpaís* west of the colonial settlement (Acuña 1987:104). The text mentions "hills…very stony and of badlands…where they [the natives] planted maize [*cerros… muy pedregosos y de malpaís…donde plantaban el maíz*]" (Acuña 1987:104). Although no archaeological work has been conducted in the area, the description is sufficiently precise for the lava flow in question to be identified. Current toponyms, such as *El Pedregal* (stony area), support the identification. Vegetation and even some modern parcels are visible on satellite images, suggesting an old *malpaís*. Antiquity is attested by geological maps that indicate a mid-Pleistocene date (Garduño-Monroy 1999) and soil maps confirm that pedogenesis is ongoing (DETENAL 1982).

A second example is found in the *Chronicle of Michoacán* (Alcalá 2000 [c. 1540]), a partial 1530s compilation from interviews of Tarascan dignitaries. A passage narrates a dispute over a land donation in the vicinity of the LPB between two protagonists. One is a hunter-gatherer recently immigrated to the area, while the other is a sedentary farmer acquainted with the local landscape. The latter explains to the former that "although it is a very stony area [the donated lot], it is all good land [*que aunque sea pedregales que todo es buena tierra*]" (Alcalá 2000 [c. 1540]:435). Precise location could not be ascertained but it has been suggested that the place—Upapo Hoato in the text—could correspond to Opepeo, south of the basin (Le Clézio 1984:79). Geoecological characteristics of the area fit the description well. *Malpaís* landforms surround the modern town and the Tarascan site of Itziparátzico has been identified upon one of these (Maldonado and Rehren 2009). Geological works date the lava flows to the mid-Pleistocene (Ramírez-Uribe et al. 2019). Satellite imagery reveals once again linear outcrops with sedimentation in between them, while soil maps confirm the presence of volcanic ash soils (DETENAL 1979).

Although caution remains in order considering the subjectivity and literary character of these examples, both tend to confirm that pre-Hispanic farmers had a much less pejorative perception of what their colonial counterparts later called *malpaises*.

Ethnopedological Evidence of Local Farmers' Perception of *Malpaís* Landforms

Ethnopedological studies conducted in northern Michoacán further corroborate this assertion. Indeed, Purhépecha people, descendants of pre-Hispanic Tarascan groups, have developed a sophisticated soil taxonomy (Barrera-Bassols and Zinck 2003; Barrera-Bassols et al. 2006; West 1948). Based on the study of a community from San Francisco Pichátaro, in the Tarascan Mountains west of the LPB, Barrera-Bassols and colleagues (2006) reported that farmers refer to *malpaí*s landforms with the term *tzacapurhu*, literally meaning place (*rhu*) of stones (*tzacapu*) (Lathrop 2007). Furthermore, *tzacapurhu*, just as any other landform, are understood as contrasted landscapes by Purhépecha people. Thus, the *malpaís* that lie near the town of Pichátaro, and whose morphology suggests a mid- to late Pleistocene edifice (Pasquarè et al. 1991), is not seen as a uniform, rocky entity. Within this *malpaís*, Purhépecha farmers notably identify *echeri tupuri zacapendini* (*terendani*) (Barrera-Bassols and Zinck 2003). In other words, stony (*zacapendini*) and powdery (*tupuri*) soils (*echeri*) that may be rich in organic matter (*terendani*, literally meaning "decayed oak leaves"). These soils need to be worked by hand but are used as *taretarhu*, which translates as "agricultural plots." Given their characteristics, they largely correspond to Andosols of world taxonomies, which are considered as quite fertile (IUSS 2015). Other explicit mentions in earlier ethnographical works conducted in northern Michoacán suggest that this perception is not limited to Picháro farmers. Thus, both Beals (1946), conducting studies in the Indigenous town of Cherán, and West (1948), examining native communities in the whole of northern Michoacán, report that Purhépecha peasants working with hand tools particularly appreciate plots located within recent lava flows. Such farmlands are designated in Spanish as "*joyas*," literally meaning "jewels." Multi-cropping is generally practiced there, combining maize—perhaps specific species (see West 1948:35)—with beans, squash, or other cultivars, depending on the context (Beals 1946; West 1948). Regarding crops, another point to note is that these plots on recent lava flows may also be referred to as *ekuaros* or *ecuaros* in Purhépecha language

(West 1948:35). This word normally designates the house-lot, closer to a garden than any other field in terms of inversion and diversity of species cultivated (Franco-Gaona et al. 2016).

Based on these ethnographic works and my own observations in Zacapu, I argue—in accordance with Barrera-Bassols and colleagues' conclusions (2006)—that positive perception of *malpaís* soils by Purhépecha people is attributable to empirically known soil properties specific to these landforms:

1. the loose texture of volcanic ash soils makes them easier to work with hand tools than other soils;
2. their porosity, which induces aeration, and allows plant respiration and root development (Shoji et al. 1993);
3. porosity, which also allows for moisture retention where internal drainage is not too rapid (i.e., where slope is not too steep)—a point noted by West (1948). This is crucial in an environment where the rainy and dry seasons contrast sharply. In that regard, terracing is a known technique to hold humidity in sloping terrains (Donkin 1979:34);
4. Stone thermal range—also noted by Barrera-Bassols and Zinck (2003)—prevents *malpaís* soils from cooling down too quickly (Gras 1994); and
5. Finally, the oak forests that naturally colonize these landforms ensure litter renewal, which in its turn preserves organic matter content in surficial soil horizons (Barrera-Bassols and Zinck 2003; West 1948).

I argue that another important parameter is risk minimization, namely, avoiding crop losses due to frost hazards and standing rot in poorly drained contexts. The Pichátaro case study actually showed that, although (and because) they require a lot of attention, *malpaís* plots yield more sustained harvests than others (Barrera-Bassols and Zinck 2003). In Zacapu, where soil preparation by hand is no longer conducted, there are few examples of such plots being exploited apart from some easy-to-access terrains. However, interviews with local non-Purhépecha farmers led me to believe that cultivating in the highlands was advantageous to avoid some hazards. As I mentioned before, waterlogging is a major constraint in the lowlands. On this matter, informants confirmed to me that upland plots, unaffected by such marked waterlogging issues, offer more secure harvests, although they may yield less than lowland areas. Similarly, it has been documented in Mesoamerica (Donkin 1979) and elsewhere (Pradana et al. 2018; Snyder and de Melo-Abreu 2005) that upland areas are less prone to frost than lowlands in tropical mountainous regions where, like in northern Michoacán, below zero temperatures are frequent on winter nights and damaging for cultures. Cold air drainage towards lowland areas makes the latter colder than surrounding slopes and fosters frost hazards. To that regard, farmers shared with me their empirical awareness of such phenomena in my study area. Although I could not investigate these questions more thoroughly, I am confident that similar conditions occur in other basins of the TMVB. Therefore, I suggest that cultivating in the uplands and within *malpaís* is a means to ensure sustained harvests. Such perspective echoes smallholders' agricultural strategies documented in various parts of the world (Netting 1993).

Implications for Zacapu Archaeology and Pre-Hispanic Farming

Correlating these ethnographical and ethnohistorical observations with the soils and archaeological landscape that I studied in Zacapu, I think that empirical soil knowledge, such as that stressed by ethnographers in Purhépecha communities, was most likely mastered by pre-Hispanic groups. This last statement is consistent with previous assertions made by other researchers on the basis of ethnohistorical documents in other parts of Mesoamerica (Sandor et al. 2006; Williams 1975). I argue that pre-Hispanic farmers in Zacapu took advantage of known properties of upland and *malpaís* soils and deliberately chose to cultivate in these areas to minimize risks. Along with soil movement management, widespread pre-Hispanic terracing in Pleistocene lava flows is a material proof of awareness of, at least, moisture retention properties in volcanic ash soils. I also suggest that stone accumulation-removal in younger *malpaises* may correspond to a means to exploit thin and stony soils, but this remains to be demonstrated through fieldwork. In contrast, lowland unsteady conditions due to seasonal fluctuations of the former lake probably made it too hazardous to build labor-intensive drains to cultivate the area. This statement, however, only applies to the studied zone of the basin. In sum, I claim that, depending on the geoecological context, upland and *malpaís* soils may prove more secure for pre-Hispanic cultivation—if not better in some cases—than wetter lowland areas.

Conclusion

Remote sensing and fieldwork in both archaeology and soil science demonstrates that pre-Hispanic groups from the Zacapu area settled and cultivated in the highlands and *malpaises* rather than favoring the lakeshores, as one might have expected from modern settlement and agricultural practices. Based on geoecological comparisons, ethnohistorical evidence, and ethnopedology, I argue that this choice was partly guided by cultivation strategies. Pre-Hispanic groups inhabiting the area indubitably possessed advanced soil knowledge and had a better perception of what we now pejoratively call *malpaises*. Conversely, I think that modern Purhépecha perception of such landforms is probably inherited from pre-Hispanic knowledge. These conclusions most likely would apply to other pre-Hispanic settlements on *malpaís* of the Mexican Central Highlands, such as Angamuco, Teotenango, or Cantona. I assert that reassessing the agronomic potential of *malpaís* landforms by taking into account geological, geopedologic, and ecological parameters will provide a better understanding of this kind of settlement. In that regard, the multiplication of LiDAR flights will no doubt uncover more and more of the complexity of these settlements by shedding light on unexpected features. I am confident that pre-Hispanic agricultural strategies will prove to be nodal in the anthropogenic landscapes revealed.

Broadening this perspective beyond *malpaises*, LiDAR-derived DEMs are uncovering ancient sites with countless agrarian remains across all of Mesoamerica. The claimed importance of agricultural strategies in pre-Hispanic settlement processes (Barthel and Isendahl 2013; Fisher 2014; Isendahl and Smith 2013) is being confirmed by increasing material evidence. In future research, interdisciplinary spatial approaches, like the one presented here, combining geosciences and archaeology, will help reassess pre-Hispanic agriculture overall and confirm the importance of rainfed cultivation within the spectrum of ancient agricultural strategies. By this, I do not claim that upland soils are necessarily always better than lowland ones, but rather invite my colleagues to address this question more empirically to avoid preconceptions.

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