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Reconstruction of Anthropogenic Land-Cover Change for Middle America, 1500 CE

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Abstract

This project demonstrates how to use existing syntheses of many decades of historical social science research to produce empirically derived land-use maps in a GIS for large regions for a specific target year at a resolution appropriate to the calibration of existing anthropogenic land-cover change (ALCC) models. Disagreement among the outputs of various ALCC models results from differing estimates of population and assumptions about how much food a given population requires and the productivity per unit area of various types of cropping systems. The resulting ALCC model output of the spatial distribution of land uses at a given time becomes input for climate models, which thereby incorporate those uncertainties. To address the issue at a global scale, the LandCover6k working group of PAGES (Past Global Changes), has undertaken an international effort to empirically calibrate the HYDE ALCC model. This report on a contribution to that effort employs empirical data from previously published scholarship in geography, anthropology, and archaeology on the land use of Middle America centered on a target year of 1500 CE. Maps from those sources were digitized and georeferenced in a GIS (Geographic Information System) and used to digitize polygons in which each category of land use is known to have occurred during late precolonial and early colonial times, centered on the target year. The land-use typology used was agreed on at the first, 2015 LandCover6k meeting and includes five top-level categories: Pastoral; Urban and Extractive; Hunting, Fishing, and Gathering; No land Use; and Agriculture. This project further includes a dozen Agricultural subcategories specifically appropriate to Middle America in 1500 CE: agroforestry; orchards and orchard gardens; shifting cultivation; short-fallow cultivation; sloping-field terraces; bench terraces; cross-channel terraces; subsurface irrigation; floodwater irrigation; canal irrigation; recessional cultivation; and intensive wetland fields. The results are presented and discussed as sixteen GIS screenshots.

Keywords
Middle America; Caribbean; Central America; Mexico; 1500 CE; anthropogenic land-cover change models; land use; land cover; climate change; climate change models

1. Introduction

Much of our general understanding of the impact of anthropogenic land-cover change (ALCC) on the global climate system during the Holocene relies on models that calculate change in the extent of various land uses by utilizing historical population estimates as the independent variable [1-4]. Wide disagreement among the outputs of various ALCC models, however, results from differing population estimates and assumptions about how much food a given population requires and the productivity per unit area of various types of cropping systems [5]. The resulting ALCC model outputs of the spatial distribution of land uses at a given time becomes input for climate models, which thereby incorporate the uncertainties of the land-cover estimates.

Efforts to test ALCC model output against empirical land-use data at local through hemispheric scales has focused on particularly significant questions. A prominent one has been whether the vast reduction of population of the Americas during the sixteenth century precipitated forest regrowth, carbon sequestration, and the cold interval of the Little Ice Age (1577-1694 CE), which was the only period of significant cooling at a global scale within the past 2,000 years [6, 7].

To systematically and comprehensively address this issue at a global scale, the LandCover6k working group of PAGES (Past Global Changes, a project of Future Earth), has undertaken an international effort to empirically calibrate the HYDE ALCC model [3, 8]. The LandCover6k effort draws on the vast but diverse repository of empirical evidence of Holocene land use assembled by historical social scientists such as geographers, anthropologists, and archaeologists.

This paper reports on a contribution to that effort: an empirically derived map of land use in 1500 CE for the region of Middle America, which consists of Mexico, the Caribbean, and Central America. The region spans temperate through tropical latitudes from northern Mexico through Panama, was in part densely populated in 1500 CE, and suffered rapid depopulation during European colonization over the sixteenth century. This report focuses on the data and methods used to reconstruct land use in 1500 CE across the region at a resolution appropriate to contribute to the broader, global LandCover6k effort.

2. Materials and Methods

2.1 Data

The empirical data for the land-use map derive from previously published, rigorously conceived, well executed, thorough, systematic syntheses of decades of scholarship in geography, anthropology, and archaeology on the land use of Middle America for that general time period centered on the 1500 CE target year [9, 10]. Other sources more limited in thematic or spatial scope provide additional detail [11]. Maps from those sources were digitized and georeferenced in a GIS (Geographic Information System) and used to map land-use polygons suitable for use in LandCover6k.

The data underlying the previously published syntheses are diverse. Written descriptions dating to the immediate contact period, 1492 through the 1520s for most of Middle America, preserve eyewitness observations of land uses, although often pertaining to periods after depopulation and other major disruptions associated with colonization. Landscape vestiges preserve field forms such as terrace walls and irrigation canals. Archaeological excavations recover botanical remains from domesticates and non-domesticates in settlements that imply particular agricultural practices in the environs of those settlements. Palaeoecological and vegetation studies reveal species compositions that similarly imply particular agricultural practices. And ethnohistoric and ethnographic studies provide more detailed understandings of more recent historical and present-day agricultural and horticultural practices that act as analogs for those of the past to understand their productivity and other attributes.

The GIS focuses on a fairly brief time period centered on the 1500 CE target year. Much of Middle America was conquered and colonized by the Spaniards between the first voyage of Christopher Columbus to the Caribbean in 1492, the conquest of Tenochtitlán (now Mexico City) in 1521, and that of considerable parts of Central America over the rest of the 1520s [12, 13]. Colonization focused on areas with dense population and agriculture, and the colonizers were accompanied by introduced epidemic diseases that resulted in dramatic depopulation and contraction of agriculture over the sixteenth century. Areas that remained largely beyond the colonial frontier by the 1520s, albeit not always beyond the devastation of epidemic diseases, included northern Mexico, the Yucatan Peninsula, and most of the Caribbean beyond the four Greater Antilles. Relative to the areas where the Spaniards focused conquest and colonization, many of the unconquered areas had sparse populations and little agricultural land use in 1500 CE.

The following maps show areas in which each land use is known to have occurred during the late precolonial and early colonial periods, centered on the target year of 1500 CE. Some of the land uses were persistent in the same place from year to year, such as urban land use and intensive wetland fields. Others were ephemeral, occurring throughout an area but not persisting in any particular location, such as hunting and gathering.

2.2 Geographic Information System

Digitization of the maps from the published syntheses produced a GIS with polygons in which different types of land use are empirically known to have occurred, classified by level of confidence on the basis of the type of evidence available, either probable or unqualified. Polygons of different land-use types overlap, as they do with actual land uses.

QGIS (Essen 2.14.0, released 26.2.15) was used to produce the GIS (figure 1). The Coordinate Reference System was set to WGS 84/Pseudo Mercator (ESPG: 3857), the standard for web mapping. To guide the level of generalization of the land-use polygons, an overlay grid with intervals of 8 km, which approximates the 5-minute (1/12th of a degree) grid cells of the highest resolution ALCC models, was added as a layer in the GIS.

Figure 1 GIS of Middle America.

Each category of land use was digitized on a separate GIS layer. The land-use categories used follow those agreed on at the first LandCover6k meeting: Putting History to Work on Climate Change (Paris, October 22-23, 2015). They include five top-level types of land use: Pastoral; Urban and Extractive; Hunting, Fishing, and Gathering; No land Use; and Agriculture. This project further breaks down the Agricultural category into a dozen subcategories appropriate to Middle America in 1500 CE: agroforestry; orchards and orchard gardens; shifting cultivation; short-fallow cultivation; sloping-field terraces; bench terraces; cross-channel terraces; subsurface irrigation; floodwater irrigation; canal irrigation; recessional cultivation; and intensive wetland fields. Each layer in the GIS, has its own attribute table with the following fields: the default Id (integer up to 10 digits long) for each polygon; Type (text string up to 50 characters for the five top-level categories); Subtype (text string up to 50 characters for the agricultural subcategories); Comments (text string set to 100 characters for supplemental information); Source (text string up to 100 characters, editable for the name of the georeferenced map used to digitize the feature); Citation (text string up to 100 characters set to editable for citation of the source of the georeferenced map and other information used to digitize the feature). Because including all dozen agricultural subcategories on one layer would have resulted in visual confusion, those land uses were grouped into five layers, each including 2-5 subcategories of land use: wetland cultivation; floodwater and irrigated cultivation; arboriculture and horticulture; rainfed cultivation; and terrace cultivation.

Digitization methods varied for each layer, depending on the data source for the relevant category of land use. Many of the agricultural land-use polygons were digitized from the maps published in Whitmore and Turner [10]. They range in scale from 1:500,000 to 1:15,000,000 and therefore allow digitization of highly precise land-use polygons. Thomas Whitmore kindly provided the maps as digital files that were georeferenced in the GIS using a set of predetermined control points to standardize the process for faster, more precise, and more consistent results. The polygons were then converted to vector layers using heads-up digitizing. In contrast, the maps from Doolittle [9] have a small scale (approximately 1:50,000,000) and use point symbols. Each relevant map was scanned, georeferenced, and the point symbols digitized onto the relevant agricultural layers as polygons so they would be commensurate with those digitized from Whitmore and Turner [10].

In cases were elevation limits to agriculture or lakes required use of the QGIS difference tool to geoprocess holes in agricultural land-use polygons, relevant shapefiles were acquired and features extracted. For Mexico, shapefiles of topographic contours, lakes, and other features digitized from 1:1,000,000 topographic maps are available from www.inegi.org.mx. For Central America and the Caribbean, elevation contours can be extracted from ASTER Digital Elevation Models available from earthexplorer.usgs.gov. In cases where Whitmore and Turner [10] represent specific types of agriculture as line symbols instead of polygons, such as cross-channel terraces along the Balsas River or recessional cultivation, the 1:1,000,000 shapefile of streams was downloaded from www.inegi.org.mx, irrelevant stream segments deleted, buffers as thick as the lines in Whitmore and Turner ([10], figures 5.8, 6.1, 6.2, 7.1) geoprocessed and merged to create polygons that replicated the published maps.

3. Results and Discussion

The following screenshots of the GIS illustrate the results for each of the five top-level categories of land use and the five groups of the dozen agricultural subcategories (figures 2-16).

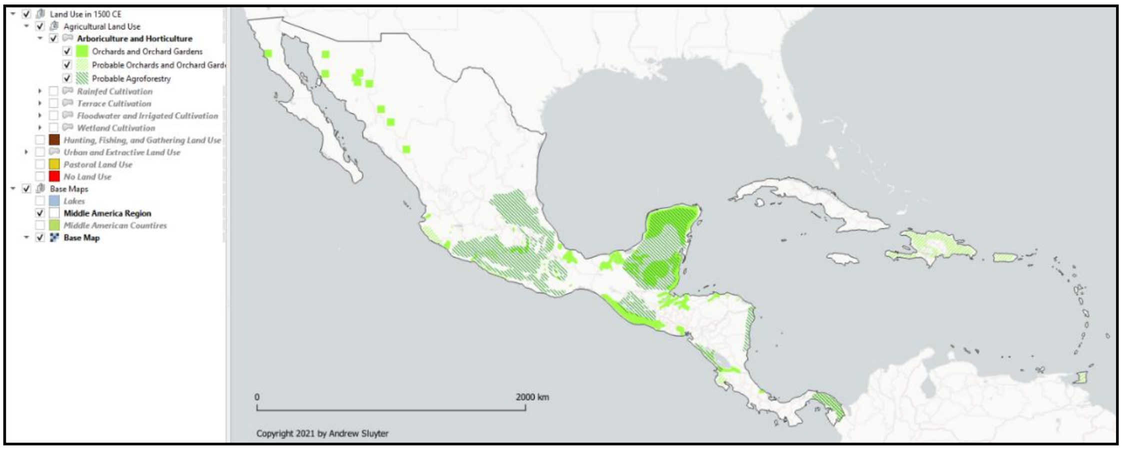

Figure 2 Arboriculture and horticulture in Middle America, 1500 CE.

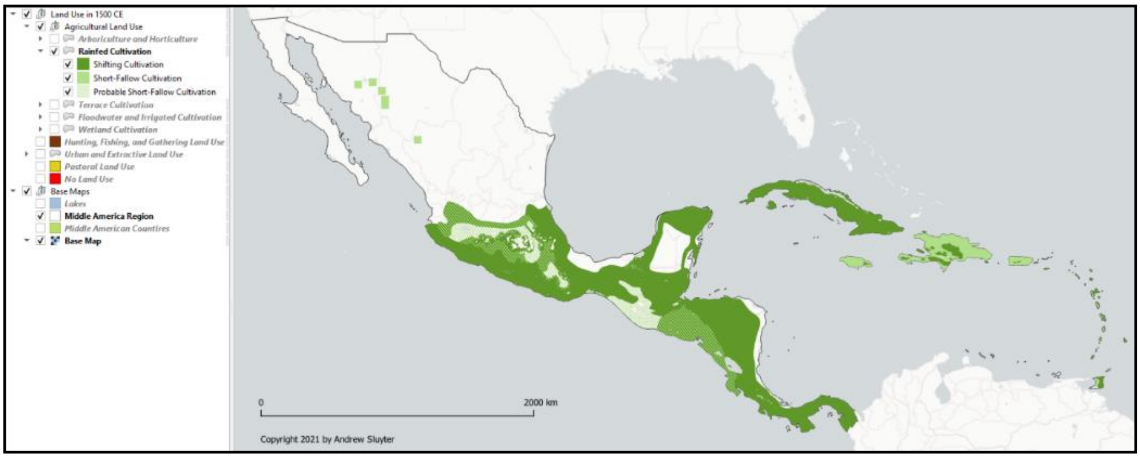

Figure 3 Rainfed cultivation in Middle America, 1500 CE.

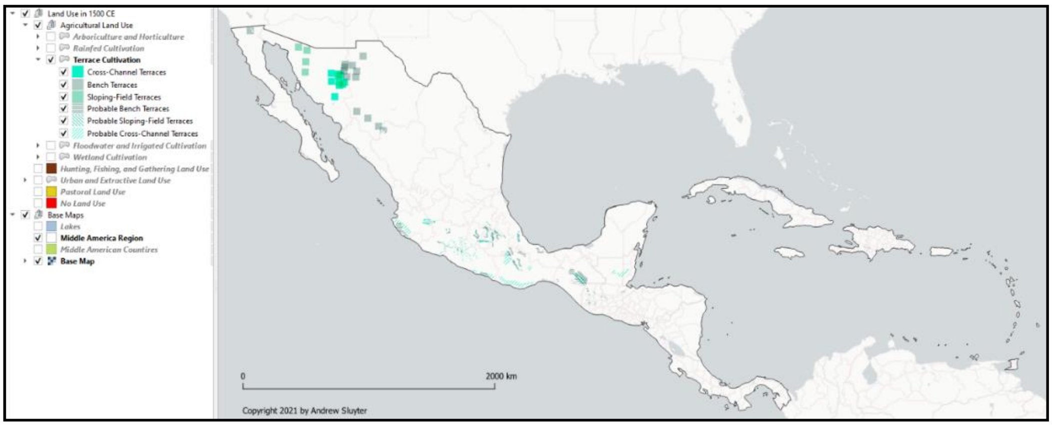

Figure 4 Terrace cultivation in Middle America, 1500 CE.

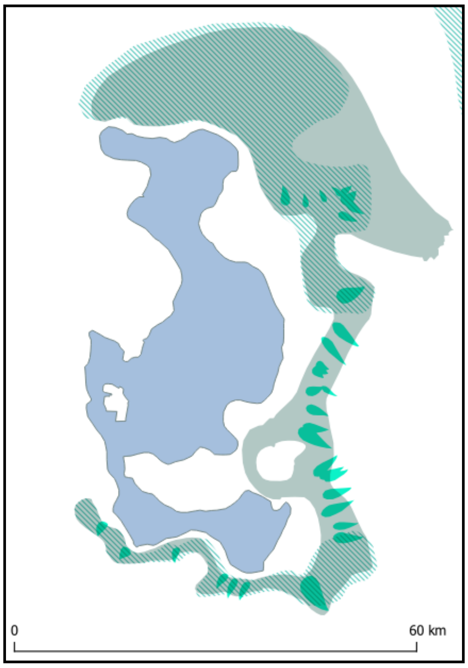

Figure 5 Detail of terrace cultivation in a lake basin, 1500 CE (see preceding figure for legend).

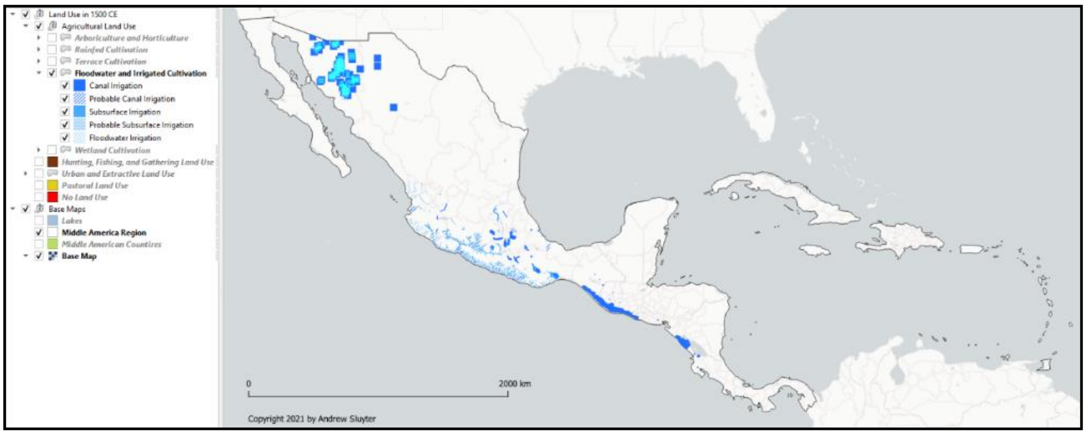

Figure 6 Floodwater and Irrigated Cultivation in Middle America, 1500 CE.

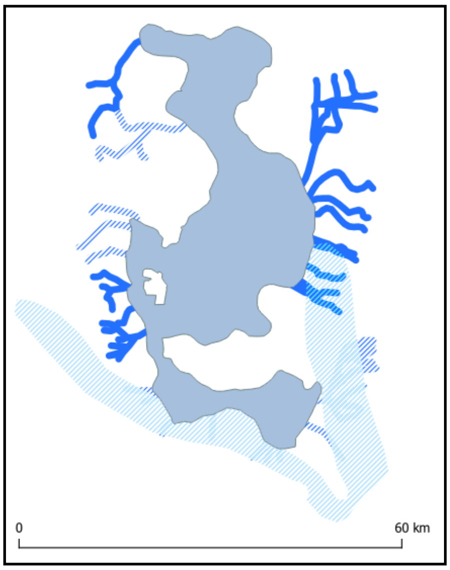

Figure 7 Detail of floodwater and irrigated cultivation in a lake basin, 1500 CE (see preceding figure for legend).

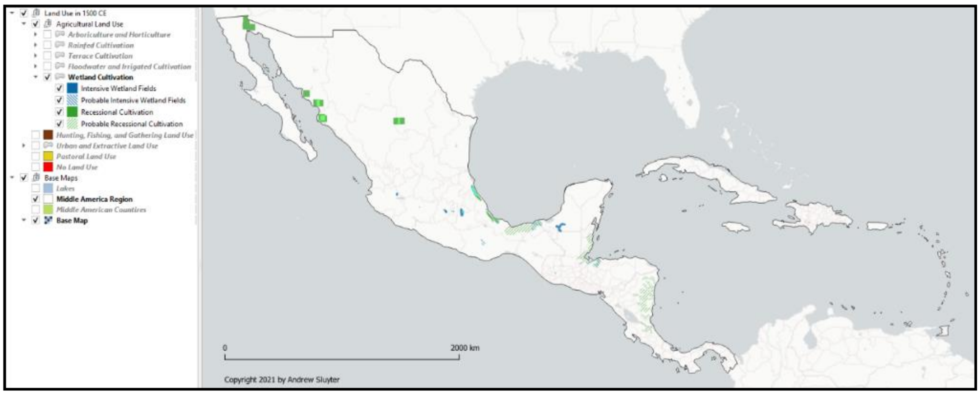

Figure 8 Wetland cultivation in Middle America, 1500 CE.

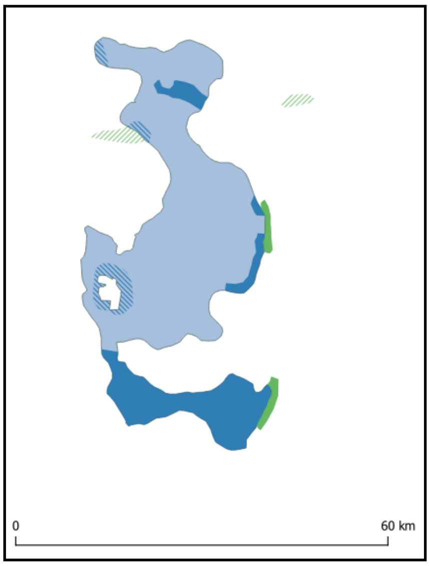

Figure 9 Detail of wetland cultivation in a lake basin, 1500 CE (see preceding figure for legend).

Figure 10 Hunting, fishing, and gathering land use in Middle America, 1500 CE.

Figure 11 Urban and extractive land use in Middle America, 1500 CE.

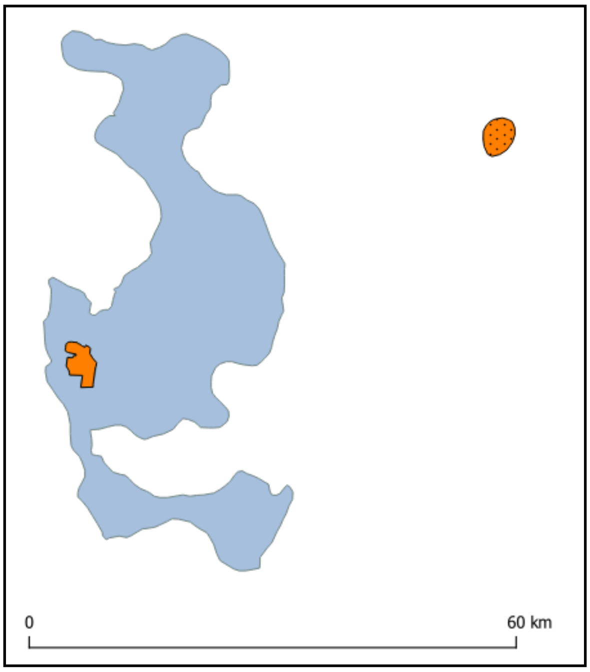

Figure 12 Detail of urban and extractive land use in a lake basin, 1500 CE (see preceding figure for legend).

Figure 13 Pastoral land use in Middle America, 1500 CE.

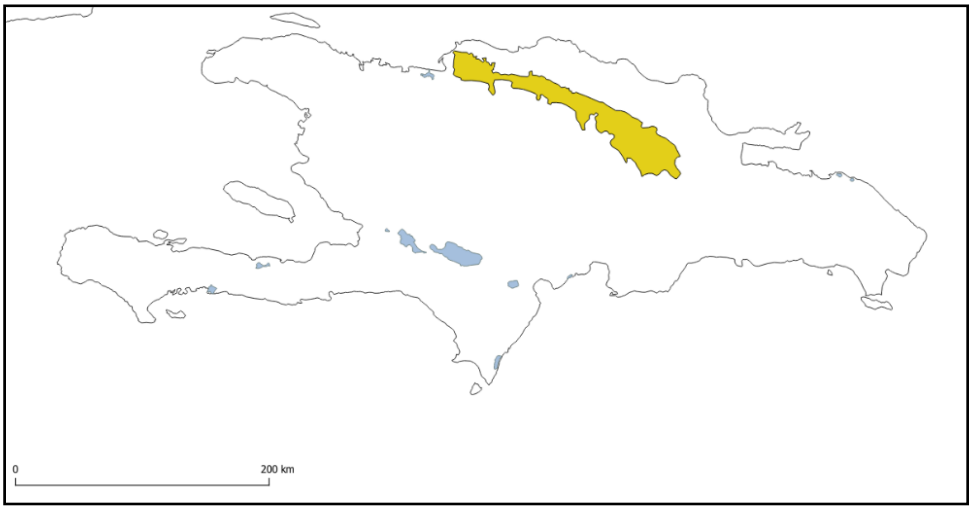

Figure 14 Detail of pastoral land use on an island, 1500 CE (see preceding figure for legend).

Figure 15 No Land Use in Middle America, 1500 CE.

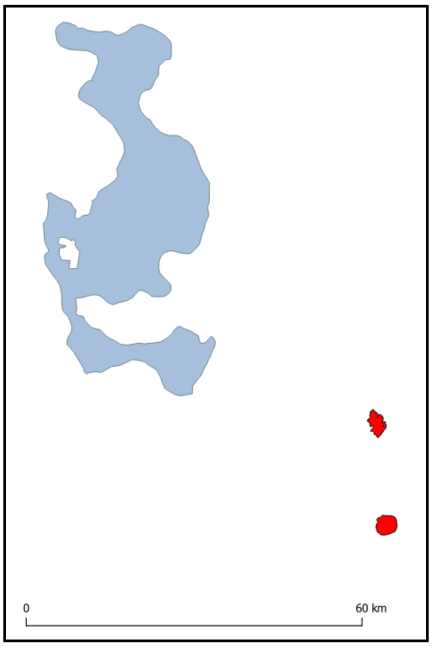

Figure 16 Detail of no land use on glaciated peaks of volcanoes around a lake basin, 1500 CE (see preceding figure for legend).

3.1 Agricultural Land Use

The project began by consolidating the 47 categories of agricultural land use and levels of confidence used by Whitmore and Turner [10], as well as relevant ones from Doolittle [9] for northern Mexico, to a dozen, each with corresponding probable and unqualified versions: agroforestry, orchards and orchard gardens, shifting cultivation, short-fallow cultivation, sloping-field terraces, bench terraces, cross-channel terraces, subsurface irrigation, floodwater irrigation, canal irrigation, recessional cultivation, and intensive wetland fields. The descriptions that follow better specify each of the twelve types of agricultural land use as well as issues related to evidence, interpretation, and level of confidence (unqualified occurrence versus probable occurrence).

3.1.1 Arboriculture and Horticulture

The first GIS layer within the Agricultural group, named Arboriculture and Horticulture, maps the two agricultural subcategories of agroforestry and orchards and orchard-gardens (Figure 2). Agroforestry, the first of the land uses, is defined by Whitmore and Turner ([10], p.77) as “the selective preservation or cultivation of multiple tree and shrub species in the context of local flora” involving “the use, management, or modification of a forest ecosystem to augment production needs by providing wood, fruits, nuts, dyes, latex, fibers, medicinal products, and other foodstuffs.” They explicitly distinguish agroforestry from hunting, fishing, and gathering because agroforestry, as they define and map it, unlike gathering, involves deliberate management and modification of forests through such practices as culling and selective propagation and preservation of select, albeit mainly non-domesticated, species. Often that management takes place in concert with shifting cultivation, with fallowed fields continuing to produce a sequence of products through a managed succession back to forest. The evidence for agroforestry remains sparse for all of Middle America in 1500 CE. Despite suspecting agroforestry throughout much of the humid and mesic tropical forests of the region, therefore, Whitmore and Turner ([10], p.79-86) remain careful to map only several areas of probable agroforestry on the mainland and none at all on the islands. Their evidence derives from a mix of ethnographic and ethnohistoric analogy as well as limited, direct observations recorded in contact-period documents.

Orchards and orchard gardens comprise the second type of land use and are defined by Whitmore and Turner ([10], 78) in the following ways. Orchards were intensively managed plots near settlements focused on monocultures or near monocultures of tree or shrub species, including succulents such as *nopal* and *maguey*. Gardens were intensively managed plots within settlements focused on the cultivation of non-staple annuals. And orchard gardens mixed those land uses on a single plot typically within settlements. Unlike agroforestry, the emphasis in orchards, gardens, and orchard-gardens was on domesticated species. The evidence in some cases is sparse, allowing mapping of probable instances only, but in other cases is strong or confirmed, allowing mapping of unqualified instances ([10], p.86-106). The evidence does not typically permit distinguishing among orchards, orchard-gardens, and gardens because of the prevalence of polyculture in the region as well as limited details provided by the evidence. Probable instances of orchards and/or orchard-gardens occur on Hispaniola, Puerto Rico, and Trinidad based on a mix of archaeological remains and limited, direct observations recorded in contact-period documents. On the mainland, similar evidence as well as ethnographic and ethnohistoric analogy allows mapping of instances of probable orchards and/or orchard-gardens; in addition, however, a relative wealth of direct observations recorded in contact-period documents allows mapping of many unqualified instances, particularly related to cacao orchards because of their value as the source of chocolate and occurrence as monocultures, but also related to other crops.

Based on similar types of evidence, gardens were grown immediately around residential structures and differentiated from orchard-gardens by a higher proportion of domesticated annuals relative to trees and shrubs. While the data sources do not permit gardens to be distinguished from orchard-gardens, they were likely plentiful, small in area, and ubiquitous in settlements throughout Middle America. They therefore cannot be mapped as a distinct category.

3.1.2 Rainfed Cultivation

The second layer, named Rainfed Cultivation, maps the two agricultural subcategories of shifting and short-fallow cultivation (Figure 3). Shifting cultivation, the first of these land uses, is defined by Whitmore and Turner ([10], p.112), using the term swidden, as characteristic of tropical lowland forests as well as having a fallow period lasting for years that exceeds the period of active cultivation, burning of regrowth to release nutrients prior to cultivation, and minimal tillage ([10], p.113). Shifting cultivation is a form of rainfed agriculture and therefore widespread throughout the tropical lowlands of Middle America but limited by arid climates in the north, rain shadows throughout, and high elevations. The evidence for shifting cultivation consists of sparse contact-period accounts as well as ethnographic and ethnohistoric analogy but tends to be general, pertaining to broad areas rather than specific locales. Whitmore and Turner ([10], p.116-117) note how problematic the use of ethnographic and ethnohistoric analogy is in this particular case because the dramatic depopulation and introduction of steel axes might have expanded shifting cultivation at the expense of more intensive, short-fallow cultivation. Nonetheless, those sources allow Whitmore and Turner ([10], p.114-123) to map broad, general areas of shifting cultivation throughout the Caribbean, limited to the windward, wetter sides of the Lesser Antilles and to areas not used more intensively for short-fallow cultivation on Hispaniola, Jamaica, and Puerto Rico; Central America except for extensive areas of wetlands along the Caribbean coast; and much of southern Mexico except for more temperate elevations, with an elevation cutoff of 2,800 meters.

Short-fallow cultivation is defined by Whitmore and Turner ([10], p.113-129) as consisting of two types: *temporal* and *conuco*. Both are forms of rainfed cultivation and therefore widespread. *Temporal* is distinguished from shifting cultivation by having annual or near annual cropping, with fallow restricted to the dry or cold season; characteristic of higher, temperate elevations of parts of mainland Middle America; and involving substantial tillage to manage soil fertility. *Conuco* occurred in the tropical lowlands of some of the Greater Antilles and Trinidad and involved intensive tillage and soil mounding (as high as 70 cm) to manage fertility and allow sustained cropping. The evidence for short-fallow cultivation consists of sparse contact-period accounts as well as ethnographic and ethnohistoric analogy but tends to be general, pertaining to broad areas rather than specific locales. Nonetheless, those sources allow Whitmore and Turner ([10], p.123-130) to map broad, general areas of short-fallow cultivation on Hispaniola, Jamaica, and Puerto Rico; higher, more temperate elevations of Central America; and much of the temperate elevations of the mountains of southern Mexico up to an elevation of 2,800 meters.

3.1.3 Terrace Cultivation

The third layer, named Terrace Cultivation, maps the three agricultural subcategories of bench terraces, sloping-field terraces, and cross-channel terraces (Figures 4-5). Bench terracing, the first of these closely related land uses, is defined by Whitmore and Turner ([10], p.145) as contouring walls of earth or rock high enough to create level planting surfaces on steep slopes, thus deepening soils, reducing soil erosion and runoff, increasing infiltration and soil moisture, and facilitating irrigation. The evidence for this type of agriculture involves vestiges of rock walls and other landscape modifications, some currently in use, archaeological excavations, scattered references in contact-period documents, and ethnographic and ethnohistoric analogy. That evidence allows mapping of many instances of this type of agriculture, mostly unqualified but some probable, throughout what are now the Mexican and Guatemalan parts of Middle America up to an elevation of 2,800 meters, although some claims of bench terraces on Puerto Rico also exist ([10], p.145-154).

Sloping-field terracing, the second land use, is defined by Whitmore and Turner ([10], p.136-137) as modifications to landscapes that reduce but do not eliminate shallow slopes, consisting of contouring rock alignments, low walls, earthen embankments, or rows of perennial vegetation that collect and deepen soil upslope, slow runoff, and increase infiltration and soil-moisture storage [14]. The evidence for this type of agriculture involves vestiges of rock alignments and other landscape modifications, some currently in use, archaeological excavations, scattered references in contact-period documents, and ethnographic and ethnohistoric analogy. That evidence allows mapping of many instances of this type of agriculture, albeit qualified as probable because of the relatively minimal landscape modifications this type of terracing entails compared to bench terraces, throughout what is now the Mexican part of Middle America as well as northern Guatemala up to an elevation of 2,800 meters ([10], p.136-145).

Cross-channel terracing, the third land use, is defined by Whitmore and Turner ([10], p.154) as weirs or dams built across ephemeral stream channels to capture sediments and moisture for cultivation in a series of small, wedge-shaped fields. The evidence for this type of agriculture involves vestiges of rock walls and other landscape modifications, some currently in use, archaeological excavations, scattered references in contact-period documents, and ethnographic and ethnohistoric analogy. That evidence allows mapping of many instances of this type of agriculture, albeit qualified as probable in many instances because they leave less landscape evidence than bench terraces, throughout what are now Mexico and northern Central America ([10], p.154-161).

3.1.4 Floodwater and Irrigated Cultivation

The fourth layer, named Floodwater and Irrigated Cultivation, maps the three agricultural subcategories of subsurface irrigation, floodwater irrigation, and canal irrigation (Figures 6-7). Subsurface irrigation, the first of these land uses, is defined by Whitmore and Turner ([10], p.170) as the excavation of shallow holes to create sunken fields that accessed the water table, often in the channels of ephemeral streams with low gradients. The evidence for this type of agriculture involves landscape vestiges, archaeological excavations, scattered references in contact-period documents, and ethnographic and ethnohistoric analogy. That evidence allows mapping of the incidence of this type of agriculture along the channels of streams that drain into the Pacific Ocean, up to an elevation of 900 m, as well as other scattered locations in what is now Mexico, with unqualified instances in the Río Balsas drainage and southward and probable ones to the north ([10], p.167, 170-71).

Floodwater irrigation is defined by Whitmore and Turner ([10], p.171) as involving the construction of cross-channel weirs or dams, similar to the walls of cross-channel terraces, across the narrow channels of ephemeral streams or broader valley bottoms to collect, spread, and direct floodwaters in combination with systems of ditches. They thereby distinguish it from “recessional cultivation” (also “floodwater farming”), which does not employ weirs or ditches and occurs in places where the unmodified topography distributes adequate water to fields, but at the same time note that areas of floodwater irrigation and recessional cultivation (floodwater farming) likely occurred in close proximity. The evidence for this type of agriculture involves landscape vestiges, archaeological excavations, scattered references in contact-period documents, and ethnographic and ethnohistoric analogy. That evidence allows mapping of unqualified instances of this type of agriculture generally along the channels of streams that drain into the Pacific Ocean as well as other scattered locations in what is now Mexico ([10], p.171-174).

Canal irrigation, the third land use, is defined by Whitmore and Turner ([10], p.174) as employing canals, meaning artificial channels, to deliver water from a perennial source such as a reservoir or spring to agricultural fields in a highly controlled manner, thus distinguishing it from floodwater irrigation systems that rely on ephemeral and unpredictable flows that are difficult to control. The evidence for this type of agriculture involves vestiges of canals, dams, and other structures, some currently in use, archaeological excavations, scattered references in contact-period documents, and ethnographic and ethnohistoric analogy. That evidence allows mapping of probable and unqualified incidences of this type of agriculture throughout the Mexican and northern Central American parts of Middle America, although some claims of canal irrigation on Cuba and Hispaniola also exist ([10], p.174-191).

3.1.5 Wetland Cultivation

The fifth GIS layer within the Agricultural group, named Wetland Cultivation, maps the final two agricultural subcategories: recessional cultivation and intensive wetland fields (Figures 8-9). Recessional cultivation, the first of these land uses, is defined by Whitmore and Turner ([10], p.199-200) as planting crops in the moist soils of the seasonally exposed margins of wetlands and floodplains as flood waters recede, for example, at the beginning of the dry season around backswamps on the backslopes of levees. For that reason, they also use the term floodwater farming for this type of agriculture. In some cases, ditches aligned with slope hastened drainage and/or provided access to shallow water tables longer into the dry season, a variant termed "subsurface wetlands cultivation" that merges into the subsurface irrigation category but is largely indistinguishable in terms of the ditches from ones dedicated to drainage in recessional fields ([10], p.200). The evidence for this type of agriculture involves vestiges of ditches and other landscape modifications, archaeological excavations, scattered references in contact-period documents, and ethnographic and ethnohistoric analogy. That evidence allows mapping of probable and unqualified incidences of this type of agriculture throughout much of mainland Middle America ([10], p.199-207).

Intensive wetland fields is defined by Whitmore and Turner ([10], p.207) as permanently altering the elevation of the cropping surface relative the water table by digging ditches in wetlands and using the spoil to elevate fields or, in the most intensive form of this type of agriculture, the *chinampas* of the Basin of Mexico, raising fields from the bottom of shallow lakes to create artificial islands separated by canals [11, 12]. Some *chinampas* were even irrigated, what Whitmore and Turner ([10], p.167, 182, 191-192) refer to as "wetland irrigation," meaning that canals delivered fresh water to them from springs and streams in order to reduce the salinity of the surrounding lake waters, as indicated in the Comments field of the attribute table. The evidence for this type of agriculture involves vestiges of ditches, raised fields, and other landscape modifications, some currently in use, archaeological excavations, scattered references in contact-period documents, and ethnographic and ethnohistoric analogy. That evidence allows mapping of probable and unqualified incidences of this type of agriculture throughout the Mexican and northern Central American parts of Middle America ([10], p.207-224).

3.1.6 Northern Mexico

Whitmore and Turner [10] do not cover the sector of Middle America that is now northern Mexico. For that area, this project drew on Doolittle [9], which includes it as a southward extension of the US Southwest. Doolittle [9] includes 17 maps showing the location of various agricultural types relevant to northern Mexico and provides detailed explanation of each type of agricultural land use and discussion of the evidence used for mapping. Some issues with using this source involve differences in the types of agricultural land use relative to Whitmore and Turner [10]; use of different qualifiers such as "suspected," "inferred," and "confirmed"; the greater use of point symbols rather than polygons; the much smaller scale of the maps (approximately 1:50,000,000); and the later contact period in that part of Middle America, meaning that the direct observations recorded in contact-period documents date not to 1492 through the 1520s, but to the late 1520s through the eighteenth century.

The issue of different agricultural types can be resolved relatively well (Table 1). Some of the agricultural types used in Doolittle [9] simply do not pertain to northern Mexico: “Husbandry of small herbaceous plants” is known there only from twentieth-century ethnographies; “shifting cultivation” likely did not occur anywhere north of the tropics ([9], p.174-190); and “ridged fields in cool environments,” “dry farming,” and “draining and ridging” did not occur in northern Mexico. “gardens” were likely plentiful, small in area, and ubiquitous within settlements but for those reasons, as for the rest of Middle America, cannot be mapped as a category distinct from “orchards and orchard-gardens.” Most of the agricultural types used in Doolittle [9] that do pertain to northern Mexico correspond directly to agricultural types used in Whitmore and Turner [10], as tabulated below. In the case of “terracing,” the use of “cross-channel terraces,” “sloping-field terraces,” and “bench terraces” all pertained to northern Mexico but are known by various terms that were converted to the three standard ones used for the rest of the map ([9], p.287-288, table 8.1; [15], p.58-61).

Table 1 Equivalent land-use categories for Northern Mexico and the rest of Middle America, 1500 CE.

Northern Mexico [9]	Equivalents used [10]
Husbandry of large, and woody plants	Orchards and orchard-gardens
Plain fields in warm environments	Short-fallow cultivation
Various terrace forms	Sloping-field; Bench; and Cross-channel terraces
Water harvesting	Floodwater irrigation
Canal irrigation	Canal irrigation
Flood recessional farming	Recessional cultivation

The maps in Doolittle [9], in general, are based on four general types of evidence: direct observations in contact-period documents, analogy based on later ethnohistoric accounts and ethnographic observations; archaeology and paleobotany; and landscape vestiges of fields such as terraces walls and canals ([9], p.7-14). All, therefore, were mapped as unqualified instances rather than probable.

Doolittle [9] uses mainly square point symbol maps rather than polygons, except in a few cases such as Figure 5.17. Each point symbol indicates an instance of that type of agriculture based on documentary, archaeological, or ethnographic evidence. In other words, Doolittle [9] does not infer polygons from evidence that relates to a point location. Each point was therefore mapped as a polygon in order to make this source commensurable with Whitmore and Turner [10] so that all could be included on the same GIS layer and in the same attribute table.

3.2 Hunting, Fishing, and Gathering Land Use

The sixth GIS layer maps the most widespread land use: hunting, fishing, and gathering (Figure 10). People were hunting, fishing, and gathering in nearly all terrestrial areas, including lakes, coastal lagoons, islands, and so on. Hunting, fishing, and gathering would have taken place even in most agricultural areas, certainly in areas of shifting cultivation but also in areas of the most intensive agriculture, such as the *chinampas* of the Basin of Mexico [12, 16]. The polygon for this land use includes nearly the entire mainland and islands of Middle America. No adjustments for Holocene sea-level rise pertain because by 1500 CE it was near current mean seal level [17].

The only areas excluded from this land-use were a few of the small islands in the western Caribbean. People did not occupy the Cayman Islands, San Andrés, and Providencia until after Christopher Columbus encountered them during his fourth voyage [18]. In contrast, it is assumed that people reached the archipelago of tiny islands off the coast of northern South America—La Blanquillo, La Orchila, and Los Roques—via similar means and during the same period as they reached the Lesser Antilles between Puerto Rico and Tobago, beginning in approximately 3000 BCE ([19], p.45).

In addition, three other types of land were, generally, not used for hunting, fishing, and gathering: urban, extractive, and permanently glaciated areas. Hunting, fishing, and gathering would have taken place within urban areas to some degree, which might well have contained substantial vegetation cover in the form of house gardens and trees, but not to the degree of agricultural and other areas outside of major settlements. Similarly, extractive areas used to mine obsidian and permanently glaciated areas at the summits of the highest volcanic peaks would also have largely precluded hunting, fishing, and gathering. The polygons of the six urbanized areas, two extractive areas, and three permanently glaciated areas discussed in sections 3.3 and 3.5, respectively, were used to geoprocess holes in the hunting, fishing, and gathering polygon.

3.3 Urban and Extractive Land Use

The seventh GIS layer maps urban and extractive land uses (Figures 11-12). For urban land use, Smith [20] lists and analyses the cities of Middle America for 1500 CE. That source comprises a recent, rigorous analysis based on thorough literature review and direct measurement from maps of the population and area of urban centers in Mesoamerica, which stretches from central Mexico eastward to northern Central America. The rest of Middle America did not have settlements large enough to be called cities in 1500 CE. Instead, people lived in numerous villages, on the order of 20-50 houses and 1,000 to 2,000 inhabitants per village ([21], p.62; [22], p.69). The Late Postclassic period, which Smith defines as 1200-1520 CE, captures the urbanized land use for the target date of 1500 CE. Smith provides estimates for urbanized areas for every known archaeological site for Mesoamerica with an area of 10 ha or larger that also has at least one public stone building (typically a pyramid). The areas of each settlement are based on the density of the remains of buildings and houses as determined by surface survey and excavation.

Since 10 ha is insignificant for the resolution used for this project, only the six largest urban sites, each with total areas equal to or greater than 500 ha were mapped (Table 2). An area of 500 ha is approximately 8% the size of the grid cells of 8,000 meters by 8,000 meters (6,400 ha) used to judge the level of generalization appropriate for the project. In the table, "Epicenter area" refers to the central, thoroughly built-up area that contained pyramids, ball courts, and other large stone structures and earthen or paved plazas as well as the quarries used to extract the building stone and lime to build those structures. "Total area" refers to the epicenter plus the surrounding, lower density residential neighborhoods, which might well have contained substantial vegetation cover in the form of house gardens and trees. The largest impacted a total area of 2,100 ha. Even the two smallest of these urban centers directly impacted a total area of 500 ha. Below that 500 ha threshold, the areas of settlements falls off rapidly, with the next nine largest in Smith's "Size Class 1," which contains the largest 15, consisting of Texcoco, 450 ha; Mayapan, 420 ha; Huexotla 300 ha; Eronguaricuaro, 275 ha; Chalco, 250 ha; Otumba, 220 ha; Zempoala 220 ha; Acambaro, 215 ha; and Yautepec, 209 ha.

Table 2 Urban land-use areas in Middle America, 1500 CE.

Rank	Urban Center	Zone	Population	Total area (ha)	Epicenter area (ha)
1	Tututepec	Oaxaca	unknown	2,100	unknown
2	Tenochtitlan-Tlatelolco	Central Mexico	212,500	1,350	16.9
3	Zacapu	West Mexico	20,000	1,100	unknown
4	Tzintzuntzan	West Mexico	30,000	674	34.4
5	El Tigre	Gulf Coast	unknown	500	unknown
5	Santa Rita Corozal	Petén/Belize	7,000	500	unknown

For Tututepec, Joyce et al. [23] provide a large-scale map that was scanned and georeferenced. Once digitized, QGIS calculated the area of the multipart polygon for the Postclassic site to be 2,186 ha, which is close to the area of 2,100 ha that Smith lists.

For Tenochtitlan-Tlatelolco, Calnek [24] provides a large-scale map that was scanned and georeferenced. Once digitized, QGIS calculated the area of the polygon to be 1,256 ha, which is close to the area of 1,350 ha that Smith lists.

For Zacapu, none of the sources Smith [20] lists has a large-scale map [25, 26]. Pollard ([26], p.366), however, claims that the Zacapu site is "known as El Palacio" and had an "estimated occupation of the *malpaís* of 11 km^2 and upward of 20,000 people…, while the lake marsh below was abandoned." Another publication ([27], figure 8) provides a map of the Late Postclassic (1200-1450 CE) sites of those badlands as a group of point symbols. That map was scanned and georeferenced to digitize a polygon that encloses the eight sites most closely clustered on the *malpaís*. Once digitized, QGIS calculated the area of the polygon to be 1,033 ha, which is close to the area of 1,100 ha that Smith lists.

For Tzintzuntzan, Pollard [28] provides large-scale maps that were scanned and georeferenced. The three different types of residential areas and the epicenter as outlined on the maps were digitized, combined into a single contiguous polygon, and QGIS calculated the area to be 639 ha, which is close to the area of 674 ha that Smith lists. Note that in 1500 CE, the level of Lake Pátzcuaro was 15-19 m higher than in the 1990s, and that the Postclassic urbanized area would therefore have been closer to the shoreline than the present-day base map suggests ([28], p.66).

For El Tigre, Ochoa and Pacheco [29] provide a large-scale map of the epicenter only. The large stone pyramids of the epicenter are clearly visible on satellite imagery. A square polygon of 500 ha was digitized and centered on the epicenter.

For Santa Rita Corozal, Chase and Chase [30] provide large-scale maps that indicate 238 structures within 16 survey squares, each 25 ha in size. They state that the site was larger in the Postclassic but currently partially covered by the spread inland of the town of Corozal ([30], p.88). Each survey square is 25 ha, so the total survey area was 400 ha, without subtracting the area of water for the square that intersects the coastline. Chase and Chase ([30], p.67, 88) also give the area of the site as approximately 400 ha. In a later publication, Chase ([31], p.205) gives the area of the site as 503 ha: “Mapping has suggested that the most dense Late Postclassic occupation was in the 2.526 km^2 area in the center of Santa Rita Corozal; this was surrounded by an area of slightly lower density occupation (estimated 50% of the core) incorporating at least an additional 2.5 km^2 as well as pockets of settlement in other areas such as along the bay.” A polygon was digitized that covered their 16 survey squares as well as 5 more that extended their survey area to the coast at the present-day town of Corazol, removing those parts of any squares that extended past the shoreline. Once digitized, QGIS calculated the area of the polygon to be 510 ha, which is close to the area of 500 ha that Smith lists.

There were few areas equal to or greater than 500 ha of extractive land-use in Middle America in 1500 CE. Although metallurgy and metalworking were sophisticated in parts of the region, mines and placers for gold, jade, and other precious metals and stones were small in scale [32]. Mining and quarrying for salt, cinnabar, jade, clay, and other materials also impacted mainly small areas [33-35]. The quarries for limestone to use for building stone and processing into lime mortar and plaster were generally located within urban epicenters, near the pyramids and other structures under construction; and in Late Postclassic cities of the northern Yucatan Peninsula that were inhabited in 1500 CE, such as Cobá, quarries impacted areas of less than 10 ha [36]. Even for large Classic period (250-900 CE) sites such as Copan, which was built of tuff from a quarry about 2.5 km north the city, the area impacted by quarrying was only 25 ha ([37], p.17-18). Moreover, the largest quarries would presumably have been within the largest urban centers, and those with areas of 500 ha and more in 1500 CE have already been included in the GIS.

The only extractive areas that reached the 500-ha threshold in 1500 CE are areas of obsidian mining on the northeastern margin of the Basin of Mexico near Pachuca and Otmuba ([34], figure 2.2). They were characterized by pits, from 1-4 m in diameter and 0.5-10 m deep, with associated debris piles and workshop and residential structures, that extended over large areas, had been mined for millennia, and were the focus of intensive extraction in 1500 CE. Published maps of those obsidian mining areas and the descriptions of their boundaries in the accompanying texts were used to digitize two polygons over which open pits, debris piles, trenches, and shaft openings extended with variable density ([38], p.11-12, figure 1; [34], p.41-47, 55-59, figure 2.75).

3.4 Pastoral Land Use

The eighth GIS layer maps pastoral land use (Figures 13-14). In 1493, the second voyage of Christopher Columbus introduced the first livestock into Middle America [21]. They consisted of cattle, horses, pigs, sheep, and goats that were largely restricted to the island of Hispaniola until introduction to the other Greater Antilles early in the sixteenth century: Puerto Rico in 1505, Jamaica in 1509, and Cuba in 1511 ([39]; [13], p.12; [40]). That said, the Spaniards habitually introduced livestock to islands even when not establishing a formal settlement, allowing them to run feral to provide a source of food for future colonization attempts. Since many such casual introductions have left no documentary trace, small numbers of livestock might have been present on other Caribbean islands besides Hispaniola by 1500 CE but are not mapped.

The livestock introduced on Hispaniola had greatly multiplied by 1500 CE. The populations of pigs and cattle grew prodigiously, those of goats, sheep, and horses more modestly ([22], p.89-90, 104-105). The growing herds roamed the savannas of the Vega Real, the fertile valley of the Río Yaque

([41], p.66-72). How many of each species and the extent of their grazing remains unknown, but they moved and bred freely on an open range, with a report by 1498 of at least one herd of 350 pigs ([42], p.74-76).

The Nature Conservancy's 1:500,000 map of the vegetation of the Dominican Republic provides the basis for mapping the probable area those livestock grazed [43]. A polygon was digitized to include all land cover in the valley of the Río Yaque classified as "Grassland (pastures)," "Rice grassland," "Sugar cane grassland," and "Mixed planted/Cultivated crops." The polygon also includes urban areas and other small areas of various land covers surrounded by the pastoral and agricultural land covers. That polygon of 3,271 km^2, therefore, imprecisely maps the savannas the Spaniards describe in the late fifteenth century and early sixteenth century as the major area of pastoral land use.

3.5 No Land Use

The ninth GIS layer maps polygons with no land use (Figures 15-16). By 1500 CE people occupied and used, to one degree or another, all parts of Middle America except some Caribbean islands and glaciated areas on the mainland. Some small islands far off the coast of Caribbean Central America were not occupied in 1500 CE. By 8000 BP, people had occupied islands such as Trinidad, Margarita, and Tobago that lay just offshore of the South American mainland ([19], p.39). The earliest evidence of occupation the Greater Antilles comes from Hispaniola and dates to between 4510 BCE and 4350 BCE ([19], p.27). The earliest evidence of occupation of the Lesser Antilles dates to approximately 3000 BCE ([19], p.45). The archipelago of tiny islands 100 and more kilometers off the coast of northern South America—La Blanquilla, La Orchila, and Los Roques—are assumed to have been occupied during the same period as the Lesser Antilles, well before 1500 CE. Only a few small islands in the western Caribbean were not occupied in 1500 CE. The three Cayman Islands were uninhabited until after Christopher Columbus encountered them in 1503, during his fourth voyage [18]. San Andrés and Providencia, about 200 km off the Caribbean coast of Central America, are also assumed to have been uninhabited until after Christopher Columbus encountered them, in 1502.

There are currently no glaciated areas in Middle America except for three volcanic peaks in Central Mexico that rise to over 5,000 m: Citlaltépetl (Pico de Orizaba), Popocatépetl, and Iztaccíhuatl. As measured in the mid-twentieth century, each peak had a small area covered by glaciers (ice and firn fields): Citlaltépetl, 950 ha; Popocatépetl, 72 ha; Iztaccíhuatl, 122 ha [44]. White [44] provides large-scale maps of the extent of that mid-twentieth-century glaciation for each of the three peaks. The maps show that the termini of the glaciers reached down to approximately 4,700 m at that time. Since the mid-twentieth century, those glaciers have been retreating upslope and decreasing in area [45].

The areas glaciated in 1500 CE are not easily derived from the published studies. Vázquez-Selem and Heine [46] determined, on the basis of relict moraines and other features, that the mean altitude of glacier termini for Iztaccíhuatl during what they term the Ayoloco advance (1300-1850 CE), to have been approximately 4,500 m, roughly 200 m lower than in the mid-twentieth century. During the warmer Holocene Climate Optimum (9,000-5,000 BP) and the Medieval Climate Optimum (950-1250 CE), the glaciers were likely much smaller, similar to the mid-twentieth century, with the termini at a mean elevation of about 4,700 m, or even smaller, as they are at present. In addition, during the Little Ice Age as well as during the Neoglacial (5,000-1,000 BP) that occurred between the Holocene Climate Optimum and the Medieval Climate Optimum, small glaciers might have formed on lower peaks, in the 4,000-5,000 m range, such as La Malinche, Cerro Ajusco, and Nevado de Toluca [44, 46]. And many more peaks, of course, display evidence of glaciation during the ice ages of the Pleistocene epoch that preceded the Holocene epoch during the Quaternary period.

For the 1500 CE map, the extent of glaciation is based on the following calculations (Table 3). Two peaks are well enough studied that maps of glaciation based on moraines and other features that date to that period are published. Vázquez-Selem and Heine [46] provide a map of the Ayoloco advance for Iztaccíhuatl. Palacios and Vazquez-Selem [47] provide a similar map for Citlaltépetl. Those maps were scanned and georeferenced, and polygons of the glaciated areas were digitized. The area of the polygons is 613 ha for Citlaltépetl and 928 ha for Iztaccíhuatl. Since Popocatépetl lacks such studies another approach was used, assuming that since the glaciation on Iztaccíhuatl covered much of the peak above 4,500 m during the Little Ice Age, Popocatépetl would have been glaciated to a similar elevation. A polygon covering the area above 4,500 m was created from the elevation shapefile of a 1: 50,000 topographic map downloaded from www.inegi.org.mx (E14-B42, Huejotzingo [48]). The 4,500 m contour was extracted and the area it encompasses measured to be 1,081 ha, probably a gross overestimate of the glaciated area for the little Ice Age because glaciation depends on many other factors besides temperature and elevation, such as precipitation and slope, but it serves as the best estimate currently available. The glaciation polygons for Citlaltépetl, Iztaccíhuatl, and Popocatépetl are therefore all larger than the 500-ha threshold and were added to the No Land Use layer in the GIS. Note that the polygons of perpetual snow for the 1:50,000 shapefiles that cover Citlaltépetl, Iztaccíhuatl, and Popocatépetl (E14-B46, Coscomatepec, 2014; E14-B42, Huejotzingo, [48]) grossly overestimate the glaciated areas, possibly because they derive from SPOT imagery of January 1, 2011, when snow would have covered those peaks far lower than the glaciated areas.

Table 3 Areas of glaciated land cover in Middle America, 1500 CE.

Volcanic Peak	Glaciated Area (ha)	Source
Citlaltépetl	613	Palacios and Vazquez-Salem [47]
Popocatépetl	1,081	1:50,000, E14-B42, Huejotzingo [48]
Iztaccíhuatl	928	Vázquez-Selem and Heine [46]
Nevado de Toluca	<82	1:50,000, E14-A47, Volcán Nevado de Toluca, 2015
La Malinche	<1.5	1:50,000, E14-B43, Puebla, 2015

In addition, two additional peaks were analyzed to consider whether they might have supported areas greater than 500 ha during the Little Ice Age: Nevado de Toluca and La Malinche. Both are located in the same general area as Citlaltépetl, Iztaccíhuatl, and Popocatépetl but lack the same sort of detailed glaciological studies. Nevado de Toluca and La Malinche have summits higher than 4,500 m, which the studies that do exist suggest was the mean elevation of the termini of glaciers during the Little Ice Age, compared to 4,700 m by the mid-twentieth century. The areas above the 4,500 m elevation contour for both peaks failed to reach the 500-ha threshold, however, and the Nevado de Toluca and La Malinche summit areas were not added to this final GIS layer.

4. Conclusions

This project has demonstrated how to use existing syntheses of many decades of historical social science research to produce land-use maps in a GIS for large regions for a specific target year at a resolution appropriate to the calibration of existing ALCC models. A similar procedure has been used to produce land-use maps in a GIS for the 6000 BP and 1850 CE target years defined for the larger, LandCover6k project at the 2016 meeting in Utrecht, The Netherlands.

While others could replicate this project but for other global regions and target years, the LandCover6k working group has just published a new land-use classification system that needs to be incorporated into any such reconstructions. The new classification has the capacity to incorporate diverse land uses over the past six millennia [49]. The original five top-level categories remain: no land use; agriculture; hunting, fishing, and gathering; pastoralism; and urban and extractive. The new classification, however, adds a sixth top-level category: extensive/minimal land use. And, for the first time, the classification adds standard subcategories and, in the case of agriculture, a third level of subcategories.

That new land-use classification will require some revisions to the Middle America, 1500 CE land-use GIS. For example, the wetland cultivation subcategory of agriculture would be renamed wet cultivation, and the two types of wetland cultivation, intensive wetland fields and recessional cultivation, would become its subcategories, raised fields/*chinampas* and wetland cultivation. Beyond such revisions to naming, labelling, and perhaps ordering of layers, some polygons would need to be divided into distinct areas that accord with new subcategories, for example, the two new urban subcategories of dense settlement and dispersed urban/peri urban.

The continuing formalization of LandCover6k methods also defines five target years: 6000 BP (circa 4000 BCE), 3000 BP (circa 1000 BCE), 1000 BP (circa 1000 CE), 1500 CE, and 1850 CE. Since the Middle America GIS thus far contains layers only for 6000 BP, 1500 CE, and 1850 CE, additional layers for 1000 BCE and 1000 CE will need to be developed.

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Competing Interests

The authors have declared that no competing interests exist.

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