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Analysis of land use by Maya civilization: Settlements patterns at El Pilar archeological site

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CONSERVATOIRE NATIONAL DES ARTS ET METIERS
ECOLE SUPERIEURE DES GEOMETRES ET TOPOGRAPHES

THESIS

submitted in order to obtain

le DIPLOME D'INGENIEUR CNAM

SPECIALTY: Surveyor and Topographer

by

Enora TANGUY

Analysis of land use by Maya civilization:
Settlements patterns at El Pilar archeological site

Defended on 31 August 2023

JURY

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President of jury
Internship supervisor
Referring teacher.

Thanks

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List of acronyms and abbreviations

AP: Appendix

DEM: Digital Elevation Model (MNT in French)

IF: Individual Features

ISBER: Institute of Social Behavioral and Economic Research

IUSS: International Union of Soil Sciences

LA: Large Architecture

LI: Labor Investment

LiDAR: Light Detection and Ranging

MARC: MesoAmerican Research Center

GIS: Geographic Information System

PRU: Primary Residential Unit

RU: Residential Unit

SRU: Secondary Residential Unit

UA: Unified Architecture

UCSB: University of California, Santa Barbara

UTM: Universal Transverse Mercator

WRB: World Reference Base for Soil Resources

Glossary

Berms, plazas, and terraces: the land modifications implemented by the Maya.

GIS: « It is a system that creates, manages, analyzes, and maps all types of data. GIS connects data to a map, integrating location data (where things are) with all types of descriptive information (what things are like there). »¹

Labor Investment: « Labor investment, measured in labor-days, represents time devoted to gathering resources for and constructing perishable structures (Ford and Clarke 2016; accord Arnold and Ford 1980; Erasmus 1965). » (FORD A., TRAN J. 2023)

LiDAR: LiDAR is a remote sensing technique based on pulsed light technology that uses round-trip time of laser to obtain distance from Earth. The interest of LiDAR is that it penetrates through canopy. At output, we obtain a cloud of points.

Metadata: « Metadata is information that describes an item. »² It can also describe a dataset, particularly GIS data.

Milpa: « Milpa system is a traditional multi-crop system of regional vegetables. Present day Maya farmers cultivate this system through practice of slash and burn together that cycles form small plots of maize and other vegetable crops such as chiles, beans, and squash to perennials for animal habitat, fruits, and construction. Maya Milpa entails a rotation of annual crops with a series of managed and enriched intermediate stages of short-term perennial shrubs and trees, culminating in re-establishment of mature closed forest on once-cultivated parcel. »³

Mounds: « In the case of Maya archaeology, they are remains of collapsed ancient Maya buildings on themselves. » (Personal communication with Anabel FORD)

Raster: « Composed of a matrix of pixels arranged in rows and columns to form a grid, a raster image can represent, with relative accuracy, a set of information. Raster can have several origins, digital aerial photographs or satellite and digital images. »⁴

Shapefile: A shapefile is a simple, nontopological format for storing geometric location and attribute information of geographic features.⁵

¹ ESRI. What is a GIS?

² ESRI. Metadata

³ MESO AMERICAN RESEARCH CENTER. Milpa Cycle. Reformulated by AF.

⁴ Translation, ESRI France. Les rasters.

⁵ ArcGIS Desktop. What is a shapefile?

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Introduction

It is undeniable that if Maya settled in regions of lowland Mesoamerica, it is because there was a possibility of living and thus of cultivating ground. With Western processes, however, these regions appear difficult to exploit. This is why sustainable approach of ancient Maya civilization offers a promising alternative to explore. Indeed, this Mesoamerican people had a unique way of working land, through a cycle called the Milpa Forest-Garden. As a result, rotation of crops and exploitation of forests allowed the Maya to maintain productivity of soil for centuries. This method and other factors certainly influenced location of dwellings, thus settlement patterns. These will be explored in this thesis.

The remains structures we study, mounds on the landscape, were previously built in Late Classic Era, which spans from 500 to 900 CE. This period represents height of Maya civilization. During this time, landscape was dotted with a multitude of buildings, including residences, temples, and plazas. Archaeologists are studying these structures to better understand the growth of the Maya civilization, and also to determine reasons for its decline.

El Pilar, archeological site of 20.4 km², binds the study area. It is located in bi-national park "El Pilar" of Belize and Guatemala, in lowlands of Mesoamerica as shown in Figure 1. A geographical region of low relief extends from south of Mexico to Honduras.

This site is special. Indeed, contrary to majority of tourist Maya sites, it is not exposed to various external alterations like rays of sun or rain episodes. Plants are conserved, they are not cut or uprooted. This allows the site to remain intact as it was found. Investigation consists, therefore, of GPS surveys, of features that can be seen under the canopy.

Figure 1: El Pilar Archaeological Reserve for Maya Flora and Fauna spans two countries



Prior to use of LiDAR at El Pilar, locations of Maya archeological sites were predicted with GIS. The first predictive model of Maya settlements was initiated at 1:50k scale (FORD AND CLARKE 2002; see SIRJEAN E, 2003). This model uses data on drainage, fertility, and slope. It was created using weight of evidence method, which is a statistical method for combining and weighting information to support a hypothesis. Several versions of this model have been further developed (MONTHUS. F, 2004, MERLET. S, 2009). The final predictive model demonstrated significant reliability (Ford et al. 2009)

In 2012, the El Pilar LiDAR coverage was flown and with this new technology a new view of El Pilar emerged. Thanks to LiDAR, the topography and large features were visible. By performing specific processing, the visualization of “Bonemap” created a view that accentuated architecture by a classification of point cloud (Pingel et al. 2015).

It is the hypothesis of the archaeology that, since agriculture is paramount in an agrarian society, civic centers, such as El Pilar, develop where people are and where they cultivate. As a result, it is suggested that Maya society developed around cultivable land.

As it is written in the book of FORD. A. and NIGH. R. (2015), “We base the investigations on archaeological and ethnological observations, field data collection, and interdisciplinary scrutiny”. Indeed, cultivable land should influence where residential structures of the farmers locate. Archaeological considerations can include architecture, social aspects such as labor investment, and population dynamics, as well as environmental data encompassing detailed topography, fertility, and drainage. All these data in the case of El Pilar are geographically referenced using the UTM 16N coordinate system. These attributes enable us to examine and analyze the land use patterns of the Maya during the Late Classic period, specifically focusing on the location of residential settlement sites at El Pilar.

First, we look at the data that are of interest to our study and how they were obtained. The aim is to validate and understand the data. In second part, we imagine and test hypotheses about social factors that could governed organization of Maya society. Finally, in last part, we combine the environmental data and the Maya structures to analyze them and obtain an explanation of Maya land use.

I Features that govern Maya organization

There are numerous Maya structures of interest at El Pilar which “are embedded within forest structure.” (FORD. A. NIGH. R., 2015). Structures playing a vital role in everyday lives of majority of Maya society are identified to define settlement patterns.

Subsequently, we examine the degree to which LiDAR proves valuable in identifying Maya features, as well as the topography of the area obtained through LiDAR. Since the ancient cultivation sites are no longer clearly visible at the archeological site of El Pilar, we develop a means of identifying potential areas. By developing information about areas dedicated to culture in Maya society, we can define cultivable land. Lastly, we analyze the recent map that focuses on soil-related aspects such as drainage and fertility.

I.1 Exploring land use through selected structures

I.1.1 Large Architecture

Some buildings stand out by their “Large architecture with plazas, palaces and temples”. (FORD. A. 2023). They are the civic remains of temples, palaces and platforms that are the remains of public civic structures. These large and prominent features are distinguished from small architecture features that are considered the remains of domestic structures, there are named “mound”.

I.1.2 Assessing Residential or Domestic Remains

Residential units are all those mapped mounds that are the remains of small and assumed domestic, as opposed to large and civic architecture. One of these large and small remains are shown in Figure 2. Mounds vary in size, height, dimensions, configurations, and groupings. These factors impact the assessment of the role of these features in these analyses. Mounded remains mapped in the field at El Pilar were constructed with limestone foundations and perishable superstructures. There will be further explanation about the type of construction of Maya structures that will be considered in the thesis of MORIAN.N (2023)

Figure 2: Mounds at El Pilar, major archaeological features



Source: ISBER/MARC, UCSB, June 22, 2023.

Most common building remains in the field are small mounds as shown in Figure 2. They vary in characteristics and may serve a variety of purposes. That is why they are

classified into three categories: Primary Residential Unit (PRU), Secondary Residential Unit (SRU) and Solitary Range Structure (SRS).

This classification is created « by evaluating several criteria: structure dimensions (diagonal length and height), structure counts within a group, plaza (raised platform) presence, and labor investment (LI) values (Ford and Clarke 2016). » (FORD A., TRAN J. 2023). PRU and SRU are explained in this part, whereas SRS are developed in part II.2.2. The definitions are statistically verified.⁶

Various approaches can be taken when representing mound in the final map, as polylines or points. A mound is drawn by several polylines, which is not conducive to calculations or understanding during analysis. For example, a line could be found on two types of soil, making it impossible to tell which soil the structure was on. That is why we decide to represent mound as point in our analysis.

I.1.2.1 Primary Residential Unit

A Primary Residential Unit, or PRU. are autonomous structural units consisting of mounds combined with other elements such as plazas that constitute primary living quarters of the ancient Maya. PRU “are defined as household groups often comprising at least two elements, structures/plazas as per traditional farming household » (TRAN J. FORD A. 2023). A PRU can be a feature that is more than one mound in a group with Labor Investment is greater than to 500. It can also be a single mound on plaza or a single mound with a height greater than one meter and diagonal less than or equal to nine meters (HORN S W III., TRAN J. FORD A. 2023). In total, within boundaries of El Pilar, there are 726 PRUs.

I.1.2.2 Secondary Residential Unit and Chultun

SRU « represent secondary residences that may have served as ancillary structures and agricultural storage in peripheral areas (Zetina Gutiérrez 2007). » Nobody live year-round in SRU, they « are not included in population [estimates]. » (FORD A., TRAN J. 2023). SRU may have been for storage and as such may have had a similar role as chultuns, storage facility excavated underground. Chultuns are features recorded in the field that have a maximum opening in the limestone bedrock of one meter and were covered by a circular stone that is sometimes visible. Due to their location and size,

⁶ Appendix 1

chultuns are not detected by LiDAR (SIMON.P, 2022). In total, within boundaries of El Pilar, there are 567 storage facility of which 405 SRUs and 162 chultuns.

I.1.3 Gathering natural resources

I.1.3.1 Aguadas and Depressions

Like chultuns, aguadas and depressions are mainly discovered during field survey. In total, within boundaries of El Pilar, there are 186 water reserves of which 29 aguadas and 157 depressions. According to Sirjean thesis in 2003, “Aguadas and Depressions are water reservoirs built to collect rainwater.” Even as they have the same purpose, their different names can be explained by their water surface area. Indeed, the surface is smaller for a depression than for an aguada.

To validate the definition of depressions and aguadas, it is essential to use the "Minimum bounding geometry" tool in ArcGIS. This tool helps in enclosing aguadas and depressions which are not a closed polygon. This ArcGIS tool for closing aguadas and depressions is very useful but may not correspond to reality on the field and thus is an approximation.

We expect to observe a surface area smaller for depression than for aguadas, however, this does not hold true for all the data. Consequently, the definition cannot be considered absolutely, as it is not verified across the entirety of the dataset. It would be worth revisiting the use of depression and aguada to insure the validity of the definition. When the average area, however, is considered, we find that the differences are marked: 431m² for aguadas and 70m² for depressions. The definition is, therefore, holds by considering the complete dataset.

Several factors can explain that the definition does not match exactly to maps. Each person mapping seems to have a different size limit in defining what is an aguada or a depression. It may be that observed depth impacted the identification, yet it is not possible to classify aguadas and depressions by volume, because data concerning depth of aguadas and depressions has not been systematically recorded. As a result, this imperfect definition will not be considered in the following analysis. Aguadas and depressions play comparable role as water reservoirs. They are therefore considered as a single entity, we call aguada.

I.1.3.2 Quarries

Quarries “were their source of stones and materials to build their buildings. Linear in shape, the traces of human work can still be seen in the form of large, worked boulders.”

(MORDANT. G. 2014). There are also quarries of hard stone materials for chert of flint tool making. We look at their location at El Pilar in Part 3.

I.2 The importance of LiDAR at El Pilar

I.2.1 The method to survey

Initially, LiDAR seems to be a valuable tool for locating Maya structures, but this proposal requires validation. To analyze the usefulness of LiDAR data, we need to understand its role in our database. El Pilar database is made up of several data sets that are tables⁷. They are fully completed with the last field survey in 2023⁸. We will explain how the database containing the Maya structures was created at El Pilar.

Firstly, processing was carried out on LiDAR data from El Pilar to create visualizations. Based on the visualizations, the laboratory team set about to isolate features that would be relevant to validate in the field. This dataset named "Origin Go To," with point shapefiles, details locations of possible archaeological sites. This point source provides the destinations in the field. The field team uses these "GoTo" points to navigate to areas marked in "Origin Go To" table for survey areas. As LiDAR visualizations are an image of the possibilities, and may not show all features, the surveys "sweep" the areas to make sure no feature is overlooked. Once the field data are gathered, the new data are compiled into the "Go To Concordance" table with attributes about the validation of LiDAR predictions and new features discovered⁹. Then, each structure is drawn and classify in the table "Individual Features," (IF). They are assembled to create groups in the final table "Unified Architecture," (UA). For example, several mounds in data set on "Individual Feature" that will be equal to one PRU in dataset "Unified Architecture".

I.2.2 LiDAR, such a significant asset?

Most articles indicate that LiDAR "has revolutionized the understanding of spatial dynamics of ancient Maya" (CHASE A F. et. al. 2014). Maya settlement analyze is based on all residential units and other elements such as chultuns, aguadas and quarries. LiDAR processing, however, does not uncover all archaeological features. We want to know how useful LiDAR is at El Pilar.

⁷ Appendix 2

⁸ Appendix 3

⁹ Appendix 4

For statistical purposes, the "Go To Concordance" table contains the necessary data. Each structure is defined by its Origin_GT and A_OR_R attributes, explained in the Table 1. Each attribute is defined by different values, but only two for each of them are used (Origin_GT = 0 or 1; A_OR_R = A or R).

Table 1 : Useful attributes to define LiDAR asset

	Origin_GT		A_OR_R	
Explanation	Was field GoTo point predicted in Origin GoTo file?		Did the GoTo point exist in field?	
Values	0	Point discovered in field survey (not predicted in Go To file).	A	Point is Accepted, it exists in field.
	1	This point is predicted by LiDAR in Go To file.	R	Point is Rejected, it does not exist in field.

Source: ISBER/MARC, UCSB, June 22, 2023.

Then, each Maya architectural structures is classified whether it came from LiDAR or from field survey in Table 2.

Table 2 : How many of accepted points are from LiDAR or field surveys?

	Accepted Points (A_OR_R = A)	Percentage
Field (Origin_GT = 0)	1 838	77.16
LiDAR (Origin_GT = 1)	544	22.84
Total	2 382	100

Personal source: data ISBER/MARC, UCSB, June 22, 2023.

The result of Table 2 indicates that most of accepted field points are not found thanks to LiDAR but in field survey. While the LiDAR visualized the topography in detail and represents geographic features with great accuracy, it is not reliable in identifying all archaeological features. The effectiveness of LiDAR in locating archaeological elements at El Pilar is therefore questioned. Another significant statistic is proportion of Accepted or Rejected points among LiDAR data calculated in Table 3.

Table 3 : How many points are accepted or rejected from LiDAR data?

A_OR_R	LiDAR (Origin_GT = 1)	Percentage
Accepted Points (A_OR_R = A)	544	57.38
Rejected Points (A_OR_R = R)	404	42.62
Total	948	100

Personal source: data ISBER/MARC, UCSB, June 22, 2023.

Table 3 suggest that, where LiDAR GoTo points are present in the dataset, 57.38% accepted. This is not an impressive percentage. One would have expected much better results. These results can be qualified. Indeed, the taller and the more imposing the element

is, the more likely it is to be identified with the LiDAR visualization¹⁰. Some of the Large Architecture had already been discovered when first LiDAR images became available for El Pilar. Nevertheless, LiDAR enabled identification other locations of a Large Architecture, such as the Citadel and E-group. At El Pilar, LiDAR is, therefore, useful for discovery of large architectural elements of significant size such as temples and other civic buildings.

I.2.3 The Detailed Topography by means of LiDAR

Given that most large-scale architectures have already been discovered, the question arises as how to take advantage of LiDAR at El Pilar. The DEM map derived from LiDAR, corresponds to a detailed topographic visualization. Vegetation or human constructions are therefore not always represented. Valuable statistical information regarding the distribution and positioning of settlements can be inferred from this representation of the geography. It is a raster image from which we can easily get slope and differences in elevation. It is necessary to rework the DEM with the “surface parameters” tool to obtain sun exposure or slope¹¹ over the area.

I.2.3.1 Elevation and Slope

Since the development of Maya society over 3,000 years ago, various alterations have occurred in most soils, resulting from processes of erosion or sediment accumulation. Despite the present-day variation in the site's configuration, the modifications made by the Maya civilization to the terrain persist, evident through the presence of mapped features identified at El Pilar including berms, plazas, and terraces.

The aim of this thesis is to determine which areas are suitable for cultivation and construction of structures. From the DEM map, two crucial pieces of information are derived: elevation and slope.

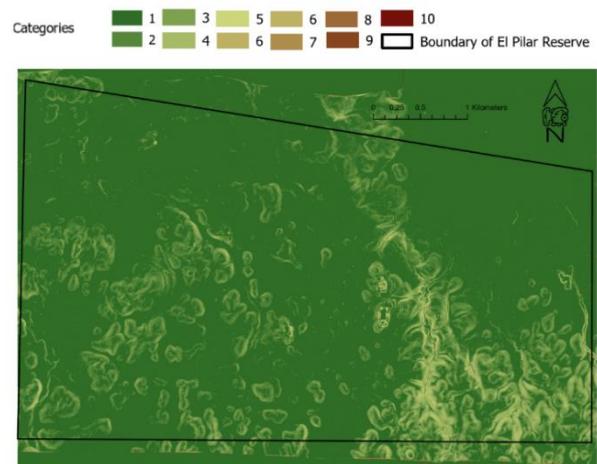
At El Pilar, the variation in elevation is not dramatic. Areas in the southeast are precipitous while in the north they are slight. These differences impact on crop growth and the positioning of architecture. Slope plays a crucial role in determining drainage patterns, which directly affect the suitability of land for cultivation. The primary interest, therefore, lies in examining the slope of the terrain.

¹⁰ Appendix 5

¹¹ Appendix 6

Elevation and slope cells are reclassified (tool: reclassify) into 10 distinct classes using equal intervals.¹² Figure 3 shows the map once the slope is classified, the range spans from 1, which denotes flat terrain, to 10, which indicates extremely steep slopes. These intervals are used in Part 3 to determine in which location are the features. They also allow to visualize that elevation is different from the slope.¹³

Figure 3: Slope, data derived from LiDAR

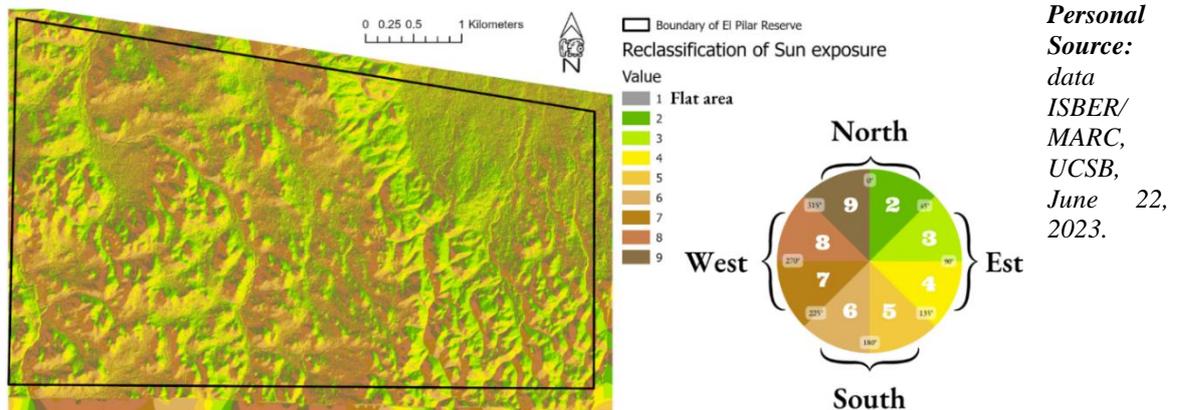


Source: ISBER/MARC, UCSB, June 22, 2023.

I.2.3.2 Sun exposure

The reclassification process for the sun exposure uses “manual interval”. Each cell is assigned to one of nine categories, signifying various orientations as shown with the circle at the right of the map in Figure 4. It is necessary to understand that the degree here is linked to the orientation of the slope to the sun and has not a relationship with the slope. The category 1 equals a flat area, thus, with no orientation to the sun. Then, the categories move by degrees and increase in 45-degree intervals. Finally, we use the categories that will have been assembled by 2 to obtain the 4 cardinal points, as shown with the circle in Figure 4. This information will be valuable in determining the orientation of slopes where the Maya structures were situated in Part 3.

Figure 4: Sun exposure, data derived from LiDAR



Personal Source: data ISBER/MARC, UCSB, June 22, 2023.

Legend: Each number of the legend is explained with the orientation circle at the right of the map.

¹² Appendix 6

¹³ Appendix 6

I.3 A well-organized forest landscapes

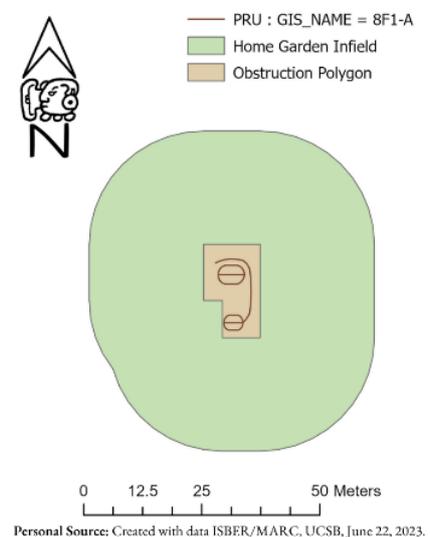
I.3.1 The importance of cultivation

Having gained an understanding of origins of structures and topography at El Pilar, the curiosity extends to surrounding environment encompassing these elements and, consequently, cultivation practices that may have been employed. Maya have a “intimate relationship to their environment” (FORD A., NIGH R. 2015). To study settlement patterns, it is necessary to understand their way of life, so, their cultivation.

I.3.2 Home-garden infield

The so-called home-garden infield is a cultivated area surrounding a PRU and intended to be an intensive area of resources to resolve subsistence needs. As shown in Figure 5, the home-garden infield is represented by a general buffer of c.24-meters extending around each PRU. The total area of infield at El Pilar is c.4000m². It has been fixed by FEDICK.S (1992). Out of the entire surface area of El Pilar, the infield accounts for 12.74%. There is more information about infield and their calculation in the book of FORD A. and NIGH R. (2015).

Figure 5: Home-garden infield



Personal Source: Created with data ISBER/MARC, UCSB, June 22, 2023.

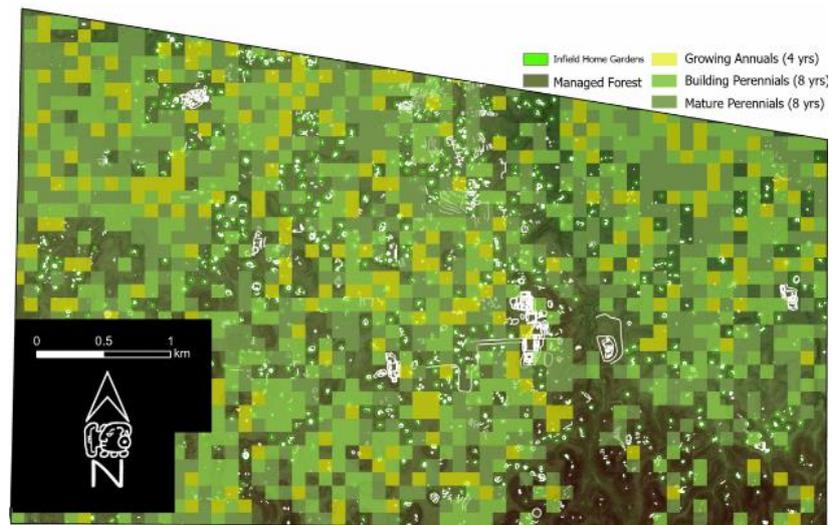
I.3.3 Milpa Cycle

“Settlement at El Pilar more likely reflects that of a population integrating numerous forest gardens into an agro-urban landscape” (HORN S. III, FORD.A. MORALES.P. 2020) Settlement patterns are, therefore, driven by Milpa cycle, a sustainable forest gardening asynchronous landscape cycle¹⁴. Horn III, Tran and Ford have devised a model of how this cycle may be envisioned at El Pilar. The total surface area of Milpa field is determined by subtracting from the overall surface area of El Pilar: slopes greater than 15%, areas occupied by all architecture, and infield areas. This model is based on the alternation of land between 3 periods that make up the Milpa-forest garden cycle.

¹⁴ Appendix 7

The depicted model can be observed in Figure 6, exhibiting variations on an annual basis. The displayed map represents a single year of a 20-year cycle. The population scenario used by Maya archaeologists assumes an average of 5 people per PRU. It is explained

Figure 6: Milpa Cycle, cultivation at core of land use at El Pilar



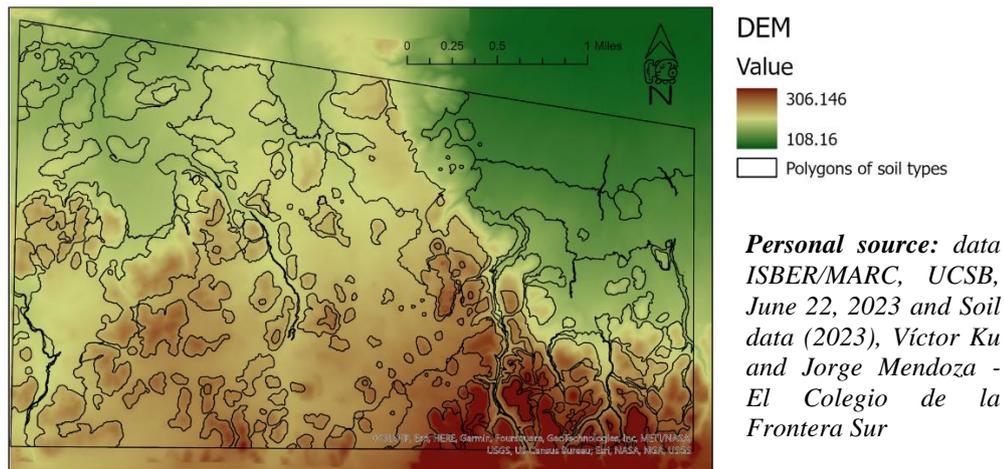
in more detail in presentations of *Source: data ISBER/MARC, UCSB, June 22, 2023.* Horn III, Tran and Ford in 2023. The Milpa Forest-Garden cycle is structured at El Pilar to occupy 64.71% of the entire area (Percentage calculated thanks to Justin Tran). As the rotation of croplands implies a certain way of occupying space, Maya society could develop cultivable lands where Milpa forest garden are located. With this model, we already know which soils are likely to be dedicated to cultivation, so we can look for the most suitable among them.

I.4 Cultivable Soil

I.4.1 The methodology behind Soil Map at El Pilar

Building on S. FEDICK previous work in 1992, a team led by Jorge Mendoza of ECOSUR Campeche Mexico worked on a new detailed soil map at a scale of 1:10 000. This new map is constructed using data such as topography and vegetation. (Project Summary, 2020). When we look at the Figure 7, the black line which delimit the area of the soil polygons seems follow the limit of the value of topography. To ensure accuracy and reliability of this new map, field samples are taken approximately every 30 hectares in the reserve. This process validates the correspondence between the actual samples and the mapping data, as well as to add characteristics.

Figure 7: The consistency between topography and soil types



I.4.2 Many characteristics to classify

The soil map includes many parameters. Thanks to these attributes and Soil Productivity Index, the soil team classified the soil into 5 classes described in Table 4. “A framework for land evaluation” of FAO in 1976 and “Towards a revised framework” of FAO in 2007 are used to create the soil classification of soils of El Pilar in 2023. Both are designed for evaluating a conventional cropping system and are preliminary assessments for El Pilar as the traditional systems of the Milpa cycle are not accounted for properly (Personal communication with Jorge Mendoza Vega)

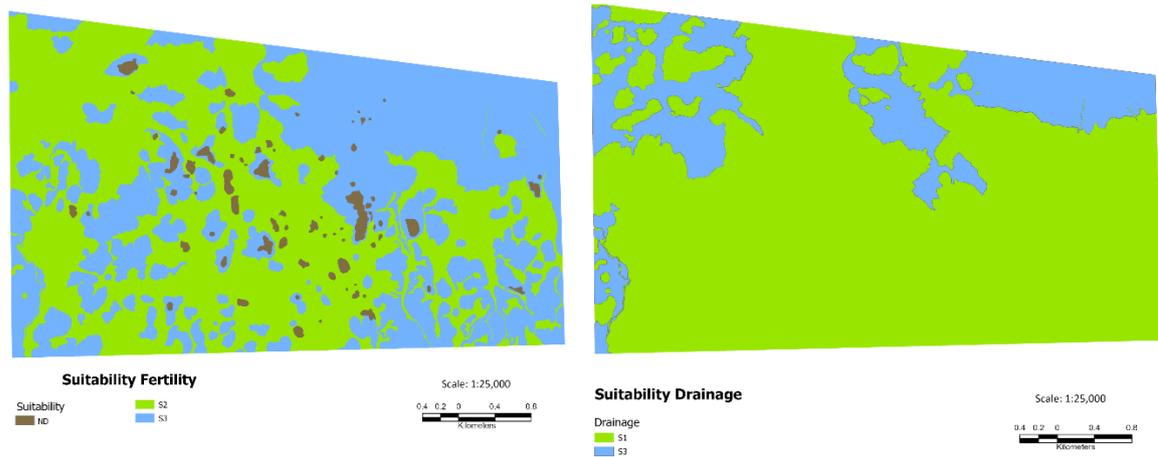
Table 4: 5 Classes of Soil Productivity

S1	S2	S3	N1	N2
Highly Suitable	Moderately Suitable	Marginally Suitable	Currently Not Suitable	Permanently Not Suitable

Source: Soil data (2023), Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur

Of these classes, the two maps of Figure 8 were established concerning soil fertility and drainage. “Fertility is a complex soil property determined by amount and availability of many essential nutrients and trace elements. Factors considered in assessing fertility include cation exchange capacity, base saturation, percent organic matter, available phosphorus, and pH” (FEDICK SL. 1995). The second characteristic is the drainage of soil, which affected «Aerobic respiration in roots” (FEDICK SL. 1995). Indeed, “Inadequate drainage prevents development of root system, decreases yield of plants, and may lead to death of roots. Less than well-drained soils are characterized by faint to well-developed mottling in profile. Excessive drainage is also a limiting factor due to loss of moisture.” (FEDICK SL. 1995). These two characteristics help to determine which location are better for cultivation.

Figure 8: Fertility and drainage map



Legend: Table 4 Colors

Source: Soil data (2023), Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur

I.4.3 Rethinking classification

Soils poorly or well suited to agriculture has the potential to explain aspect of land use. Fortunately, most of El Pilar's soils are of good quality. The classification of fertility and drainage is based on FAO. It is a standard established for soil from a western point of view. Maya Milpa system cannot be compared to a conventional cropping system. (Personal communication with Jorge Mendoza Vega) The classification is valuable while not adapted to the traditional land use described for the site of El Pilar. It will still be tested in Part 3. There are many additional parameters for evaluating soil potential for food production these will be considered by the soil team lead by Mendoza. We will take a closer look to the field soil types.

In this field describing soil types at El Pilar, there are seven different soil types. Each name of soil types consists of the soil group name and a primary qualifier, determine with the soil composition. The name and qualification of each soil came from the results of the IUSS WRB working group in 2015. Some soil types are suitable for cultivation, and some are not. We therefore suggest that these seven different soils enable us to draw conclusions about the location of the various elements.¹⁵

The Primary Residential Unit, the living quarters of Maya society, and environmental parameters that could play a role are now identified. We can turn to social aspects.

¹⁵ Appendix 8 and 9

II Social factors influenced land use

There are many articles on the social, political, and economic organization of the population in Maya cities. Some work has already been done on the organization of El Pilar. According to HORN S. III, FORD.A. and MORALES.P. (2020), there are " very few well-defined settlement clusters that conform to the expectations of neighborhoods". This is, therefore, not the preferred model at El Pilar. This study focuses on another aspect: the organization of the different population classes in El Pilar.

II.1 Property and Social Organization at El Pilar

II.1.1 Common spaces, a specific characteristic of Maya world

One parameter to be considered before analyzing environmental factors is settlement dynamics defined by Maya society. The appropriation of land, and more particularly property, must have been organized and governed. Firstly, as Hunt (in LECOUNT L J. et al., 2019) points out, "It is important to define three major forms of property—common, private, and state". Maya descendants of Belize said that until few years ago, notion of ownership was not really established from a Western point of view (Personal communication with A. FORD and Forest Gardeners). This coincides with the sentence "a common property regime was established" in the article of LECOUNT L J. et al. (2019). It matches also with the information of the association "Cultural Survival" saying that "Traditionally, Maya have held lands in common and derive individual rights of use from community through collective process"¹⁶. It is therefore necessary to think about territorial organization in terms of common areas. If we consider that all Residential Units are private and Large Architecture is state, common area could be all land outside architecture. To conclude, governance grew with use of lands.

II.1.2 The organization of different classes at El Pilar

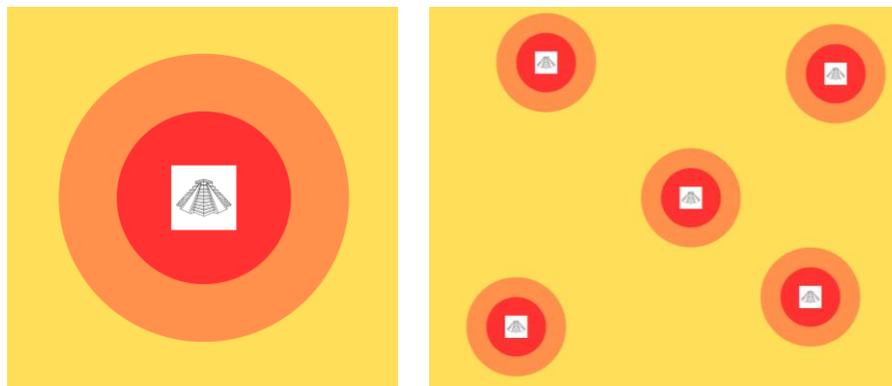
A Concentric Settlements Patterns is the type of territorial organization favored by some archaeologists for Maya organization (FOLAN W J. et al. 1979). This hypothesis is based on texts describing Maya world of Bishop Diego De Landa: "in middle of town were their temples with beautiful plazas and all-around temples stood houses of lords and priests, and then [those of] most important people. Thus, came houses of richest and of

¹⁶ CULTURAL SURVIVAL. Belize Failing to Implement Binding Court Orders to Respect Maya Land Rights, [online].

those who were held in highest estimation nearest to these, and at outskirts of town were houses of lower class”. (In article of FOLAN W J. et al. 1979). From this information, two initial hypotheses are identified about organization of El Pilar.

Both hypotheses share the notion of concentric pattern. However, they differ in their interpretation. The first hypothesis posits that the concentricity is around a central source of power. The second hypothesis introduces a more nuanced perspective, suggesting several central powers as you can see on the Figure 9. The organization is the same. On red ring, the elite social class are concentrated. On orange ring, it is an inner zone with a mixture of elite and more common people. On yellow ring, it is an outer zone with mainly common people housing. The concentricity hypotheses are tested in part II.3.

Figure 9: One central power or several central power?



Legend: **red ring:** elite housing, **orange ring:** mixture of elite and common people housing, **yellow ring:** common people housing - **Personal Source**

II.2 Places of power

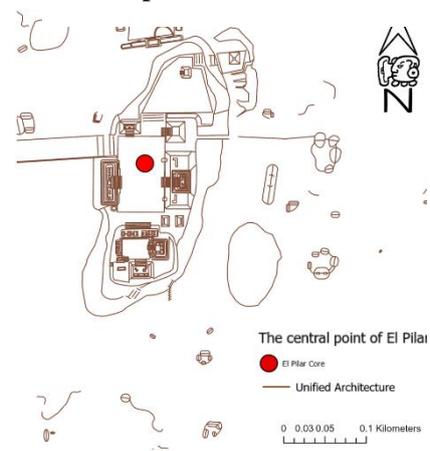
II.2.1 Central civic ceremonial centers

The Large Architecture are “hallmarks of civic centers.” (FORD. A. 2023).

The first hypothesis rests on a central point. El Pilar Core is a remarkably prominent structural complex. We designate middle of Plaza Copal as the central focal point as shown in Figure 10.

Taking a broader perspective of the map of the civic monuments reveals a potential between El Pilar Core, Pilar Poniente, and Citadel structures. Consequently, it is plausible to consider that the central

Figure 10: El Pilar Core, central point of El Pilar

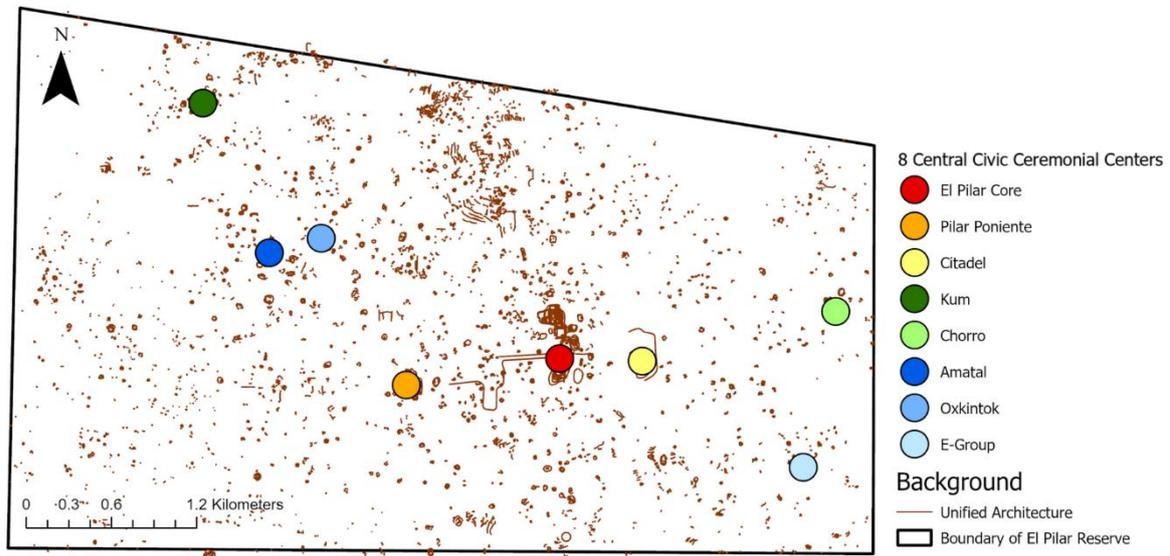


Personal Source: Created with data ISBER/MARC, UCSB, June 22, 2023.

complex encompasses these three areas as a unified entity.

The second hypothesis is based on various central places of power which will be Large Architecture explained in Part I.1.1. These eight points representing eight centers are based on the defined LA and are depicted by points on Figure 11.

Figure 11: Well-distributed central powers



Personal source: data ISBER/MARC, UCSB, June 22, 2023.

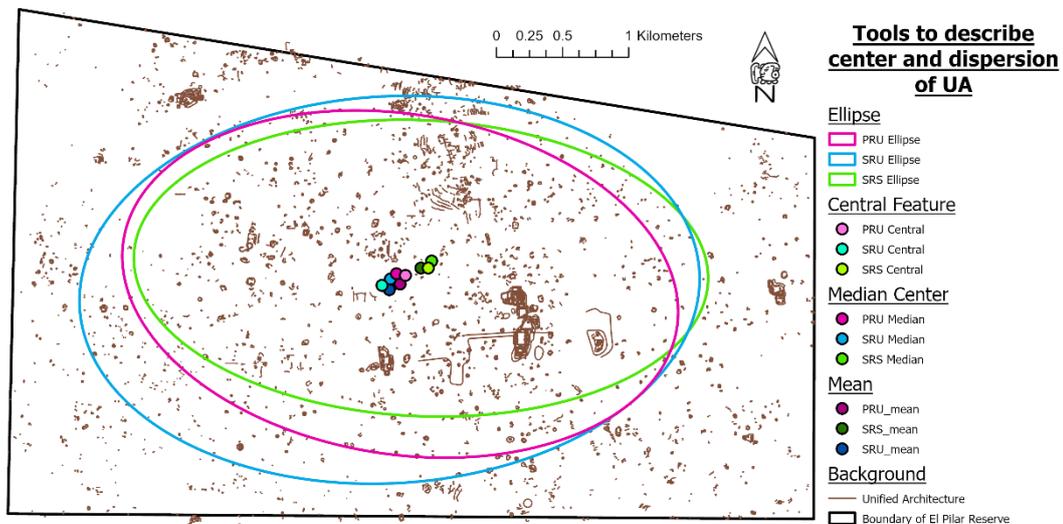
II.2.2 Solitary Range Structure

The 107 Solitary Range Structure, SRS, at El Pilar can be defined as “a large, single-mound structure with a high labor investment. Its size and footprint are determined by a structure diagonal greater than or equal to 9 meters and a designation of high (one meter or more)” (personal communication with Sherman Horn III). These criteria are verified¹⁷.

We want to know if the SRS seems to have a different distribution than PRU and SRU. That could explain their role in the territory. SRS are less numerous than other residential units and more dispersed, with an average distance between them of 184 meters, in contrast to 79 meters of PRU, and 101 meters of SRU. In the Figure 12, the median, the average and the central points of SRS (green) converges in the center of El Pilar with those of PRU (pink) and SRU (blue). Whether PRU, SRU or SRS, their ellipses have similar shape. PRU, SRU and SRS are not located only in one area of the territory but everywhere as shown by these points and ellipses. This reflects a geographical uniformity in the distribution of structures at El Pilar.

¹⁷ Appendix 1

Figure 12: Similar center and Dispersion for RU and SRS at El Pilar



Personal source: Created with data ISBER/MARC, UCSB, June 22, 2023.

In conclusion, there are fewer SRS, and they are far from each other. In view of their characteristics, there are several possibilities for their use. One of which is that these structures are RU of social elite. Another possibility that could make sense is that these structures are administrative buildings. Population, therefore, could settle around these central administrative powers. These are questions that we will leave open.

II.3 Labor investment: a tool to explain organization of territory

II.3.1 Labor investment analysis

II.3.1.1 About Labor investment

A labor investment (LI) is calculated for each RU based on mapping data from the field including structure diagonal, height, presence of plaza, and collective elements (ARNOLD J.E., FORD A. 1980). A higher LI generally means a higher construction asset. RUs with high labor investments are suggested to be elite as the labor to construct the RU suggests more control more labor directed to their own private RU ends. There are two types of data about LI:

- LI: invested workdays in constructing individual feature in IF layer.
- SUM_LI: invested workdays of an architectural group in UA layer.

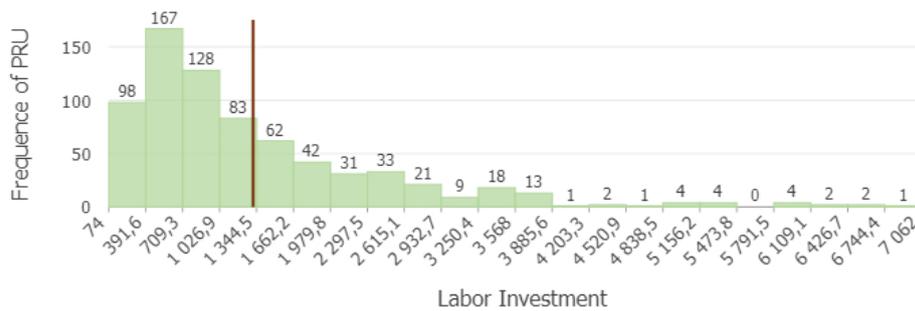
The SUM_LI in UA holds greater significance as it implies the value of a group of features combined, as a PRU. The next statistics will therefore be calculated with SUM_LI in UA which corresponds to LI of PRU. We are testing only PRU as they are the houses where the Maya live all year-around.

II.3.1.2 Trends in maya organization

To better understand the location of PRUs with high Labor Investment, LI, suggested to belong to elite, we created a series of graphs.

We start by making the scatter plot of Figure 13 at the frequency of each LI. There is considerable data and thus we use a diagram of 22 classes with no transformation. We can see that there is an uneven distribution of LI. There are few PRUs with a high LI when compared with lower that the elite would be less numerous.

Figure 13: Frequency per LI of PRU (no transformation)

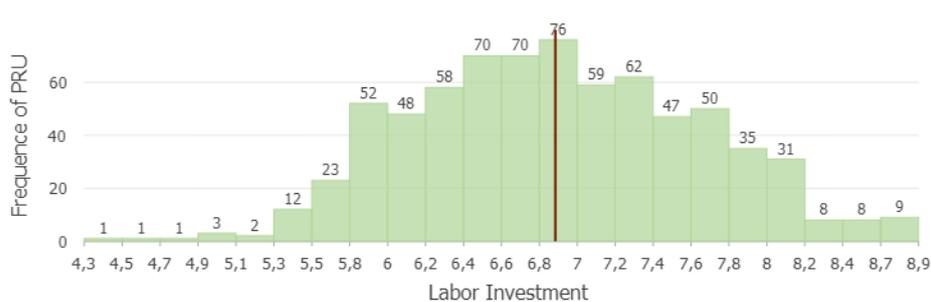


Legend: Vertical line is the mean of LI of PRU: 1315.

Personal source: data ISBER/MARC, UCSB, June 22, 2023.

The second graph used logarithmic transformation. This makes it possible to bring extreme values closer together to obtain less extensive distribution graphs. As shown on the Figure 14, the LI of PRU is not normally distributed. It is skewed far to the right by the few PRUs with very large LI. Now, the dataset is log-normally distributed with logarithmic transform of LI. These values will be used in II.3.2.2.

Figure 14: Frequency per LI of PRU (logarithmic transformation)



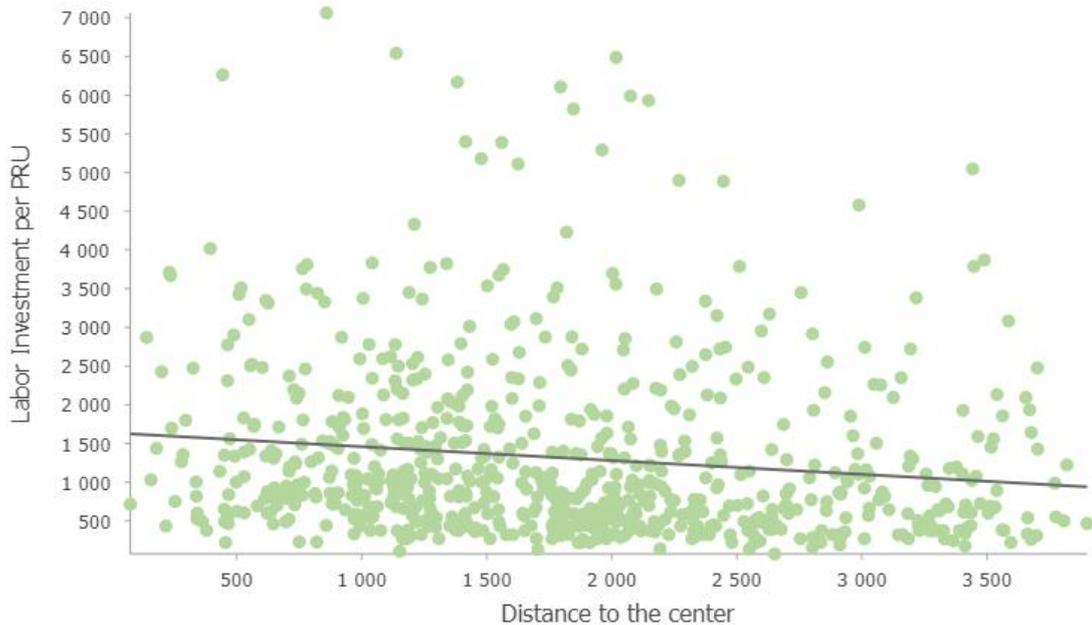
Legend: Vertical line is the mean of LI for PRU: 6.88

Personal source: data ISBER/MARC, UCSB, June 22, 2023.

II.3.1.3 PRU of elite status

The Figure 15 is a scatter diagram which is inspired by article of FOLAN W J. et al in 2009. It is created with two dimension to explore the relationship between two key factors: the distance between each PRU and central power defined in the middle of plaza of El Pilar core; and the labor investment per PRU.

Figure 15: Is LI of PRU related to distance to center?



Legend: The R^2 value = 0.02 and the trend line (grey) are calculated from the regression equation associated with the scatterplot. R^2 value quantifies the fit of the data in the model. The same scatter plot has been created with the logarithmic transformation.¹⁸

Personal source: data ISBER/MARC, UCSB, June 22, 2023.

An examination of Figure 15 shows a trend that decreases very slightly the further away from center. The same test was run for each center with their nearest PRU¹⁹. Whether the test is run with one center or several centers, it is not possible to deduce any indisputable trend as shown with the coefficient R^2 . That is why the hypotheses of concentricity are tested with other ArcGIS tools and methods in the next part.

There are some PRU stand out from crowd in the Figure 15. If we assumed that the elite are represented by the 21 PRU with a LI equal or greater than 4000, this corresponds to 3% of total PRU. This would represent the proportion of PRU that are part of the organizers of the society. We use this 21 PRU in Part II.4.

II.3.2 Statistics about Labor Investment: PRU and distance to power centers

II.3.2.1 Test with ArcGIS

II.3.2.1.1 A multitude of concentric rings

¹⁸ Appendix 10

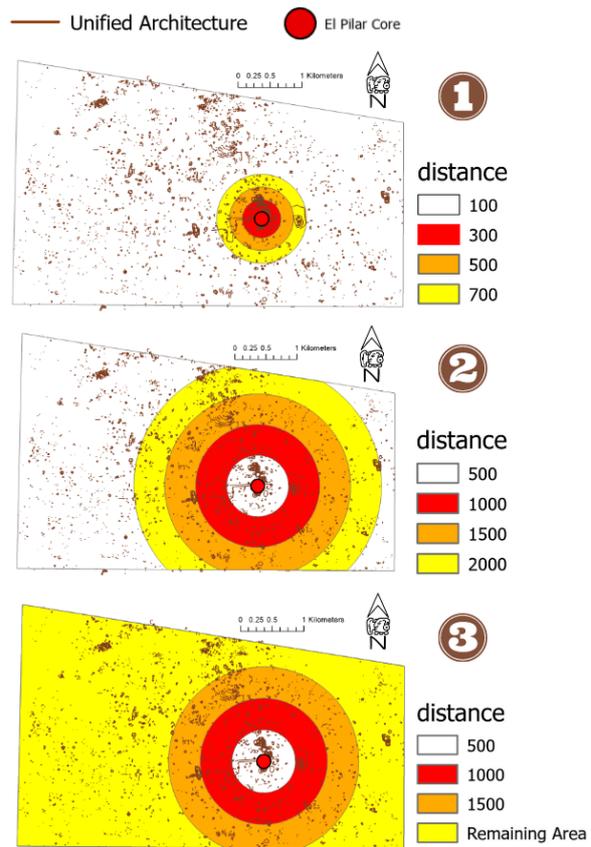
¹⁹ Appendix 11

To explore the organization of classes, we are considering the locations of the high LI PRU, the assumed elite. We are expecting a concentration of elite PRU near major centers and a decrease in LI as one moves away from centers.

We use 3 rings to represent the 3 zones defined in Part II.1.2. Firstly, we experiment with two different sizes rings as in first and second map in Figure 16, but all areas of El Pilar was not accommodated within a ring. Consequently, this issue is addressed by incorporating all spaces that do not fall within final ring, as demonstrated in third map of Figure 16.

Within each ring, the average LI of PRU is computed. If the hypothesis is confirmed, it is expected that these averages will gradually decrease as one moves towards the outermost ring.²⁰

Figure 16: Several possibilities of concentric rings



Personal Source: Created with data ISBER/MARC, UCSB, June 22, 2023.

Table 5: Results of rings test about the organization of classes around one or several powers

	Hypothesis 1 : one central power		Hypothesis 2 : several central power
	El Pilar Core	El Pilar Core + Pilar Poniente + Citadel	8 centers
Rings 100, 300, 500 and 700	NOT Validated	NOT Validated	NOT Validated
Rings 500, 1000,1500 and 2000	Validated	NOT Validated	Validated
Rings 500, 1000, 1500 and All area	Validated	NOT Validated	Validated

Legend: validated: concentricity is validated. not validated: concentricity is not validated.

Personal source: Calculated with data ISBER/MARC, UCSB, June 22, 2023.

Based on the results presented in Table 5, the possibility of having three centers and rings with sizes of 100, 300, 500, and 700 is eliminated. Indeed, the averages of LI PRU in each ring are not decreasing the further away from center. The locations of the high LI PRU, the assumed elite, are not concentrated close to center. It is, therefore, necessary to explore alternative approaches. This exercise had provided valuable insights and ideas.

²⁰ Appendix 12

II.3.2.1.2 ArcGIS tool: Local Bivariate Relationships

We carried out tests using ArcGIS tool “Local Bivariate Relationships”²¹ to determine if variables LI of PRU and distance between PRU and center are related, and how they are related. The tool is applied to analyze all the previous achievements. All the conducted tests led to the same conclusion²²; no significant relationship could be observed between the SUM LI and the distance to the center. This means that the relationship between LI of PRU and distance is either non-existent or very weak between the LI of PRU and distance to centers.

II.3.2.2 Correlation’s Pearson, Kendall, and Spearman

Correlation calculations are used to determine whether two variables are associated and strength of their relationship. There are several calculation methods.

II.3.2.2.1 Pearson with one center

The best-known method, Pearson’s r correlation, applies to variables following a normal distribution and analyzes linear relationships. The test is, therefore, run with logarithmic distribution of the values. The resulting coefficient is -0.2. This number means that they are a very weak correlation between the values. The negativity shows that, as the LI increases, the distance to the center tends to decrease. The hypothesis cannot therefore be related.

II.3.2.2.2 Kendall with one center

The Kendall's tau B was carried out on an area of Tikal and explained in the article of ARNOLD and FORD (1980). It does not require a normal distribution. After sorting the LI in ascending order, a rank is assigned to each of them. The operation is repeated for the distances. The tau-b obtained is equal to -0.14. “If there is little or no relationship between two sets of rankings, tau-B value approach or attain zero.” (ARNOLD J.E., FORD A. 1980) The conclusion drawn from this test aligns with the findings from the analysis conducted in Tikal. There is therefore a “doubt on assumption that Classic period Maya centers manifested a pattern of concentric zonation in terms of status of residents.” (ARNOLD J.E., FORD A. 1980). However, “Kendall’s tau-B test may not be most adequate statistical approach.” (FOLAN W J. et al. 2009)

²¹ ArcGIS Pro. Fonctionnement de l’outil Relations bivariées locales

²² Appendix 13

II.3.2.2.3 Spearman with one center

Even if the Kendall coefficient seems to be the most popular method, the Spearman correlation coefficient is calculated. The result obtained is equal to -0.21. The same conclusion applies as for Pearson's and Kendall's correlation.

II.3.2.2.4 Correlations with the 8 centers

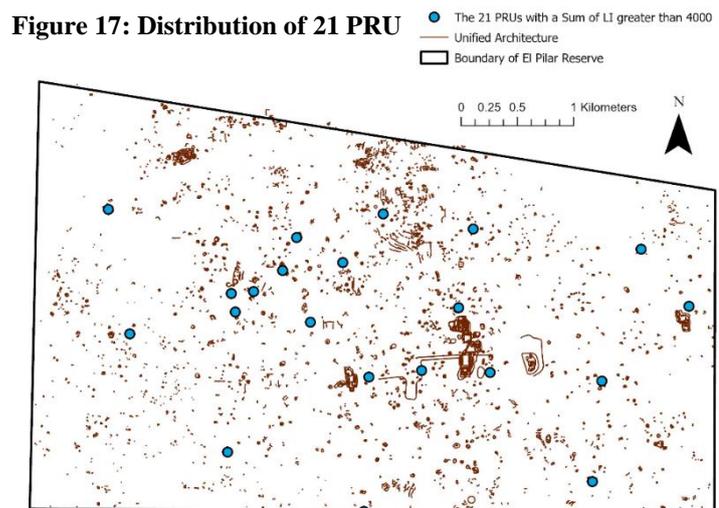
The three previous correlations are applied to the eight centers²³. The results are similar to the results with one center. The centers of power Kum and E-Group, however, have positive results as their trend in the scatter diagram. Although considered a power center, E-Group is small in comparison to the others. This raises the possibility that it may not be a center after all. The same reasoning cannot be applied to Kum because it is a big center. The positive result could be explained with its distance from the center or a different role.

II.4 Potential access to superior resources for elite PRUs

II.4.1 Access to central power

The 21 largest PRUs (with a LI greater than or equal to 4,000) are assumed here the residents of the elite. Might it be that the elites would have placed their house in the best locations and that these PRUs have more resources than the other PRUs. These 21 points are represented in Figure 17, and from an overall point of view they seem to be well distributed in space. This confirms that PRUs with a large LI are not only located in the center.

The average distance between the 21 largest entities and the central power of El Pilar Core is 1642 meters, while it is 589 meters for the eight central powers. These 21 PRU are, therefore, far from centers, whether it is the central point or the eight other centers.



Personal source: data ISBER/MARC, UCSB, June 22,

²³ Appendix 14

II.4.2 Access to water

A statement issued by FOLAN W J. et. Al. (1979) in their article said that “wells are close to houses of wealthiest.” This information contradicts example of Acuntun, where it is stated that "Commoners lived near aguada and elites in sacred locations." (LECOUNT L J. et. al. 2019). To assess the situation at El Pilar, the average distance is calculated separately for the 21 largest entities and for all the other PRU. The average distance to an aguada, for the 21 largest entities is found to be 219 meters, while for all the other PRU it is 159 meters. In conclusion, PRU with a large LI are not closer to aguadas than other PRU.

An alternative method was employed to verify this hypothesis. Considering that Maya individuals typically walk for less than five minutes to access water, a radius of 350 meters was established around each aguada. Subsequently, it was observed that out of the total 186 areas around aguadas, 77 of them exhibited a LI higher than the global average of LI. This means that not even half of the areas around the Aguadas have a high LI. Based on these results, it can be concluded that the placement of aguadas does not appear to be intentionally influenced by proximity to elite or common people.

II.4.3 Access to soil

Another objective is to examine whether the PRUs have access to a broader range of soil types. The availability of diverse soil types is considered advantageous and valuable. To investigate this, we calculated the number of distinct soil types in the vicinity of the PRU (the PRU area and the inner field of the allotment garden). We then averaged these counts separately for the 21 elite PRU and for the others and obtain the Table 6.

Table 6: Availability of diverse soil types

	Mean count soil in 24.1 meters (Infield)
21 largests	2.33
Other	1.56
Difference	0.77

Personal source: soils data Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur (2023) and data ISBER/MARC. UCSB. June 22, 2023.

Upon examining the data of Table 7, it appears that there exists a relationship between the presence of a greater number of soils in the vicinity of the largest PRUs. Further research is needed to determine whether this disparity is intentional. We therefore calculate the tau of Kendall and Pearson to examine the relationship between the count of soil in the infield of PRU and their LI. The hypothesis is that greater the LI, the more the higher the count of soil types. We obtain 0.17 and 0.22. We cannot conclude about a better access to soil for the 21 largests PRU.

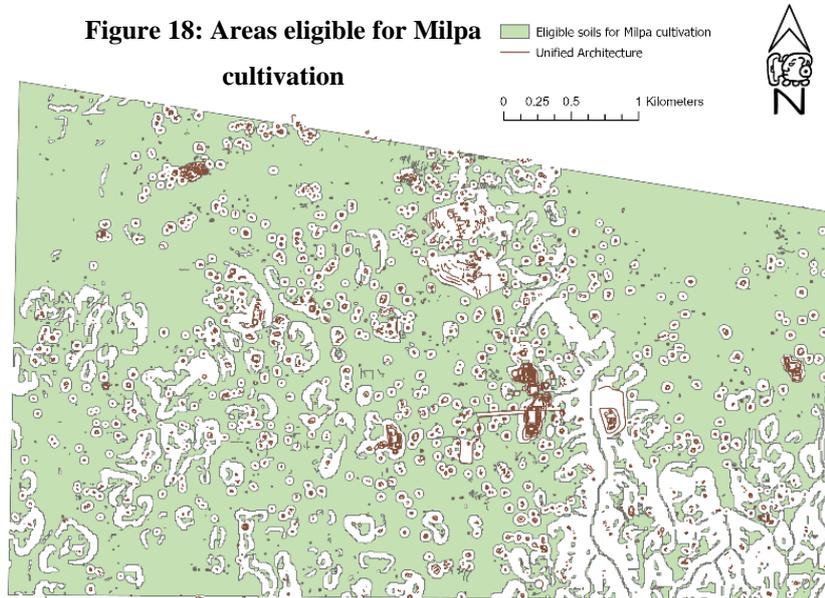
III Archaeological features and environmental interactions

Concentricity tested previously cannot explain the location of Maya structures. For this reason, environmental aspects must not be neglected. Environmental data are cross-referenced with the various features, be they aguadas, quarries or any other element useful to Maya daily life. The aim is to explain the location and relationship between archaeological elements and environment.

III.1 Cultivable Land

When examining the map displaying drainage and soil fertility, it is challenging to identify specific areas more suitable for cultivation. Although there are archaeological indicators, such as berms, that suggest intensified land modifications for agricultural practices, there are no definitive archaeological elements that outline specific plots. Consequently, determining the precise location of crops is difficult. The calculations performed by the MARC Team regarding the Milpa system are based on the premise that any land without other activities and with a slope under 15% is suitable for Milpa cultivation. We continue to adhere to this principle. By following this approach, we can identify areas of cultivation as depicted in Figure 18.

We think that by considering all the statistics related to other elements, we gain a better understanding of land use, specifically of settlements patterns. The idea is therefore to stress the areas where structures are located, to deduce information about the empty areas.



Source: data ISBER/MARC, UCSB, June 22, 2023.

III.2 Location of Residential Units

III.2.1 Soil fertility and RU

We want to know if the drainage and fertility data can be used to analyze land use. In effect, we are looking where the RUs are located with respect to drainage and fertility classification of land. Our hypothesis is that RU are placed on the lowest quality soils in terms of drainage and fertility. Calculations specifically addressing these aspects are presented in Tables 7 and 8. We count the number of residential units per categories.

Table 7 : How many RUs per soil fertility?

	ND	S2	S3	Sum
PRU Count	87	289	340	716
SRU Count	10	207	182	399

Legend: in blue: Soil with the highest number of RU

Personal source: soils data Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur (2023) and data ISBER/MARC, UCSB, June 22, 2023.

This result is not conclusive. There is no significant gap observed between the two classes. Some RUs are not classified, they are in ND. The distribution between the two types of soil (S2/S3) can still change and in any case, all soil classes at El Pilar are of good quality.

III.2.2 Soil drainage and RU

The same calculations are done for the drainage in Table 8.

Table 8 : How many RUs per soil drainage?

	S1	S3	Sum
PRU count	625	91	716
SRU count	318	81	399

Legend: in blue: Soil with the highest number of RU

Personal source: soils data Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur (2023) and data ISBER/MARC, UCSB, June 22, 2023.

Most of PRUs and SRUs are located on land with a highly suitable drainage. This is not surprising as majority of map of El Pilar is S1 type. Once again, this result lacks conclusiveness, whether for fertility or drainage, we cannot draw any conclusions about their links with the location of the RUs. Fertility and drainage data are not determinant.

III.2.3 Type of Soil and RU

As there are more categories in the soil types, we think this will lead to more concrete results and work with this data. The objective is to determine whether certain soil types were more associated with RUs. Table 9 shows the number of RUs per soil type.

Table 9 : How many RU per soil type?

	Leptosol	Rendzic Leptosol	Leptic Calcaric Phaeozem	Calcaric Phaeozem	Eutric Vertisol	Vertic Phaeozem	Arenic Fluvisol	Sum
PRU count	87	226	197	65	91	50	0	716
SRU count	10	100	139	37	81	31	1	399

Legend: in blue: soil for which count of RU is highest.

Personal source: soils data Víctor Ku and Jorge Mendoza - *El Colegio de la Frontera Sur (2023)* and data ISBER/MARC, UCSB, June 22, 2023.

There is a distinct preference of PRU and SRU to be located in Rendzic Leptosol and Leptic Calcaric Phaeozem soils as shown in Table 10. These soils are also best quality and most represented soils in El Pilar²⁴. To obtain a more relevant result, the density of PRU per soil is calculated in Table 10.

Table 10 : Density of RU per soils type in hectare

	Leptosol	Rendzic Leptosol	Leptic Calcaric Phaeozem	Calcaric Phaeozem	Eutric Vertisol	Vertic Phaeozem	Arenic Fluvisol
Density of PRU per hectare	1.84	0.37	0.31	0.35	0.23	0.33	0.00
Density of SRU per hectare	0.21	0.17	0.22	0.20	0.21	0.21	0.07

Legend: in blue: soil for which count of RU is highest.

Personal source: soils data Víctor Ku and Jorge Mendoza - *El Colegio de la Frontera Sur (2023)* and data ISBER/MARC, UCSB, June 22, 2023.

The significant result in Table 10 is dominance of PRU on “Leptosol.” These are well-drained soil, ideal for construction and the land the least suitable for cultivation. Leptosols for water to drain off quickly, reducing the risk of water accumulation. For PRU minimizing moisture-related problems around the foundations of living spaces would be

²⁴ Appendix 15

important. It makes sense, therefore, that the power centers are also located on "Leptosol" soil type.

Unlike PRUs, SRUs are not exclusively located in a particular soil type. The number of SRUs is almost equivalent for all the category of soil type. Leptosols are, indeed, ill-suited for agriculture and Leptic Calcareous Phaeozem for example is very suitable. The result is in line with our expectations because as SRUs are intended for storage, and ancillary purposes and can be located adjacent to PRUs as well as located in field areas.

III.2.4 DEM and RU

III.2.4.1 Slope and RU

As explained in part I.2.3, the detailed topography used is the slope. These data are cross-referenced with the location of the PRU in Table 11.

Table 11 :Number of RU per slope

Slope classification	1	2	3	4	5	6	7	8	9	10	Sum
	Flat → to → Very steep										
PRU Count	606	109	10	0	0	0	0	0	0	0	725
SRU count	372	31	1	0	0	0	0	0	0	0	404

Legend: in blue: soil for which count of RU is highest.

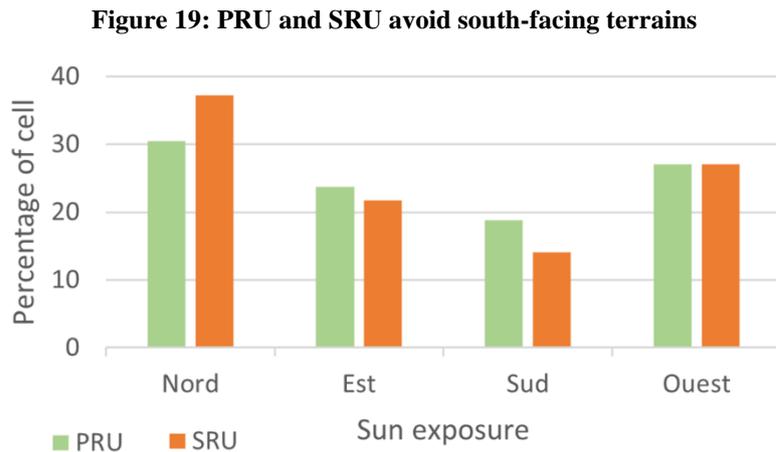
Personal source: data ISBER/MARC, UCSB, June 22, 2023.

What can be concluded from Table 11, is that regardless the type of RU, a flat surface is preferred as shown with the PRU count 606 and the SRU count 327 in the first class. This result is consistent, it is obviously easier to build on flat land that steep lands.

III.2.4.2 Sun exposure and RU

The sun exposure data are in raster format and calculated for 1m-by-1m cells, therefore, we chose to use PRU and SRU polygons, covering the entire surface of the structure. We then selected cells whose sun exposure data fell within these polygons. This selection process was used to generate Figure 19 and show the sun exposure of cells (in percentage) for the four cardinal directions.

The Figure 19 clearly shows that even if PRUs and SRUs were built on flat land (III.2.4.1), the lands favor a very slight slope with northern or western exposure. The first explanation we came up was that Maya positioned their residential units to leave the land



Personal source: data ISBER/MARC, UCSB, June 22, 2023.

exposed to the sun for their crops, which also kept the dwellings and storage facilities cool. El Pilar is close to the equator; therefore, the sun's rays strike the ground at near-perpendicular angles. This explanation is therefore called into question. The location of RU in relation to exposure to the sun should be explored further.

III.3 Relationship between features, environment and PRU

III.3.1 The storage facilities

III.3.1.1 The soil type of chultun

Since we are interested in the soil types of RU, it is appropriate to examine chultuns and soils. We count the number of chultun per soil²⁵ and calculate the density.

Table 12 : Density of chultun per soil type (in hectare)

	Leptosol	Rendzic Leptosol	Leptic Calcaric Phaeozem	Calcaric Phaeozem	Eutric Vertisol	Vertic Phaeozem	Arenic Fluvisol
Density of Chultun	0.53	0.14	0.04	0.05	0.03	0.04	0.00

Legend: in blue: Soil with the highest number of chultuns

Personal source: soils data Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur (2023) and data ISBER/MARC, UCSB, June 22, 2023.

Like the PRU, most of the chultuns are located in leptosols. Chultuns are excavated into bedrock and leptosols are near bedrock. The question must be raised, however as to whether this is really a choice or whether it is due to their proximity to the PRU.

²⁵ Appendix 16

III.3.1.2 Exploring Connection between a PRU and storage facilities

Numerous unanswered questions remain about location of SRU and Chultun. The assumption that each storage facility is linked to a PRU is more complex since total number of storage sites is only half of total number of PRUs. Upon examining distribution, some of these storage facilities are situated adjacent to PRUs, while others are in field areas. The objective is, therefore, to determine predominant locations of SRU and chultun facilities.

Our approach involves examining the number of SRUs or chultuns within the area including the PRU and its infield. As a result, it has been determined that out of a total of 405 SRUs, 68 of them (16.79%) are located within this area. Similarly, out of a total of 162 chultuns, 89 of them (54.94%) are found within the area.

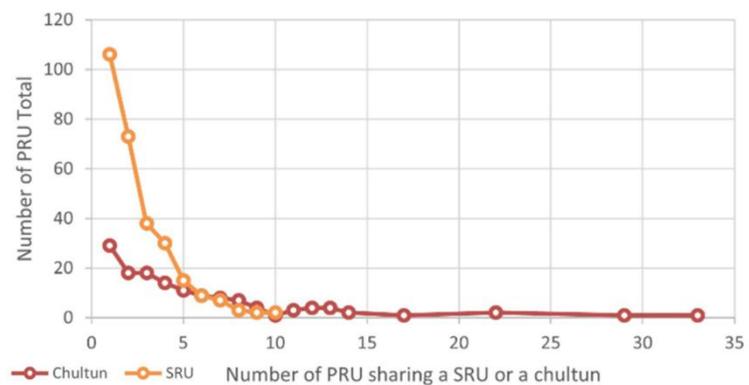
In conclusion, SRU are mostly located in fields rather than in close proximity to PRUs. Chultuns are equally distributed, half of them are located in fields, while the other half are close to PRUs. Given their very different percentages, we can assume that the roles of SRU and chultuns are not exactly identical. PRU are more numerous than SRU and chultuns, therefore, SRUs and chultuns are probably shared. Indeed, we have already established that Maya shared their Milpa among themselves. Most of the storage sites located in field, therefore, they would be likely shared.

III.3.1.3 The sharing of SRU and Chultun

We want to verify the assumption that SRU and chultun are shared between PRUs. By examining the closest SRU and

chultun to each PRU, we obtain the distribution in Figure 20. It shows a noticeable trend for SRUs in proximity to a PRU. This indicate that most of SRUs are utilized by a single PRU. The same trend seems to be followed for chultuns, but it is not as clear-cut.

Figure 20: SRU and Chultun, shared features?



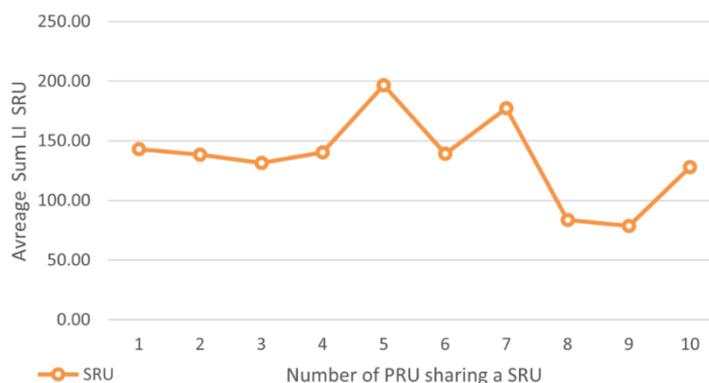
Personal source: data ISBER/MARC, UCSB, June 22, 2023.

Surprisingly, it is observed that some storage facilities are shared by multiple PRUs. One possible explanation for this phenomenon is that larger SRUs or chultuns are

more likely to have a greater number of PRUs in proximity. Although we lack data regarding the size of chultuns, we do have information about the LI of SRUs.

In Figure 21, therefore, the relationship between the average of LI and the number of nearest PRUs to the SRU is explored. The observed trend does not align with our expectations. So, if we want to qualify our hypothesis, it is nevertheless possible to imagine other perishable structures in the past that are no longer visible today.

Figure 21: Is the sharing of SRUs linked to their size?



Personal source: data ISBER/MARC, UCSB, June 22, 2023.

III.3.2 The natural resource collection features

III.3.2.1 Aguadas

III.3.2.1.1 The soil type of aguadas

Aguadas are essential elements of Maya life. « These Maya reservoirs, or aguadas, continue today as most reliable water sources » (FORD. A. 1996). The location of aguadas could potentially be explained by a relationship with different types of soil. To explore this further, we assess the count of aguada per soil²⁶ and the density of aguadas per soil type in Table 13.

Table 13 : Density of aguadas per soil type (in hectares)

	Leptosol	Rendzic Leptosol	Leptic Calcaric Phaeozem	Calcaric Phaeozem	Eutric Vertisol	Vertic Phaeozem	Arenic Fluvisol
Density of Aguadas	0.19	0.14	0.07	0.05	0.04	0.1	0.00

Legend: in blue: Soil with the highest number of Aguadas

Personal source: soils data Víctor Ku and Jorge Mendoza - El Colegio de la Frontera (2023) Sur and data ISBER/MARC, UCSB, June 22, 2023.

After having made this report, as for the previous structure, the only significant result is presence of aguadas in “Leptosol” type soils. So, we wonder whether this is linked to a possible proximity to the PRU.

²⁶ Appendix 16

III.3.2.1.2 Aguadas next to PRU

The average distance between PRUs and their nearest aguadas is calculated to be 165.4 meters, indicating that aguadas are not located in close proximity to PRUs. Like the approach used for analyzing storage features, we examine the number of aguadas within the infield layer and the area of each PRU. As a result, we have identified 60 aguadas out of a total of 186 (32.26%) within these areas.

In conclusion, most water reserves, represented by aguadas, are situated in fields rather than in the immediate vicinity of the PRUs. This is explained by the risk of overflow of Aguadas. Their location on the "leptosol" soil type is therefore probably deliberate.

III.3.2.1.3 The sharing of Aguadas

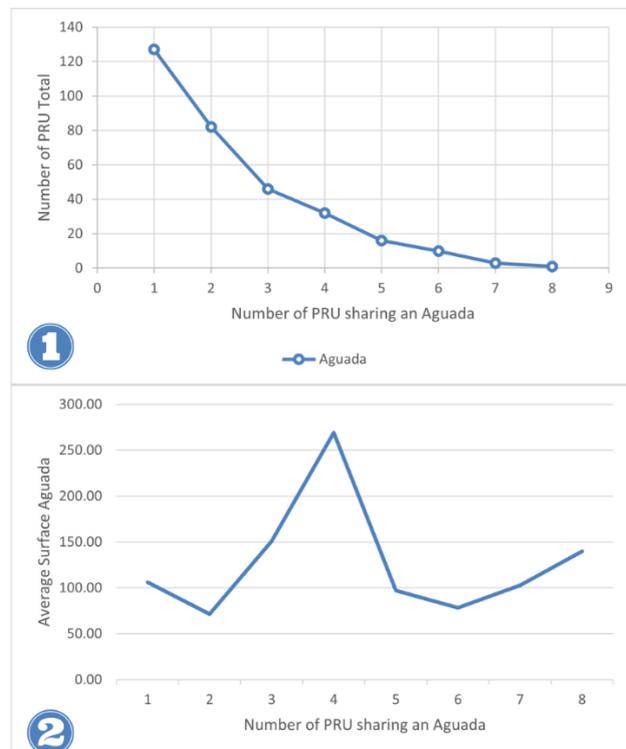
By identifying the nearest water source for each PRU, it is possible to determine whether the majority of aguadas are shared among multiple PRUs. Recalling that aguada's surface polygons were created with an ArcGIS tool, we caution the reliance on our results.

In the first graph presented in the Figure 22-1, it is observed that majority of aguadas are not shared, approximately 130 aguada are shared with only one PRU. However, surprisingly, there are instances where some aguadas are shared by multiple PRUs. For example, on the Figure 22-1,

one aguada is shared with 8 PRU. This unexpected finding could be attributed to the presence of larger aguadas attracting more PRUs.

The second graph of Figure 22-2 illustrates the average size area of aguadas in relation to the number of nearest PRUs. The observed trend does not align with our expectations which is: the more PRUs, the larger the aguada surface area. This result suggests that there is no relationship between the size area and the sharing of aguadas as water sources.

Figure 22: Aguadas, shared features?



Personal source: data ISBER/MARC, UCSB, June 22, 2023.

III.3.2.2 Quarries

III.3.2.2.1 The soil type of quarries

After counting the number of quarries per soil type²⁷, we examine density in Table 14.

Table 14 : Density of Quarries per soil type (in hectare)

	Leptosol	Rendzic Leptosol	Leptic Calcaric Phaeozem	Calcaric Phaeozem	Eutric Vertisol	Vertic Phaeozem	Arenic Fluvisol
Quarries density	0.84	0.40	0.11	0.07	0.07	0.08	0

Legend: in blue: Soil with the highest number of quarries

Personal source: soils data Víctor Ku and Jorge Mendoza - El Colegio de la Frontera (2023) Sur and data ISBER/MARC, UCSB, June 22, 2023.

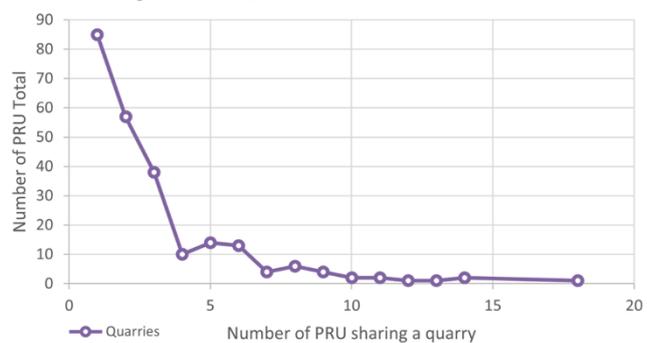
As before, leptosols are the soils containing the highest density of quarries. We may wonder whether this is due to their presence in the vicinity of PRUs, yet it must be understood that the quarries are limestone and leptosols feature shallow soil accessible to bedrock. Quarries for stone would be expected in these areas.

III.3.2.2.2 Sharing of Quarries

The average distance between PRUs and the nearest quarries is 154 meters. We assessed the number of quarries situated within the infield layer and the PRU's area. As a result, out of a total of 413 quarries, we identified 145 quarries (35.11%) in the infield.

In conclusion, most quarries, are situated in fields rather than in the immediate vicinity of the PRUs and are not shared features as shown with Figure 23. We did not expect so many quarries in the vicinity of PRUs, as we assumed that a single quarry was used for multiple construction purposes. It is possible that inhabitants specialized in this trade would have set up their homes as close as possible to their place of work.

Figure 23: Quarries, shared features?



Personal source: data ISBER/MARC, UCSB, June 22, 2023.

In conclusion, this study highlights an important aspect of Maya society: the sharing of features of the landscape. This finding emphasizes the significance placed on communal ownership and the importance of community in Maya culture. It serves as a reminder of the values and principles that guided Maya society, showcasing their communal spirit.

²⁷ Appendix 16

Conclusion

Despite recent technological advancements, the use of LiDAR has proven to be less useful than anticipated in discovering ancient features at El Pilar. LiDAR is critical however in understanding topography and geography of El Pilar. A comprehensive view of the various constructions and architectural elements of the site demonstrate the necessity to conduct on-site exploration. At the heart of the development of the Maya civilization lies their ability to harness the land. In the landscape configuration of El Pilar, two elements play a significant role: infield home-gardens and the Milpa farming system. These specific agricultural practices have shaped the landscape and greatly influenced the overall structure of the patterns. The Maya utilized these methods to maximize food production and create a harmonious environment between dwellings and cultivated lands. An intriguing characteristic of El Pilar is that all the soils present in the region are fertile and exhibit good drainage according to FAO criteria. These criteria do not allow, however, for a clear distinction between soils intended for Milpa cultivation. To better understand soil usage, it is necessary to consider the different soil types present at the site.

Environmental criteria, such as soil types, are crucial, but we should not overlook the potential impact of social organization on land management. Studies have been conducted to test various hypotheses, such as the concentricity of dwellings and the location of elites housing. We concluded that there is a slightly higher concentration of elite houses near the center of El Pilar, but this criterion is certainly not predominant in understanding the overall territorial organization. Furthermore, we questioned whether elite residences had access to more abundant resources. While elite houses are neither closer to the centers nor to water sources than ordinary dwellings, they may have an advantage in access to more soil varieties. Further investigation of this results will reveal its significance. In conclusion, the results suggest that social factors do not play a predominant role in land organization. Other social, economic, or political considerations may exert influence on settlement patterns, such as the role of SRS and will be the subject for further study.

We delve into the environmental criteria and cultural features to better understand the land organization at El Pilar. It is noteworthy that the majority of aguadas, quarries, PRU, SRU and even sites of power were constructed on Leptosol soil types. These soils are not suitable for cultivation, which helps to explain this choice of location. Furthermore, PRU and SRU were primarily built on flat or north-facing soils. This specific geographical

arrangement may have been considered to optimize cultivation and living conditions for the inhabitants. Additionally, storage spaces, along with aguadas and quarries, appear to have been shared among the residents. If land is shared, it is not surprising that other features are too. Location choices based on soil characteristics, sun exposure, and the availability of resources such as aguadas and quarries were key considerations for the inhabitants of this ancient civilization. These elements highlight the importance of environmental criteria in the land organization at El Pilar. Several ArcGIS, Excel, and Python files have been generated for the calculations²⁸. We used ArcGIS tools²⁹ for our analysis, however, there are probably other ArcGIS tools that haven't been used that might be of interest. This thesis provides me with the opportunity to delve deeper into my knowledge of ArcGIS. I also developed my research skills by reading numerous scientific articles, as well as my critical thinking skills. Moreover, I have the privilege of collaborating with researchers from diverse fields, including archaeologist Anabel Ford and soil specialist Jorge Mendoza, which is both stimulating and highly enriching. Since this internship is being conducted in an American research laboratory, it has also been instrumental in enhancing my English writing and communication skills.

²⁸ Appendix 17

²⁹ Appendix 18

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Appendix 1

Validation of definition: PRU, SRU and SRS

There is a clear distinction between the table Individual Features (IF) and Unified Architecture (UA). IF refers to a single feature (mounds, plazas, chultuns, aguadas, quarries etc.), whereas UA pertains to a group of features. The attributes of these tables are explained below thanks to the metadata of shapefiles created by MARC Data. They are used to validate the stated definitions of PRU, SRU and SRS in AP1 Table 1.

Individual Features:

- Diag - length, measured diagonally, of individual feature.
- LI - labor investment (in workdays) invested in constructing individual feature.
- StrMxHt_Num - height of mound.
- StrHt_Num - Whether mound is considered “low” (below 1 meter) or high (above 1 meter). 2 for low, 1 for high

Unified Architecture:

- Group Diagonal - length, measured diagonally from one end to another of an entire architecture group.
- SUM_LI - total labor investment (invested workdays) of an architectural group.
- Shape_Length - A perimeter all features within a group. Automatically generated by ArcGIS Pro.

AP1 - Table 1: Statistics about PRU, SRU and SRS

	PRU	SRU	SRS
Mean Diag (IF)	8	6	13
Mean LI (IF)	388	113	717
Mean StrMxHt_Num (IF)	1.46	0.49	1.79
Mean StrHt_Num (IF)	1.32	2	1
Mean Sum LI (UA)	1315	141	732
Mean Group Diagonal (UA)	23	8	13
Mean Shape Length (UA)	75	27	48

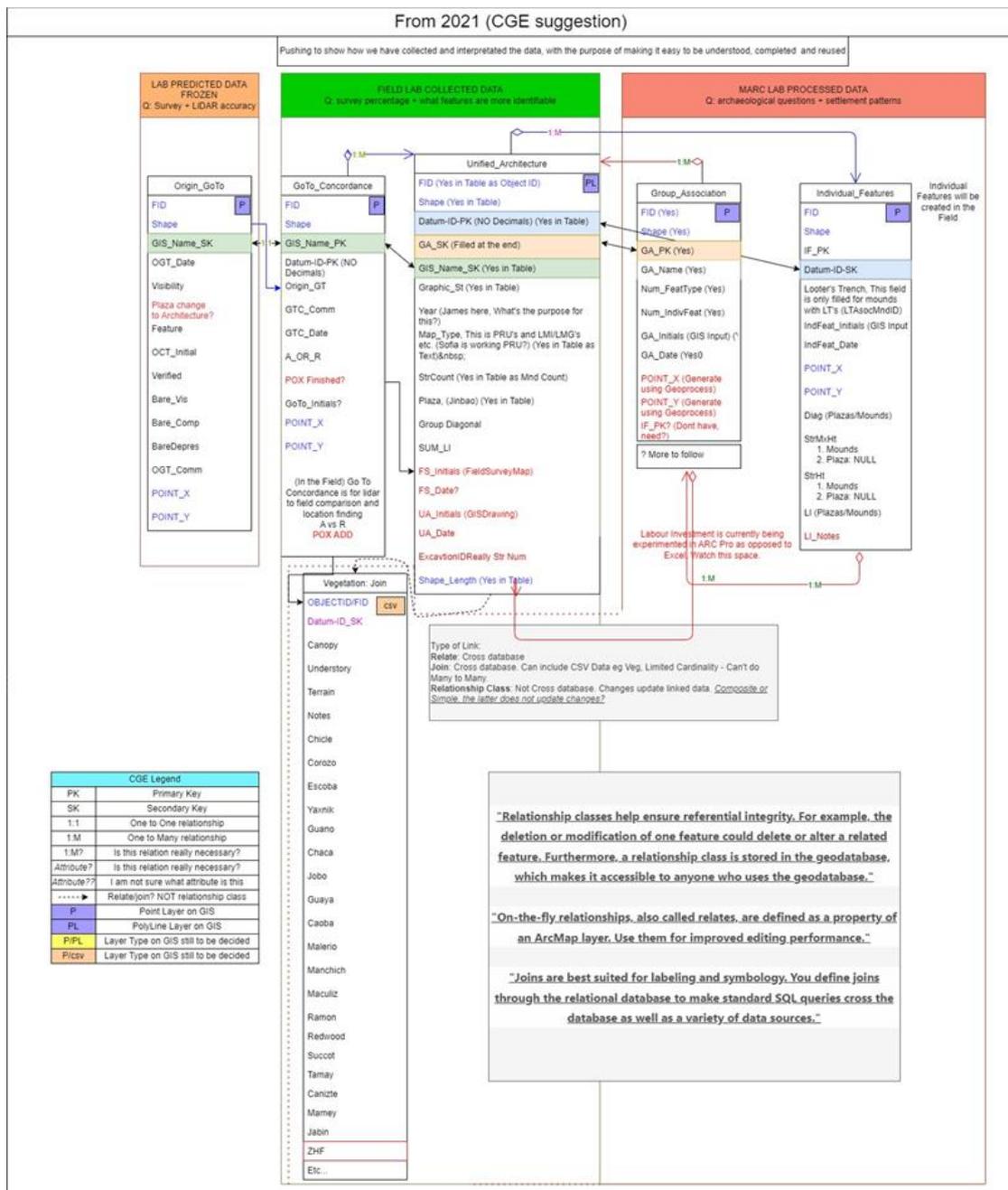
Personal source: Calculated with data ISBER/MARC, UCSB, June 22, 2023.

Our calculated averages for PRU, SRU and SRS validate our definitions. However, on a case-by-case basis, the definitions are variable.

Appendix 2 Database of El Pilar

El Pilar database has been developed since 2021. The diagram in AP2 Figure 1, however, shows the links between the tables.

AP2 - Figure 1: Database of El Pilar in 2021

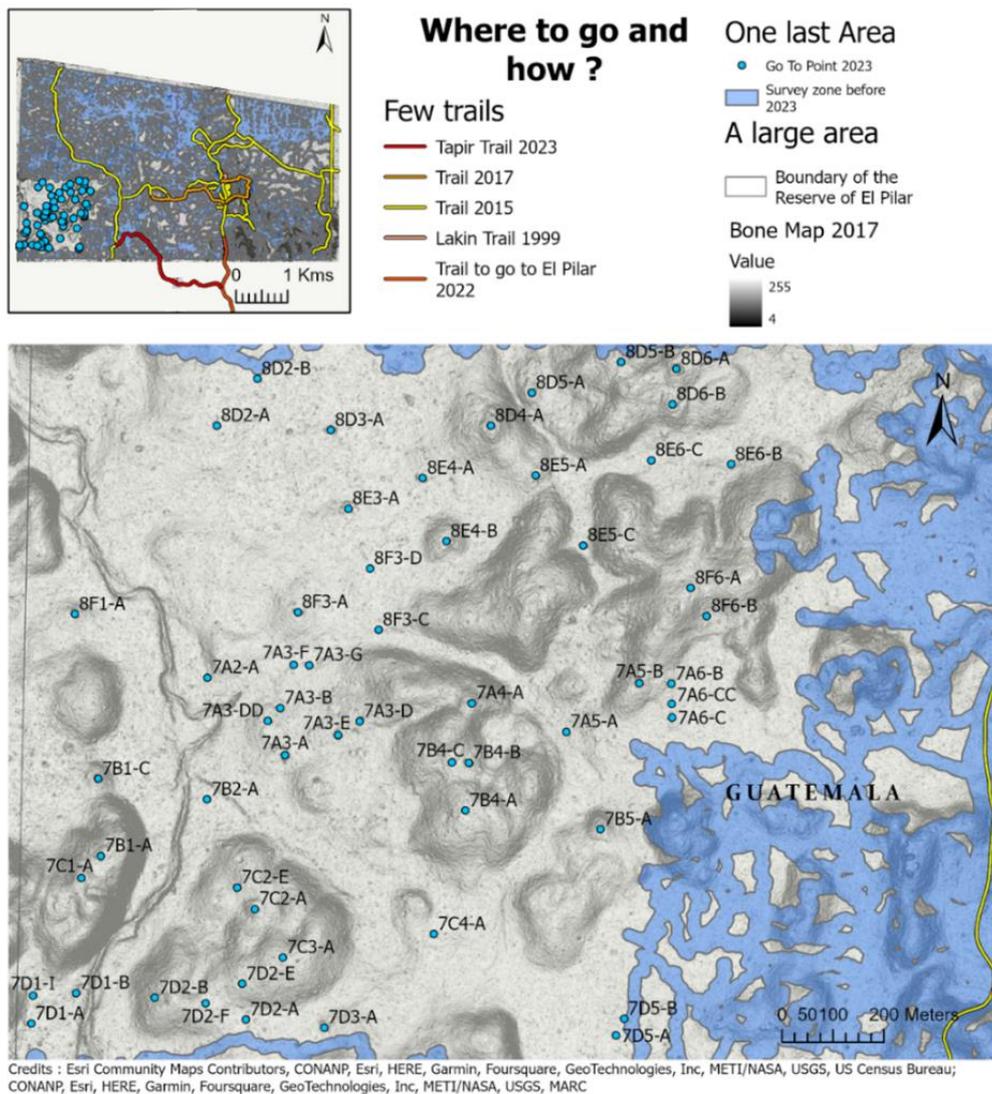


Source: ISBER/MARC, UCSB, June 22, 2023.

Appendix 3 The field survey in 2023

The map in AP3 Figure 1 locates the points that the MARC laboratory team led by Anabel Ford visited during the 2023 field season. These points are derived from LiDAR data based on the Bonemap. Bonemap is used for the navigation to assess the presence of Maya architecture at their location. The completion of this survey area will finalize the 20sq km map of the El Pilar Archaeological Reserve. Areas surveyed before 2023 is shown by the blue traces (12-meter buffer around the survey paths). The surface to survey in 2023 is about 2 square kilometers containing 57 Go To points. That is the grey area on the map.

AP3 - Figure 1: Site locations obtained by LiDAR to be verified in 2023

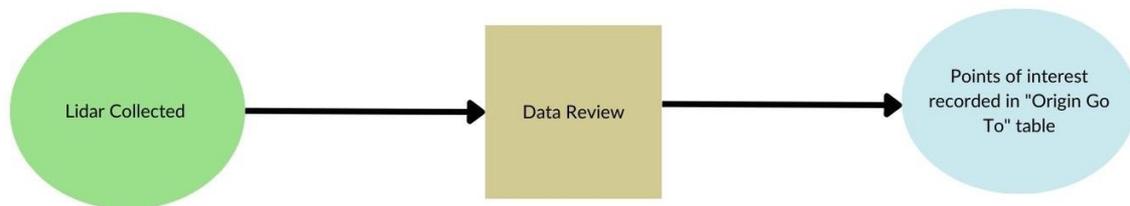


Personal source: data ISBER/MARC, UCSB, June 22, 2023.

Appendix 4 LiDAR data initial processing

Once the LiDAR data has been retrieved, several steps are required to obtain the desired data used in this thesis. The first step is diagrammed in AP4 Figure 1. “Origin GoTo” and “GoTo Concordance” are point shapefiles detailing locations of possible archaeological sites at El Pilar.

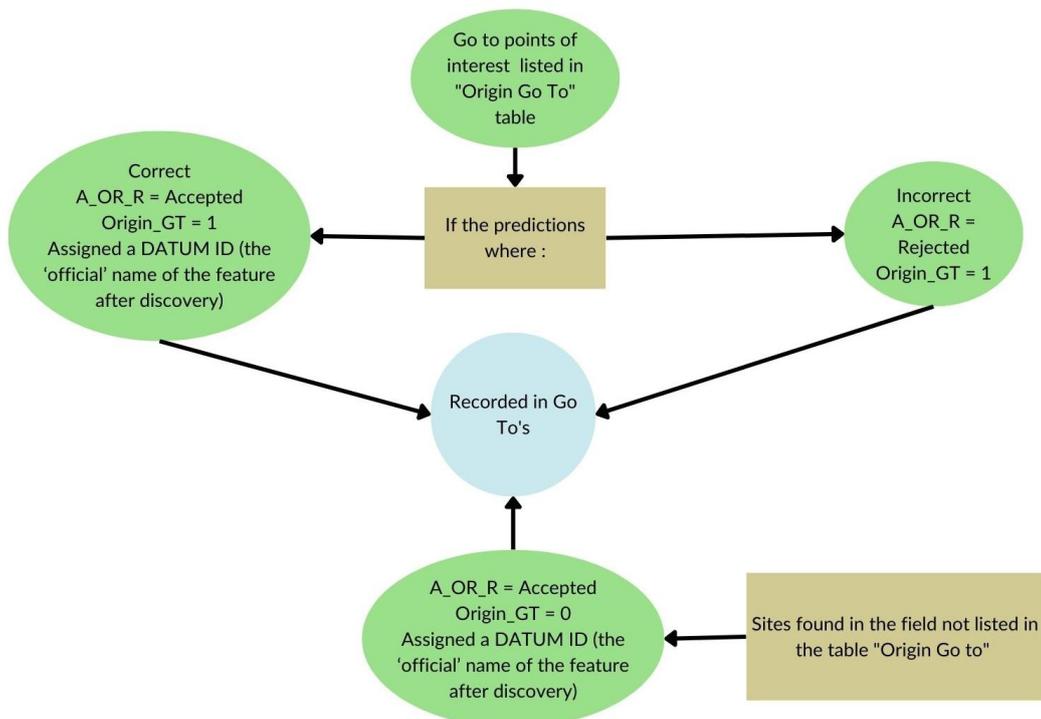
AP4 – Figure 1: First step in using LiDAR data



Personal source: Created with data ISBER/MARC, UCSB, June 22, 2023.

After retrieving the “Go To Origin” table, points are check on the field with the method explained in AP4 Figure 2.

AP4 – Figure2: Method on the field



Personal source: Created with data ISBER/MARC, UCSB, June 22, 2023.

Appendix 5

Statistics on detection of large architectures by LiDAR

LiDAR detection of Primary Residential Unit (PRU) and Secondary Residential Unit (SRU) is shown in AP5 Table 1. These statistics are calculated based on relationship among the files: Go To Concordance, IF and UA.

AP5 – Table 1: Comparison of LiDAR detection: PRUs and SRUs

	PRU		SRU	
Field Identification (Origin_GT = 0)	276	45.25%	241	78.25%
LiDAR Detection (Origin_GT = 1)	334	54.75%	67	21.75%
Total	610	100%	308	100%

Personal source: Calculated with data ISBER/MARC, UCSB, June 22, 2023.

Bearing in mind that SRUs are smaller than PRUs, the percentages confirm the hypothesis that LiDAR detects large structures more easily than small ones, but we verify it in AP5 Table 2.

AP5 - Table 2: Comparison of LiDAR detection: high and low structure

	High structure, mounds of 1m height or higher (StrHt = 1)		Low structure, mounds less than 1m in height (StrHt = 2)	
Field Identification (Origin_GT = 0)	268	43.09%	373	61.45%
LiDAR Detection (Origin_GT = 1)	354	56.91%	234	38.55%
Total	622	100%	607	100%

Personal source: Calculated with data ISBER/MARC, UCSB, June 22, 2023.

The percentages in AP5 Table 2 verify the hypothesis that Lidar detects high structures more easily than low ones.

Appendix 6

Elevation, Slope and Sun exposure

A. Surface parameters tool

We already had the layer corresponding to the elevation. It is, however, necessary to rework the DEM layer using the ArcGIS tool “Surface Parameters” to obtain slope and sun exposure. This tool is explained in AP6 Table 1.

AP6 – Table 1: The use of Surface parameters tool

	Slope	Sun exposure
Option	Slope	Aspect
Output	“represents the rate of change of elevation for each cell.” It is calculated in degrees.	“identifies the compass direction that the downhill slope faces for each location. It is expressed in positive degrees from 0 to 360, measured clockwise from north”

Source: ArcGIS Pro. *Surface Parameters* [online] <https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/surface-parameters.htm>

B. Reclassify Elevation and Slope

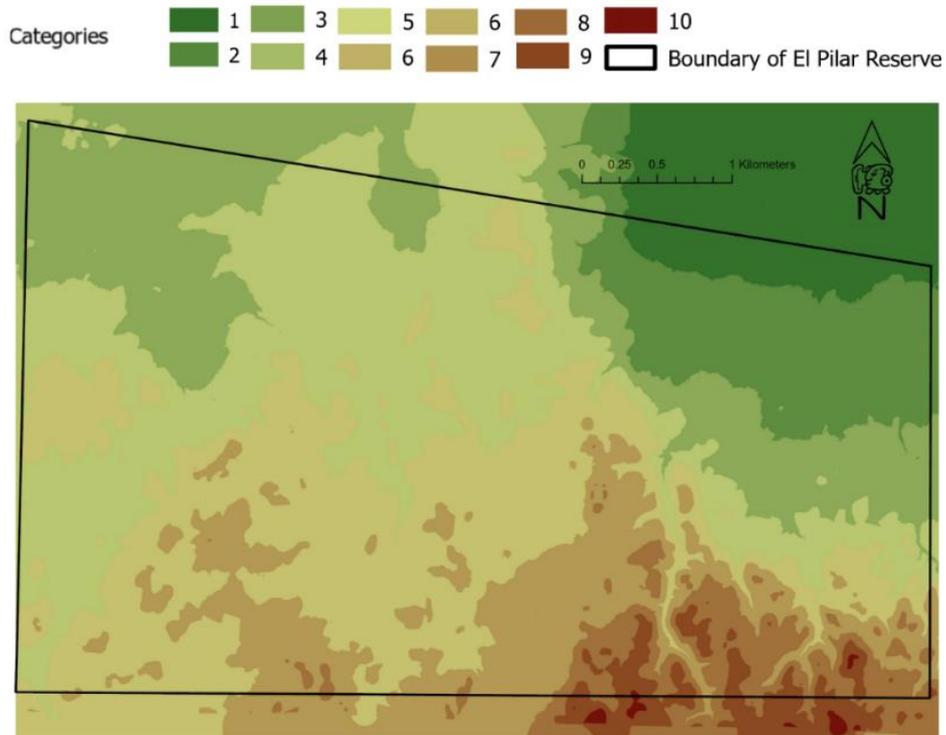
Elevation and slope cells are reclassified (tool: reclassify) into 10 distinct classes using equal intervals shown in AP6 Table 2. For elevation, the range extends from 1, representing the lowest altitude, to 10, signifying the highest altitude. The result map is the AP6 Figure 1. Regarding slope, the range spans from 1, which denotes flat terrain, to 10, which indicates extremely steep slopes. These classification are used in calculation in Part 3 of the thesis.

AP6 - Table 2: Altitude and Slope classification in 10 categories

	Altitude		Slope	
Range of values	From 108.16 to 306.15 meters.		From 0.000351 to 84.692688.	
Classification	Start	End	Start	End
1	108.160004	127.958578	0.000351	8.469584
2	127.958578	147.757153	8.469584	16.938818
3	147.757153	167.555728	16.938818	25.408052
4	167.555728	187.354303	25.408052	33.877286
5	187.354303	207.152878	33.877286	42.346519
6	207.152878	226.951453	42.346519	50.815753
7	226.951453	246.750027	50.815753	59.284987
8	246.750027	266.548602	59.284987	67.75422
9	266.548602	286.347177	67.75422	76.223454
10	286.347177	306.145752	76.223454	84.692688

Personal source: Created with reclassify tool of ArcGIS used with 10 equal intervals, data ISBER/MARC, UCSB, June 22, 2023.

AP6 - Figure 1: Elevation, data derived from LiDAR



Personal source: data ISBER/MARC, UCSB, June 22, 2023.

Appendix 7

Milpa Forest Garden Cycle

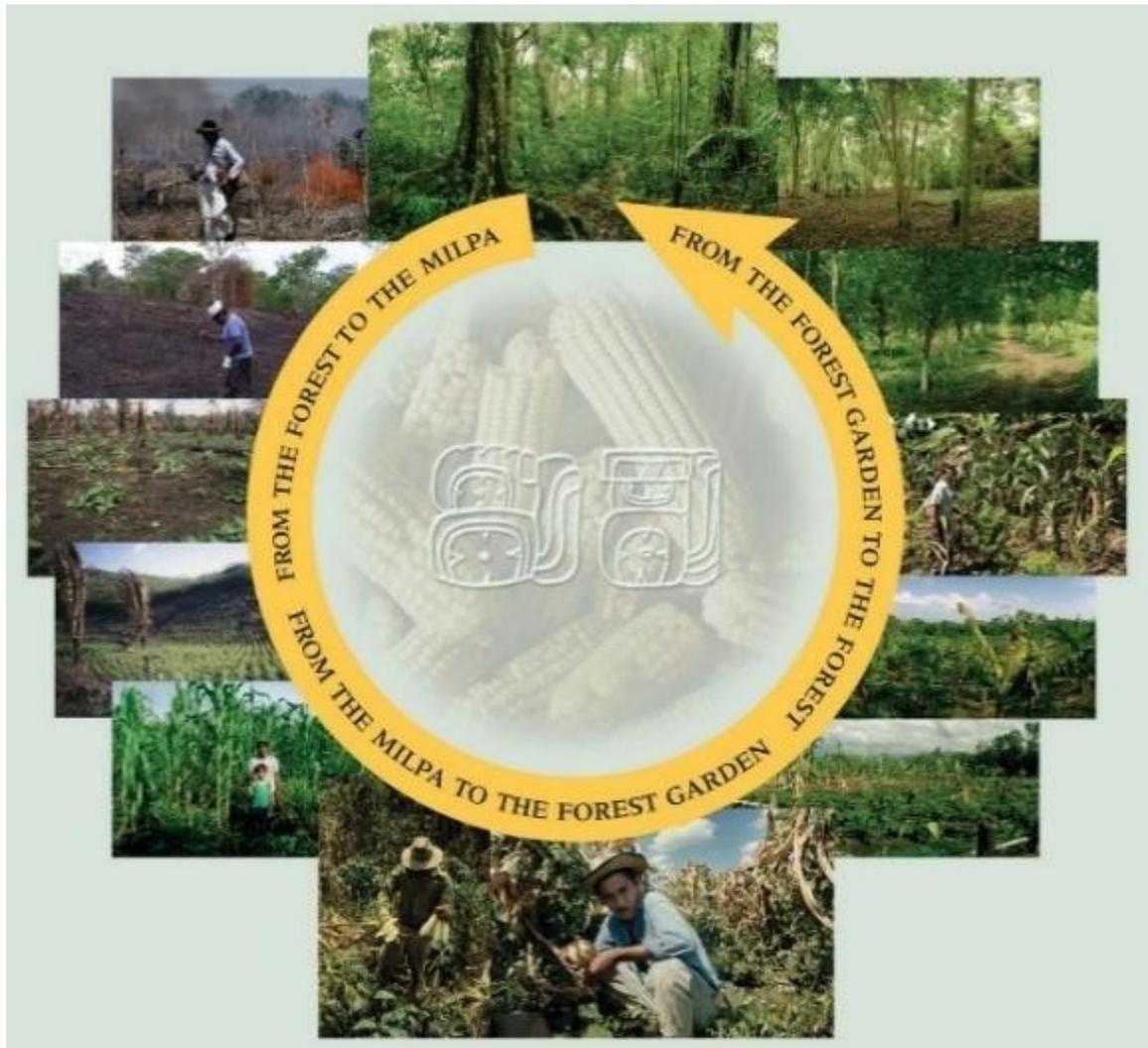
The Maya attributed utility to approximately 90% of the trees in the Maya Forest. The diverse range of trees planted for medicinal, culinary, and construction purposes, facilitated the enrichment and diversity of the forests. It supports animal life. Within this forest, there exist 20 dominant plant species. The forest itself can be seen as a meticulously tended "garden" maintained by the Maya civilization. In contrast to Western agricultural practices characterized by large monoculture fields, the Maya employed a different approach, cultivating small plots with mixed crops. This sustainable and intricate technique allowed for more than half of the land to remain as forested areas.

The different stages of Milpa cultivation :

- Step 1:** Before planting, farmer cuts and burns part of forest. Fire is not seen as a destructive factor, but as a controlled tool. In addition, fire allows microelements to return to soil in form of charcoal.
- **Step 2:** Farmer plants the varied seed including maize seeds among the slashed and burned organics.
 - **Step 3:** Farmer sows more seeds.
 - **Step 4:** After circa four years, with at least two harvests per year, farmer begins to let tree seedlings reinvest in the Milpa from surrounding forest.
 - **Step 5:** The farmer keeps trees that are useful to daily life. The farmer nurtures new trees and shrubs for another eight years or until there shade.
 - **Step 6:** For another eight years, trees, which grow rapidly in tropical climate, produce an enclosed canopy. It quickly becomes a shelter for monkeys, parrots and other rainforest animals. Farmers then go to perform same process at another location in forest.
 - Land is not plowed, so when it rains, water is absorbed. There are no artificial fertilizers, pesticides, or herbicides. All amendments are locally derived and organic.

The AP6 Figure 1 illustrates the stages of the Milpa cycle with more detailed steps and images.

AP7 – Figure 1: Milpa cycle, an agro-forestry system



Source figure and information: HORN S W III., TRAN J. FORD A. Presentation and AMERICAN SCIENTIST. The Enduring Legacy of the Maya and POPULAR ARCHEOLOGY. The Milpa Way.

Appendix 8 Soils

A. Plants in tropics

Soil may explain places of Maya settlements. In using soil data, it is interesting to appreciate chemical and biological aspects. Soils provide rooting medium for almost all plants, including crops. Rates of productivity of plants and therefore crops is different depending on qualities of the soil. Indeed, it varies according to region. In temperate geography, limiting factor to this productivity is climate during winter months while in tropical regions it can be humidity or other factors such as intense biotic interactions or soil nutrient limitations. Plants need carbon, hydrogen, oxygen and 13 other elements (micronutrients and macronutrients) to live. (KELLMAN M., TACKABERRY R. 1997).

B. Classification: Fertility and Drainage

To create the classification, the Soil Productivity Index is used. It is based on a calculation using various attributes (MENDOZA-VEGA. J. ET. AL. 2021) as you can see it in formula:

$PI_{soil} = \sum_{i=1}^n (A \times B \times C \times D \times E \times F \times WF)$ with n is number of each soil type.

Each letter is equal to a soil parameter: A=CEC; B=P; C=TN; D=OC; E=K; F=Available water; G=Stone and gravel; WF=Effective soil depth. Some of these parameters are explained. (MENDOZA-VEGA. J. 2023)

The El Pilar soil samples and therefore parameters that define them are variable according to places of collection according to depth level. The CEC and pH are two parameters important in this thesis and are explained in the following Part C.

C. Soils Parameters

1. CEC, Cation exchange capacity (Cmol kg⁻¹)

CEC is a measure of how much positive ions (cations) can be hold on soil particle surfaces (with negative charge) and can be exchange per mass of soil cmolc/kg soil. It is a measure of soil fertility because calcium, magnesium and potassium are cations and important plant nutrients. Types of clay minerals and amount of organic matter (OM) in a

soil have an important influence on its CEC. Clays developed under mild weathering conditions such as those found in El Pilar soils (e.g., smectites) and have much higher CEC levels than those developed under more extreme weathering processes (Weil and Brady, 2017). Organic matter has a high CEC, but it is pH dependent. (Personal communication Jorge Mendoza Vega)

2. pH

The nature of pH can cause issues for plants and condition nutrient availability. At a high pH as at El Pilar, there may exist P and K fixation in soil, thus they are not available for plants. There are levels of pH where nutrients are more available for plants, e.g., between 6 and 7 tend to be the best for crops. (Personal communication Jorge Mendoza Vega)

D. Classification : Soil types

Soil types can be deduced with these soil parameters from the results of the IUSS WRB working group in 2015. The soil types located at El Pilar and some explanation about them are in AP8 Table 1.

AP8 - Table 1: Explanation of soil types

Soil groups	Dominant identifiers	Soil qualifier ad to soil groups
Phaeozem	Pronounced accumulation of organic matter in the mineral topsoil	Leptic Calcaric Phaeozem
	Dark topsoil, no secondary carbonates (unless very deep), high base status	Calcaric Phaeozem
		Vertic Phaeozem
Fluvisol	Soils with little or no profile differentiation Stratified fluvial, marine and lacustrine sediments	Arenic Fluvisol
Leptosol	Soils with limitations to root growth	Rendzic Leptosol
	Thin or with many coarse fragments	Leptosol
Vertisol	Soils with limitations to root growth Alternating wet-dry conditions, shrink-swell clays	Eutric Vertisol

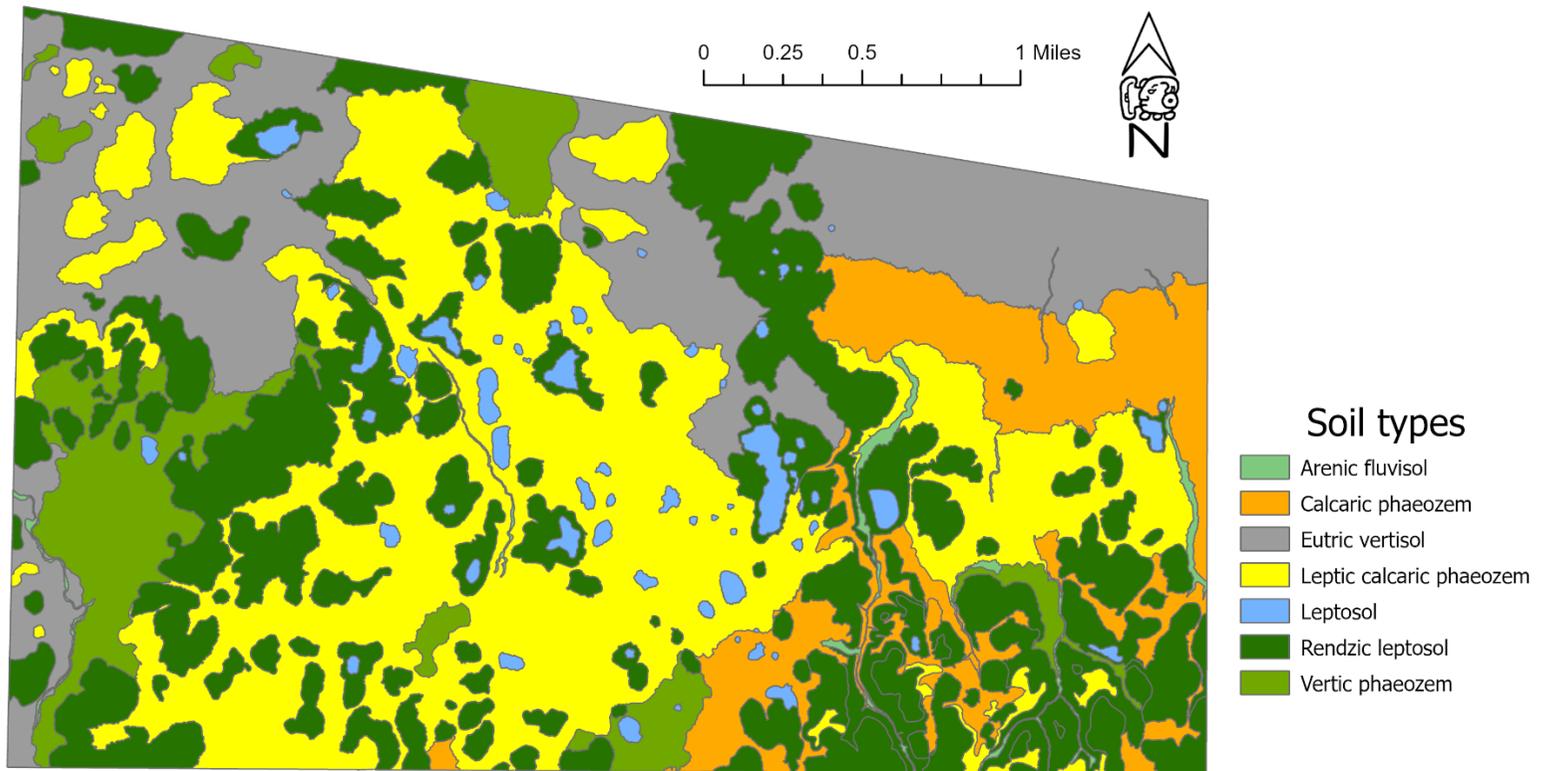
Source: FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS. World reference base for soil resources 2014 International soil classification system for naming soils and creating legends for soil maps.

Appendix 9 Soil map types

AP9 - Figure 1: A diversity of soil types

The soil data we use comes from the work of Jorge MENDOZA and his team. AP9 Figure 1 shows the seven soil types present at El Pilar according to the classification established by the IUSS WRB working group in 2015.

Personal source: Soils data, Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur (2023) and data ISBER/MARC, UCSB, June 22, 2023.

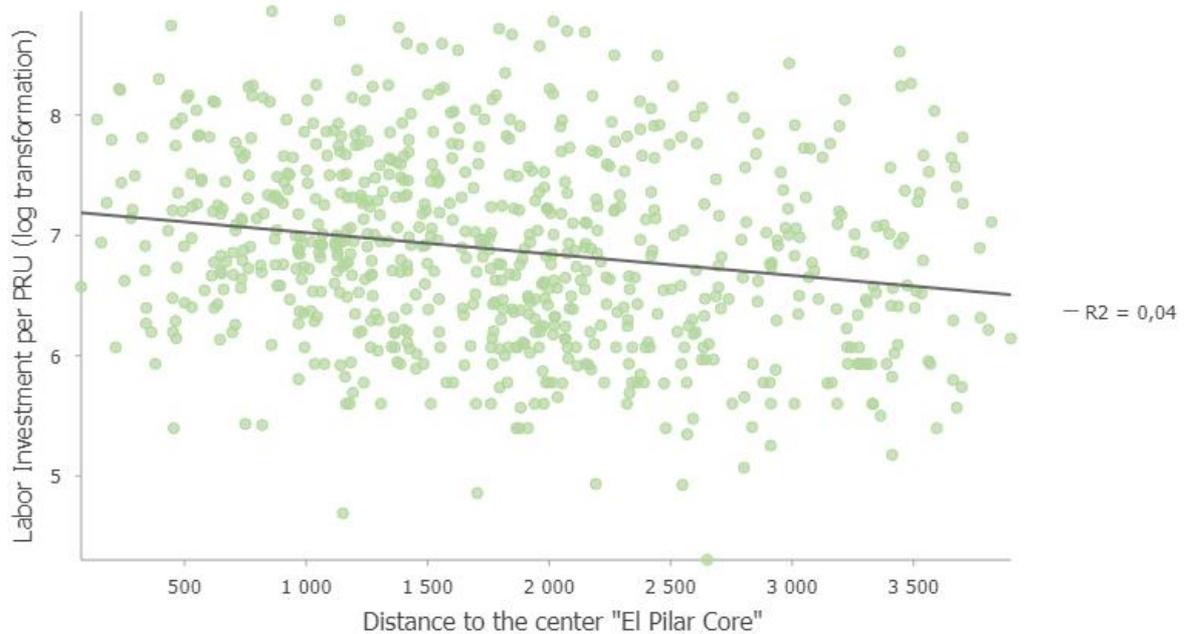


Appendix 10

Scatter plot of PRU with logarithmic transformation

Examination of the factors of distance and LI are shown in AP10 Figure 1. The difference between Figure 15 and AP10 Figure 1 is that a logarithmic transformation has been applied to the LI of PRU. This R^2 result is an accurate assessment of the lack of relationship between these two variables. The scatter plot without transformation cannot validate a trend.

AP10 - Figure 1: Is LI of PRU related to distance to center? (Logarithmic transformation)



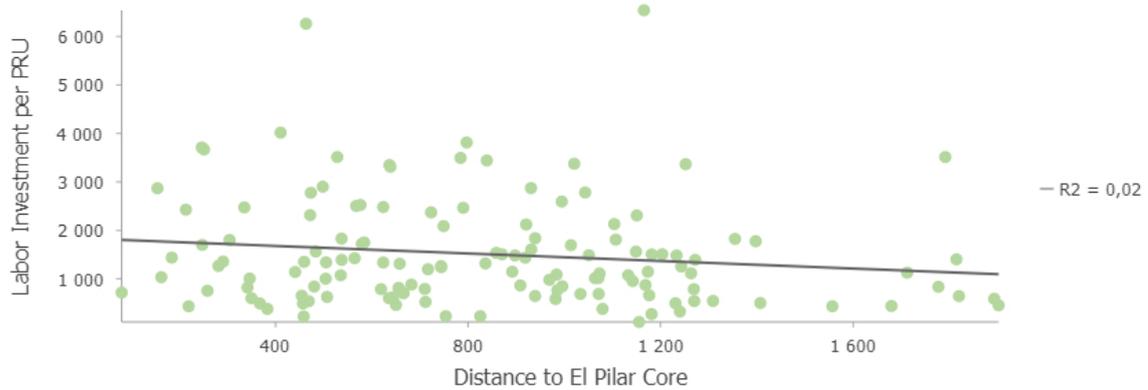
Personal source : Soils data, Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur (2023) and data ISBER/MARC, UCSB, June 22, 2023.

Appendix 11

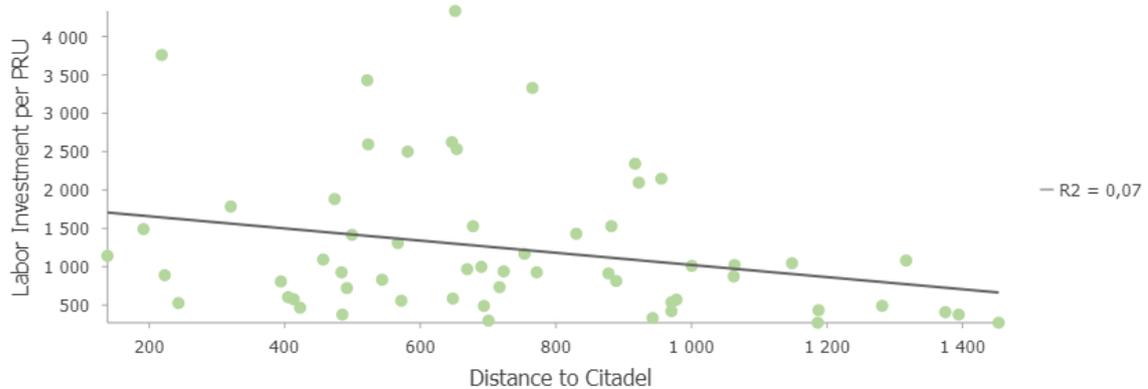
Scatter Plot for each center and Distance to the center

Scatter plot for each of the eight possible civic centers of El Pilar area are created with respect to their closest PRU. The R^2 results do not allow us to conclude that there is a definite relationship between the labor investment of PRU and the distance to the center.

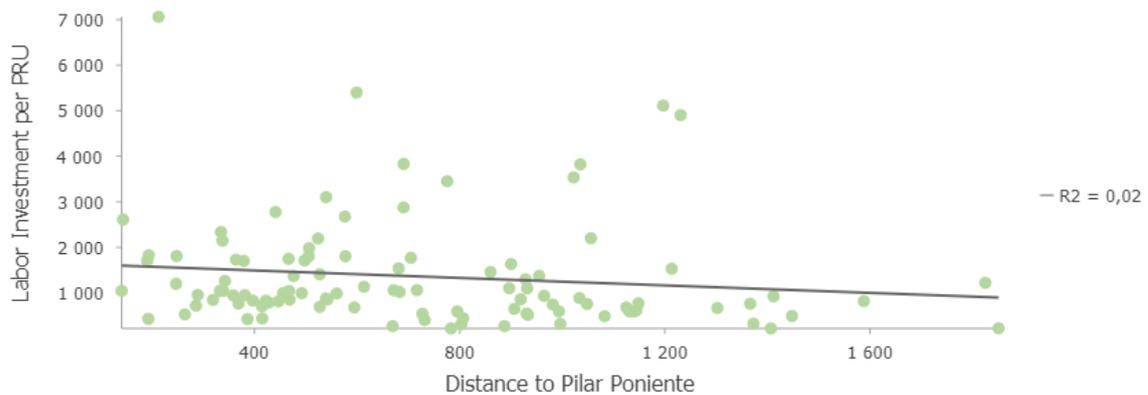
AP 11 – Figure 1: Scatter Plot El Pilar Core



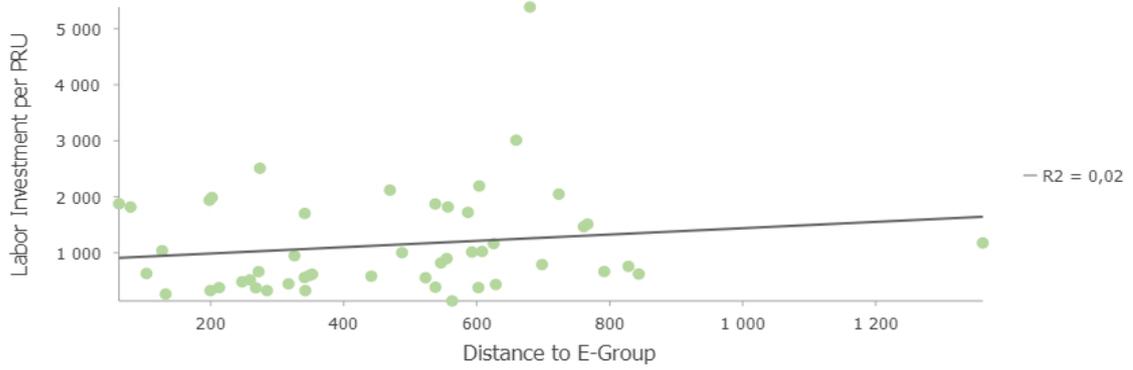
AP 11 – Figure 2: Scatter Plot Citadel



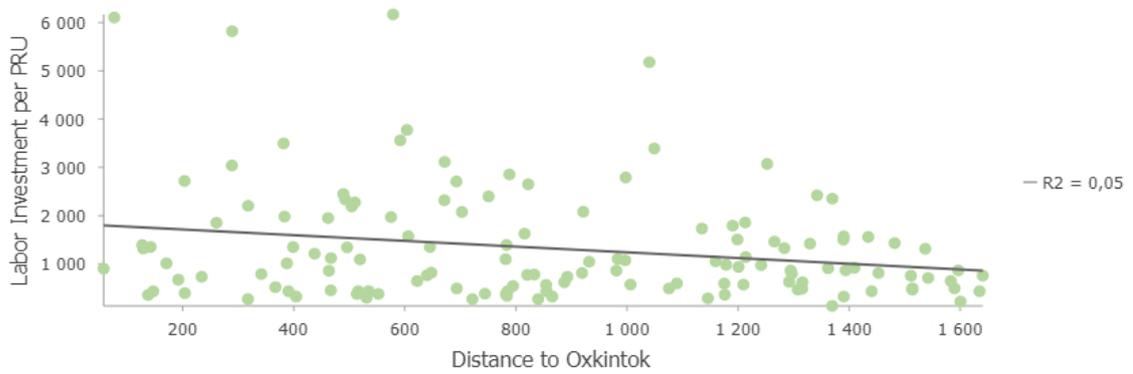
AP 11 – Figure 3: Scatter Plot Pilar Poniente



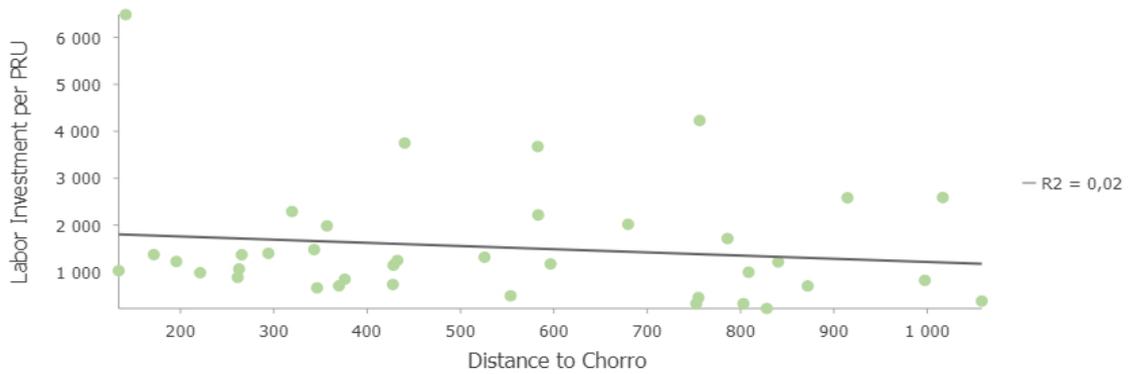
AP 11 – Figure 4: Scatter Plot E-Group



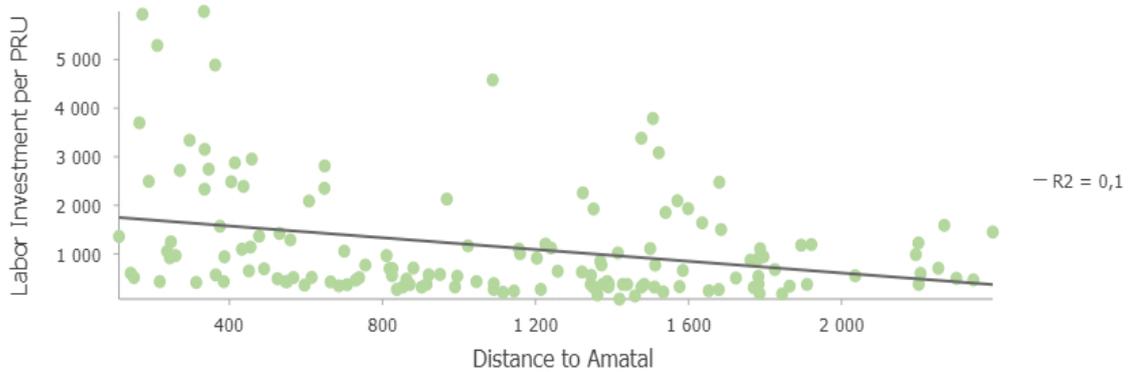
AP 11 – Figure 5: Scatter Plot Oxkintok



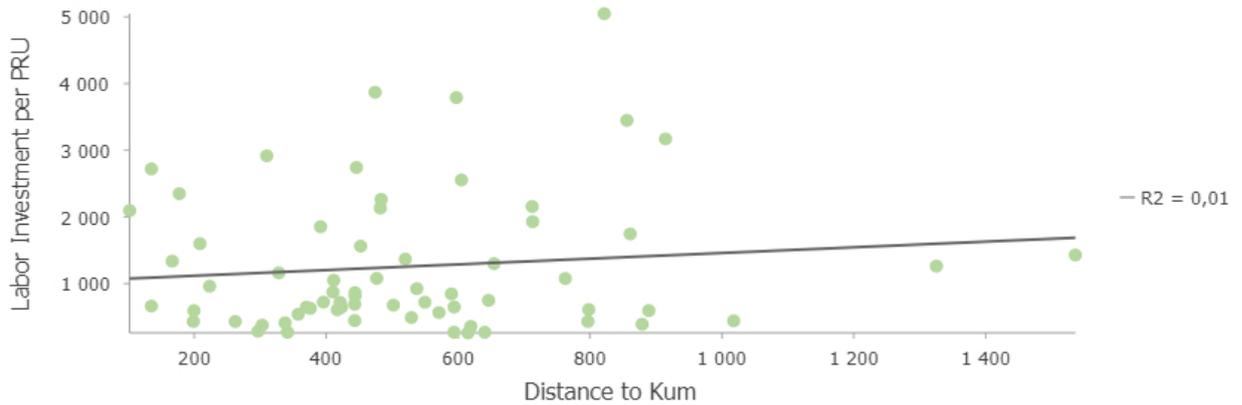
AP 11 – Figure 6: Scatter Plot Chorro



AP 11 – Figure 7: Scatter Plot Amatal



AP 11 – Figure 8: Scatter Plot Kum



Personal source: data ISBER/MARC, UCSB, June 22, 2023.

AP11 Figure 1 shows a trend for most of the scatter plot: the LI decreases very slightly the farther one moves away from a center. Distance from the El Pilar core, Pilar Poniente, the Citadel, Chorro, Oxkintok, and Amatal show a trend that is insignificantly negative in slope, comparable to the results of El Pilar center. The overall picture, however, is that there is little evidence of a relationship between distance and high LI for any civic center of the El Pilar area.

AP 11 – Table 1: Distance to the center for each central power

	Distance to the center El Pilar Core (meters)
El Pilar Core	0
Citadel	583
Pilar Poniente	1096
E-group	1880
Oxkintok	1883
Chorro	1972
Amatal	2177
Kum	3099

Personal source: data ISBER/MARC, UCSB, June 22, 2023.

Group E and Kum are opposite showing a slight positive trend. Initially, we believed that the distance from the center could serve as an explanation. AP11 Table 1 shows that its holds true for Kum, the farthest central power. However, we discovered that this reasoning does not apply to E-Group, making it an invalid explanation for this case.

Appendix 12 Concentric Ring

An analysis using ArcGIS was conducted to examine the potential relationship between the LI and the distance to centers at El Pilar. This investigation involved utilizing various ring sizes and several center points. For each ring, the average LI for the PRUs was computed. It was anticipated that these averages would progressively decrease as one moved towards the outermost ring. The results of these calculations, displaying the average values for each ring, are presented in AP12 Table 1.

AP12 - Table 1: Mean LI of PRU per ring.

	Hypothesis 1		Hypothesis 1
	El Pilar Core	El Pilar Core + Pilar Poniente + Citadel	8 centers
Ring 100/300/ 500/700	716	716	2283
	1877	1791	1618
	1528	1305	1373
	1537	1671	1512
Ring 500/1000/ 1500/2000	1617	1453	1485
	1479	1387	1331
	1427	1436	1152
	1289	1165	976
Ring 500/1000/ 1500/all area	1617	1136	1485
	1479	1387	1331
	1427	1436	1152
	1205	1136	955

Legend: in green: data validating the concentricity test

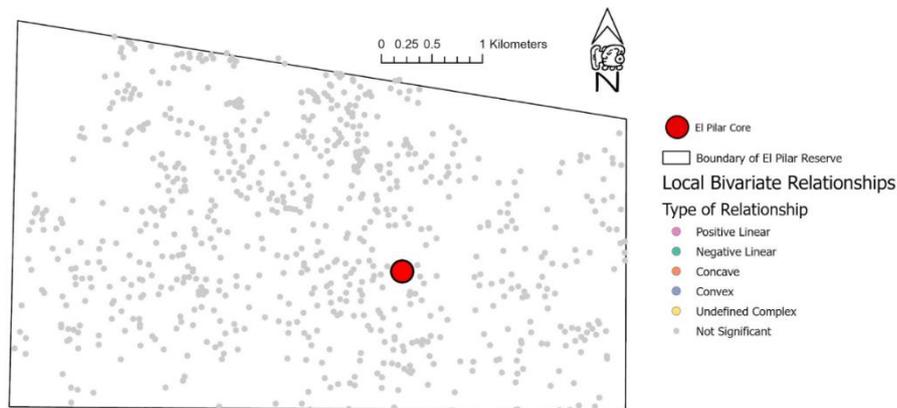
Personal source: data ISBER/MARC, UCSB, June 22, 2023.

Appendix 13

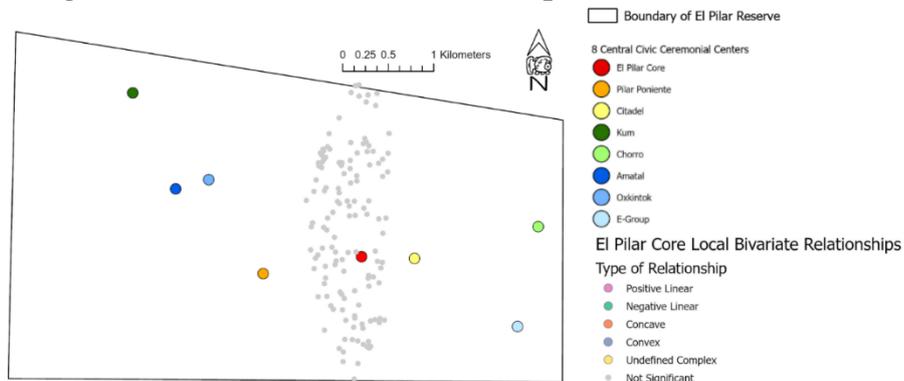
Local Bivariate Relationship

The ArcGIS tool “local bivariate relationship” is used for the hypothesis of concentricity with one center as shown in AP13 Figure 1 and with the eight possible civic centers of El Pilar as shown with the AP13 Figure 2 to the AP13 Figure 9. All figures show that there is no significant relationship between the labor investment of PRU and the distance to the center. The hypotheses of concentricity are refuted.

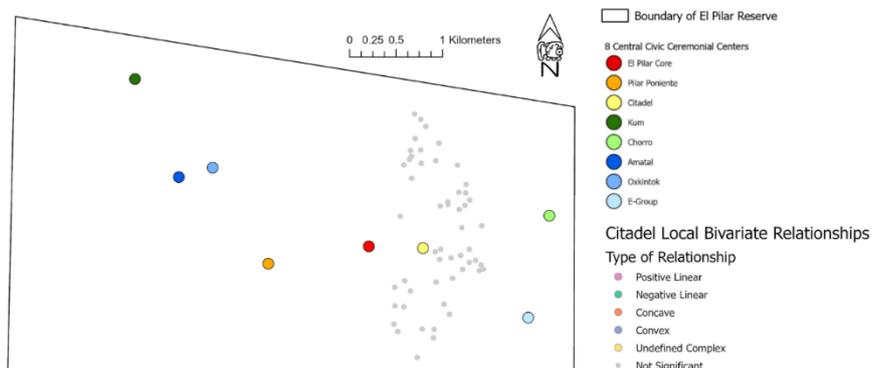
AP13 – Figure 1: Local Bivariate Relationship – One center El Pilar core



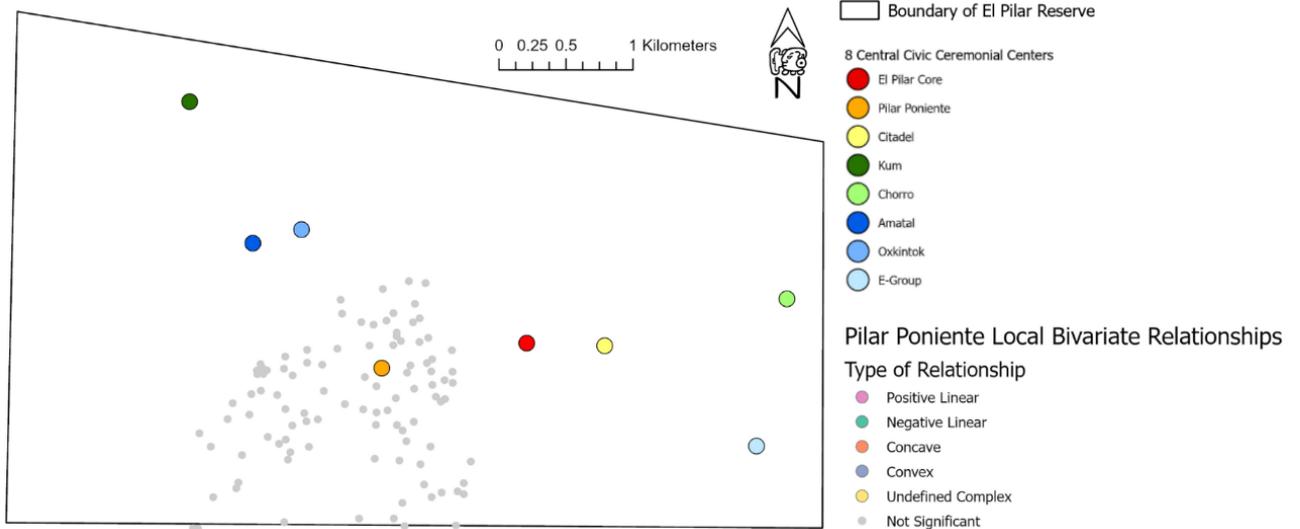
AP13 – Figure 2: Local Bivariate Relationship – Several Center El Pilar Core



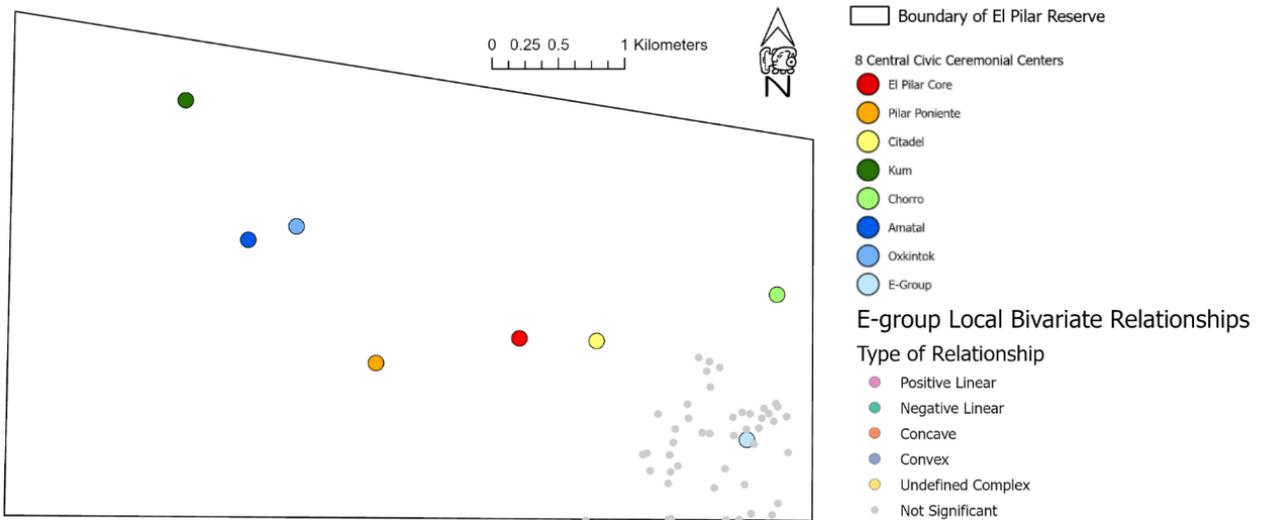
AP13 – Figure 3: Local Bivariate Relationship - Several Center Ciudadel



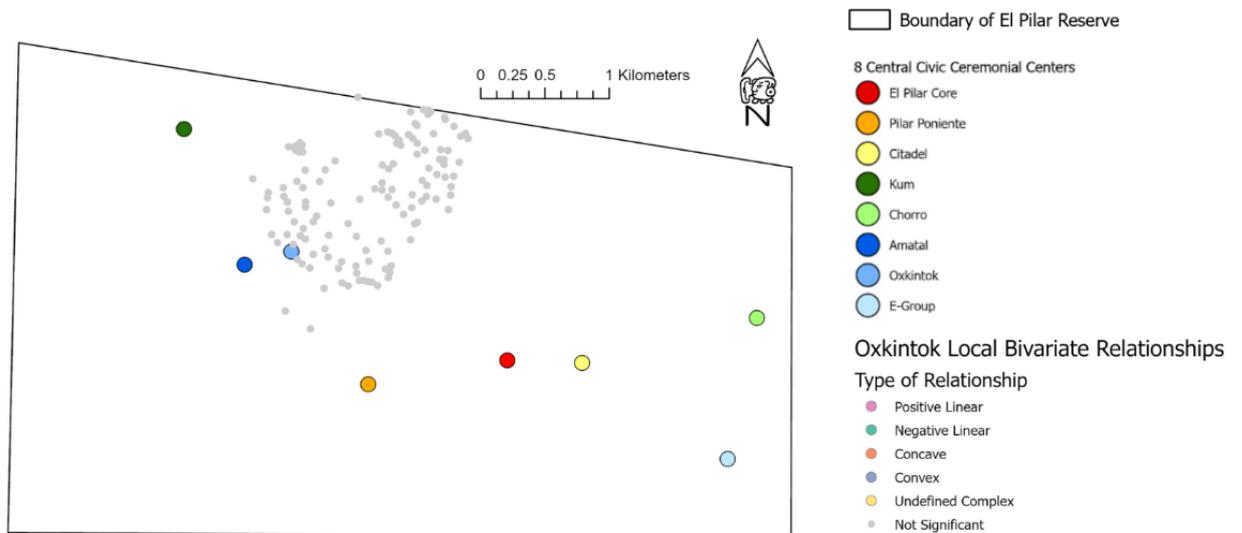
AP13 – Figure 4: Local Bivariate Relationship – Several Center Pilar Poniente



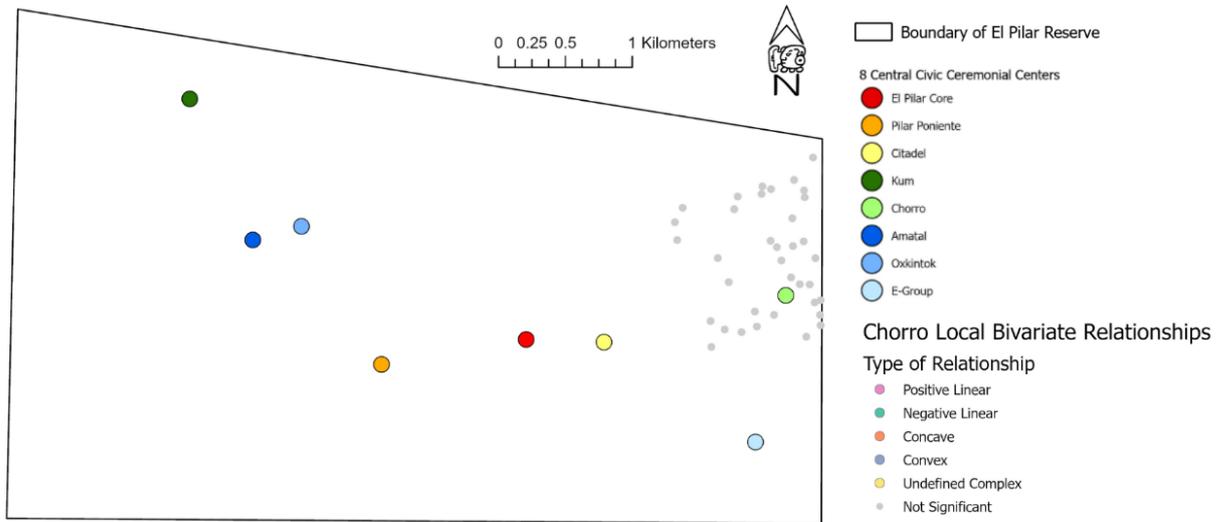
AP13 – Figure 5: Local Bivariate Relationship – Several Center E-Group



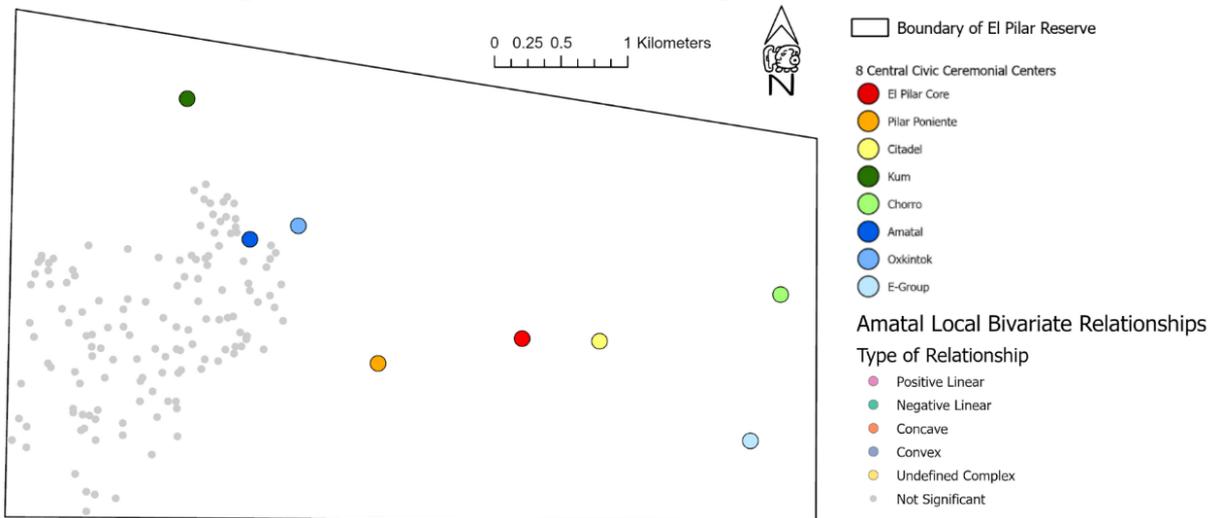
AP13 – Figure 6: Local Bivariate Relationship – Several Center Oxkintok



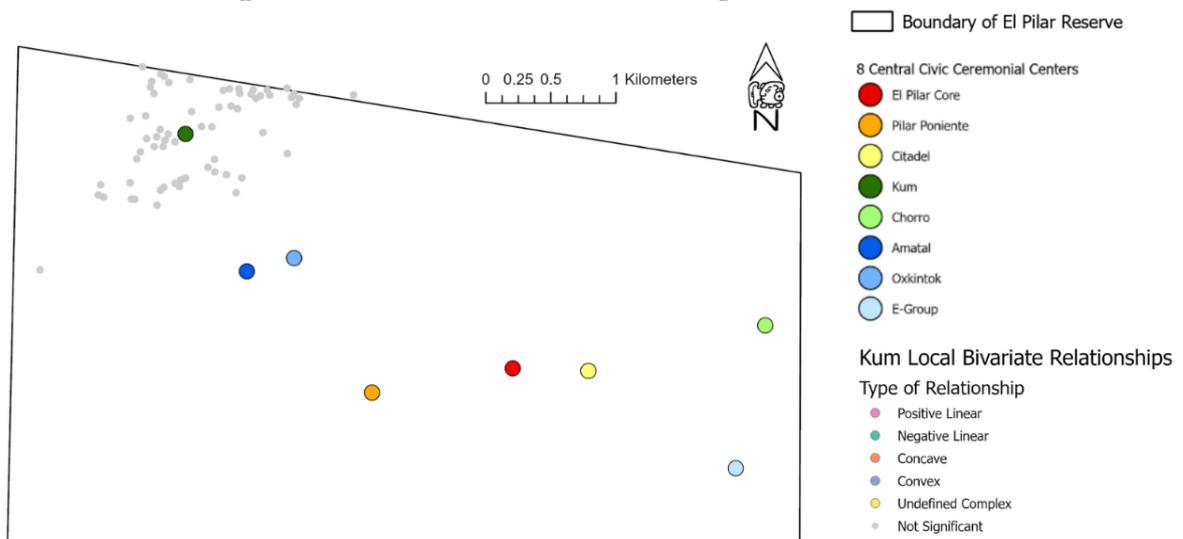
AP13 – Figure 7: Local Bivariate Relationship – Several Center Chorro



AP13 – Figure 8: Local Bivariate Relationship – Several Center Amatal



AP13 – Figure 9: Local Bivariate Relationship – Several Center Kum



Personal source: data ISBER/MARC, UCSB, June 22, 2023.

Appendix 14

Correlations of the 8 central powers

The correlation of Pearson, Kendall and Spearman are calculated for the eight possible civic centers of El Pilar in the AP14 Figure 1. The results obtained do not allow us to conclude that there is a definite relationship between the labor investment of PRU and the distance to the center.

AP14 - Table 1: Correlations of the 8 central powers

	Pearson	Kendall	Spearman
El Pilar Core (134)	-0.16	-0.10	-0.15
Citadel (58)	-0.35	-0.19	-0.29
Pilar Poniente (104)	-0.25	-0.16	-0.25
E-group (49)	0.19	0.16	0.21
Oxkintok (134)	-0.18	-0.10	-0.15
Chorro (38)	-0.24	-0.11	-0.17
Amatal (143)	-0.29	-0.20	-0.28
Kum (66)	0.09	0.06	0.08

Legend: The number in brackets corresponds to the number of PRUs closest to the center.

Personal source: data ISBER/MARC, UCSB, June 22, 2023.

Appendix 15

Area of soil

Each analysis is related to number of hectares over which soil types extends at El Pilar. The area of each soil at El Pilar per hectare and percentage is summarized in AP15 Table 1. That is the table used for each density calculation.

AP13 - Table 1: Numerous Soils in boundaries of El Pilar

	Leptosol	Rendzic Leptosol	Leptic Calcaric Phaeozem	Calcaric Phaeozem	Eutric Vertisol	Vertic Phaeozem	Arenic Fluvisol	Sum
Area of each soil (in ha)	47.37	603.48	643.58	186.59	394.05	150.29	15.28	2040.64
Area of each soil (in %)	2.32	29.57	31.54	9.14	19.31	7.36	0.75	100

Legend: in blue: most common soils at El Pilar

Personal source: Soils data, Víctor Ku and Jorge Mendoza - *El Colegio de la Frontera Sur (2023)* and data ISBER/MARC, UCSB, June 22, 2023.

At El Pilar, two primary types of soil prevail: the Rendzic Leptosol and the Leptic Calcaric Phaeozem, both of which are highly suitable for crop cultivation. This further reinforces the idea that El Pilar is situated on fertile land ideal for cultivation purposes.

Appendix 16

Count of Chultuns, Aguadas and Quarries

AP16 Tables 1,2 and 3 shows the count of Chultuns, Aguadas and Quarries per soil types at El Pilar.

AP16 - Table 1: How many Chultuns per soil type?

	Leptosol	Rendzic Leptosol	Leptic Calcaric Phaeozem	Calcaric Phaeozem	Eutric Vertisol	Vertic Phaeozem	Arenic Fluvisol	Sum
Chultuns Count	25	82	25	9	10	6	0	157

Legend: in blue: Soil with the highest number of Chultuns

Personal source: Soils data, Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur (2023) and data ISBER/MARC, UCSB, June 22, 2023.

AP16 - Table 2: How many Aguadas and Depressions per soil type?

	Leptosol	Rendzic Leptosol	Leptic Calcaric Phaeozem	Calcaric Phaeozem	Eutric Vertisol	Vertic Phaeozem	Arenic Fluvisol	Sum
Aguadas Count	9	87	45	10	17	15	0	183

Legend: in blue: Soil with the highest number of Aguadas

Personal source: Soils data, Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur (2023) and data ISBER/MARC, UCSB, June 22, 2023.

AP16 - Table 3: How many Quarries per soil type?

	Leptosol	Rendzic Leptosol	Leptic Calcaric Phaeozem	Calcaric Phaeozem	Eutric Vertisol	Vertic Phaeozem	Arenic Fluvisol	Sum
Quarries Count	40	243	68	13	26	12	0	402

Legend: in blue: Soil with the highest number of quarries

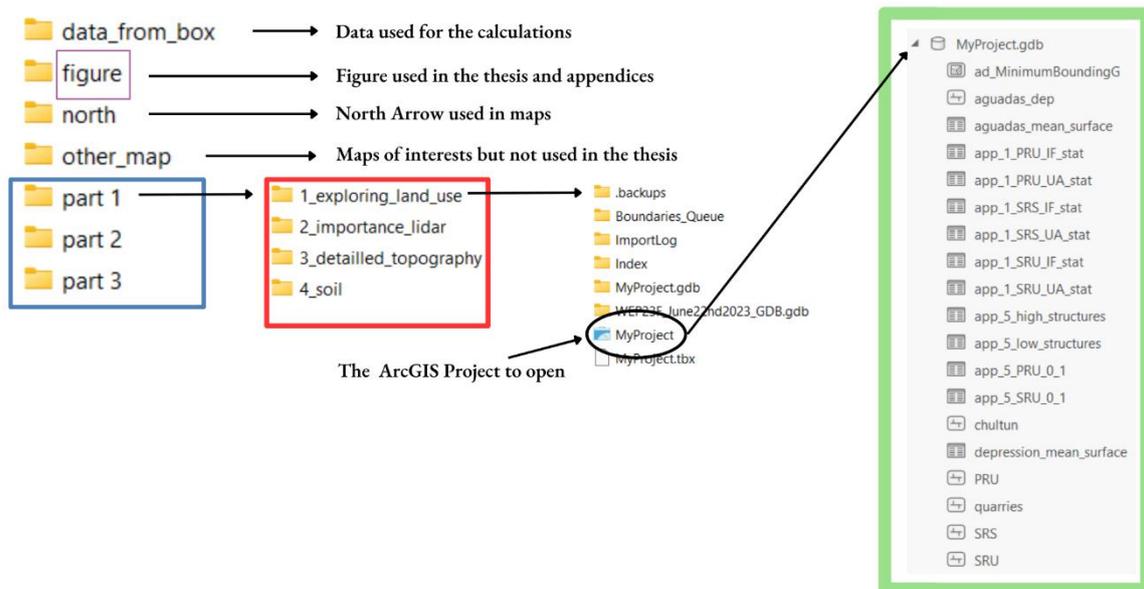
Personal source: Soils data, Víctor Ku and Jorge Mendoza - El Colegio de la Frontera Sur (2023) and data ISBER/MARC, UCSB, June 22, 2023.

Appendix 17 Folder hierarchy

This appendix is a note explaining where you can find results for each part of my thesis. Look at the AP17 Figure 1 while reading the explanatory text.

There are three folders corresponding to the three parts of my thesis (blue). In each of them, there are numerous subfolders (red). Within each subfolder, you will find the ArcGIS Project file (.aprx) and sometimes an Excel Table (pink). Once you open the ArcGIS Project, the name of the layer of interest for each part is written in the explanation below (green). Additionally, the folder hierarchy where the figures were created is described below in purple. Some of the figures have been reworked or created using Canva. The final figures are therefore located in the 'figure' folder.

AP17 – Figure 1: Example of folder hierarchy



I. FEATURES THAT GOVERN MAYA ORGANIZATION

I.1. EXPLORING LAND USE THROUGH SELECTED STRUCTURES

I.1.1 Large Architecture

I.1.2 Assessing Residential or Domestic Remains

I.1.2.1 Primary Residential Unit

Part 1 → 1_exploring_land_use → PRU

I.1.2.2 Secondary Residential Unit and Chultun

Part 1 → 1_exploring_land_use → SRU

Part 1 → 1_exploring_land_use → chultun

I.1.3 Gathering natural resources.

I.1.3.1 Aguadas and Depressions

Part 1 → 1_exploring_land_use → aguadas_dep

Part 1 → 1_exploring_land_use → ad_MinimumBoundingG

Part 1 → 1_exploring_land_use → aguadas_mean_surface

Part 1 → 1_exploring_land_use → depressions_mean_surface

I.1.3.2 Quarries

Part 1 → 1_exploring_land_use → quarries

I.2 THE IMPORTANCE OF LIDAR AT EL PILAR

I.2.1 The method to survey

I.2.2 LiDAR, such a significant asset?

Part 1 → 2_importance_lidar → A_0_1

Part 1 → 2_importance_lidar → A_R_1

I.2.3 The Detailed Topography by means of LiDAR.

I.2.3.1 Elevation and Slope

Part 1 → 3_detailed_topography → slope

Part 1 → 3_detailed_topography → reclass_slope

Part 1 → 3_detailed_topography → reclass_elevation

Part 1 → 3_detailed_topography → Figure 3

I.2.3.2 Sun exposure

Part 1 → 3_detailed_topography → sun_exp

Part 1 → 3_detailed_topography → reclass_sun_exp

Part 1 → 3_detailed_topography → Figure 4

I.3 A WELL-ORGANIZED FOREST LANDSCAPES.

I.3.1 The importance of cultivation

I.3.2 Home-garden infield

Part 3 → 1_cultivable_land → HomeGardenInfield_Statistics

Part 1 → 1_cultivable_land → Figure 5

Part 1 → 4_soil → Figure 7

I.3.3 Milpa Cycle

I.4 CULTIVABLE SOIL

I.4.1 The methodology behind Soil Map at El Pilar

I.4.2 Many characteristics to classify.

II. SOCIAL FACTORS INFLUENCED LAND USE.

II.1 PROPERTY AND SOCIAL ORGANIZATION AT EL PILAR.

II.1.1 Common spaces, a specific characteristic of Maya world

II.1.2 The organization of different classes at El Pilar

II.2 PLACES OF POWER

II.2.1 Central civic ceremonial centers

Part 2 → 2_1_Central civic ceremonial centers → Figure 10 and Figure 11

II.2.2 Solitary Range Structure

Part 2 → 2_2_SRS → SRS → ..._FeatureToPoint_GenerateN1

Part 2 → 2_2_SRS → center_dispersion → ..._ellipse

Part 2 → 2_2_SRS → center_dispersion → ..._central

Part 2 → 2_2_SRS → center_dispersion → ..._median

Part 2 → 2_2_SRS → center_dispersion → ..._mean

(... = PRU, SRU or SRS)

Part 2 → 2_2_SRS → center_dispersion → Figure 12

II.3. LABOR INVESTMENT: A TOOL TO EXPLAIN ORGANIZATION OF TERRITORY.

II.3.1 Labor investment analysis

II.3.1.1 About Labor investment

II.3.1.2 Trends in maya organization

Part 2 → 3_1_Labor_investment_analysis → Figure 13 and Figure 14

II.3.1.3 PRU of elite status.

Part 2 → 3_1_Labor_investment_analysis → Figure 15

II.3.2 Statistics about Labor Investment: PRU and distance to power centers.

II.3.2.1 Test with ArcGIS

II.3.2.1.1 A multitude of concentric rings.

Part 2 → 3_2_stat_PRU_LI_DIST → Concentric_rings_correlation_one_center_BR_corr → Figure 16

II.3.2.1.2 ArcGIS tool: Local Bivariate Relationships

Part 2 → 3_2_stat_PRU_LI_DIST → Concentric_rings_correlation_one_center_BR_corr → LocalBivariateRelationships → Figure 17

Part 2 → 3_2_stat_PRU_LI_DIST → Each_center_BR_corr → ...LocalBivariateRelationships

II.3.2.2 Correlation's Pearson, Kendall, and Spearman.

II.3.2.2.1 Pearson with one center

Part 2 → 3_1_Labor_investment_analysis → one_center

II.3.2.2.2 Kendall with one center

Part 2 → 3_1_Labor_investment_analysis → one_center

II.3.2.2.3 Spearman with one center

Part 2 → 3_1_Labor_investment_analysis → one_center

II.3.2.2.4 Correlations with the 8 centers

Part 2 → 3_2_stat_PRU_LI_DIST → Each_center_BR_corr → each_center_pearson

Part 2 → 3_2_stat_PRU_LI_DIST → Each_center_BR_corr → each_center_spearman_kendall

II.4 ARE ELITE PRU ENDOWED WITH SUPERIOR RESOURCES?

II.4.1 Access to central power

Part 2 → 4_superior_ressources → Access to central power

II.4.2 Access to water

Part 2 → 4_superior_ressources → Access to water

II.4.3 Access to soil

Part 2 → 4_superior_ressources → Access to soil

III. ARCHAEOLOGICAL FEATURES AND ENVIRONMENTAL INTERACTIONS.

III.1 CULTIVABLE LAND.

Part 3 → 1_cultivable_land → Figure 18

III.2 LOCATION OF RESIDENTIAL UNITS.

III.2.1 Soil fertility and RU

Part 3 → 2_location_ru → soil_PRU_fert

Part 3 → 2_location_ru → soil_SRU_fert

III.2.2 Soil drainage and RU

Part 3 → 2_location_ru → soil_PRU_drain

Part 3 → 2_location_ru → soil_SRU_drain

III.2.3 Type of Soil and RU

Part 3 → 2_location_ru → soil_type_PRU

Part 3 → 2_location_ru → soil_type_SRU

III.2.4 DEM and RU

III.2.4.1 Slope and RU

Part 3 → 2_location_ru → Tabulate_Reclass_slope_...

III.2.4.2 Sun exposure and RU

Part 3 → 2_location_ru → Tabulate_polygon_...

Part 3 → 2_location_ru → Excel: sunexposure → Figure 19

III.3. RELATIONSHIP BETWEEN FEATURES, ENVIRONMENT AND PRU.

III.3.1 The storage facilities

III.3.1.1 The soil type of chultun

Part 3 → 4_gathering → soil_chultun

III.3.1.2 Exploring Connection between a PRU and storage facilities.

Part 3 → 3_vicinity → Chultun_in_infield_poly

Part 3 → 3_vicinity → SRU_in_infield_poly

III.3.1.3 The sharing of SRU and Chultun

Part 3 → 3_vicinity → NEAR_SRU

Part 3 → 3_vicinity → NEAR_SRU_stat

Part 3 → 3_vicinity → NEAR_CH

Part 3 → 3_vicinity → NEAR_CH_Stat

Part 3 → 3_vicinity → NEAR_SRU_SUM

Part 3 → 3_vicinity → NEAR_SRU_SUM_Stat

Part 3 → 3_vicinity → Excel: sunexposure → Figure 20 and Figure 21

III.3.2 The natural resource collection features.

III.3.2.1 Aguadas

III.3.2.1.1 The soil type of aguadas

Part 3 → 4_gathering → soil_ad

III.3.2.1.2 Aguadas next to PRU

Part 3 → 3_vicinity → AD_in_infield_poly

III.3.2.1.3 The sharing of Aguadas

Part 3 → 3_vicinity → NEAR_AD

Part 3 → 3_vicinity → NEAR_AD_Statistics

Part 3 → 3_vicinity → Excel: sunexposure → Figure 22

III.3.2.2 Quarries

III.3.2.2.1 The soil type of quarries

Part 3 → 4_gathering → soil_quarries

III.3.2.2.2 Sharing of Quarries

Part 3 → 3_vicinity → QUA_in_infield_poly

Part 3 → 3_vicinity → NEAR_QUA

Part 3 → 3_vicinity → NEAR_QUA_Statistics

Part 3 → 3_vicinity → Excel: sunexposure → Figure 23

Appendix 1:

Part 1 → 1_exploring_land_use → app_1_...

Appendix 5:

Part 1 → 1_exploring_land_use → app_5_...

Appendix 6:

Part 1 → 3_detailed_topography

Appendix 9:

Part 1 → 4_soil → AP9F1

Appendix 10:

Part 2 → 3_1_Labor_investment_analysis → AP10F1

Appendix 11:

Part 2 → 3_2_stat_PRU_LI_DIST → AP10F1

Appendix 12:

Part 2 → 3_2_stat_PRU_LI_DIST → Concentric_rings_correlation_one_center_BR_corr

AP17 – Table 1: Layer in the Folder Concentric_rings_correlation_one_center_BR_corr

	Hypothesis 1		Hypothesis 2
	El Pilar Core	El Pilar Core + Pilar Poniente + Citadel	8 centers
Rings 100, 300, 500 and 700	pop_1_1_sw	pop_3_1_sw	pop_8_1_sw
Rings 500, 1000, 1500 and 2000	pop_1_2_sw	pop_3_2_sw	pop_8_2_sw
Rings 500, 1000, 1500 and All area	pop_1_3_sw	pop_3_3_sw	pop_8_3_sw

Appendix 13:

Part 2 → 3_2_stat_PRU_LI_DIST → Concentric_rings_correlation_one_center_BR_corr

→ LocalBivariateRelationships → AP13F1

Part 2 → 3_2_stat_PRU_LI_DIST → Each_center_BR_corr → ...LocalBivariateRelationships → AP13F2 AP13F3 AP13F4 AP13F5 AP13F6 AP13F7 AP13F8 AP13F9

Appendix 14:

Part 3 → 3_vicinity → Excel: corr_without_transfo + corr_with_transfo

Appendix 15:

Part 1 → 4_soil → Polygonsofsoiltypes_Statisti

Part 1 → 4_soil → Excel: area_soil_type

Appendix 16:

Part 3 → 3_vicinity → Excel: aguadas + quarries + chultun_sru

Appendix 18 ArcGIS tools

Lots of tools have been used in this thesis. The AP17 Table 1 summary tools mostly used with ArcGIS in each part of my thesis.

AP17 - Table 1: Tools used

Tools	Tools explanation
Minimum Bounding Geometry	closes lines to define a surface for aguadas and depressions.
Summarize	extremely useful tools for averaging, summing, counting the number of elements, etc.
Statistics/ create Chart	to obtain a chart or scatter plot from the attributes of my table
Near / Generate Near Table	find the element(s) closest to a structure
Surface Parameters	calculates slope (slope) or sun exposure (aspect) from DEM for 1m-by-1m cells
Reclassify / Classify (appendix 9)	defines categories, simplifies interpretation
Summarize center and dispersion	for a set of data to obtain the center, median and mean points and the ellipse
Tabulate Area	allows raster data to be crossed with other data to obtain a count
Summarize within	count the number of elements in a polygon
Buffer / Ring buffer	as its name suggests, creates one or more zones around an element
Transform Field	Transform a field in a new field with logarithmic transformation
Point to raster / Feature to point.	There are many tools available for switching from one type to another. These two tools are the most widely used.
Local Bivariate Relationship	Test the relationship between two data.

Personal source: Named of tool came from ArcGIS, personal explanation.

The Excel data analysis module XLSTAT is used to calculate correlations. The same results are obtained with a Python script.

Thanks to the relationship in the database, it became feasible to access the same element in another layer by simply clicking on the corresponding layer element and navigating to the "related data" option.

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Analysis of land use by Maya civilization: Settlements patterns at El Pilar archeological site

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RESUME

De nombreuses structures attestent de la présence de la civilisation Maya à El Pilar. Ces structures sont agencées d'une certaine manière, probablement en raison de facteurs sociaux ou environnementaux.

L'organisation sociale pourrait fournir une explication concernant la localisation des différentes structures ou des lieux de culture. Certains archéologues penchent pour une organisation concentrique, cette hypothèse est testée et réfutée sur le site d'El Pilar. D'autre part, les aspects environnementaux tels que les sols et la topographie ne doivent pas être négligés. Pour le moment, ils ne permettent pas d'expliquer pleinement la localisation des lieux de culture. Néanmoins, ils offrent une meilleure compréhension de l'emplacement des habitations, des lieux de stockage et d'autres éléments. Enfin, selon les statistiques effectuées, le partage des terres et la répartition des structures semblent être au cœur du mode de vie des Mayas.

Mots clés : LiDAR, modèle de peuplement, utilisation des sols, investissement en main d'oeuvre, sociaux, environnementaux

SUMMARY

Numerous structures attest to the presence of the Maya civilization at El Pilar. These structures are arranged in a certain way, probably due to social or environmental factors.

Social organization could provide an explanation for the location of different structures or cultivation sites. Some archaeologists favour a concentric organization, but this hypothesis has been tested and disproved at the El Pilar site. On the other hand, environmental aspects such as soils and topography must not be overlooked. For the moment, they do not fully explain the location of cultivation sites. Nevertheless, they do offer a better understanding of the location of dwellings, storage facilities and other elements. Finally, according to the statistics, the sharing of land and the distribution of structures seem to be at the heart of the Maya way of life.

Key words: LiDAR, settlements patterns, land use, labor investment, social, environmental.