GEOSPATIAL INTEGRATION IN MAPPING PRE-HISPANIC SETTLEMENTS WITHIN AZTEC EMPIRE LIMITS

INTEGRACIÓN GEOESPACIAL PARA MAPEAR ASENTAMIENTOS PREHISPÁNICOS EN LOS LÍMITES DEL IMPERIO AZTECA

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Highlights:

- A pre-Hispanic settlement within the southern limits of the Aztec Empire (Lerma River Basin-Balsas River Basin, State of Mexico, Mexico) was systematically surveyed based on GIS integration data from optical sensors.

- The combination of varied input data (Sentinel 2, UAV, DTM and NDVI) can be replicated as an alternative research method for similar mountainous landscapes with dense vegetation cover in emerging market economies.

- The result is a binary map of potential anthropic features, with field validation in rugged terrain to distinguish anthropic anomalies (75%) from those of natural origin (25%).

Abstract:

Mexico's vast archaeological research tradition has increased with the use of remote sensing technologies; however, this recent approach is still costly in emerging market economies. In addition, the scales of prospection, landscape, and violence affect the type of research that heritage-culture ministries and universities can conduct. In Central Mexico, researchers have studied the pre-Hispanic Settlement Pattern during the Mesoamerican Postclassic (900-1521 AD) within the scope of the Aztec Empire and its conquests. There are settlements indications before and during the rule of the central empire, but the evidence is difficult to identify, particularly in the southwest of the capital, in the transition between the Lerma and Balsas River basins and their political-geographical complexities. This research focuses on a Geographic Information System (GIS)-based processing of multiple source data, the potential prospection of archaeological sites based on spatial data integration from Sentinel-2 optical sensors, Unmanned Aerial Vehicle (UAV), Digital Terrain Model (DTM), Normalized Difference Vegetation Index (NDVI) and field validation. What is revealed is the relationship between terrain morphologies and anthropic modifications. A binary map expresses possible archaeological remnants as a percentage; NDVI pixels and the morphometry values were associated with anthropic features (meso-reliefs with a tendency to regular geometries: slope, orientation, and roughness index); they were then interpreted as probable archaeological evidence. Within archaeological fieldwork, with limited resources (time, funding and staff), this approach proposes a robust method that can be replicated in other mountainous landscapes that are densely covered by vegetation.

Keywords: Mesoamerican Postclassic; Aztec Empire; Sentinel-2 optical sensors; Unmanned Aerial Vehicle (UAV); Digital Aerial Photogrammetry (DAP); Normalized Difference Vegetation Index (NDVI)

Resumen:

México tiene una vasta tradición de investigación arqueológica que, en las últimas décadas, se ha incrementado con el uso de tecnologías de percepción remota; sin embargo, este enfoque sigue siendo costoso en el contexto de las economías emergentes. Además, las escalas de prospección, paisaje e inseguridad influyen en el tipo de investigación que realizan los ministerios de patrimonio cultural y las universidades. En el Centro de México, el Patrón de Asentamiento Prehispánico durante el Posclásico Mesoamericano (900-1521 d.C.), ha sido estudiado dentro del alcance del Imperio Azteca y sus conquistas. Hay indicios de asentamientos antes y durante el dominio del Imperio central, pero la evidencia es difícil de identificar; particularmente en el suroeste de la capital, en la transición entre las cuencas de los ríos Lerma y Balsas y sus complejidades político-geográficas. Esta investigación se centra en el procesamiento basado en GIS de

datos de múltiples fuentes, la prospección de sitios arqueológicos apoyada en la integración de datos espaciales de los sensores ópticos Sentinel-2, el vehículo aéreo no tripulado (UAV), el modelo digital del terreno (MDT), el índice de vegetación de diferencia normalizada (NDVI) y la validación de campo, que revelan la relación entre las morfologías del terreno y las modificaciones antrópicas. Un mapa binario expresa los posibles remanentes arqueológicos como un porcentaje; los píxeles del NDVI y los valores de morfometría se asociaron a características antrópicas (mesorrelieves con tendencia a geometrías regulares: pendiente, orientación e índice de rugosidad), y se interpretaron como probable evidencia arqueológica. Dentro del trabajo de campo arqueológico, con recursos limitados (tiempo, finanzas y auxiliares), este enfoque sugiere un método robusto que puede ser replicado en otros paisajes montañosos que están densamente cubiertos por vegetación.

1. Introduction

Limited time and financial resources in specific geographic areas impose constraints on archaeological surveys, particularly in emerging market regions such as Latin America (Ledergerber-de-kohli, 1984; McAnany & Rowe, 2015). Mesoamerican Archaeology focuses on prospecting and preserving monumental sites, while smaller sites are relegated to and even destroyed by urbanization (López Wario, 2016). This generates a bias in understanding the historical processes of ancient societies (Sugiura & Nieto, 2014). Therefore, affordable prospection and interpretation methodologies are critical to continuing research and preserving heritage. As a result, the application of remote sensing improvements — combining different scales, types of sensors (Red-Green-Blue (RGB) and infrared (IR), on satellite devices and UAV), radiometry capacities and spatial resolutions— to land use analysis has been a challenge compared to traditional archaeological prospection.

Currently, open-source data represents a broad advantage for archaeological prospection (Agapiou, Alexakis, Sarris & Hadjimitsis 2014; Parcak, 2017), compared to the restrictions of other resources with a resolution greater than 10 m per pixel and commercial software. In addition, the use of UAV has been widely adopted as an important archaeological tool, as technology improves and costs plummet (e.g., Lasaponara & Masini, 2016; Hill, 2019) with the application of photogrammetry (e.g. Fernández-Hernández, González-Aguilera, Rodríguez-González & Mancera-Taboada, 2015; O'Driscoll, 2018). In Mesoamerican research, there are more products such as Digital Surface Models (DSMs), geo-referenced orthophotos, Digital Elevation Models (DEMs), and pseudo-3D models for topographic mapping (Gutiérrez, Erny, Friedman, Godsey & Gradoz, 2016; Hinojosa Baliño, 2016). The purchase of airborne photography is potentially lower than the acquisition cost of Light Detection and Ranging (LiDAR) technology (Jensen & Mathews, 2016; Stone, Webster, Osborn & Iqbal, 2016; Fernández-Lozano & Gutiérrez-Alonso, 2016).

However, the visibility of micro-reliefs depends on many factors, especially the presence of vegetation. Multispectral image analysis for detecting crop marks is used in specific channels more sensitive to vegetation, such as near-infrared (NIR) or spectral indices (Bennett, Welham, Hill & Ford, 2012; Calleja et al., 2018). In arable lands, the airborne detection of archaeological features depends on the properties of the vegetation cover as a proxy for sub-surface features. Under proper conditions, the formation of vegetation marks allows archaeologists to identify and interpret ancient remnants (Stott, Boyd, Beck & Cohn, 2015). Nevertheless, in densely forested highlands, visibility conditions complicate prospection (Golden et al., 2016).

Mountainous ecosystems are among the most extensive in Mexico. They were preferred settlements due to the provision of multiple ecological services (Cantú Ayala, Estrada Arellano, Salinas Rodríguez, Marmolejo Monsiváis & Estrada Castillón, 2013), dependent on climate, hydrology, and soil fertility.

The volcanic landscapes in the central-south of the Trans-Mexican Volcanic Belt (TMVB), present particular complications for archaeological fieldwork due to scales of prospection (including the availability of images with the appropriate resolution and their cost), road infrastructure and social conflicts. Although prospection geotechnologies are more common at the local level in mountainous areas (e.g. Castillo Serván & Patroni ,2019; Rouse & Krumnow, 2020), these are regularly applied in low topographies with scarce vegetation, providing some advantages in locating anthropogenic geoforms (Fernández-Lozano & Gutiérrez-Alonso, 2016; Brooke & Clutterbuck, 2020). Such conditions, at least in Central Mexico, are not the most frequent for human settlements. The environmental conditions and archaeological records at each site are decisive factors affecting investment and risk in prospection activities; hence, it is important to generate predictive models to clarify the strategy and priorities under consideration (e.g. Vaughn & Crawford, 2009; Danese, Masini, Biscione & Lasaponara, 2014; Kirk, Thompson & Lippitt, 2016; Noviello, Cafarelli, Calculli, Sarris & Mairota, 2018).

In this work, we conducted archaeological prospection analysis in Meyuca de Morelos, Coatepec Harinas, Mexico, based on the remote sensing data from different sensors, spectral capacities, spatial resolution and scale. The challenge was to conduct a spatial correlation and data fusion between the sources to detect settlement patterns on the ground and then validate them in the field.

1.1. The Postclassic in the Central Highlands and southern Matlazinca province

In Central Mexico, during the Postclassic Period (900-1521 AD), the majority of the indigenous population was organized in *altépetl* or city-states (Carrasco,1996; Lockhart, 1999; Fernández Christlieb & García Zambrano, 2006; Smith, 2008), with a settlement pattern that frequently dispersed over ravines and slopes (Garza Merodio & Fernández Christlieb, 2016). The ruler and a sizable proportion of the population resided in the eponymous capital of the *altépetl*, whose size and importance overshadowed other villages in its territory (Borejsza, 2018).
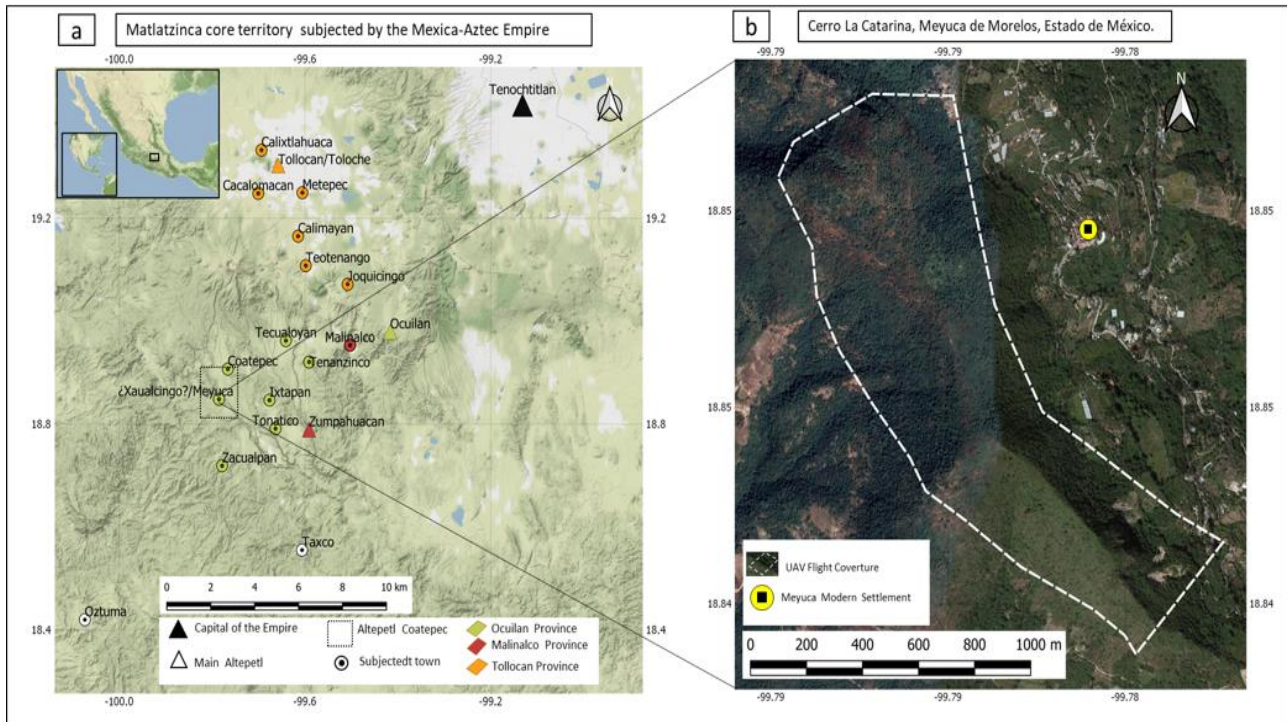
Figure 1: a) The modern settlement of Coatepec Harinas is a direct remnant of a territorial-political entity dominated by the Aztec Empire (or the Triple Alliance, a confederation of indigenous states centered in the Valley of Mexico); b) The Meyuca de Morelos settlement, and the hill at Cerro La Catarina.

In the Basin of Mexico (Sanders, Parsons & Santley, 1979), the Toluca Valley (Tomaszewski & Smith, 2011, Nieto, 2012; Sugiura & Nieto, 2014), and the southern section of the modern province of the State of Mexico (Jaramillo, 1987; Arana, 1990; De la Peña Guevara, Favila & Siles, 2008; García Castro, 2013; Palma, 2014; Garza Merodio & Fernández Christlieb, 2016), research has developed that centres on minor-scale archaeological sites, to understand the territorial dynamic prior to the Spanish conquest.

Local analysis, such as at Tenango (Garza Merodio & Fernández Christlieb, 2016), proposes landscape changes during the Mesoamerican Postclassic and the Colonial Epoch, particularly within the Matlatzincas settlements; it suggests that its core territory (Fig. 1a) spanned from Calixtlahuaca, Calimaya and Tenango to Coatepec-Harinas and Texcaltitlán. These are considered to be a series of villages mainly established along the Upper Lerma River Basin, whose expansion to the southern lowlands was facilitated through mountain passes. In the southernmost sites (Tenancingo, Ocuilan, Malinalco, Teotenango, and Tecualoyan), the complexities of the settlements are associated with their cultural affiliation and landscape and are even related to the Balsas River Basin provinces (Smith & Berdan 1996; Gutiérrez, 2017). This latter area served as a supplementary passage for resources, as well as the main route to southwestern Mesoamerica, even during the Spanish conquest (Garza Merodio & Fernández Christlieb, 2016).

As a result, it is challenging to distinguish well-defined boundaries between these southern territories (Tomaszewski & Smith, 2001), particularly after their conquest and subjection to the Aztec Empire (Isaac,

1983; Hassig, 1988; León-Portilla, 2000; Albores, 2006; Gutiérrez, 2017). There are additional interpretations inferred from historical documents (García Castro, 1999, 2013; Vázquez, 2008; González 2010, 2013) and toponymy that allude to the sites before the Spanish conquest. There are only a few records of archaeological site interventions corroborated by the *Instituto Nacional de Antropología e Historia* (National Institute of Anthropology and History - INAH), which described sites such as Coatepec (INAH, 2018) and El Jagüey (INAH, 2018); both sites are associated with the chronology of the Aztec Empire (1200-1521 AD). The Coatlán Project mentions the Coatepec settlement (Arana, 1990); however, the research focuses on the southernmost locations, some of which are adjacent to the modern municipality of Coatepec Harinas.

The modern settlement of Coatepec Harinas is a direct remnant of a territorial-political entity dominated by the Aztec Empire (e.g. Smith & Sergheraert, 2012; Berdan, 2017; Gutiérrez, 2017) during its control over the area of Matlatzinca (Isaac, 1983; Hassig,1988; Ruz Barrio, 2019), and which used the tax system as a mechanism to obtain resources (Berdan, 1996). On Folio 34r of the Codex Mendoza (2014) and the Tribute Registry ('*Matrícula de tributos*'), the Coatepec settlement is mentioned (Barlow, 1992, p. 34) (Fig. 1a) as belonging to the province of Ocuilan along with Tenancingo, and Tecualoyan. Therefore, it was one of the distant *Altepemes* under the tributary and provincial division system of the Aztec Empire (Carrasco, 1996).

The need to record and recover archaeological evidence that has been subject to different environmental conditions (natural and induced) requires researchers to develop affordable and relatively easy-to-read

prospection methodologies in order to plan interventions on complex territories, avoid the loss of sensitive information on these peripheral regions of the great empire, and add to the discussion on "strategic provinces" (e.g. Smith & Berdan, 1996, Sergheraert, 2017).

1.2. Study area

The research was conducted within the current borders of the municipality of Coatepec Harinas (Fig. 1a). In order to lead the regionalization and identification of sites with high archaeological potential, the authors reviewed historical cartography manufactured during the 15th through 17th centuries (with clear references to Coatepec, Meyuca, Acuitlapilco and Chiltepec and the remnants of their pre-Hispanic settlements). These documents are under the custody of the General Archive of the Nation (AGN) in Mexico City.

Based on satellite remote sensing, and corroborated with documents and local informants, the Meyuca de Morelos settlement (18.55° 142' N; 99,78° 143' W), and the Hill at Cerro La Catarina (Fig. 1b) show high archaeological potential based on the artefacts, terrace structures, discontinuous walls and looting at the site (Fig. 2).

The area is located on the border of the physiographic provinces of the TMVB and the Sierra Madre del Sur (SMS), in the Balsas-Mexcala Basin Sub-province, and in part of the Guerrero Terrain, based on the tectonostratigraphic classification (Campa & Coney, 1983). The volcanic lithology is extensive; however, low-grade metamorphism and sedimentary outcrops are evident in the base of the mountain ranges flanking the municipality of Coatepec Harinas. The Mexican Geological Survey (SGM, 2013) ties these volcanic rocks to pyroclastic flows and rhyolitic lava emplacement during the Oligocene. Ancient volcanic activity was controlled by tectonic processes that generated faults, fractures and mineralization, affecting the stratigraphic column, including the distal deposits of the Nevado de Toluca volcano, until recently (Capra & Macias, 2000; García-Palomo et al., 2002). Scarps are clearly visible on the eastern slope of Cerro La Catarina, where translational landslides have directly affected the modern settlement of Meyuca de Morelos. The recent deposits are related to rock detachments and alluvial sediments that serve as parental material for Vertisols (over the pyroclastic flows from the Nevado de Toluca volcano), Phaeozems on the low slopes, and Lithosols directly over the rhyolitic flows that make up Cerro La Catarina (INEGI, 1999).

The region presents a temperate subhumid climate with rains in summer and annual precipitation of 1100-2000 mm/year; the average yearly temperature ranges between 6 °C and 20 °C. The maximum rainfall is from June to September (INEGI, 1999). The main rivers correspond to the hydrological regions of the Balsas Basin and the Amacuzac Basin (the Alto Amacuzac Sub-Basin), with important tributaries of perennial currents that actively shaped the landscape.

Evidence of the original vegetation, such as the mountain mesophilic forest, which can grow to more than 25 m high, is still present at Cerro La Catarina; timber trees, including oak, fir, poplar, red oak, cedar and ash, are presented in patches, most growing in the highest reliefs. The area is part of the "Floricultural Corridor of the Southern State of

Mexico" (Ramirez & Avitia, 2018), where the change in land use has generated greenhouse production of fruit trees, including avocado (*Persea americana*), white sapote (*Casimiroa edulis*), capulin cherry (*Prunus salcifolia*), Mexican hawthorn (*Crataegus mexicana*), peaches (*Prunus persica*), Japanese plum (*Prunus salicina*), common pear (*Pyrus communis*), apple (*Malus domestica*), English walnut (*Juglans regia*), lemon (*Citrus limon*) and others.
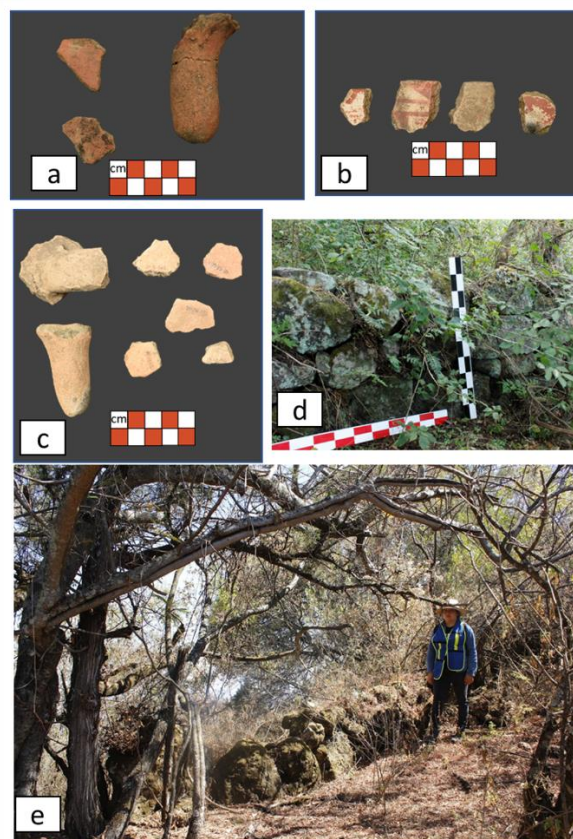
Figure 2: Archaeological evidence and features at the site of Cerro La Catarina: a) Fragment of ceramic vessel; b) Matlatzinca ceramic fragment; c) Ceramic vessel fragment; d) Stone structure alignment on slope; and e) Stone structure alignment on summit.

2. Materials and methods

The workflow in Fig. 3 shows the four progressive research stages:

2.1. Phase A. Remote sensing analysis with Sentinel-2 and UAV

Remote sensing analysis was conducted using open-access data from satellite images generated by multispectral sensors. The sensors are part of the Sentinel 2 mission of the European Space Agency's (ESA) Copernicus program, launched in 2014 and acquired on July 21, 2018, at 16:58:51 (ESA, 2018), at processing level 1C (Table 1).

Since the launch of the Copernicus program, there has been an increase in satellite data to analyze land use and plan territory management. Constant monitoring and

accurate spatial detection of varied ground phenomena make the data an efficient tool for archaeological prospection studies and other disciplines, since they enable constant spatial data acquisition with mid-to high-resolution over extensive areas, resulting in more effective land monitoring systems.

Bands 4 and 8 were resampled with values of 10 m/pixel (considering the atmospheric, reflectance and geometric corrections). NDVI analysis was applied to generate an approximation to susceptible areas with anomalies associated with stressed vegetation (Agapiou et al., 2014; Abate, Elfadaly, Masini & Lasaponara, 2020); using the European Space Agency (ESA) SNAP v. 6.0 software, the index is expressed as:

$$NDVI = (B8-B4)/(B8+B4)$$

Table 1: Sentinel 2 parameters.

Bands	Central wavelength (nm)	Spatial resolution (m)
1	0.443	60
2	0.490	10
3	0.560	10
4	0.665	10
5	0.705	20
6	0.740	20
7	0.783	20
8	0.842	10
8a	0.865	20
9	0.945	60
10	1.375	60
11	1.610	20
12	2.190	20

Table 2: UAV specifications.

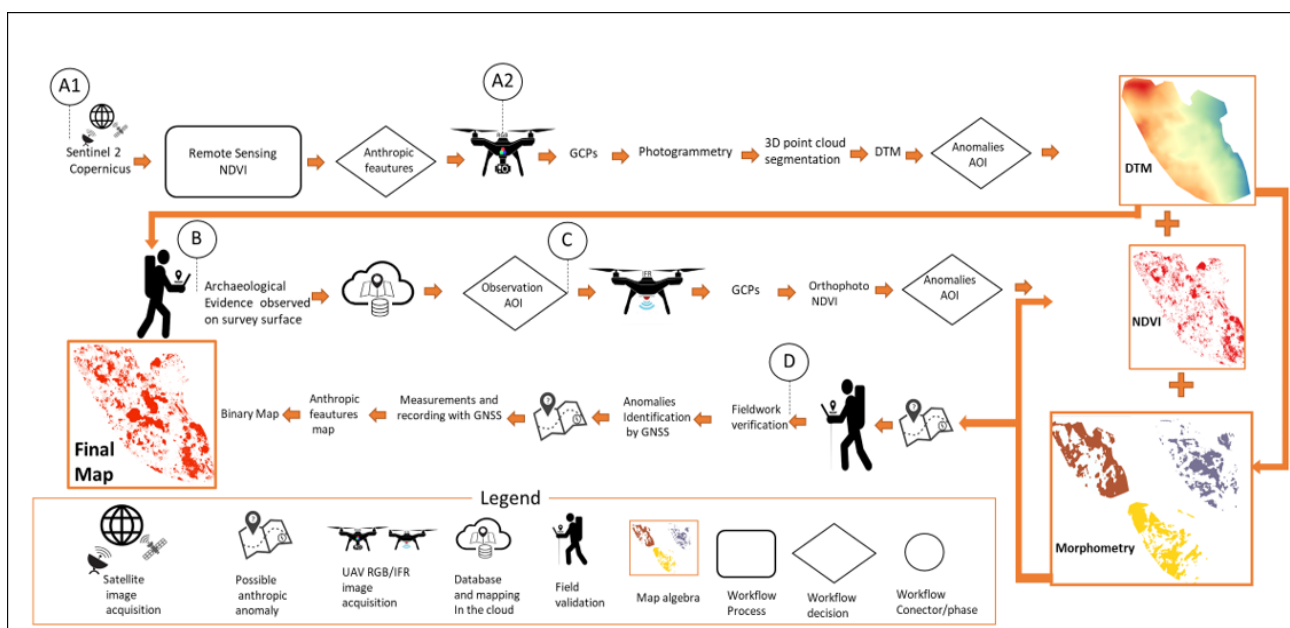| UAV-DAP for DMT (overlap > 70%), applying the SIFT operator (Lowe, 2004)	DJI Phantom 3 advanced (Sensor1) Quadcopter. Autonomy 17 min. HD 4k Resolution RGB	DJI Inspire one (Sensor2) Quadcopter. Autonomy 22 min. HD 4k Resolution R edge / NIR
Sensor	RGB Sony Exmor R BSI 1 / 2.3 Effective pixels: 12.4MP. FOV 94°, lens 20 mm f/2.8, focus at ∞ ISO range 100-3200 (video) 100-1600 (photo) Shutter speed 8s -1 / 8000s Max size Image 4000 × 3000 Photographic modes: Single shot Burst shooting: 3/5/7 shots	Multispectral Parrot Sequoia RGB camera 16 MP Definition: 4608 x 3456 pixels HFOV: 63.9° VFOV: 50.1° DFOV: 73.5° 4 cameras 1.2 MP single band global shutter Definition: 1280 x 960 pixels HFOV: 61.9° VFOV: 48.5° DFOV: 73.7° Bands: Green (550 BP 40), Red (660 BP 40), Red Edge (735 BP 10), NIR (790 BP 40)
Flight height	40-50 m	30-40 m
GSD	2 m	2 m
Flight plan	Yes	No
Post-processing software	Agisoft Photoscan 1.5	Pix 4D mapper 4.5.2

Figure 3: Research workflow.

This index is based on the combination of bands located in red and near-infrared spectrum areas. It is based on the fact that healthy plants absorb red light and reflect infrared light. While a greater difference between the two bands indicates the plants are green, healthy and exist under normal humidity conditions, a lesser difference suggests that the plants present unavoidable stress, they do not completely cover the soil, and vegetation may even be absent. Therefore, this index is an indicator of green biomass present in the study area and takes values between –1 and 1, where positive values represent the presence of vegetation: a value closer to 1 indicates healthy vegetation), and negative values or values closer to 0 indicate lack of vegetation or bare soil.

The authors defined two areas, the summit and the eastern slope, for the pilot tests with UAV acquisition (Table 2) under current SCT (2019) flight regulations in Mexico) at Cerro La Catarina. The decision to propose pilot test sites and their contrasting methodologies depended on how easily the anomalies were visually detected, and their enhancement using NDVI analysis based on two different sensors (RGB and near-infrared (NIR) on UAV), to detect linear morphologies associated with anthropogenic structures.

The research replicated similar LiDAR technology (Štular, Nuninger & Oštir, 2012; Zhang, Hu, Dai & Qu, 2020). However, features in the scene were calculated using predetermined algorithms where the type of landscape is defined based on the point cloud, the predominant vegetation and its density, the average height of the canopy and the understory. This process enabled the configuration of the type of outputs, the DTM and the contour lines, both in vector formats, and specified the sampling resolution in the digital model.

2.2. Phase B. Surface archaeological record

The systematic reconnaissance consisted of topographic ascent and recording the distance and time invested in the prospection. At Cerro La Catarina, 83 ground control points (GCPs) were selected through opportunistic sampling. The descriptions of the survey and collected material may be consulted inside the Google Maps platform (Link). To improve the efficiency and accuracy of the archaeological data, particular attention was focused on areas with rock alignments, apparent retaining walls and terrace systems associated with clear pre-Hispanic archaeological evidence. The topographic survey was conducted using a Geomax® GNSS Zenith 25 system (GLONASS/GPS reception, horizontal kinematic accuracy ±20 mm).

2.3. Phase C. UAV multispectral sensor on a pilot test (NIR record) to generate morphometry analyses and NDVI interpretation of anthropogenic geoforms

With the data derived from the previous phases, the authors selected distinctive areas for using NIR records based on the artifactual evidence and site accessibility to generate an orthomosaic. This enabled the interpretation of the highest NDVI values associated with structures, along with algorithms related to the terrain ruggedness index, slope, and orientation. The final composition was the cartography derived from map algebra due to the sum of each value where spatial coincidences occurred. All images were georeferenced in a WGS84 14 N projection; the DTM considered 7324 points per image as average, with a 75% overlap.

2.4. Phase D. Field validation and binary map of potential archaeological prospection

Considering the binary map of potential archaeological features, certain "anomalies" were selected for field validation based on visual inspection (Roman, Tudor-Mihai, Fărcaş, Opreanu & Lăzărescu, 2019), and their morphlogical patterns (tendency toward regular geometry and orientation) could be associated with anthropic landscape modifications. The topographic survey supported by differential GNSS was applied to archaeological remnants, elements, and structures that were directly visible in the field. Additionally, "natural features" (rock joints, detached rock blocks, fractures) were considered in the validation to differentiate them from anthropogenic relief modifications.

3. Results

3.1. From the satellite image

The NDVI analysis on the Sentinel 2 sensor (Fig. 4a, Fig. 5a), shows the result with a raster type to identify vegetation contrasts associated with hydric stress. The legend displays a range of -1 to +1 to visualize sparse to dense vegetation cover (Abate et al, 2020; Brooke & Clutterbuck, 2020); the range +0.68 to +0.78 is the vegetation related to anthropic relief features. These were verified in the field (methodological phases B and D), and most were associated with an intermittent pre-Hispanic wall alignment (Fig. 4b).

3.2. UAV remote sensing at Cerro La Catarina

3.2.1. The summit

The DTM (Fig. 4c) is the result of three flights, using a visible (RGB) sensor, with an approximate coverage of 15 ha and a GSD of 5 cm per pixel; after the photogrammetry process, the model was segmented to remove the canopy (Salach et al, 2018). The point cloud generated was published via open-source web visualization (Martinez-Rubi et al, 2015) and is available online. Due to logistical problems, such as difficult access, the photogrammetric survey was recorded only in the northern portion of the summit, while the southern region was documented with a NIR sensor.

At the northern and southern limits of the model with the RGB survey, two positive morphologies are distinctive with NW-SE general orientation, comprising a section of the Meyuca local watershed. Particularly interesting is the main elevation in the north of the model and its progressive stepping down to the south, where the aperture of the contour lines at the flanks of the highest elevation (2260 m) suggests a tendency for a flatter surface. Some steps have a large surface, as with the elevation at 2190 m, and it leads to the promontory located to the south of the model through a narrow corridor.
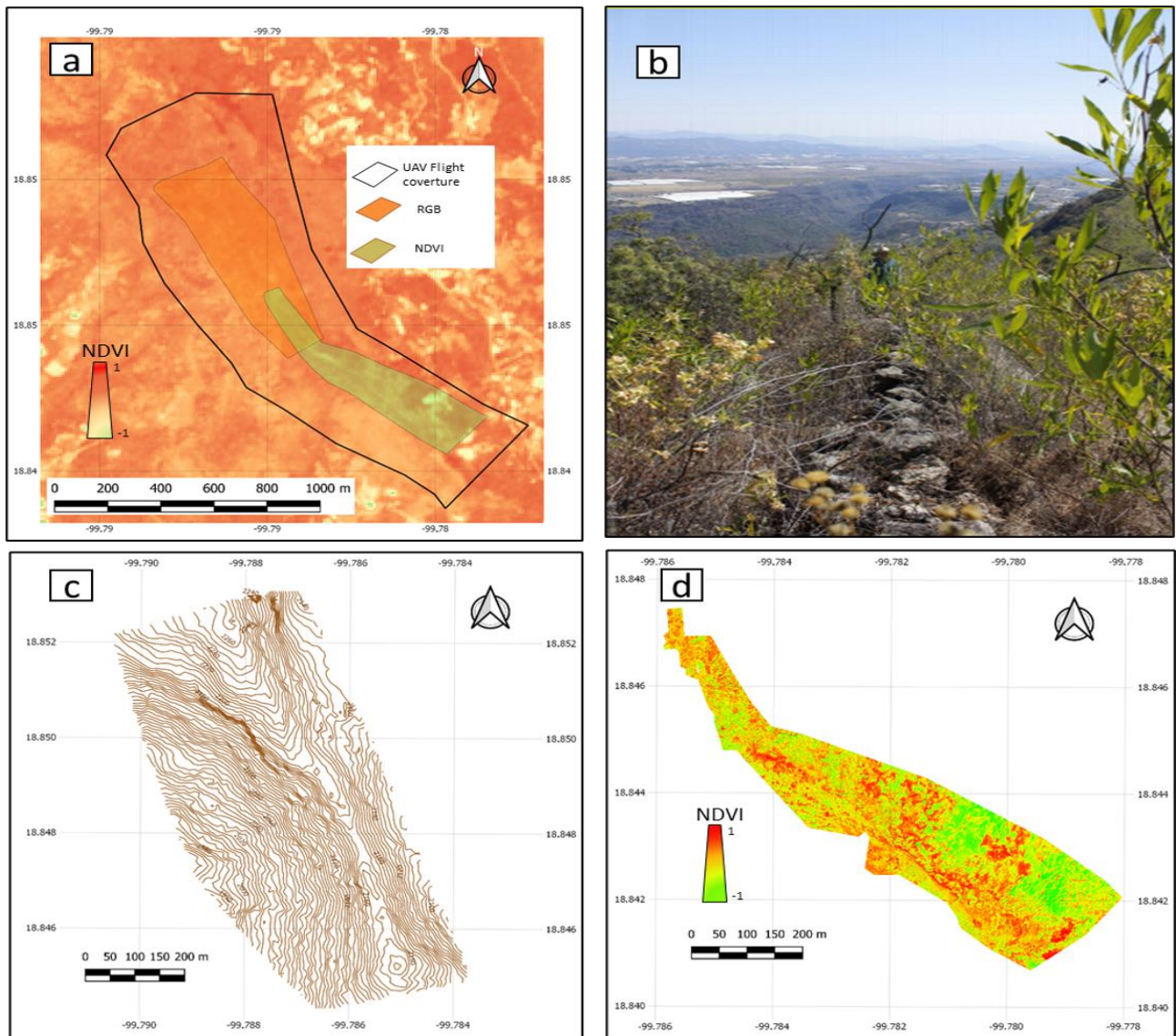
Figure 4: The Summit (Pilot Test 1- PT1). Remote Sensing anomalies associated with anthropic alteration at Cerro La Catarina:
a) NDVI satellite remote sensing study area with flight coverage; b) Alignment of the stone structure at the summit;
c) contour lines from photogrammetric DTM; and d) NDVI orthomosaic.

With respect to the NIR sensor record in the southern portion of the summit, two flights were made at an average height of 40 m. Fig. 4d shows the resulting NDVI orthomosaic, where it is possible to observe the vegetation with NDVI values as a result of the images obtained from the multispectral camera (NIR-RED)/(NIR+RED). The most distinctive aspect is that the highest NDVI values reveal discontinuous linear patterns, with a general NW-SE orientation associated with wall structures that have subsequently been verified in the field (Abate et al, 2020; Brooke & Clutterbuck, 2020).

3.2.2. The eastern slope

This area is located 200 m to the NE of the summit pilot test. Fig. 5c is the result of four staggered flights (using the RGB sensor) with an average height of 40 m; the topographic gradient decrease to the east, with the highest elevations in a range of 2000 to 2010 m. The centre of the DTM is of particular interest, with a ground sampling distance (GSD) of 5 cm; it clearly shows the largest spacing

between contour lines. These define the tendency to flat surfaces, bounded by the grouped union of contour lines (with a range elevation between 1985 to 1995 m) that resemble a pseudo polygon pattern. This geometry suggests a possible gentle dip and terraces created by building sustaining walls and basal surfaces that contrast with the general orientation of the natural slope.

The NDVI image generated consistently expresses the spectral response of the vegetation, resulting from the band combination of Red and NIR. Orthophoto resolution has a GSD of 2.88 cm on a 1.56 ha surface (Fig. 5c). The image shows the values in red associated with the highest index levels (19.9% of the total area); in some cases, these coincide with the topographic survey (intermittent lines). Figure 5b shows vegetation on the archaeological element and the limited visibility conditions which, with this technique, allow for differentiation of the anomalies in the landscape. This link compared the prospected area with the result obtained with the surplus of vegetation.
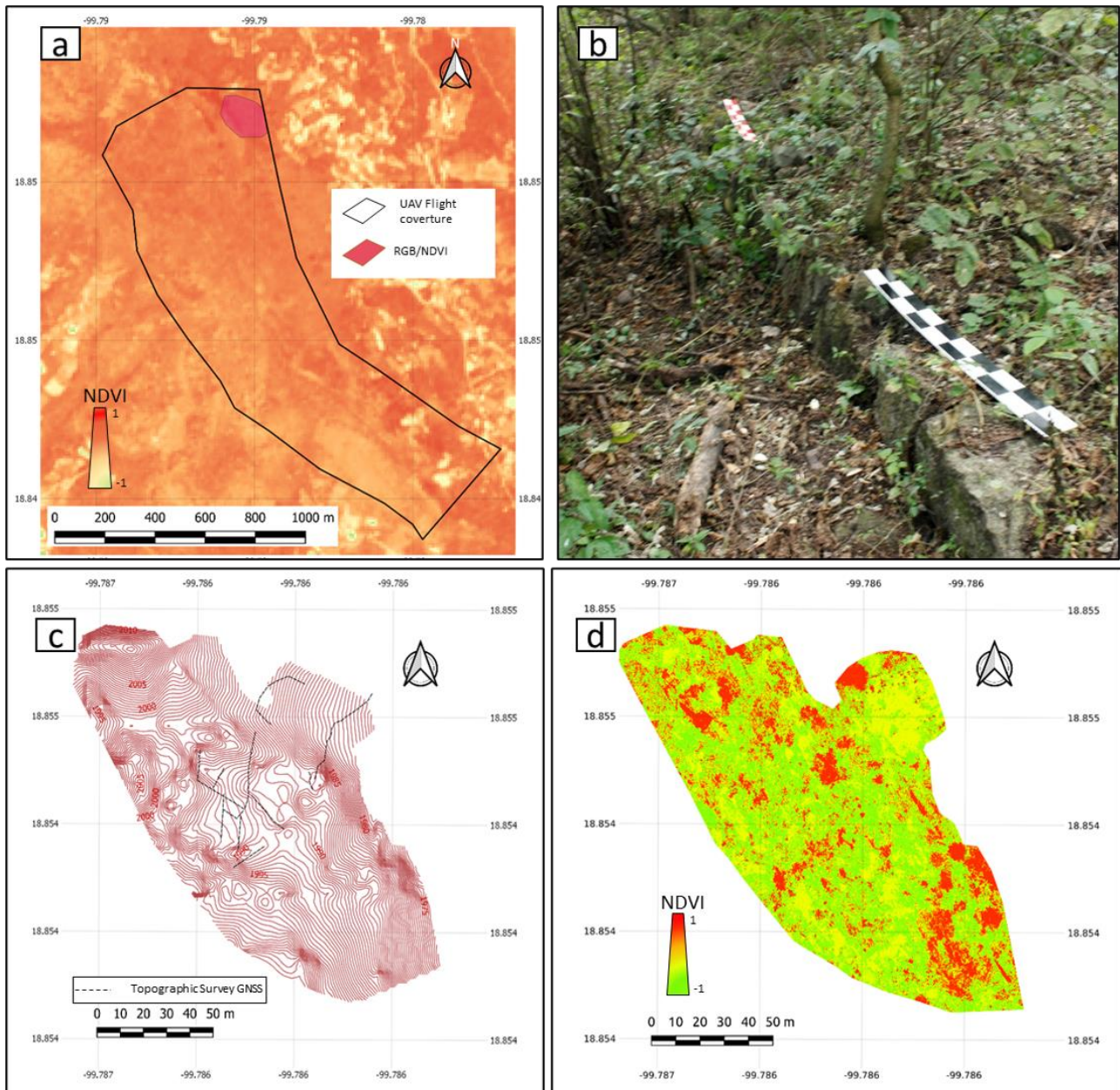
Figure 5: The Eastern Slope (Pilot Test 2 -PT2). Remote Sensing anomalies associated with anthropic alteration, at Cerro La Catarina: a) NDVI satellite remote sensing study area with flight coverage; b) alignment of the stone structure at the eastern slope; c) contour lines from photogrammetric DTM; and d) NDVI orthomosaic.

3.3. Binary map of potential archaeological prospection (Eastern slope pilot site)

The relief and vegetation conditions limited the observations resulting from the NDVI applied to UAV acquisition, particularly to the Eastern Slope Pilot Test; the lack of sharpness at scale and the resolution used was insufficient to differentiate anthropic features in the landscape (in contrast with the relatively easy detection of intermittent alignments on the summit). This led to the proposal to integrate morphometrical techniques, in addition to photogrammetry and NDVI.

The algorithms were applied to find slope percentages in a range of 0-20°, which represents geoforms that are susceptible to agricultural and residential use (Wasowski,1998; Ardizzone, Cardinali, Galli, Guzzetti &

Reichenbach, 2007, Giordan Cignetti, Baldo, & Godone, 2017; Patruno, Fitrzyk & Delgado, 2020) (Fig. 6b). At the same time, a map showing the potential slope modification was considered (different to the natural orientation to the East) (Fig. 6c), and finally, the terrain roughness index (TRI) was represented (Riley, Degloria & Elliot, 1999; Skentos & Ourania, 2017) as shown in Fig. 6d.

The final cartography representation was provided using map algebra on QGIS v. 3.10.6, consisting of the sum of each spatially coincident value, including the NDVI analysis (Fig. 7). The output map shows a simple representation of both the qualitative information (probability of event) and the quantitative information (percentage of the result), divided by category with a total surface area of 1488 ha and displays the potential area for identifying anthropic features based on

predictive models (Espa, Benedetti, De Meo, Ricci & Espa, 2006; Mink, Ripy, Bailey & Grossardt., 2009; Malaperdas & Zacharias, 2019) of relief modifications, which correspond to 0.38688 ha and represent 26.0% of the total surface area.

3.4. Field validation

Taking the binary map of potential anthropic features into consideration (Fig. 7), certain anomalies were selected for field validation based on visual inspection and their morphological patterns (tendency toward regular geometry and orientation) that could be associated with anthropic landscape modifications. The topographic survey supported by differential GNSS was applied to archaeological remnants, elements, and structures visible directly on the field. Additionally, natural features (rock joints, detached rock blocks, fractures) were considered in the validation to distinguish them from anthropogenic relief modifications.

The binary map in Fig. 8 displays red anomalies derived from the high values in the qualitative (high and medium categories) information and distinguish field validation points (27 GCPs were selected through the opportunistic

sampling of which 20 were anthropic evidence) in 75% of anthropic structures (apparent retaining walls, rock alignments on the surface, terraces) and 25% of natural geometric features (mainly, detached rock blocks by erosion/deposition).

4. Discussion

4.1. Remote sensing in mountainous regions: technical challenges

In terms of the UAV-DAP (digital aerial photogrammetry) and the rugged terrain (Goodbody et al., 2017; Moe, Owari, Furuya & Hiroshima, 2020), the flight strategies balanced the maximum autonomy of the UAV with an emphasis on flight performance. The pilot test of the summit achieved limited coverage for the area of interest that had previously been observed with the satellite sensor; with the point cloud produced through photogrammetry, the extension was reduced to generate greater resolution and precision based on the visual effect of the relief, because the points at the top are denser (due to the proximity of the sensor to the surface).
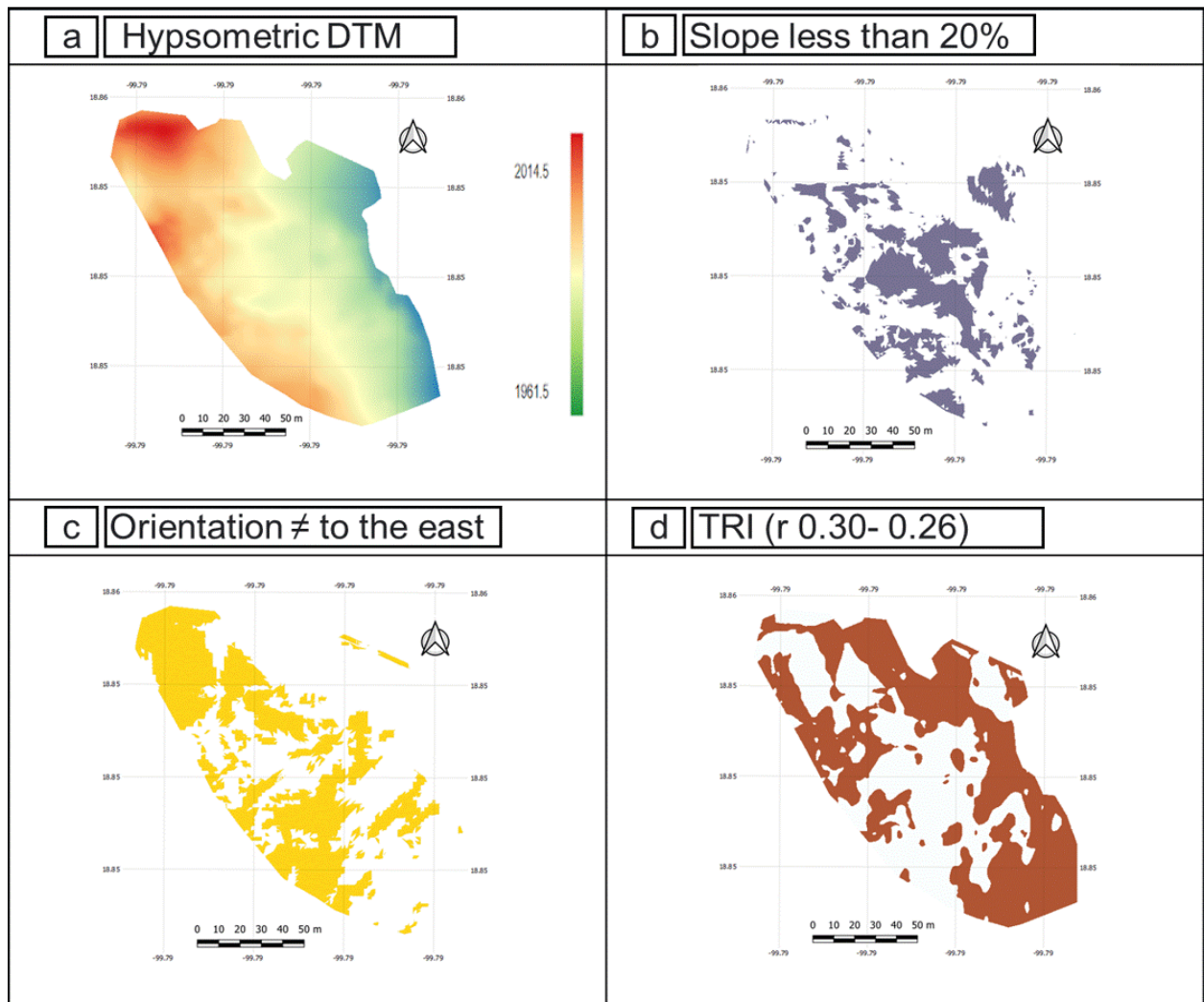
Figure 6: Morphometry analyses applied to the eastern slope (Pilot Test 2). Segmentation process using morphometry: a) Hypsometric DTM; b) Slope less than 20º; c) Orientation different to the east; and d) TRI with r = [0.30 - 0.26].

This decreased the level of accuracy, so to ensure a better result, the most dispersed and remote data from the top were excluded. Salach et al. (2018) have experimented with the level of accuracy of UAV-LiDAR data, based on their work and the variables used (overlap >70%, vertical flight above 45 m and density of 180 points/m^2); the adjustment presents an acceptable level of reliability.

The case of the Eastern Slope Pilot Test required a strategy of staggered flights in rugged relief (Rouse & Krumnow, 2020). This presented an advantage over the top because it remained at a constant vertical distance from the surface of the terrain, which helped the features to appear in greater detail. Once the roughness of the terrain was resolved, the focus was on fixing the limited visibility resulting from the excess surface vegetation.

The NDVI derived from the multispectral camera displayed acceptable performance considering the landscape conditions, based on Adamopoulos & Rinaudo (2020). The radiometric response was optimal, and the multispectral sensor mounted on the UAV generated sufficient information to identify variations associated with plant coverage. It was possible to identify stressed vegetation with a high potential for being archaeological evidence. Brooke & Clutterbuck (2020) show that the correlation between plant coverage and archaeological remains may not be as high, mainly in grasslands, a situation that hinders the detection of traits in dry seasons.

Landscape conditions displayed low performance compared to other studies (Calleja et al., 2018; O'Driscoll, 2018; Rouse & Krumnow, 2020) in which the projected vegetation is less dense or consists of grassland or crops. One factor to consider is the seasons in which flights take place (summer). To increase certainty regarding the use of NIR, it would be worthwhile to do a comparative analysis in the rainy and dry seasons and thus compare its performance.
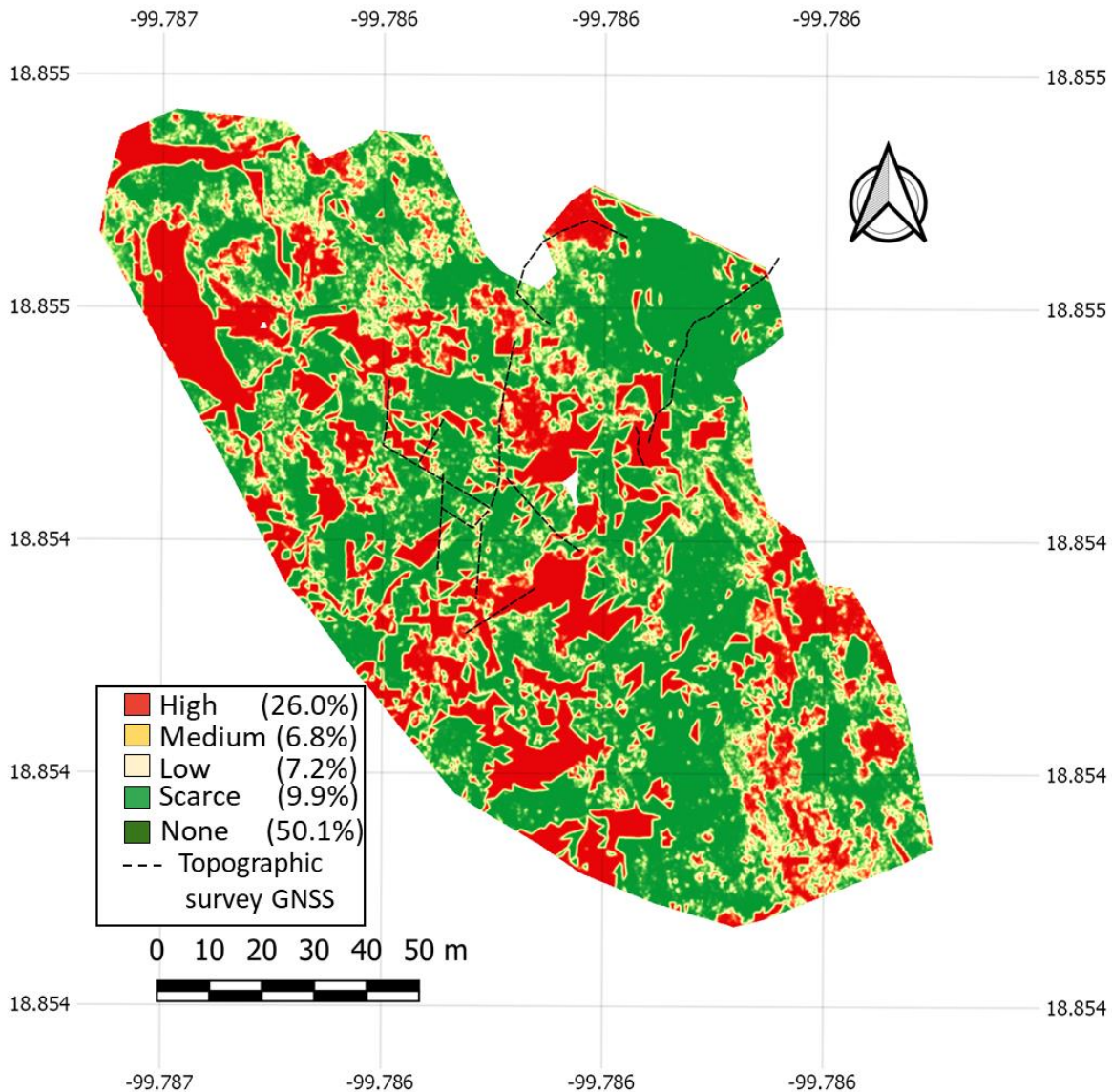
Figure 7: Binary map of potential anthropic features applied to the Eastern Slope (Pilot Test 2) at Cerro La Catarina.
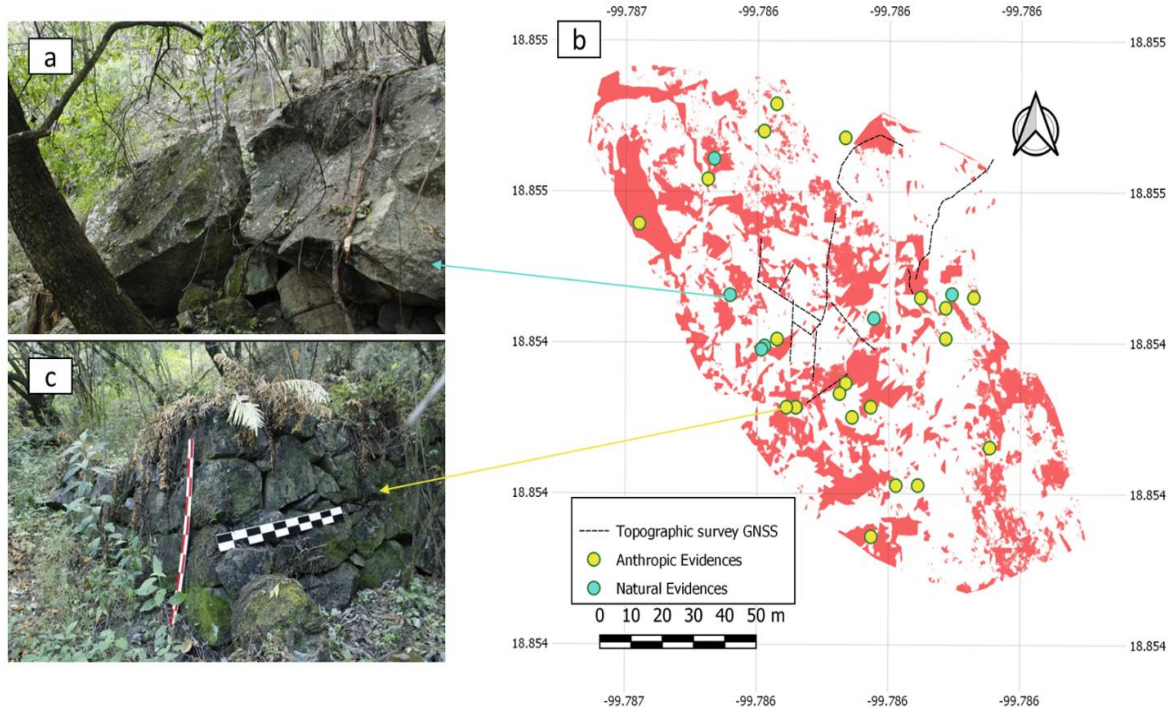
Figure 8: Final map: a) Natural evidence; b) Binary map that exposes the differentiated anomalies in the landscape; and c) anthropic evidence.

4.2. Potential archaeological prospection map: certainty

The NDVI outcomes from free satellite data displayed moderate to low spatial accuracy due to spatial resolution. However, Sentinel-2 data permitted a general approach to NDVI analysis. The Sentinel-2 free data can help address geological prospection in those countries where satellite resources are scarce, such as Mexico. The implementation of low-cost UAV-DAP ensured a degree of reliability, as Hill (2019) suggests, with sub-metric accuracy.

The acquisition of UAV images with the multispectral sensors made interpretation at the summit of Cerro La Catarina (Pilot Test 1) more feasible, due to the more regular morphologies that were visible. There are observable rocky lineaments with an NW-SE direction, made more traceable because of the relatively flat micro-relief and more open plant cover. However, some caution must be applied to direct interpretation, due to the presence of faults and fractures associated with the Coatepec Graben as a predominant geological structure (SGM, 2013). The authors suggest that the exploitation of these natural structures must not be discarded when configuring ancient and modern settlements.

The binary map of the eastern slope (Pilot Test 2) showed that 26% of the total surface contained potential archaeological evidence based on the combined morphometry-NDVI. Fieldwork was required to corroborate the degree of uncertainty for the areas that could be anthropic. The proposed segmented anomalies were differentiated by the degree of geometry, slope and high NIR values associated with the vegetation cover. Of the

total anomalies on the binary map, visual inspection ruled out 6.5% due to their natural origin.

Archaeological studies have found a way to increase the certainty of false-positive findings (Bannig, Hawkins & Stewart, 2006; Menze & Sherratt, 2006; Soroush, Mehrtash, Khazraee & Ur, 2020). They discuss several reasons for confusing evidence in the resulting binary mapping of landscape features, including size, shape, geometry, and association with geographical elements. Wiratama & Sim (2019) have suggested applying this strategy to sensors with panchromatic images to estimate errors in classification; Bourgeau-Chavez et al. (2016) used the Topographic Position Index (TPI), whose algorithm is "highly dependent on input parameters such as the shape and size", similar to the TRI that was used in our research for morphometric analyses.

To determine the analysis of certainty in Pilot Test 2, more than half of the pixels on the binary map were classified as potential sites. Finding the false positive rate is essential to achieving more accurate estimates. The reader is referred to Kirk et al. (2016), who suggest that changes in ecological diversity also occur at elevation, and the physiographic differences in vegetation and their causes have been discussed for LiDAR and SAR sensors (Bourgeau-Chavez et al., 2016; Chase, Chase & Chase, 2017, Murtha et al., 2019; Van Valkenburgh et al., 2020). The purpose of that research was to identify wetlands and their vulnerability to anthropogenic influence. Bourgeau-Chavez (2016) is limited to deciduous forests, where accuracy and interpretation are related to forest cover. Therefore, landscape features and false positives can be related to the existence of anthropic features below the canopy.

However, in an archaeological study, these anomalies are advantageous given the intention of finding anthropic evidence, thereby ensuring research reliability. Wallach (2019) mentions maximum likelihood as a statistical strategy in archaeology. Used in remote sensing to reduce the degree of uncertainty, its effectiveness is known in archaeological contexts (De Laet, Paulissen & Waelkens, 2007; Sober, 2009; Yaworsky, Vernon, Spangler, Brewer & Codding, 2020). In Pilot Test 2, the prospected area yielded better results by *not* taking a regional approach, and verification with solid data was obtained. Although the pilot test is considered a sample of the total topography, field verification found anthropic evidence in 75% of the total binary map. Based on Yaworsky et al. (2020), the best archaeological practices understand the limitations of data and encourage conservative predictions. So, although the study is limited to a local approach, the intentional selection of pilot tests provides a presence-absence test to assess possible results. Future research must extend these tests over a broader context to determine the false positives and eventually produce comparable data in adjacent regions.

5. Conclusions

The observation of cultural and natural phenomena has benefited archaeological research, with open-access satellite images and free software (Sentinel, SNAP), used for this project. It represents a broad advantage over the restrictions of other resources that feature images with a resolution greater than 10 m and commercial software. However, for the research, the NDVI derived from satellite images had an adequate resolution, and an approximation of features imperceptible to the human eye was achieved. This served as the basis, along with the previous documentation, to decide where to prospect using accurate UAV information and maps with better-georeferenced data.

The combination of different tools (UAV-DAP, remote sensing, surveying, morphometry-NDVI, fieldwork and verification based on visual inspection and their morphological patterns) is useful when conducting archaeological research with limited resources. Once identified, field validation differentiated anthropic anomalies (75%) from those of natural origin (25%), demonstrating the effectiveness percentage for the selected pilot area.

Top hierarchy sites such as Tenancingo and Ocuilan (De la Peña et al., 2008; Palma, 2014) have been addressed in systematic studies of surface archaeology, geography, relief and vegetation, and resemble the landscape observed at Cerro La Catarina. In terms of the settlement located on the periphery of the Aztec Empire, it represents a strategic site between the basins and the villages near the northern mountain of the present state of Guerrero (Silverstein, 2001, 2017; Gutierrez, 2017).

In addition to an integrated prospecting analysis (NDVI/morphometry) in other sectors within the same topographical shape and intensive surface routes, and a thorough study of the artifactual inventory recovered so far, Cerro La Catarina has been profiled as the archaeological remnant of a settlement from before the Spanish conquest; we propose that it is the *altépetl* of Xahualcingo. Based on the model proposed by Feuer (2016) and the evidence from remote sensing, this settlement belonged to the semi-periphery of the far western section of the empire. Under this structure, it is possible to identify the remnant of Matlatzinca communities away from their core areas and power centres, which show differentiated areas and boundaries between ethnic groups.

Acknowledgements

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