Volume XV • Issue 1/2024 • Pages 9–29

INTERDISCIPLINARIA ARCHAEOLOGICA
NATURAL SCIENCES IN ARCHAEOLOGY

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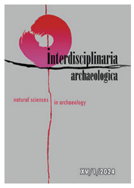

The Use of Innovative Techniques to Decodify Early Anthropic Activity in the Sonoran Desert (NW Mexico)

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ARTICLE INFO

Article history:
Received: 2nd November 2022
Accepted: 12th April 2023

DOI: http://dx.doi.org/10.24916/iansa.2024.1.1

Key words:
phosphorus fractionations
anthropic activity
paleosol
micromorphology features

ABSTRACT

The Early Agriculture Period (EAP) in the southwest of USA and northwest of Mexico began just after the Altithermal period (7500–4500 years BP). During the EAP, agricultural societies cultivated corn and constructed canals for irrigation; however, searching for the sites of this period and reconstruction of the ancient activities surrounding them meets difficulties and requires the development of geoarchaeological indicators. The present study aims to identify anthropic processes from three paleosols in the arid Northwest Mexico using physical, micromorphological and biogeochemistry characteristics. In addition, the physical and biogeochemical variables were analysed by redundancy analysis. Results show that the combination of physical, micromorphological-micromorphometric and biogeochemistry analyses are an accurate indicator of agriculture during the Early Agriculture Period (4500 years BP); additionally, the soil organic P (P_o) fraction extracted by HCl (HCl-P_o) is also a good indicator of soil changes induced by human fire management. The integrated analyses of these methods thus had a higher potential for determining the human activities effect on paleosols from the Late Holocene.

1. Introduction

In the last 25 years, deposits related to ancient human occupation have been analysed through archaeological, ethnoarchaeological, and experimental studies (Goldberg and Macphail, 2006). However, studies using traditional methods and techniques have demonstrated the complexity of processes occurring around sites. Therefore, to recover all the cultural and ecological information, it is necessary to apply different methodologies (*e.g.*, Albert *et al.*, 2016; Gutiérrez-Rodríguez *et al.*, 2018; Frank *et al.*, 2021). Considering the soil as one of the most abundant materials in archaeological excavations, the analysis of the physical and chemical, organic, and inorganic micro-remains of pedological units can provide information for the study of anthropic activities and the use of space, especially if combined with the records from the artifacts (Barba, 2007; Middleton *et al.*, 2010).

The Sonoran Desert in Northwest Mexico hosts one of the key sites for initial peopling of America during the Pleistocene-Holocene transition (Sanchez *et al.*, 2014). This area, belonging to Oasisamerica, also presents one of the largest sites of the Early Agriculture Period (EAP), named La Playa, with permanent human occupation (Carpenter and Sanchez, 2013) and agricultural villages (Sanchez, 2016). To the Sonoran coast, in the margins of the Gulf of California, there is also evidence of human activities (1750–1150 BP and 1150–450 BP), but in this case, the archaeological findings are the rests of burned shells, ceramics, lithics, and mussel ovens. These archaeological contexts are not free of contradictions regarding the evaluation of human impact in comparison to Mesoamerican sites, where monumental architecture is a common characteristic. This increases

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the need for a set of reliable geo- and pedoarchaeological indicators which could complete the archaeological record and contribute to the reconstruction of these ancient anthropic activities.

In this work, a set of properties of paleosols and sedimentary strata were selected from three profiles: Maravillas, Cuatro Suelos, and coast-Hornos, with evidence of past human activity. Through biogeochemical tools, anthropic soil management in Northwest Mexico of the Late Holocene is characterised. These biogeochemical analyses are integrated into a series of paleopedological and micromorphological studies in an interdisciplinary way. The use of these biogeochemical tools allows the development of a new approach within paleoenvironmental and archaeological reconstruction. Therefore, the objective of the present study is to identify anthropogenic and pedogenic processes from three paleosols in the arid Northwest Mexico by using P fractionation, physical and micromorphometric analyses.

1.1 Phosphorus extraction methods in archaeology

The analysis of phosphorous associated with archaeological deposits gained particular attention in the 1970s with the rapid expansion of methods and applications (Wells, 2004; Holliday and Gartner, 2007), following on from the pioneering work of Arrhenius (1929). The phosphorous content in cultural layers has been considered a relevant marker of human settlements or activity areas (Arrhenius, 1931; Rivera-Uria *et al.*, 2007; Holliday and Gartner, 2007; Barba, 2007). Phosphorus forms stable organic and inorganic compounds that are persistent in the environment and can be related to site use in, for example, domestic waste deposits, cemeteries, food storage, and consumption-preparation, use of fertilisers, and ash from fires (*e.g.*, Proudfoot, 1976; Eidt, 1984; Rivera-Uria *et al.*, 2007; Couture *et al.*, 2016; LeCount *et al.*, 2016). In Mesoamerica, the analysis of chemical residues in occupation surfaces has become a powerful technique to define the functionality of architectural spaces and has been applied extensively and increasingly throughout the region (Barba and Bello, 1978; Barba and Denis, 1981; Barba and Ortiz, 1992; Manzanilla, 1993; Sánchez and Cañabate, 1999; Terry *et al.*, 2000; Wells *et al.*, 2000; Middleton *et al.*, 2010).

Soil P exists in a complex equilibrium of different forms, including: fixed inorganic P absorbed to aluminium, calcium, and iron compounds; soluble and labile inorganic P; and organic P. Several analytical methods are used to measure the different portions of soil P, and their archaeological implications should be evaluated (Terry *et al.*, 2000). The "simple" field methods and more complex laboratory methodologies produce different results depending on the extractant agent (summarised by Holliday and Gartner, 2007). In general, five large groups of phosphorus determination methods can be defined: a) Spot Test or Ring Test, a qualitative method based on the colour rings that develop on the filter paper (Eidt, 1973; 1977; Cavanagh *et al.*, 1988; Lippi, 1988); b) the determination of the amount of soluble and labile phosphorus by a simple colorimeter extraction, helping to establish the activity areas in the site (Terry *et al.*, 2000); c) acid digestions to evaluate the amount of total phosphorus present in a sample (Terry *et al.*, 2000); d) phosphorus fractionation, which segregates both organic and inorganic forms of soil P into stability pools (Eidt, 1973; 1977; 1984; Lillios, 1992); e) agronomic kits that provide quantitative results, based on a qualitative determination, comparing the colour developed in the sample with a predefined colour scale (Díaz-País and Kligmann, 2009). Thus, a wide variety of methods for P analyses are available to archaeologists and geoarchaeologists. The best method for a particular project will depend on the research questions, equipment, time, and funds.

The phosphorus fractionation method, although complex, allows differentiating phosphorus of anthropic origin from the natural one present in deposits (Bethell and Máté, 1989). Furthermore, several studies show that the concentration of one of the phosphorus fractions is significant, and its relationship with the other chemical forms of phosphorus can be very informative for determining past anthropic activity (Ahler, 1973; Bethell and Máté, 1989; Eidt 1977; Ottaway, 1984; Woods, 1977).

2. Site description

2.1 Characteristics of the study area

2.1.1 La Playa

The archaeological site La Playa is in Sonora, Northwest Mexico (30° 29′ 58″ N, 111° 31′ 44.6″ W) (Figure 1) where the average annual temperature and annual precipitation range from 18 to 22 °C, and 200–400 mm, respectively, with rainfall mainly concentrated between summer and winter (Vidal-Zepeda, 2005). The desert scrub-type vegetation is represented by the following plant species: mesquite (*Prosopis spp.*), palo verde (*Cercidium spp.*), ironwood (*Olneya tesota* A.Gray), chollas (*Cylindropuntia cholla*. Engelm. & Bigelow. F.M.Knuth), nopales (*Opuntia spp.*), ocotillo (*Fouquieria splendens.* Engelm), saguaro (*Carnegiea gigantea* Britton & Rose), pitahaya (*Lemaireocerus turberi*. Engelm. Britton & Rose), vinoramas (*Acacia farnesiana.* L. Willd), candles and cat's claw (*Mimosa spp.*) (Pérez, 1985). The site is distributed along 12 km^2 on both sides of the Rio Boquillas, on the alluvial fan (Ibarra-Arzave *et al.*, 2018), which is fed by sediments coming from the Sierra Boquillas, whose outcrops include Proterozoic intrusive igneous rocks, metamorphic gneiss and schists, and folded sedimentary rocks (Valencia Moreno, 2007).

La Playa has been extensively studied during the last decades because it is one of the most important archaeological sites of Northwest Mexico (Carpenter, 2009). The studies comprise: the Late Pleistocene early human occupation (Hayden, 1967; 1976; García, 2005; Gaines, 2006; Carpenter *et al.*, 2015); the Archaic human abandonment and occupation (Carpenter, 2009); the Early Agriculture Period (4500–1800 cal BP), when the highest population density occurred (Mabry, 2002; Carpenter *et al.*, 2005; 2009; Diehl, 2009); and the late occupation (Carpenter *et al.*, 2005; 2015). Besides these archaeological studies, the site has been investigated from a different point of view: geological (McLaurin and Elliott, 2009); stratigraphical and geomorphological (Copeland *et al.*, 2012; McLauring *et al.*, 2012; Schott, 2017); and paleopedological (Cruz-y-Cruz *et al.*, 2014; 2015; 2019; Ibarra *et al.*, 2018; 2019; 2020). The archaeological evidence includes houses, irrigation canals, earth ovens, roasting pits, and pre-Ceramic burials (Carpenter *et al.*, 2005; 2009). The high amounts of ovens, cremations, and roasting pits (Carpenter *et al.*, 2015) have severely impacted the soils and sediments of the area (Cruz-y-Cruz *et al.*, 2019).

2.1.2 Coast-Hornos

The site lies in the Sonora state's coastal plain and marine terraces, Northwest Mexico (29° 32′ 27.14″ N, 112° 25′ 45.95″ W), in the Gulf of California, near Desemboque de Los Seris (Figure 1). This area is characterised by the following typical coastal landscapes: rocky cliffs, sandy beaches, eolian dunes, and piedmont sequences (bajadas) forming vertical cliffs (Ortlieb, 1991). The pre-Quaternary granitic and volcanic rocks are covered by Pleistocene marine and fluvial sediments, capped by late Pleistocene eolianites and Holocene dunes (Ortlieb, 1991).

The site corresponds to an open-air camp located on a dune, with an extension of ca. 500 m in length and 36 m in width, covering the dune completely. The site is divided into three parts (Locus 1 – dune principle, Locus 2 – hill, and Locus 3 – landslide). Locus 2 has "reddish" sand; unlike the other locii, the extent of this is 115 m. Various types of ceramic and carved lithic material of outstanding quality have been observed scattered on the surface, for example, remains of tools such as side scrapers and end scrapers. It is an extensive site with buried elements.

There are mussel ovens with the presence of archaeological materials (Villalobos-Acosta, 2016). Four boreholes were drilled at this site, two at locus 2, recovering malacological remains and debitage. The presence of material was very superficial, just 50 cm deep. At locus 3, we observed an area with a black line that appeared to be a long oven or hobs set. The cores were obtained from 5 m depth, and charcoal in the third stratum was observed in both cores. In locus 3, ceramic pots affiliated with the Central Coast tradition and the Trincheras tradition were recovered, the latter in a very low proportion. The malacological elements present in the first stratum are superficial, as in locus 2. The concentration of evidence of combustion and the presence of charcoal was used to collect samples for dating (Villalobos-Acosta, 2016).

2.2 Archaeological characteristic of the studied sites

La Playa is one of the biggest sites in northern Sonora, Mexico. Carpenter (2009), based on archaeological research, proposed that the site of La Playa has a long history of about 10 000 years of human occupation. Archaeological evidence shows anthropic features from the Terminal Pleistocene (14500–10500 cal BP) through the middle Holocene (7500–4500 cal BP) and nearly continuous human occupation from the end of the Altithermal (4500 cal BP) to the present (Carpenter *et al.*, 2005; 2009).

The Late Pleistocene occupation of the La Playa has been represented by a Clovis occupation with the presence of a Clovis point, a Clovis preform, and a Malpais complex (Hayden, 1967; 1976; García, 2005; Gaines, 2006; Carpenter *et al.*, 2015). The Malpais artifacts consist of crude stone tools (mainly cutters and scrapers) with a thick patina; these materials are found on ancient alluvial terraces and surfaces of the Pleistocene paleosols. The Malpais complex is represented on the La Playa site (García, 2005; Sánchez and Carpenter, 2003) with a chronology that spans from 32000 to 2000 BC (Hayden, 1976; Carpenter *et al.*, 2003; Sánchez and Carpenter, 2003; Gaines, 2006). There are, at present, no instrumental dating associated with Malpais artifacts (Gaines, 2006).

The middle Holocene corresponded to a gradual shift towards drier conditions (less precipitation and higher temperatures), which resulted in changes in the ecosystem. This period is referred to as Altithermal (Antevs, 1955). The absence of archaeological artifacts in the Sonora desert suggests the inhospitable environmental conditions. The site of La Playa shows partial and intermittent abandonment (Carpenter, 2009). At the end of the Archaic, human occupation increased in the Boquillas Valley, which coincided with the return to better climatic conditions. In this period, cultivation arises, and the EAP emerges, around 4500 years BP; the human groups developed new artifacts, such as hunting instruments for small mammals and the use of molluscs. In addition, there is evidence of maize cultivation (probably one of the earliest dates for Northwest Mexico), earth ovens, roasting pits, storage pits, burials (human inhumation and cremation); several domestic structures and an extensive canal irrigation system have also been documented at the site (Carpenter *et al.*, 2009). These features share similar characteristics with contemporaneous sites in southern Arizona. The abundant archaeological remains at La Playa highlight the site's significance in the region, reflecting the extensive prehistoric use of the site that culminated with a large, complex agricultural village during the Early Agricultural Period (Copeland *et al.*, 2012).

Cultural data registered in the middle portion of the Gulf of California confirm ancient human occupation, within a complex interaction in a period that covers the Ceramic period within an extended temporality, 1–1700 AD. Through the spatial and temporal distribution of the sites registered by the Bahía Tepoca project, it is concluded that these type-sites, should not be understood as isolated sites but as a complex system of seasonal camps in which a complex cultural interaction can be highlighted. Although some areas can be characterised by the abundance of shells (the most abundant data), cultural-symbolic factors could be more significant, than practical, in the interaction between sea, desert, and humans.

The SON: I: 7:33 site (here called "Hornos site"), can be used to mention cultural interactions that could be taken

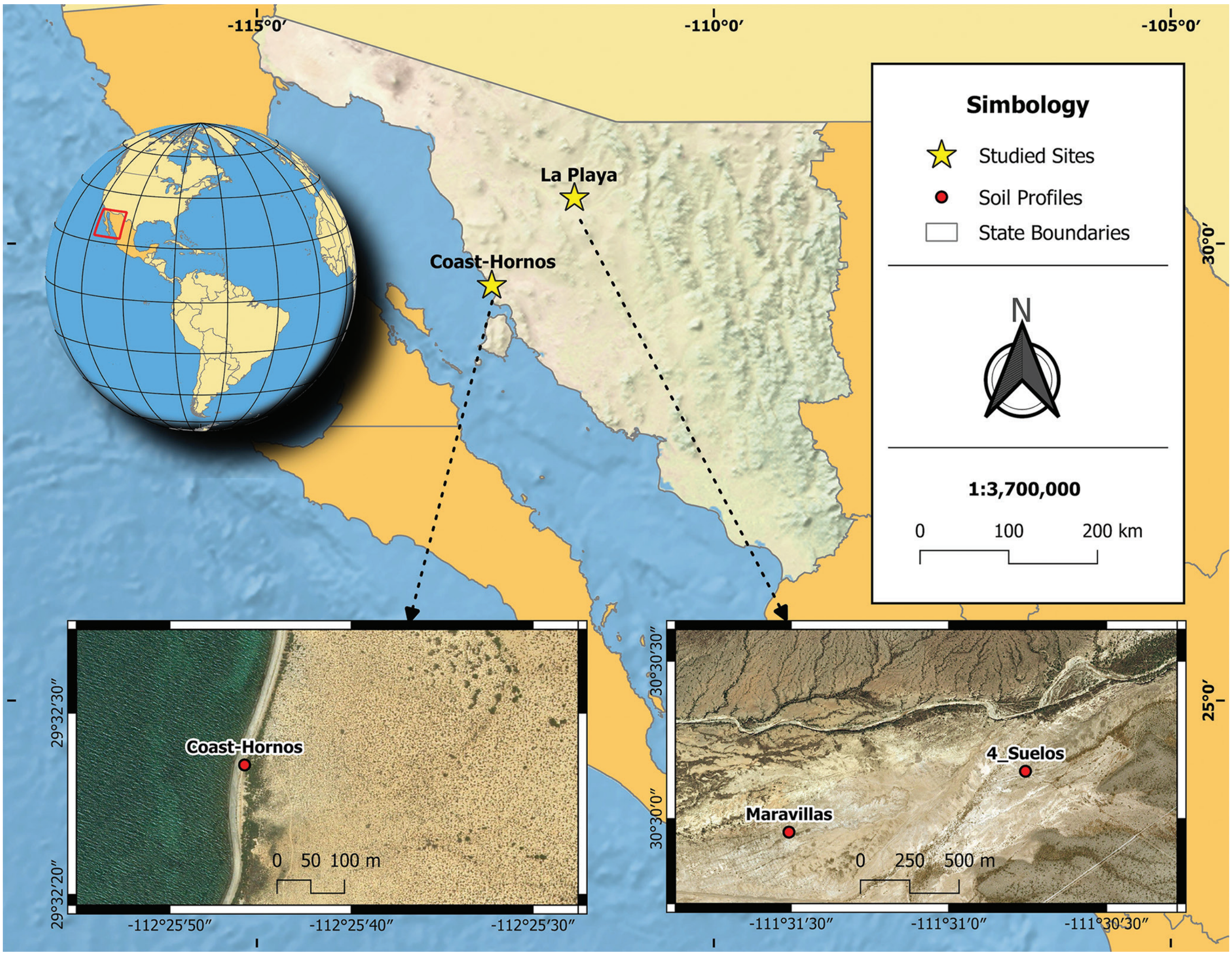

Figure 1. Location of the study area. The satellite image of Hornos and La Playa sites. Satellite image taken from Google Earth and modified by Emmanuel Ayala Rangel. Data sources: 1) Natural Earth Data; 2) INEGI and 3) Microsoft Bing.

as a general interpretation of archaeological remains in the area. With the data collected, evidence of human occupation confirms the presence of the Trincheras cultural tradition in a period including Atil (200–800 AD) and Altar (800–1300 AD) phases (sensu McGuire and Villalpando, 1993), as well as the Central Coast groups between 700 AD and 1700 AD. To assess the temporality of occupation, some original samples were analysed and processed at the IIA-UNAM Radiocarbon Laboratory (Villalobos Acosta, 2018), with dating results confirming the above, that is, an early presence with the occupation of the Trincheras Culture (612–778 AD) and a late occupation of materials from the Central Coast (940–1168 AD). The type of materials found indicates intensive anthropic activity at coastal sites.

3. Materials and Methods

3.1 Field Survey

Paleosols were described following the WRB guidelines (IUSS Working Group WRB 2006). For this work, three profiles were considered: Maravillas, Cuatro Suelos, and coast-Hornos (Figure 1). The morphology and micromorphology of the Maravillas and Cuatro Suelos profiles were already published by Ibarra-Arzave *et al.* (2018; 2019). However, we took part of the information (grain size distribution, magnetic susceptibility, and micromorphology) and added new analyses not considered before (micromorphometric, chemical, and phosphorus fractionation). Although the information has already been published (Ibarra-Arzave *et al.*, 2018; 2019), we present a summary of the main characteristics to facilitate the understanding of the analytical results.

The Maravillas profile (30°29′57.44″ N, 111°31′30.41″ W) is in the central part of an alluvial fan, at a gully (Figure 1). This profile consists of three pedostratigraphic units, described by Ibarra-Arzave *et al.* (2018) from bottom to top: San Rafael Paleosol (SRP), middle sedimentary layers (SI), and the Boquillas Paleosol (BOP, Figure 2a). In this work, we only focused on the BOP unit, which includes, from top to bottom, the following horizons: C, 2Ap, 3Ap, and 3C (Figure 2b). This unit has a clayey-silt texture in all its horizons. The Ap horizons show greyish colours, with organic matter contents ranging from 0.5 to 0.8% (Ibarra-Arzave *et al.*, 2019).

The Cuatro Suelos profile (30 °30′9.02″ N, 111°30′45.42″ W) is located at the NE of the alluvial fan, near the apex. This soil-sedimentary sequence is made up of weakly developed paleosols, with the following horizons: C, 2Ah, 2C1, 2C2, 2C3, 3Ah, 3C, 4Ah, 4C1, 4C2, 5Ah, 5C, 6Ah, and 6C (Figures 2c and 2d), (Ibarra-Arzave *et al.*, 2019). The TOC-richer horizons (2Ah, 3Ah, 4Ah, 5Ah, and 6Ah) have a darker greyish-brown colour and a silty texture. The C horizons are also silty, lighter in colour, and have a subangular blocky structure, with carbonates in the groundmass (Ibarra-Arzave *et al.*, 2019).

The BOP unit has abundant anthropogenic materials/features, *e.g.*, human cremation burials, roasting pits for food processing, cornfields, irrigation canals, artificial reservoirs, shell ornament production, and ground stones (Carpenter *et al.*, 2015; Cruz-y-Cruz *et al.*, 2018). The Maravillas, and Cuatro Suelos profiles show evidence of this intensive use, with ages ranging from 4500–1800 cal BP (Cruz-y Cruz *et al.*, 2014; Ibarra-Arzave *et al.*, 2018; 2019).

The bulk samples for laboratory analyses and unaltered blocks for thin section preparation were collected from the genetic horizons and the sedimentary layers. In addition, the samples for magnetic susceptibility measurements were taken in coast-Hornos, every 10 cm, along the profile. Thus,

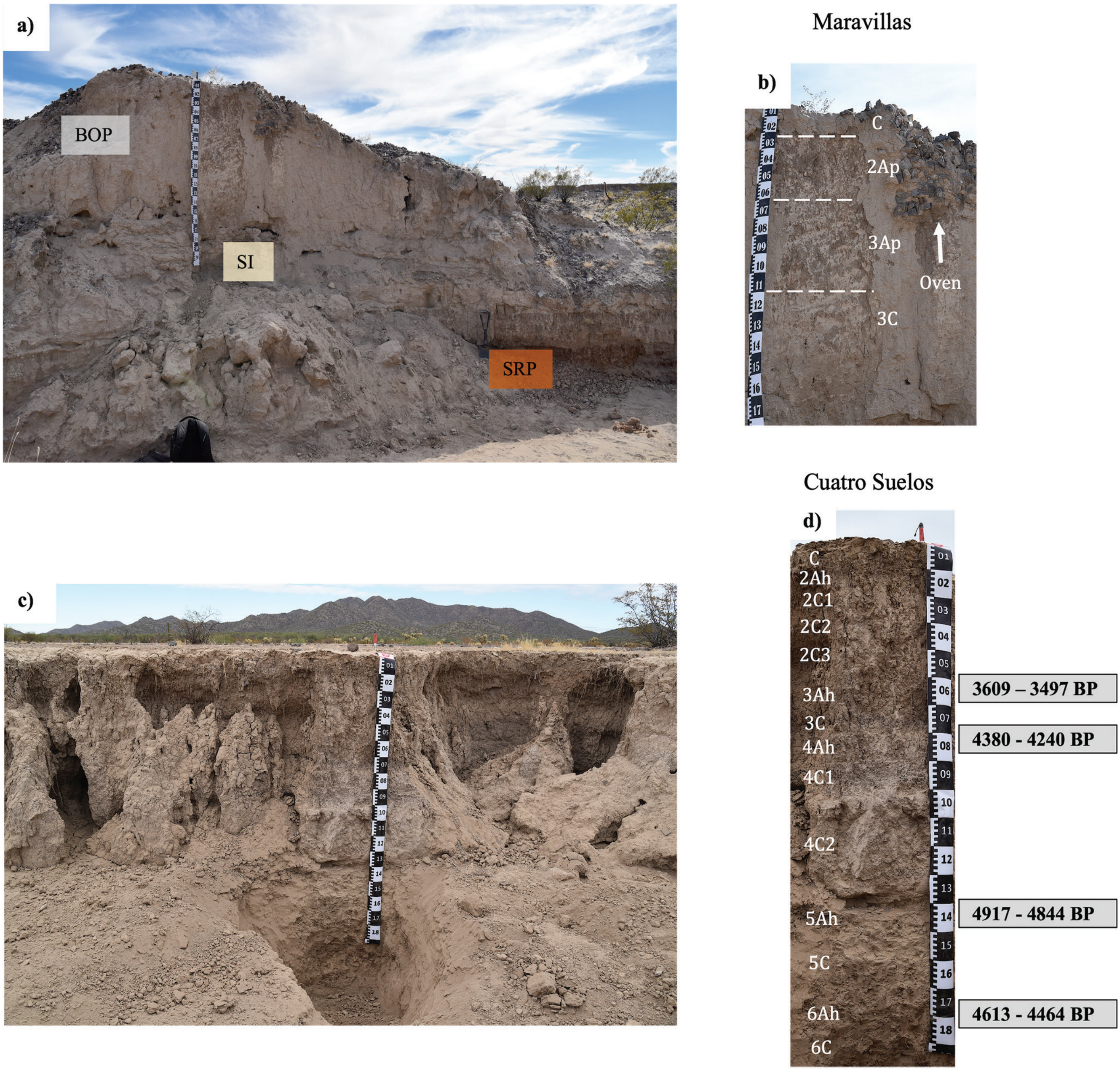

Figure 2. La Playa site. a) Landscape photo of Maravillas profile. b) Maravillas profile. c) Landscape photo of Cuatro Suelos profile. d) Cuatro Suelos profile. The depth scale is in centimetres. Photos taken by Ibarra-Arzave, 2015.

four samples were obtained from the Maravillas profile, 14 samples were from the Cuatro Suelos profile, and ten samples were from the coast-Hornos profile.

3.2 Micromorphological-micromorphometric analysis

The thin sections were prepared as follows: after air-drying, the undisturbed soil blocks were impregnated with low viscosity polyester resin and solidified samples were cut and polished until a thickness of 30 µm. For the present study, the micromorphological observations were done under an Olympus petrographic microscope using transmitted, polarised, and reflected light, following Stoops *et al.* (2003) terminology. The observations were mainly focused on the features of pedogenic, sedimentary, and diagenetic processes as well as on the human-induced components and properties. Special attention was paid to the components which contained phosphorus (as a bone fragment) or could influence the phosphorus mobility and transformation, *i.e.*, organic materials, carbonates, and iron oxides.

The micromorphometric analysis was carried out to quantify the percentage of features related to the anthropic activity in the soil: pores, charcoal, surface soil crusts, and burned materials. This analysis was done using the Image-Pro Plus version 5.0 program. The analytical procedure consisted in scanning the thin sections at a high resolution with transmitted and reflected light (Hernández-Escobar, 2009). Four main areas were separated in each image: in red, the pores were identified; blue colour showed the surface soil crusts; purple represented the charred materials; and the green areas indicated the presence of charcoal (Figure 3).

For the percentage of porosity, an adjustment was made in the technique to not bias the estimate. First, the morphometric analysis was done using microphotographs obtained with a Cool Snap Pro Color camera using transmitted, polarised, and reflected light. The images were observed under the same petrographic microscope 4X objective (area 1.94 mm^2) (Rivera-Uria *et al.*, 2018). Four images were taken for each thin section. Then, the images were calibrated and analysed with the Image-Pro Plus version 5.0 program.

3.3 Physical analyses

Grain size distribution was determined by physical separation and the sedimentation rate of the particles (Rouiller and Jeanroy, 1971; Avery and Bascomb, 1974). Each soil sample (15 g) was saturated with sodium hexametaphosphate $(NaPO_3)_6$. The sands fraction (2–0.063 mm) were determined by wet sieving, and the silt (0.063–0.002 mm) and clay (<0.002 mm) fractions were separated by sedimentation and pipette.

The magnetic susceptibility (MS) (χlf) and the frequency-dependent magnetic susceptibility (FD) (χhf) reflect the total magnetic minerals' contents and allow one to discriminate roughly the contribution of the components associated with pedogenetic processes and fire effects (Maher, 1986). There are four particle sizes, the smallest has a diameter between 0.1 and 0.01 µm and corresponds to superparamagnetic particles (SP). The size of the domains is significant in environmental magnetism studies because fine particles can usually be associated with diagenetic processes in sediments and pedogenetic in soils (Evans and Heller, 2003).

Magnetic properties were measured by an MS2B Bartington susceptibility meter with a dual sensor. For this work, we analysed the grain size distribution and magnetic properties only of the coast-Hornos profile. The soil data from the Maravillas and the Cuatro Suelos profiles were previously published by Ibarra-Arzave *et al.* (2018; 2019).

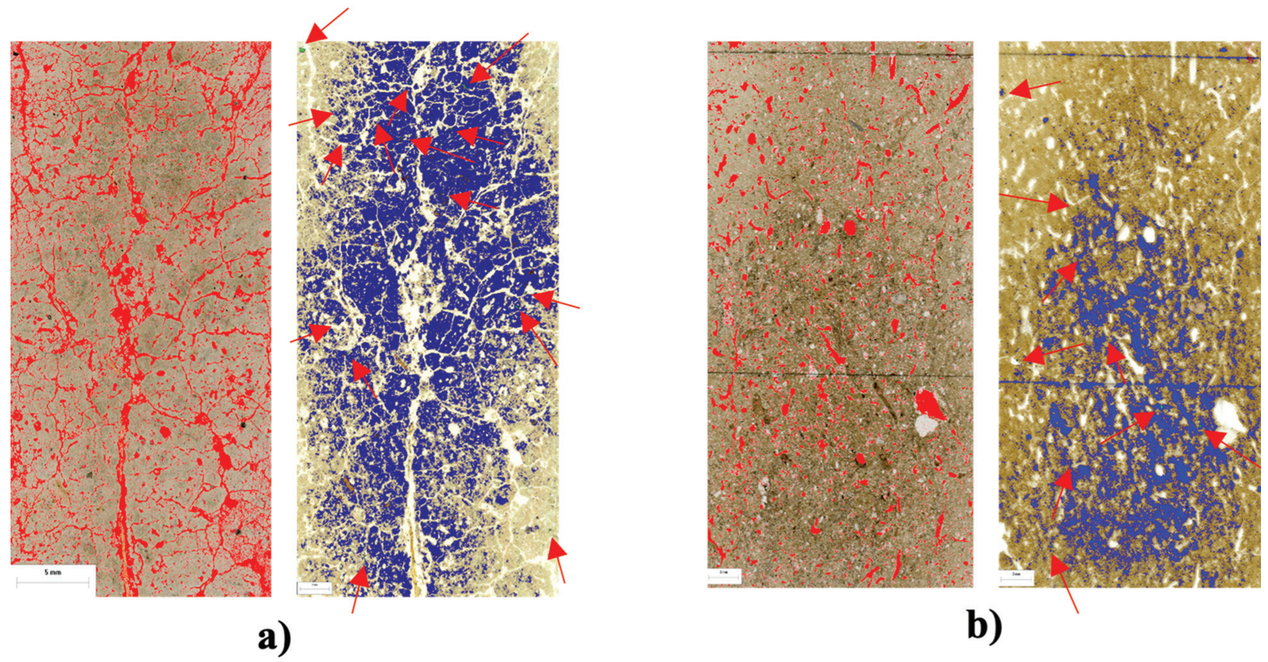

Figure 3. Images analysed by the program Image Pro Plus 5.0. Thin sections from the Cuatro Suelos, Maravillas and coast-Hornos profiles. a) 2Ah horizon, Cuatro Suelos profile. b) 2Ap horizon, Maravillas profile. Red – pores, green – charcoal (arrow), blue – surface soil crust, purple – charred materials.

3.4 Chemical analyses

Chemical analyses were done at both sites. The pH was measured in a 1:10 soil to water ratio and measured with a digital pH meter (Thermo Scientific Orion 3star Plus). For total nutrient determination, the soil samples were dried (105 °C for 72 h), pulverised (<100 mesh), and ground into an agate mortar and homogenised. The total carbon (TC) and total inorganic carbon (TIC) were determined by coulometric detection (Huffman, 1977) using a total carbon analyser (UIC model CM5012, Chicago, USA). The total organic carbon (TOC) was calculated as the difference between TC and TIC. Total nitrogen (TN) and total phosphorus (Pt) were acid digested at 375 °C with H_2SO_4, H_2O_2, K_2SO_4, and $CuSO_4$. After the extract was filtered through Whatman No. 1, TN was determined by the macro Kjeldahl method (Bremner, 1996), while P was determined by the molybdate colorimetric method after ascorbic acid reduction (Murphy and Riley, 1962). N and P were determined colorimetrically in a Bran-Luebbe Auto analyser 3 (Norderstedt, Germany).

Inorganic forms of N (NH_4^+ and NO_3^-) play an important role in soil fertility since NH_4^+ and NO_3^- are the biological forms that plants and microorganisms use to form cell mass. However, these forms are usually forming complexes with other compounds in such a way that they can be replaced by ion or cation exchange in nature (Paul and Clark, 1989). Inorganic forms of N (NH_4^+ and NO_3^-) were extracted from 10 g of soil sample with 50 ml of KCl 2 N and filtered through Whatman N° 1 (Robertson *et al.*, 1999), and determined colorimetrically by the phenol-hypochlorite method in a Bran-Luebbe Auto analyser 3 (Norderstedt, Germany).

3.5 Phosphorus fractionation

The determination of P fractions was done according to Hedley (1982) and modified by Tiessen and Moir (1993). This procedure is based on the separation of phosphorus fractions extracted sequentially.

The procedure consists of separating the P into fractions from 1 g of soil.

The first fraction with $NaCO_3$ consisted of the labile P and easily dissociable from the soil surface; this fraction was obtained by adding 30 ml of $NaHCO_3$ 0.5M to the sample. The solution was shaken for 16 hours at 150 rpm (in a mechanical stirring plate), then the samples were centrifuged at 3500 rpm. The supernatant was filtered through a Whatman No. 42 paper. The extract obtained was left to rest overnight in refrigeration to separate the organic from the inorganic phase. Subsequently, the inorganic P (P_i) and the total P (Pt) were determined.

The P_i was obtained by taking an aliquot from the top of the refrigerated extract. Deionised water was added to the aliquot. It was acidified with 0.55 ml of 5M HCl. Then a drop of phenolphthalein was added. The sample was neutralised with a few drops of NaOH 5M and HCl 5M. Finally, it was placed in 25 ml volumetric flasks and make up the volume with water. The P was read as phosphates (PO_4^{3-}).

The Pt was obtained by taking an aliquot of 5 ml of the extract. The aliquot was placed in vials and H_2SO_4 11N and ammonium persulfate were added. The vials were

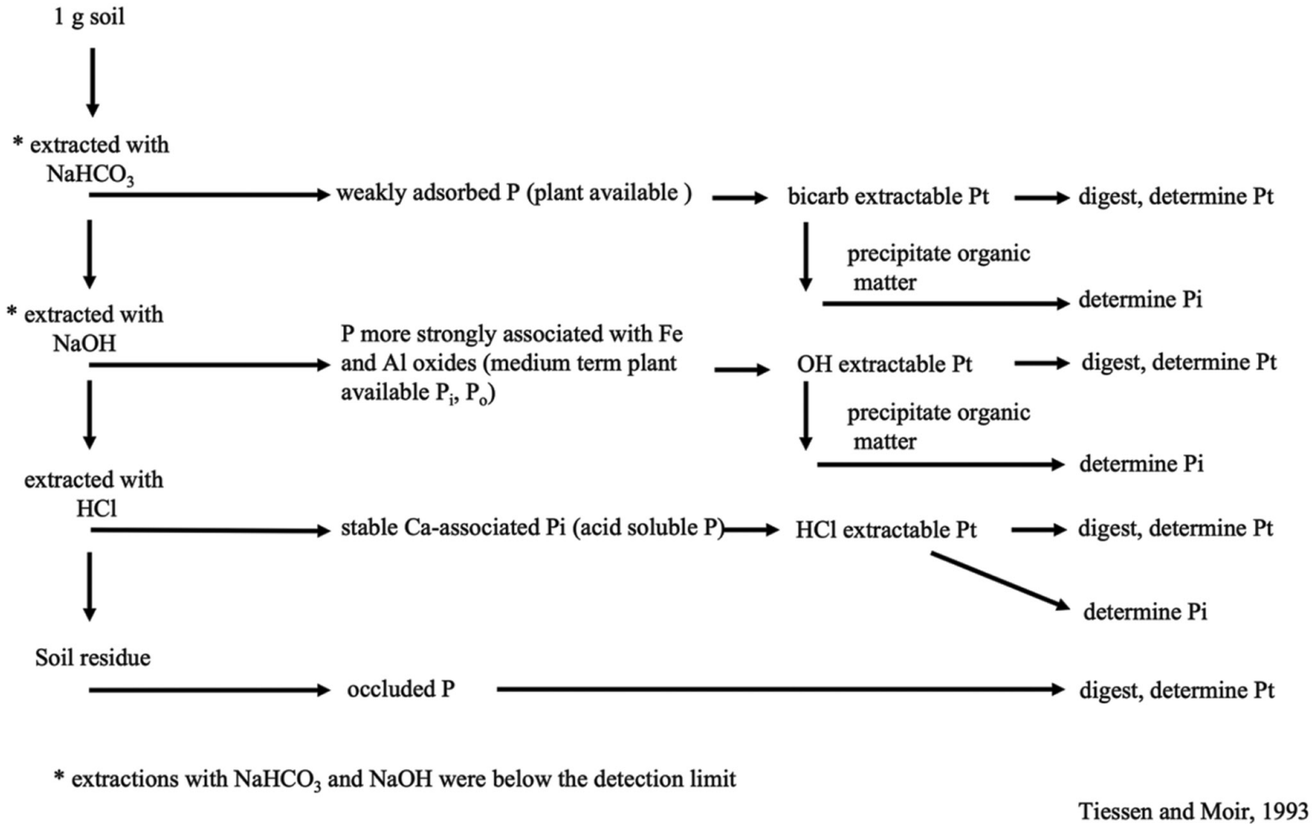

Figure 4. Sequential extraction procedure for soil phosphorus.

semi-covered, and the samples were autoclaved at 121 °C for one hour. We adjusted the pH of the final solution to ≈7 using *p*-nitrophenol and a pH meter and added standard acid molybdate reagents (Olsen and Sommers, 1982) to develop the samples' colour, and measured P colorimetrically in a Bran-Luebbe Auto analyser 3 (Norderstedt, Germany).

To obtain the second fraction with NaOH and third fraction with HCl, the precipitate of the previous fraction was used. For these fractions, the steps performed in the extraction of inorganic and total forms with $NaHCO_3$ were repeated. In the second fraction, NaOH 0.1M was used as an extractant; with this it is possible to obtain the P that is strongly attached to compounds of Fe and Al. In the third fraction, HCl 1M is used as an extractant to obtain P bound to Ca and Mg complexes, as well as relatively insoluble mineral P.

The fourth and last fraction was extracted with H_2SO_4. In this fraction, the residual mineral P was obtained. For this fraction, the remaining precipitate from the previous extraction was used, H_2O_2 was added to 30% and H_2SO_4 1M, and it was digested at 275 °C for 1 hour, and the samples then filtered by Whatman No. 1 paper. The residue was transferred into a volumetric flask of 25 ml, and the P was read as phosphates (PO_4^{3-}).

All fractions were worked; however, extractions with $NaHCO_3$ and NaOH were below the detection limit (Figure 4). Therefore, we only determined Pt in the HCl and H_2SO_4 extracts. Organic phosphorus (P_o) fraction was estimated by subtracting inorganic P (P_i) from the digestion P measured in each extract.

3.6 Statistical and data analysis

We gathered all the horizons for this analysis to observe the most significant influence on total variance: the pedogenesis or other processes associated with human activity. For this objective, redundancy analyses (RDA) were made with the physical properties' matrix as dependent variables (grain size distribution, magnetic rock properties, micromorphology, and morphometric analysis) and the biogeochemistry characteristics matrix as the independent variable (carbon, nitrogen, and sequential phosphorus extraction). The RDA analysis was performed using the Vegan package in R software (R Core Team, 2020). In addition, a negative logarithm regression was done between the RDA2 axis and the P_i:P_o ratio extracted with HCl.

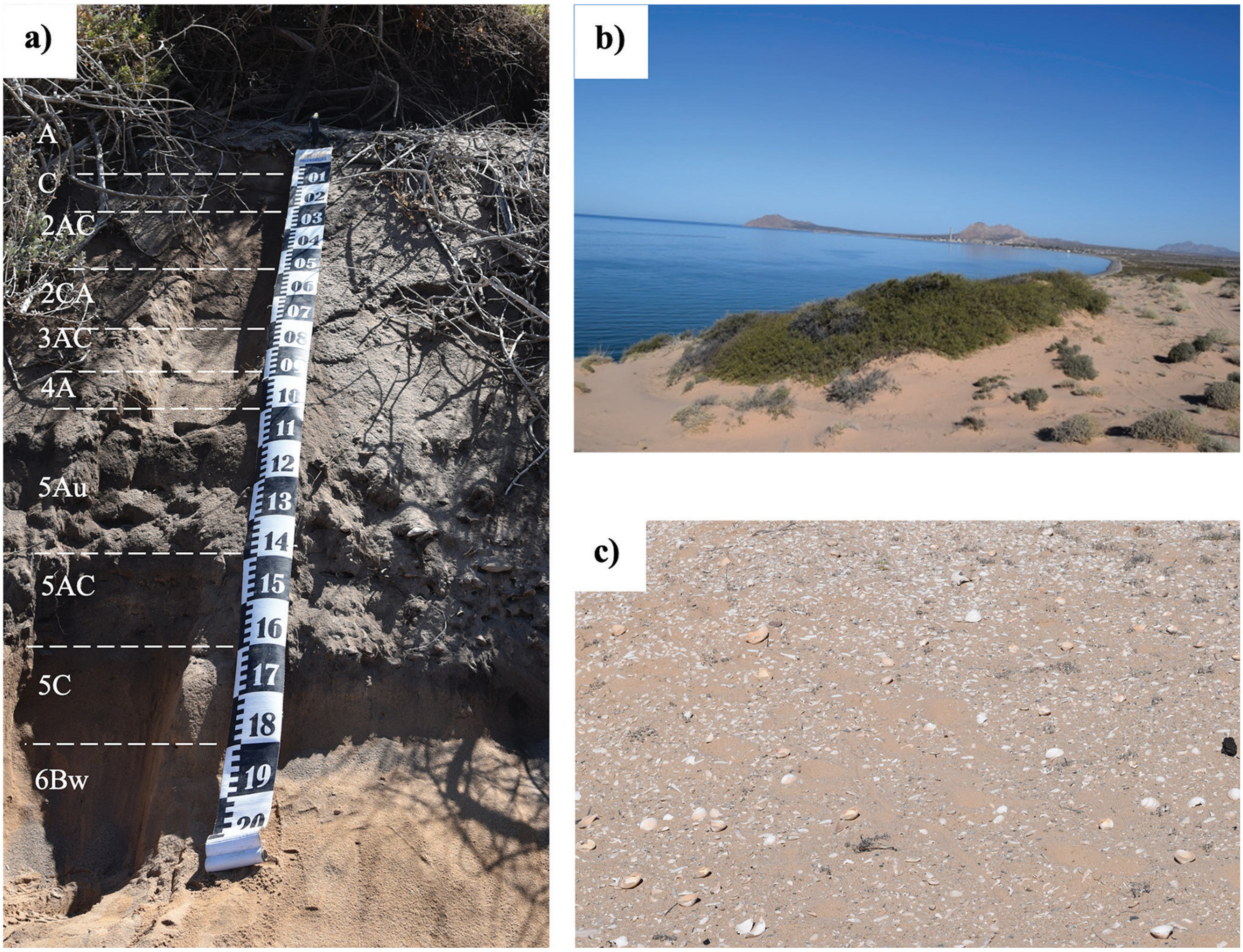

Figure 5. Hornos site. a) coast-Hornos profile. b) Landscape photo of Hornos site. c) Malacological material on landscape photo of Hornos site. Depth scale in centimetres. Photos taken by Ibarra-Arzave, 2015.

4. Results

4.1 Field morphology of the coast-Hornos profile

The studied profile had a total thickness of 2.20 m. Basal alluvium around 0.5 m thick was found, but the horizons were developed in the overlying dune sediments. The profile consists of the following horizons: A (0–10 cm), C (10–20 cm), 2AC (20–50 cm), 2CA (50–70 cm), 3AC (70–85 cm), 4A (85–100 cm), 5Au (100–140 cm), 5AC (140–160 cm), 5C 160–180 cm), and 6Bw (180–220 cm) (Figure 4). Abundant vegetation covered the surface of the dunes. Most of the horizons were greyish and sandy; only the 6Bw horizon was reddish-brown and had a higher proportion of clay. A weak subangular blocky structure characterised the 2AC, 5C, and 6Bw horizons, while the 4A horizon had a fragile granular structure. This horizon had a dark brown colour with darker spots and abundant fine roots. The 5AC underlaid the 5Au horizon and showed bioturbation and even small krotovines.

The 5Au horizon was sandy, structureless, although there were small dark granules. Archaeological material included lithic, shells, and charred shells, which belonged to the Ancestral Seri Period. However, we did not find charcoal particles, but dark patches of charred organic matter were observed.

4.2 Micromorphological and micromorphometric observations

4.2.1 Micromorphological observations of coast-Hornos profile

The micromorphological analysis revealed contrasting differences between pedogenic and sedimentary features through the coast-Hornos profile. Most horizons were dominated by a grain-supported microstructure. Quartz, plagioclase, and amphibole were present in the coarse material and were abundant throughout the sequence. Moderately-weathered biotite with exfoliation and deformed sheets (parallel linear alteration pattern) was present in the

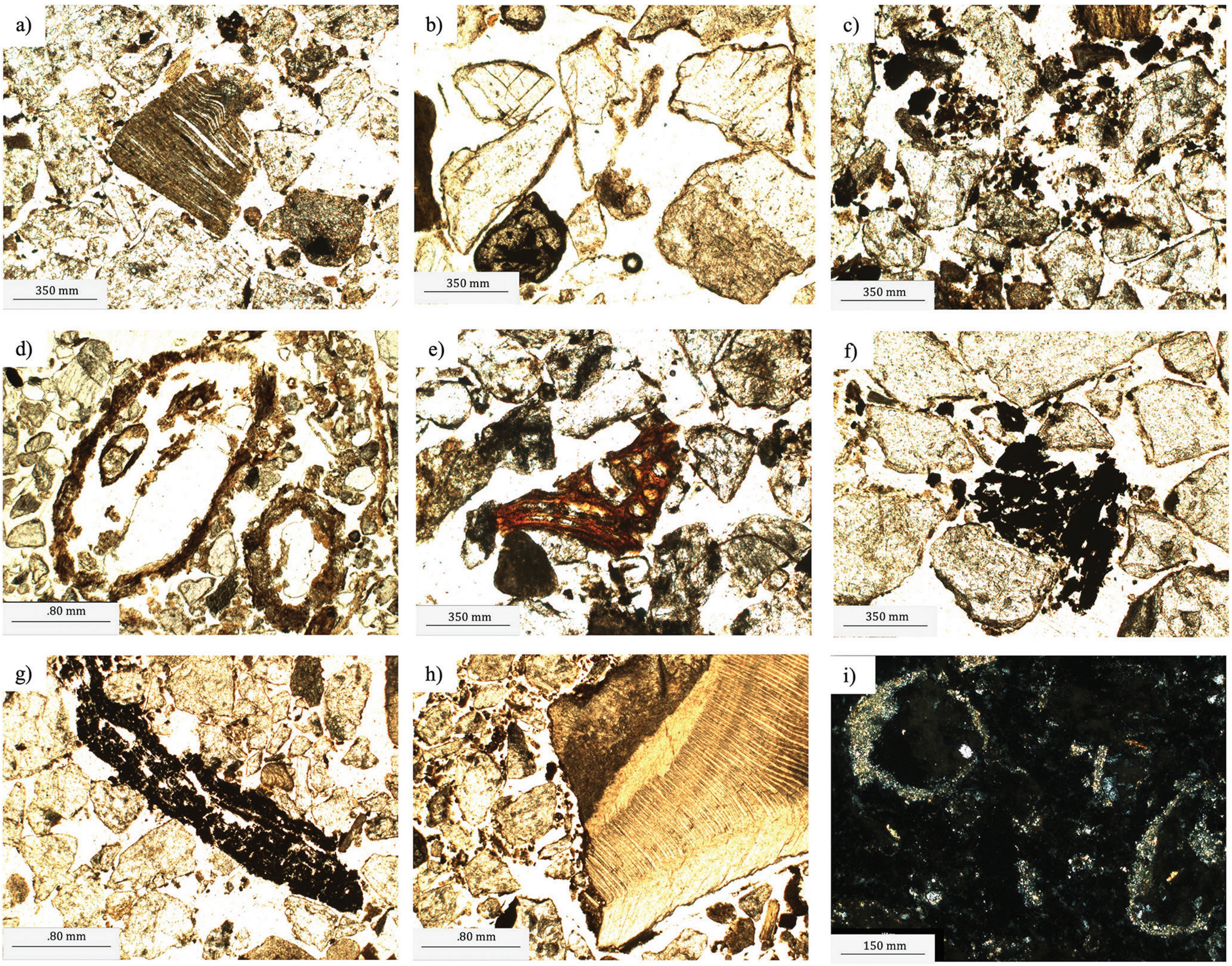

Figure 6. Micromorphology of Hornos site. a) Weathered biotite with exfoliation and deformed sheets, 5Au horizon; b) The chitonic coarse/fine related distribution, 2AC horizon; c) Micro granular biogenic zones, highlighted by fine dark humus pigmentation, 4A horizon; d) Highly decomposed but uncharred organic matter, 5AC horizon; e) Fragment of charred bones, 5Au horizon, f) Charcoal particles, 4A horizon; g) Burned organic components in coarse fragments, 5Au horizon; h) Shell fragment, 4A horizon; i) Secondary carbonates, micrite coatings, 6Bw horizon.

4A and 5Au horizons (Figure 6a), in minor quantities, and less altered in the 5AC horizon.

In the 2AC horizon, a chitonic coarse/fine related distribution was observed: thin discontinuous clay coatings pigmented by iron oxides and organic-matter-covered sand particles (Figure 6b). Biological activity was evident in the 4A horizon: clusters of the small granular aggregates, highlighted by a fine dark humus pigmentation (Figure 6c) were observed between larger sand grains. These aggregates were also present in the 5Au and 5AC horizons. The 5AC horizon showed highly decomposed but not charred organic matter (Figure 6d).

In the 4A horizon, some fragments of bones were encountered. The 5Au horizon also showed bone fragments but charred (Figure 6e) and in greater quantity. Few charcoal particles were encountered in the 4A horizon (Figure 6f), whereas in the 5Au horizon these were also present but in larger numbers and sizes. Burned organic components were observed in coarse fragments as well as fine particles, some charcoal fragments conserving a vegetal tissue structure (Figure 6g).

Shell fragments were observed in the 4A horizon (Figure 6h), and in the 5AC horizon were also present but in minor sizes and fewer quantities. Burned shells were observed in the 5Au horizon.

The lowermost horizon (6Bw) was much richer in fine clayey material than the upper horizons; it showed a locally close porphyric coarse/fine related distribution. This abundance of fine material filling all spaces between sand grains produces an effect of stronger pigmentation. Ferruginous typical nodules occur in the groundmass and few clay coatings were encountered. Secondary carbonates were represented by micritic coatings (Figure 6i).

4.2.2 Micromorphometric observations of Maravillas, Cuatro Suelos and coast-Hornos profiles

Both profiles of the La Playa site (Maravillas and Cuatro Suelos) showed high heterogeneity in the porosity values,

Table 1. Morphometrics results of Cuatro Suelos, Maravillas and coast-Hornos profiles.

Profile	Horizon	Pores (%)	Charcoal (%)	Surface soil crust (%)	Charred material (%)
Maravillas	2Ap	10.29	0.02	11.33	*
	3Ap	13.30	0.02	11.47	*
	3C	9.74	0.04	13.20	*
Cuatro Suelos	C	32.42	0.87	14.10	*
	2Ah	24.96	0.05	68.36	*
	2C1	15.22	0.06	17.25	*
	2C2	15.22	0.06	17.25	*
	2C3	7.79	0.12	16.30	*
	3Ah	17.43	0.43	19.01	*
	3C	16.00	1.48	16.40	*
	4Ah	15.15	0.61	38.00	*
	4C	9.82	0.20	13.17	*
	4C2	8.63	0.05	20.00	*
	5Ah	22.00	0.03	31.06	*
	5C	25.00	0.13	12.33	*
	6Ah	14.00	0.03	56.00	*
	6C	8.47	0.03	49.00	*
Coast-Hornos	A	25.79	1.02	*	1.82
	C	18.11	0.60	*	4.10
	2AC	29.50	0.15	*	1.26
	2CA	30.59	2.14	*	1.82
	3AC	19.28	0.51	*	4.73
	4A	17.45	1.68	*	21.21
	5Au	29.76	2.26	*	18.34
	5AC	15.22	0.43	*	13.80
	5C	27.18	0.12	*	7.41
	6Bw	18.40	0.33	*	0

* not detected

ranging from 7.79 to 32.42% (Table 1). The highest percentage of charcoal was present in the C, 3C, and 4Ah horizons of the Cuatro Suelos profile, although the amount was less than 1.48%. Additionally, the surface soil crusts were also evident in the TOC-richer horizons of the Cuatro Suelos profile. However, in Maravillas, their percentage was lower (Table 1).

In contrast, in the coast-Hornos profile, the identified materials were different. The morphometric results showed higher porosity, reaching almost 30% in the 2AC, 2CA, 5Au, and 5C horizons. The amount of charcoal fragments was also higher, with more high proportions in 2CA and 5Au horizons. This profile did not show surface soil crusts, but there was charred material (Table 1). An increase in burned material was observed on the 4A, 5Au, and 5AC horizons (Table 1).

4.3 Physical analyses of the coast-Hornos profile

As mentioned previously, the coast-Hornos profile had never been studied before; for this reason, we present the results of the physical analyses. Concerning the grain size distribution, the texture was homogeneous throughout the profile, where the sand fraction dominated (83%–95%) (Figure 7). However, a slight increase in the silt and clay fractions was observed within the A, C, 5C, and 6Bw horizons. Measurements of low-frequency magnetic susceptibility (χlf) showed low values (<0.3 ×10^{-6}m^3/kg). The highest values were registered in the upper horizons. The χfd showed more variation along the profile. The 2AC, 3AC, and 5Au horizons had the highest percentages, which evidenced the presence of SP ultra-fine-grained minerals (Figure 7).

4.4 Chemical analyses

In the Maravillas profile, the pH values ranged from 8.3 to 8.6 (Table 2). The C and the 3C horizons had the highest and lowest TOC, NH_4^+ concentrations, respectively; consequently, the C:N ratio decreased with depth (from 8.2 to 4.6; Table 2). In contrast, the NO_3^- concentration was similar throughout the profile, with the lowest value in the C horizon. The C:P_o ratio increased in the 3Ap horizon (76.6, Table 2). The lowest TIC concentration was found in the 2Ap horizon (0.88, Table 2).

In the Cuatro Suelos profile, pH values were higher than in Maravillas. The uppermost C horizon pH value was 8.7, rising with depth. The highest TOC and NH_4^+ concentrations were found in the buried TOC-richer horizons at different depths (2Ah, 3Ah, 4Ah, and 6Ah; Table 2). These results agreed with the idea that this profile is polycyclic, as suggested before by Ibarra-Arzave *et al.* (2019). The highest and lowest TIC concentrations were in 4C (4.1 mg g^{-1}) and 4C2 (0.3 mg g^{-1}), respectively. The maximum TN concentration was detected in the two first horizons (C and 2Ah). Therefore, the C:N ratio increased with depth (Table 2). The available NO_3^- concentration increased from the 2C2 to the 4Ah horizon, reaching a maximum in the 3Ah horizon (Table 2). The highest C:P_o ratio was observed in 2C1 (190); in the middle of the sequence, the values decreased, and finally, at the end of the profile, the values increased again (76 and 74; Table 2).

In the coast-Hornos profile, pH values increased with the depth (range from 9.0 to 10.1; Table 2). There was an increase in TOC and TIC values in organic and transitional horizons, but the highest TOC, TIC, and TN concentrations were in the superficial A horizon (Table 2). The highest available NH_4^+ and NO_3^- concentrations and C:N and C:P_o ratios were found in the A and C horizons. The C:P_o ratios of the middle and lower part of the profile decreased drastically (Table 2).

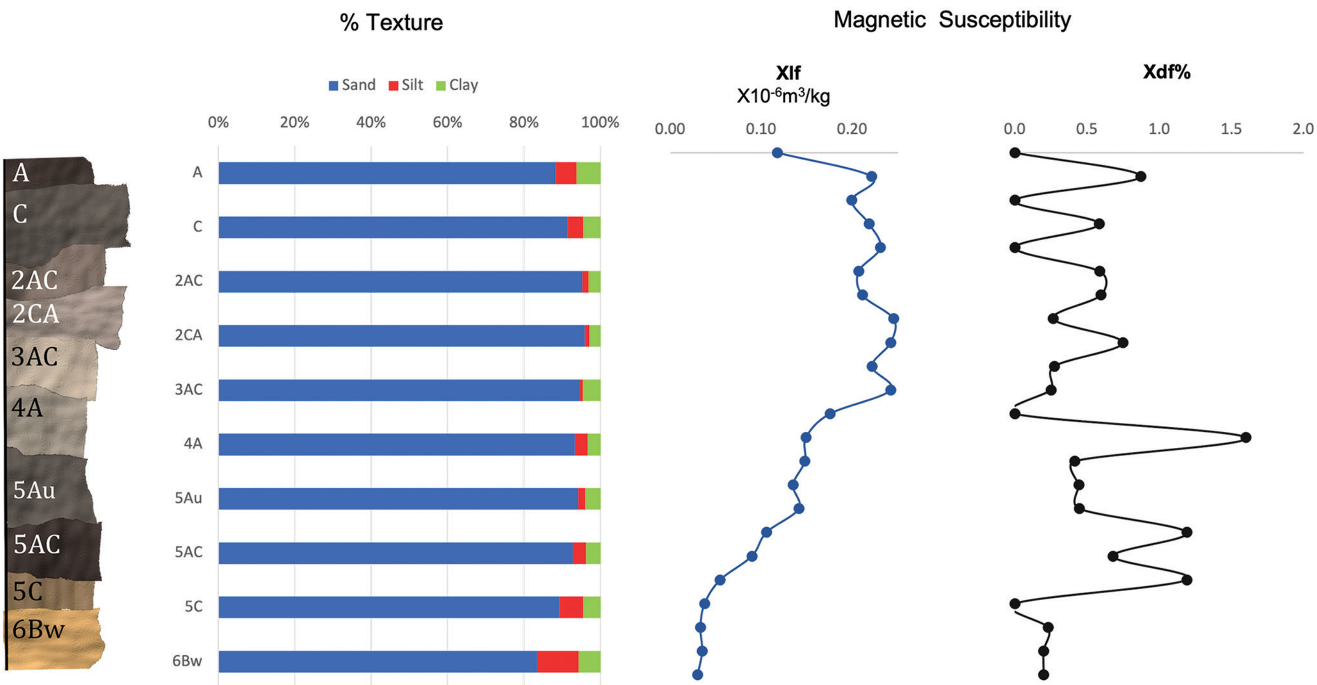

Figure 7. Physical analyses of coast-Hornos profile. Grain size distribution and Magnetic Susceptibility.

Table 2. Selected chemical properties of the study objects.

Profile	Horizon	pH	TOC (mg/g)	TIC (mg/g)	TN (mg/g)	NH_4^+ available (µg/g)	NO_3^- available (µg/g)	C:N	C:Po
Maravillas	C	8.58	8.62	4.91	0.90	6.3	760	8.2	52.1
	2Ap	8.25	3.21	0.88	0.12	6.1	868	6.3	23.3
	3Ap	8.43	3.16	1.18	0.16	4.6	882	6.1	76.6
	3C	8.41	2.14	1.31	0.17	2.7	830	4.6	47.4
Cuatro Suelos	C	8.67	3.48	0.31	0.31	6.3	0	11.1	10.8
	2Ah	9.63	3.72	1.30	0.31	4.5	9	11.9	23.1
	2C1	9.70	2.46	0.76	0.20	4.1	78	12.5	190.4
	2C2	9.52	2.36	0.43	0.24	4.8	121	9.8	13.8
	2C3	9.51	3.17	0.61	0.19	3.9	147	16.7	14.8
	3Ah	9.68	3.69	0.32	0.24	5.4	150	15.5	43.1
	3C	9.58	2.55	0.63	0.18	5.2	129	14.4	26.8
	4Ah	9.45	2.93	0.42	0.21	5.3	136	13.7	11.5
	4C	9.95	1.31	4.13	0.12	5.7	41	11.0	13.5
	4C2	10.20	0.78	0.28	0.07	3.5	2	10.9	4.7
	5Ah	10.01	1.91	1.31	0.14	4.1	8	13.3	34.5
	5C	9.71	3.07	1.48	0.19	4.4	0	16.5	51.6
	6Ah	10.01	2.47	1.75	0.18	4.6	0	13.6	76.4
	6C	9.93	2.34	1.19	0.12	2.1	0	20.1	74.3
Coast-Hornos	A	9.04	15.02	6.28	1.02	2.9	118	14.8	105.6
	C	9.46	2.32	5.30	0.33	1.9	86	6.9	40.8
	2AC	9.84	1.84	4.39	0.13	0.7	10	14.0	27.4
	2CA	9.91	0.48	3.91	0.18	0.2	1	2.6	7.2
	3AC	10.01	0.65	4.24	0.10	0.6	0	6.7	12.9
	4A	9.78	3.99	5.62	0.18	0.9	0.6	22.3	4.4
	5Au	10.08	2.43	5.74	0.13	1.0	0	18.3	2.3
	5AC	9.94	0.84	5.59	0.11	0.9	0	7.5	0.7
	5C	10.08	0.02	4.09	0.05	0.7	0	0.3	3.3
	6Bw	9.88	1.06	3.20	0.03	1.0	0	32.2	27.7

4.5 Phosphorus fractions

The C horizon had the highest Pt concentration in the Maravillas profile, and the HCl-P_i (inorganic phosphorus) fraction was the dominant in all horizons (Table 3). The highest HCl-P_i value corresponded to the 3Ap horizon and the lowest to the 2Ap horizon. The HCl-P_o (organic phosphorus) fraction increased in the 2Ap horizon and decreased in the 3Ap horizon. The lowest values were in the most recalcitrant inorganic form (H_2SO_4-P_i). The total-P_o fraction showed a high percentage in the 2Ap horizon, while the total-P_i percentage was higher in the 3Ap horizon (Table 3).

As to the Maravillas profile, in the Cuatro Suelos profile, the HCl-P_i fraction was also dominant throughout the profile (Table 3). The highest and the lowest HCl-P_i fraction and the Pt concentrations were detected at the 2C1 and 4C2 horizons, respectively. The HCl-P_o fraction is high in the uppermost C horizon, 2C3, and 4Ah horizons. The values of recalcitrant inorganic form, H_2SO_4-P_i, were homogenous throughout the profile (Table 3). The highest percentage of the total-P_o corresponds to the 4Ah horizon, reaching 64%. On the other hand, the highest percentages of the total-P_i corresponded to the 2C1 horizon.

The highest and lowest Pt concentrations in the coast-Hornos profile were quantified at the A and 2CA horizons, respectively (Table 3). The HCl-P_i fraction dominated in the uppermost A, C, and 2AC horizons and the lowermost 5C and 6Bw horizons. The HCl-P_o fraction increased in the fourth pedogenic cycle and then dropped at the final sequence. The high values of the recalcitrant inorganic form, H_2SO_4-P_i, were in the superficial A horizon, the middle 4A and 5Au horizons, and the lowermost 6Bw horizon (Table 3). The highest total-P_o percentages were found in the 4A, 5Au, and 5AC horizons, which coincided with the lowest total-P_i percentages.

4.6 Integrated Statistical Analyses

The redundancy analysis results showed that the biogeochemical characteristics of the soil explained 55%

Table 3. Phosphorus fractions values of the study objects.

Profile	Horizon	TP (mg/g)	HCl-Pi (µg/g)	HCl-Po (µg/g)	H_2SO_4-Pi (µg/g)	PO (%)	PI (%)
Maravillas	C	1.05	837.60	165.60	125.01	14.68	85.32
	2Ap	0.51	339.2	137.7	100.9	23.83	76.17
	3Ap	0.52	432.3	41.3	85.2	7.38	92.62
	3C	0.46	349.5	45.1	77.8	9.56	90.44
Cuatro Suelos	C	0.39	263.40	322.20	47.23	50.91	49.09
	2Ah	0.37	269.55	160.65	82.50	31.33	68.67
	2C1	0.54	551.70	12.90	77.55	2.01	97.99
	2C2	0.44	264.00	171.00	81.65	33.10	66.90
	2C3	0.48	356.10	214.05	82.50	32.80	67.20
	3Ah	0.42	349.95	85.65	79.65	16.62	83.38
	3C	0.35	273.00	95.25	69.25	21.77	78.23
	4Ah	0.34	81.00	253.65	63.53	63.70	36.30
	4C	0.36	266.10	97.35	76.23	22.14	77.86
	4C2	0.33	185.85	166.80	85.40	38.08	61.92
	5Ah	0.38	334.20	55.20	66.63	12.10	87.90
	5C	0.38	348.30	59.55	89.08	11.98	88.02
	6Ah	0.41	376.20	32.25	85.80	6.53	93.47
	6C	0.39	355.80	31.50	82.48	6.71	93.29
Coast-Hornos	A	1.43	1163.1	142.2	102.2	10.10	89.90
	C	1.31	966.2	56.9	83.8	5.14	94.86
	2AC	0.98	804.2	67.2	76.7	7.09	92.91
	2CA	0.81	675.6	66.2	73.5	8.11	91.89
	3AC	0.94	726.8	50.7	77.0	5.93	94.07
	4A	1.02	28.4	909.5	86.7	88.77	11.23
	5Au	1.30	79.5	1053.9	92.3	85.98	14.02
	5AC	1.24	104.4	1129.7	65.2	86.95	13.05
	5C	1.33	1344.6	5.4	67.4	0.38	99.62
	6Bw	1.18	1131.2	38.3	91.8	3.03	96.97

(P = 0.001) of the physical properties. The first axis separated the samples by pedogenesis, explaining 47% of the variance. The second axis separated the horizons with anthropic influence with two burning scenarios: on the one hand a domain of carbonised remains, and with less charred material, on the other hand. This axis was explained by 4% of the total variance (Figure 8). This second-axis had a significative negative logarithm regression with the Pi: Po ratio extracted with HCl (R^2= 0.11, p= 0.05; Figure 9).

5. Discussion

5.1 Morphological and physical soil properties as an indicator of anthropogenic processes

During the Holocene, it is registered that climatic variations affected the natural landscapes. However, there is a continuous interest to document the interactions between humans and the environment that can also affect climatic trends (Lawrence *et al.*, 2016; Kaniewski and Van Campo, 2017; Palmisano *et al.*, 2021). In La Playa, the Late Holocene soil cover has been modified by anthropic activities (Carpenter *et al.*, 2005; Cruz-y-Cruz *et al.*, 2019; Ibarra-Arzave *et al.*, 2019), resulting in a pedological unit of the Boquillas Paleosol (BOP) (Cruz-y-Cruz *et al.*, 2014), which clearly shows the effect of such alterations. Ibarra-Arzave *et al.* (2019) even suggest the BOP can be classified as an anthrosol. The human activities in the area resulted in changes in the soil properties. One such activity is agriculture (Carpenter *et al.*, 2005; 2009; Diehl, 2009). During the Early Agriculture Period (EAP), when the population increased (Mabry, 2008), the landscape was modified with the construction of earthen irrigation canals (Cajigas *et al.*, 2020). A typical feature of irrigated soils of arid regions is the development of surface crust (Bishay and Stoops, 1975). In this work we have described the physical surface soil crusts, which are specific

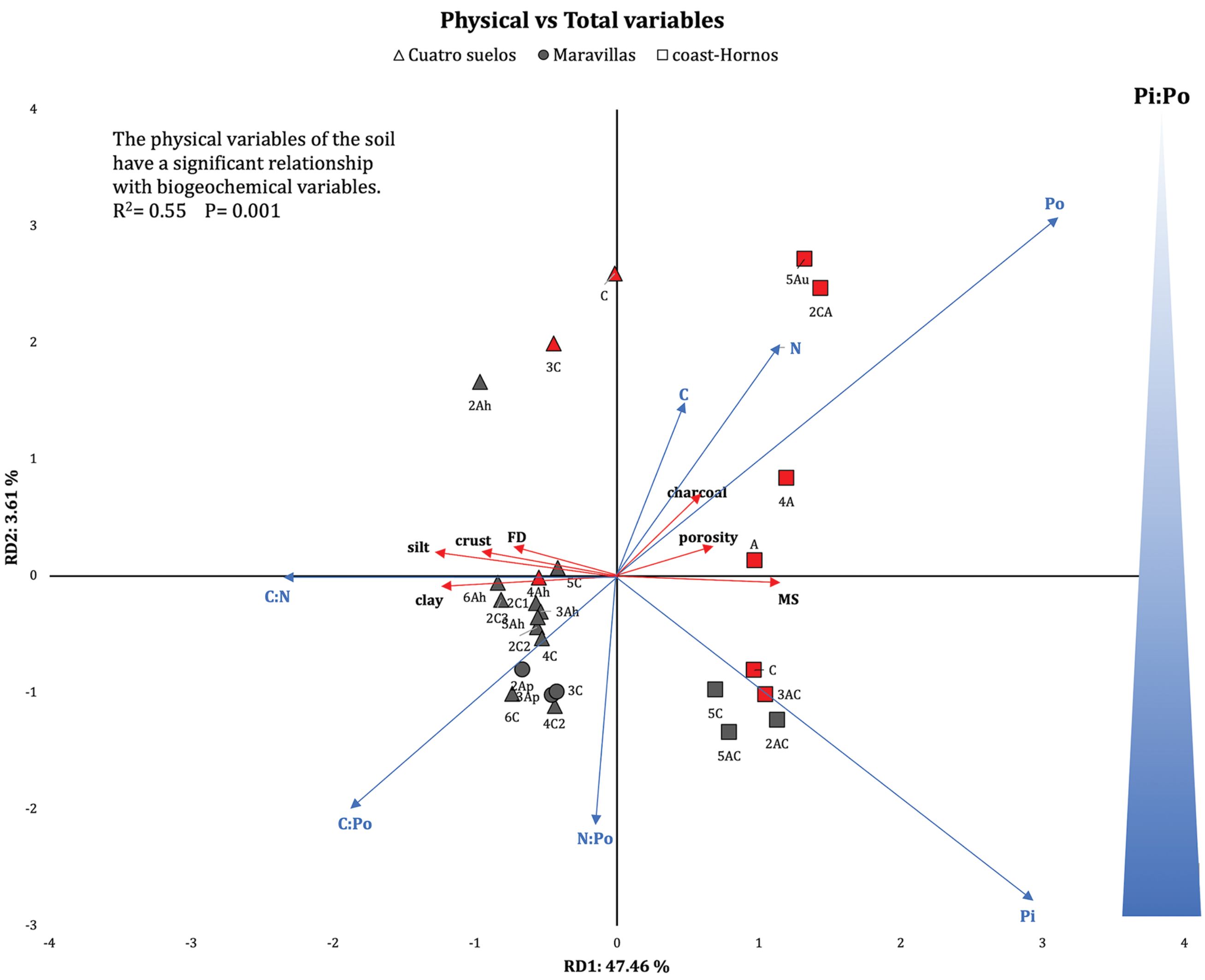

Figure 8. Redundancy analyses. The blue arrows are the total variables, and red arrows correspond to the physical and micromorphometric variables. The sites are distinguished by different symbols. Sites in red show evidence of burning.

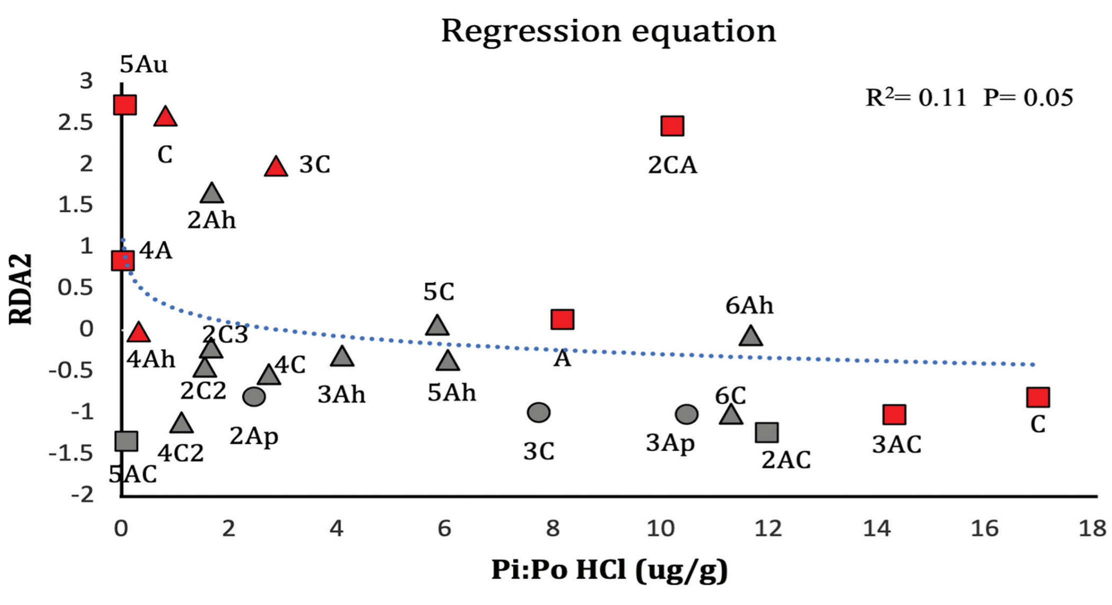

Figure 9. Regression equation. A negative logarithm regression was done between the RDA2 axis and the P_i:P_o ratio extracted with HCl.

modifications of the topsoil caused by natural or other events, such as raindrop impact or sedimentation and subsequent drying, and consist of a hard thin surface layer with reduced porosity and increased bulk density. Physical crusts can also be the result of the impact of man (Pagliai and Stoops, 2010). We observed multiple crust fragments in the thin sections from the Maravillas and Cuatro Suelos profiles, accounting for a high percentage of all the horizons (Table 1).

Another anthropic material, typical of irrigation sediments, is the micro bone fragments, common in the La Playa profiles (Ibarra-Arzave *et al.*, 2018; Cruz-y-Cruz *et al.*, 2019). Cajigas *et al.* (2020) documented the erosion and destruction of the earthen canals in different periods. During these erosional phases, the sediments of the canals were exposed, removed, and further incorporated into the fluvial sediments.

On the other hand, the several thousand roasting features, several cremation burials, and ground stone artifacts are continuously being exposed and eroded by massive sheet and gully erosion. The abundant rocks are not the remains of architectural features, but the remnants of countless disarticulated roasting pit features (Carpenter *et al.*, 2015). The effect of fire on some soil properties has been documented in several studies (DeBano *et al.*, 1979; Doerr and Cerdà, 2005; Certini, 2005; Almendros and González-Villa, 2012; Merino *et al.*, 2018). The abundance of charcoal fragments is probably the most evident feature of soils modified by fire. However, in La Playa, the amount of charcoal fragments is not high (Table 1), but they were observed in the thin sections (Ibarra-Arzave *et al.*, 2018; 2019). However, burnt rocks around the site are evident as 3000 to 4000 roasting pits have been estimated to have existed (Cruz-y-Cruz *et al.*, 2019). LeBorgne (1960) and Kletetschka and Banerjee (1995) have documented that fire produces an enhancement of magnetic susceptibility in soils and increases the concentration of fine and ultra-fine grains of low coercivity magnetic particles. However, in the case of La Playa, we did not observe such behaviour, as the maximum of χlf was detected at the surface of the silty sediments where a low number of ultrafine particles is detected (Barceinas *et al.*, 2018; Ibarra-Arzave *et al.*, 2019). This could be related to the contribution of lithogenic particles from the Sierra Boquillas. It is likely that the increase in χlf corresponds to the current erosion in the area that has mobilised materials from various sources (Barceinas *et al.*, 2018). On the other hand, the increase in the concentration of ferrimagnetic particles with a fine and ultrafine size can be associated with human activities, probably by the pyrogenic organic matter due to the induced fires (Ibarra-Arzave *et al.*, 2019). These observations are in good agreement to the rock magnetic properties found in the studied horizons, where a dominance of superparamagnetic magnetite particles formed by fires is observed (Barceinas *et al.*, 2018; Ibarra-Arzave *et al.*, 2019).

In contrast, pedogenetic features were scarce at the coast profile formed on dune sediments: the horizons were dominated by a grain-supported microstructure (Figure 6b), rich in sand (Figure 7), where grains were subrounded and sorted. The 6Bw horizon at the bottom of the profile was more developed than the upper part of the sequence (Figure 7). It showed a subangular blocky structure (Figure 10), and increasing silt and clay fractions. In addition, the microstructure presented redoximorphic pedofeatures as Fe-Mn mottles and nodules in the groundmass. Also, granostriated b-fabric and secondary carbonates including micrite coatings (Figures 6I and 10), and the absence of artifacts (Table 1), was registered. We propose that these pedogenic characteristics are related to the more humid soil cover conditions that correspond to the Late Pleistocene–Early/ Middle Holocene, characterised by the San Rafael Paleosol (SRP) documented by Cruz-y-Cruz *et al.* (2014; 2015; 2018). Furthermore, the 6Bw horizon, like those studied in La Playa, El Gramal, and El Fin del Mundo sites (Ibarra-Arzave *et al.*, 2019; 2020), corresponds to a profile truncated where it lacks the TOC-richer horizon. Thus, these features can be related to the climatic instability recorded in North America during the Late Holocene (Rasmussen *et al.*, 2006; Perez-Cruz, 2006; Brunelle *et al.*, 2010; Antinao and McDonald, 2013; Ortega-Rosas *et al.*, 2017). However, there is the necessity to investigate this in more detail.

The effect of fire, such as burned shells and bones (Figure 6e), was observed in all the horizons, but particularly in the cultural ones 4A, 5Au, 5AC, where a high concentration of charcoal (Figure 10) and charred materials was also measured (Table 1). These pyrogenic features were accompanied by higher values of χlf and χfd (Figure 7). This magnetic enhancement could not be explained by pedogenesis, which would be expected in the case of soils with a high degree of development. However, the coast-Hornos profile had a poor development of pedofeatures. Hence, a more likely explanation is related to ancient human activities. Magnetic properties indicate that magnetic particles in the profile probably were produced by heating in the ovens made by the settlers of the coast, who occupied the site as an open-air camp located on a dune with mussel ovens (Villalobos-Acosta, 2016).

Additionally, in the coast profile, the absence of surface soil crust (Table 1 and Figure 10) provides evidence that the site was not used for agriculture as in the case of La Playa. However, it should also be considered that the formation of such a crust is hampered in sandy soils. According to the archaeological materials, the age of the oven is around 1350 to 1050 AD (Villalobos, in prep.).

5.2 Biogeochemical soil properties as an indicator of anthropogenic processes

In the previous section, we suggested a set of morphological and physical properties resulting from human alteration. Besides this aspect, which can be controversial, we analysed the biogeochemical properties. Although the soils are alkaline, the highest pH values are observed in deeper horizons, which can be due to the leaching of salts other than calcium carbonates and their accumulation in the lower parts of the profile (Table 1), probably due to a diagenetic process.

Generally, soils of arid and semiarid environments

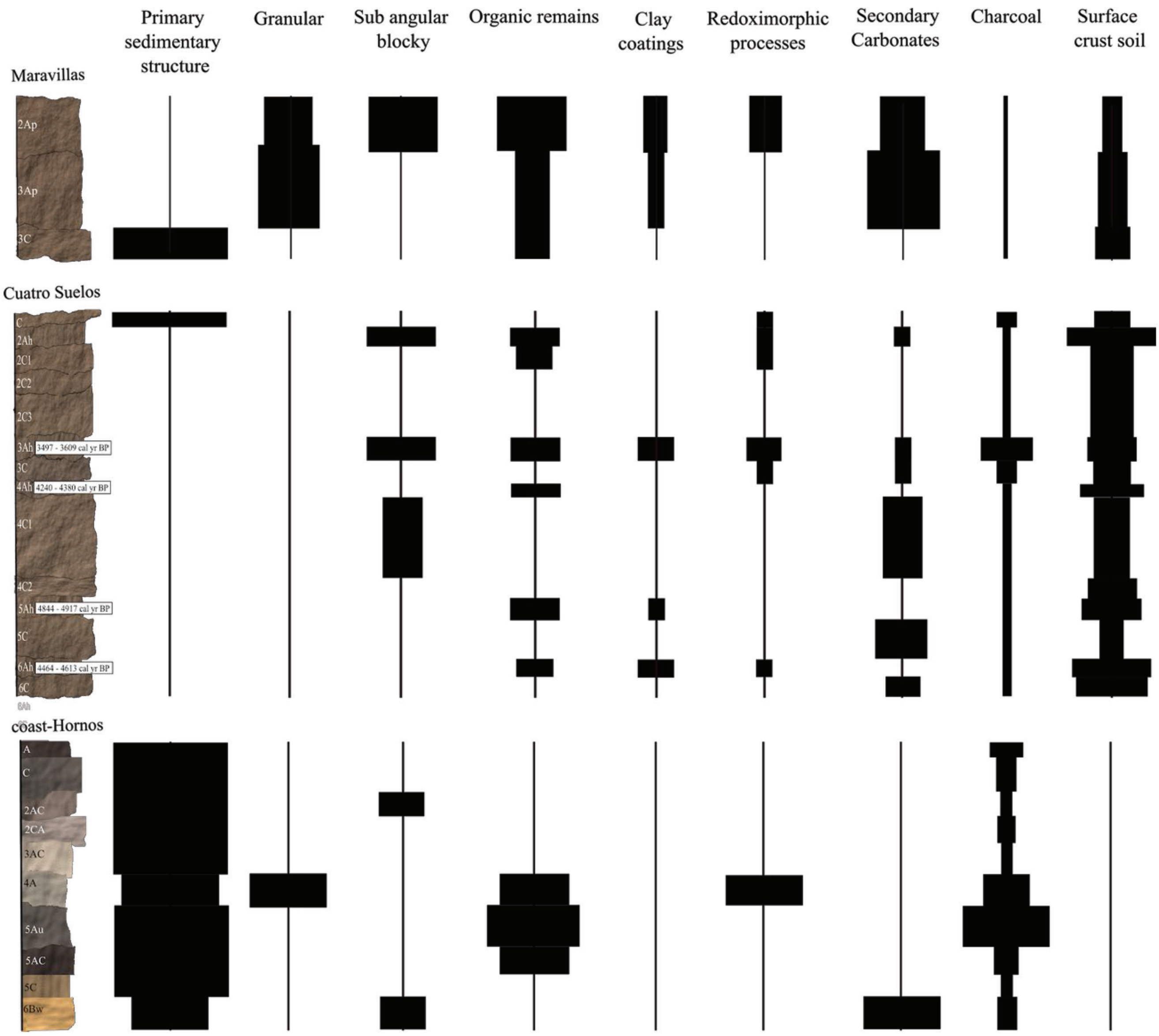

Figure 10. Semi-quantitative differences in the micromorphological properties of Maravillas, Cuatro Suelos and coast-Hornos profiles.

have low organic carbon and nitrogen content due to the scarce plant cover and limited primary productivity due to the low precipitation (Peterjohn and Schlesinger, 1990; Augusto *et al.*, 2017). On the other hand, the La Playa site was strongly affected by the EAP occupation. The pollen record found cereal-type pollen around 4500 years BP in the Cuatro Suelos profile, indicating cultivation activities at the site. However, these conditions were not permanent, and drier environments appeared during the beginning of the Late Holocene with the presence of drier vegetation (Ibarra-Arzave *et al.*, 2019).

Although the values of TOC and TN in the studied profiles are low (as expected in arid ecosystems), there is an increase in the TOC-richer horizons, mainly in the Cuatro Suelos profile (Table 2). Additionally, these horizons had a higher proportion of soil crust fragments than the other horizons (42 and 19%, respectively; t-value: –2.8, p=0.01). As mentioned in the previous section, the soil crust fragment can be related to irrigation canals during EAP (Mabry, 2008; Cajigas *et al.*, 2020). These results suggest that organic carbon and nitrogen increments resulted from anthropogenic activity by irrigation in the EAP. During this period, it was evident that the extensive occupation and complexity of the agricultural system sustained intensive agriculture for long periods with the creation of an agricultural system with irrigation channels.

The superficial soil (A–C horizons) in coast-Hornos is the only one that is currently exposed to formation factors with abundant dune-like vegetation; consequently, this is the sequence with higher C and N concentrations. But in subsurface horizons, the C and N values in the coast-Hornos profile have no apparent relation with agriculture effects (soil crust fragment), suggesting that this site had no EAP during the Late Holocene, as mentioned in a previous section.

The paleosols at the La Playa is an alluvial synsedimentary soil composed of several incipient Ah horizons separated by alluvial sediments. The BOP unit shows an incipient accumulation of humus and a weak development of the pedogenic structure, so it is classified as a Fluvisol according to the IUSS Working Group WRB classification (2006) (Cruz-y-Cruz *et al.*, 2014), while the coast-Hornos profile corresponds to dune sediments. In dryland soil, the ability of P to move from one fraction to another is largely controlled by mineralogy (Cross and Schlesinger, 2001; Lajtha and Schlesinger 1988a; Neff *et al.*, 2006), and several different minerals can play important roles in the stabilisation and release of P. In this case, low P inputs characterise all three profiles via weathering under basic conditions (Walker and Syers, 1976; Porder and Ramachandran, 2013; Augusto *et al.*, 2017). Additionally, because of the high alkaline condition of the three profiles, the HCl-P_i fraction dominates because P is strongly bound to Ca (Tiessen *et al.*, 1984; Lathja and Schlesinger, 1988; Cross and Schlesinger, 2001; Perroni *et al.*, 2014). In alkaline soils, Ca^{2+} reacts with phosphate ions and decreases P availability by forming different insoluble phosphate products (Eidt, 1977; Harris *et al.*, 2006; Havlin *et al.*, 2013; Siebielec *et al.*, 2014). Table 3 shows that most horizons are dominated by P_i and occluded P fractions (extracted with HCl and H_2SO_4) which are inaccessible to biota. The P_o extracted with HCl, corresponds to one of the most recalcitrant fractions, although it can be accessible to biota through biochemical mineralisation.

The amounts of atmospheric deposition of P in the upper horizons of the La Playa sequence could be evidence of the involvement of aeolian processes; this supposition fits well to the reconstructed dry environmental conditions for this depositional period. The concept of "desert loess" (Smith *et al.*, 2002), which explains the formation of silty sediments in an arid environment due to combined effect of physical weathering and pulsing fluvial and wind transportation, could be considered to explain these high values. However, the presence of very poorly-sorted coarse sand casts doubts on the aeolian hypothesis (although does not deny incorporation of the windblown component) (Ibarra-Arzave *et al.*, 2019).

We suppose that the human-induced deposition due to artificial irrigation is the process, which provides the best explanation for the observed properties of the upper La Playa horizon. Ibarra-Arzave *et al.* (2019) argue that this can be the principal deposition mechanism. Water management for agricultural purposes, which has proceeded in La Playa continuously for a long-time, can supply the material for persistent aggradation. The irrigation water from the canals carries heterogeneous suspensions that give rise to poorly-sorted sediments. As mentioned in a previous section, the coast-Hornos profile was used as an open-air camp located on a dune with mussel ovens (Villalobos-Acosta, 2016). Therefore, the effect of human activities on the different horizons has resulted from the use of fire, mainly in the cultural horizons (4A, 5Au, 5AC), which have the highest proportion of charred materials (14–21%). Additionally, these horizons had the lowest C:P_o ratio (0.7–4), the highest proportion of P_o (86–89%), and the lowest P_i:P_o HCl ratio among all horizons.

Normally, high C:P_o ratios (200 or more) are associated with soils "deficient" in P, whereas soils well supplied with available P or on which there is no yield response to added P have C:P_o ratios which are generally <100 (Barrow, 1961).

These results suggest that the organic P-HCl (HCl-P_o) fraction is an accurate indicator of the fire effect by past human activities, as confirmed by the redundancy analysis (Figure 8). Furthermore, the HCl-P_o represents the more soil-stable organic molecules with P (Cross and Schlesinger, 1995; Levy and Schlesinger, 1999) because these organic molecules form non-crystalline organic molecules with Ca and Mg (Ryan *et al.*, 1985; Yuan and Lavkulich, 1994). These molecules can also be related to high P sorption in charred material of the P previously released by the combustion of labile compounds (Huang *et al.*, 2020). Therefore, the organic HCl-P_o fraction could be low degraded over time, keeping the environmental and anthropic influenced conditions since when they were formed. The use of P_i:P_o HCl ratio as a good indicator of past human activities for the three paleosols was confirmed by the redundancy analyses (Figure 8) and the regression of the second redundancy axis with the P_i:P_o HCl ratio (Figure 9).

6. Conclusions

In the Northwest Mexico, the combination of physical, micromorphological-micromorphometric (soil crust), and biogeochemistry (C and N) analyses are an accurate indicator of agriculture during the Early Agriculture Period (4500 years ago), as well as the soil HCl-P_o fraction also being a good indicator of soil changes induced by human fire management.

The main findings can be synthesised as follows:

The soils in La Playa clearly show the effects of cultivation during the EAP, reflected in a high proportion of surface soil crusts that are related to the irrigation by use of canals.

Soil magnetic properties point to the effect of fire in the coast-Hornos site, by increasing the magnetic susceptibility values, which coincides with the high amount of burned materials quantified by the morphometric analysis. In the case of the La Playa site, where abundant ovens and crematories are found, no increment of the magnetic signal has been observed. This can be caused by the reworking of the material due to the cultivation activities.

There is an increment of the TOC and TN in La Playa profiles associated with the anthropic activities, as the non-affected soils have lower values.

The organic P-HCl (HCl-P_o) fraction is an accurate indicator of the effect of fire by past human activities.

The use of P_i:P_o HCl ratio is a good indicator of past human activities, confirmed by the redundancy analyses and the regression of the second redundancy axis with the P_i:P_o HCl ratio.

In short, the integrated analyses of these methods thus show a high potential for analyses of the effect of human activities on paleosols from the Late Holocene.

7. Acknowledgments

Georgina Ibarra-Arzave is grateful for a fellowship awarded by DGAPA, UNAM for a postdoctoral stay at IIES, UNAM. This research was funded by the PAPITT-DGAPA, UNAM (Grant number IN207721 to F. García-Oliva and IN103617 to E. Solleiro-Rebolledo). Thanks to the Archaeological Projects La Playa of INAH – Sonora and Cambio Climático y Diversificación Sociocultural en el Norte de México. We acknowledge the technical assistance of Rodrigo Velázquez, Jaime Díaz Ortega, and Ofelia Beltrán Paz.

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