Archaeological Prospection

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RESEARCH ARTICLE

Geolocation and Spatial Analysis of Underground Fired Earth Structures (UFES) on the Southern Coast of Laguna Mar Chiquita, Cordoba, Argentina

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Keywords: archaeological prospection | digital elevation model | GNSS positioning system | optical satellite images | spatial distribution

ABSTRACT

Underground fired earth structures (UFES) are features excavated directly into the substrate, with ovoid, hemispherical, pyriform or bell-shaped forms, open at the top and varying in size and depth. They have rubified walls with diverse textures and lack a neck. Inside, they often contain layers of fine sediments over a base of charcoal and ashes. Although they are recurrently found at archaeological sites in central Argentina, their function remains uncertain, and the exact time of their initial construction and abandonment has not been determined. This pioneering study on the southern coast of Laguna Mar Chiquita, in the northeast of the Córdoba Province, aims to identify and map UFESs across five archaeological sites, focussing on their distribution, diameter and shape to detect possible patterns. The research included systematic surveying through the implementation of transects parallel to the coastline, using tools such as digital cartography, Garmin GPS, the Geo Tracker app for waypoint and transect track recording, a digital camera, compass, measuring tape and a GNSS (differential GPS) positioning system to obtain precise geolocations. The results identified 260 UFES, randomly dispersed within the sites but concentrated in a specific section of the beach. The UFESs were located between the coastline and the forest/shrub area, below an ellipsoidal height of 95 m, on a consolidated loess-like sedimentary substrate. Medium-sized UFESs, with diameters between 30 and 70 cm predominated accounting for 84% of the total. The selection of these locations suggests practices related to the use of saltwater, in a space conducive to social gatherings and communal activities. This study offers a comprehensive view of the presence and distribution of UFESs in the landscape and provides a solid foundation for future archaeological investigations in the area, thanks to the use of advanced technology and methods that improve geolocation accuracy.

1 | Introduction

Laguna Mar Chiquita is a large saline lake located in the northeastern plain of Córdoba Province, Argentina, between coordinates 30° 45′ S and 62° 30′ W. It occupies a tectonic depression associated with the Tostado-Selva-Melincué fault to the east (Kröhling and Iriondo 1999; Brunetto et al. 2015; Brunetto et al. 2019). To the north, it connects with the Chaco-Santiagueña region, whereas to the south, it transitions into the Pampas Plain (Bucher 2019). Its formation is estimated to date back to the Middle Pleistocene, although the lack of absolute chronological data prevents confirmation of this hypothesis

(Mon and Gutierrez 2009). It is the largest saline wetland in South America and one of the largest saline lakes in the world. Its biodiversity and environmental significance led to its designation as a Ramsar Site in 2002[1] and as a National Park in 2022.[2]

The earliest archaeological references document findings both on the southern coast of the lake and in the wetlands of the Río Dulce (Frenguelli 1932, 1933; Aparicio 1942; Oliva 1947). Although some of these archaeological and paleontological discoveries were interpreted as evidence of early occupation in the area during the Late Pleistocene (Montes 1960), currently available chronological and bioarchaeological data indicate that human occupation on the southern coast of the lake began in the early Late Holocene, approximately 4500 years BP, and intensified around 1200 years BP (Fabra 2020).

Much of the research has focused on this area, addressing various lines of study such as bioarchaeology (Fabra and Demarchi 2009, 2013; Fabra et al. 2012, 2014; Fabra and González 2019; González and Fabra 2019; Salega 2020), archaeobotany (Tavarone et al. 2019, 2023; Cuña Rodriguez et al. 2024) and palaeogenetics (Nores et al. 2022). These studies have allowed for the characterization of the history and evolutionary dynamics of these populations, including their lifestyle, diet, body practices, mortuary customs and the impact of plant domestication around 1200 years BP.

Pioneering research, such as that by Serrano (1945) and lately Bonofiglio (2004, 2009, 2011), based on the styles and shapes of ceramic vessels, suggests that the inhabitants of Mar Chiquita maintained links with populations from the Chaco-Santiagueña plains and the northern Pampas. These biological ties were also supported by bioanthropological studies, such as craniofacial morphometry analyses (Fabra and Demarchi 2009, 2013) and molecular studies (Nores et al. 2022). On the southern coast of the lake, archaeological evidence includes human burials, ceramic fragments, lithic artefacts, archaeofaunal and archaeobotanical remains and underground fires earth structures (UFES) (Fabra 2020).

The UFES, known as 'hornitos', 'hornillos' or 'botijas', have a circular or semicircular shape with fired clay edges and are widely distributed across various landscapes, primarily in arid and semi-arid regions of several Argentine provinces, including Jujuy (Alavar et al. 2023; Alavar and Ortiz 2024), Santa Fe (Ceruti 2006; Cornero et al. 2013; Del Rio et al. 2016; among others), Santiago del Estero (Lorandi 2015; Leon and Sbattella 2023; among others), San Luis (Heider 2020; Heider et al. 2020; among others), La Rioja (Martín 2006; Wachsman et al. 2020), San Juan (Ots and Cahiza 2014), Mendoza (Lagiglia 2006; Andreoni 2015; Chiavazza 2015), Formosa (Calandra et al. 2005; Lamenza et al. 2019) and Córdoba (Hierling 1986; Laguens 1993) (Figure 1). However, in the northeastern plain of Córdoba, they are the only ones associated with both water bodies (lakes and rivers) and early Late Holocene human burials (the last 4500/4000 years BP).

Despite their abundance, distinctive characteristics and recurrent presence in the regional archaeological landscape, UFES have received little attention in archaeological research until recent years, when they began to be studied in greater depth (Laguens 1993; Andreoni 2015; Del Rio et al. 2016; Heider 2020;

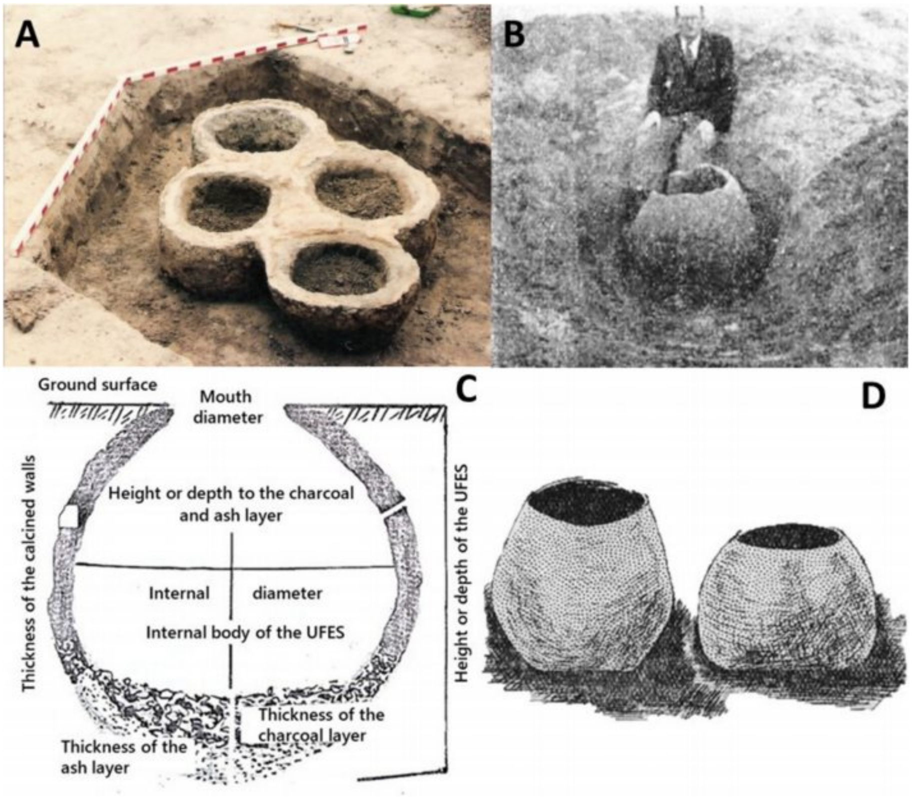

FIGURE 1 | UFES through time. (A) Taken from Del Rio et al. (2016), 74, figure 5. (B) Taken from Castellanos (1938), 27, figure 18. (C) Taken from Lagiglia (2006), 79, figure 14 (translation by the authors). (D) Modified from Castellanos (1938), 28, figure 9.

Alavar and Ortiz 2024 among others). Previously, references to these structures were often isolated and appeared as part of studies focused on other topics, without a comprehensive analysis having been conducted. Furthermore, the consensus on their possible uses remains limited, and theories about their function vary considerably. According to Laguens and Bonnin (2023), demographic growth could be key to understanding the emergence of UFES, interpreted as deposits for the storage or long-term preservation of food to cope with climatic fluctuations. Other hypotheses suggest functions related to the collection, preservation and decontamination of water (Heider 2020), the cooking of vegetables (Alavar et al. 2023; Alavar and Ortiz 2024) and other foods, acting as ovens (Castellanos 1938; Cornero et al. 2013), or even as crematories (Martín 2006). It has also been proposed that they could have been used to efficiently maintain fire for relatively short periods (Hierling 1986; Lagiglia 2006), or to optimize the use of woody resources in contexts of intensified subsistence activities, linked to population growth (Andreoni 2015). Additionally, it has been suggested that they may have been used for ceramic firing (Frenguelli and De Aparicio 1932; Ots and Cahiza 2014; Wachsman et al. 2020). The variability in the shapes, size and wall thicknesses of these structures raises questions about whether they all served the same function, whether they were used for a short period and then discarded, whether they were repeatedly used for the same purpose or if their function changed over time.

In this context, we ask: What is the exact location of the UFES on the southern coast of Laguna Mar Chiquita? What variations are observed in the diameter of the UFES? How is their distribution related to geographical and environmental features, such as proximity to bodies of water?

The aim of this work is to analyse the distribution pattern of the underground earthen structures (UFES) on the southern coast of Laguna Mar Chiquita using surface prospection techniques and differential GPS mapping. This study stands out for its innovative approach in the region, as it applies advanced archaeological survey method. Unlike previous studies that have primarily focused on the possible functions of these structures, this research represents the first systematic attempt to detect and map UFES in the region using high-precision geospatial techniques. This methodological contribution not only enriches the archaeological record but also establishes a replicable framework for future investigations of similar underground features.

1.1 | Study Area

Laguna Mar Chiquita receives inflow from Argentina's largest endorheic basin, covering nearly 127 000 km^2. It is located in a semi-arid region with a subhumid climate, experiencing annual rainfall between 800 and 900 mm, primarily concentrated during the summer months (October to March), which contrasts with the arid environment typical of most saline lakes. These conditions result in significant fluctuations in water levels and salinity (Bucher 2019). The soils are hydromorphic, with high salinity, predominantly consisting of sodium chloride and sulfates (Gorgas and Tassilej 2003). Their texture is loam-clay, composed of fine sand and silty clay, characteristics contributed by the rivers. Additionally, a basic pH (≥ 8) has been recorded (Tavarone et al. 2016). The region hosts a hypereutrophic saline body of water known as Laguna del Plata, which is part of the hydrological system of the main lake, into which the Suquía River flows (Campodonico et al. 2019).

A multiproxy model has been developed to describe its climatic variations (Costamagna et al. 2022), which aligns with the model proposed by Piovano et al. (2009). This model reflects an alternation between dry and cold phases and wet and warm phases over the last 13 000 years. During the Late Holocene, an extremely dry phase is recorded, reaching its maximum extent around 4700 years BP. These arid conditions, characterized by sedimentary hiatuses due to evaporation, prevailed from the Middle Holocene until the mid-first millennium. Subsequently, wetter phases are inferred around 1500 years BP (372–612 cal AD) and 1100 years BP (920–960 cal AD). However, following this period, there is a shift back to dry and cold phases, the precise dating of which has not been possible due to the lack of sedimentary records caused by evaporation (Piovano et al. 2009).

The current climate is subtropical semi-arid monsoonal, with temperatures ranging from mild to warm. The annual average temperature is 19°C, with average highs of 32°C in January and lows of 3.5°C in July. The lagoon, generally shallow, reaches depths of up to 10 m at its highest recorded levels and is fed by three main rivers: the Primero (or Suquía), the Segundo (or Xanaes) and the Dulce, along with several smaller streams on the western shore, known as the western dispersed streams (Bucher 2019).

Originally, the environment around the lagoon was surrounded by the Chaco dry forest, characteristic of this region. Today, the landscape presents a heterogeneous and complex structure that includes the flow of the Río Dulce, temporary and permanent ponds, vast grasslands, halophytic shrublands and elevated areas with woody vegetation (Bucher 2019). The communities of halophytic and subhalophytic plants are primarily represented by succulent shrubs such as *Salicornia ambigua*, *Atriplex lorentzii* and *Allenrolfea patagónica* (jume negro). This area experiences occasional and brief flooding, and the groundwater is very close to the soil surface (Bucher 2019).

The recent creation of Ansenuza National Park reinforces the ecological and cultural significance of the region. Encompassing Laguna Mar Chiquita and the Bañados del Río Dulce, the park protects the largest saline lake in South America and a globally important wetland. It is a key habitat for emblematic and endangered species, such as flamingos and the maned wolf (*Chrysocyon brachyurus*), and plays a crucial role in international bird conservation networks. Additionally, the park promotes sustainable tourism and strengthens ties with nearby towns, fostering public engagement in scientific and heritage conservation initiatives. This broader environmental and social context highlights the importance of studying and preserving the archaeological record within the area.

In this study, the research design included the systematic prospection of UFES at archaeological sites previously studied by the team, namely, Campo Tomasini, Bahía de Ansenuza, Laguna del Plata, Punta del Silencio and Playa Grande, located on the southern coast of Laguna Mar Chiquita (Figure 2). These sites were named and delineated primarily based on local toponymy, used as a practical reference for their identification and communication within the research. However, their spatial delimitation was not solely based on this criterion but also on the distribution of archaeological materials in both surface and stratigraphy, including ceramics, lithic artefacts, human burials and UFES.

Since 2005, human remains have been recovered through accidental discoveries, and information about the broader archaeological context in which the burials are situated has also been recorded. To date, three radiocarbon datings are available for individuals recovered at the Laguna del Plata (1241 ± 54 ^{14}C radiocarbon years BP), Playa Grande (1191 ± 58 ^{14}C radiocarbon years BP) and Punta del Silencio (690 ± 50 ^{14}C radiocarbon years BP) sites. However, no systematic prospection had been conducted previously in these sectors to define the extent and specific archaeological characteristics of each one. Table 1 summarizes the available information on the sites at the beginning of the UFES survey, detailing their location, general characteristics and bibliographic references.

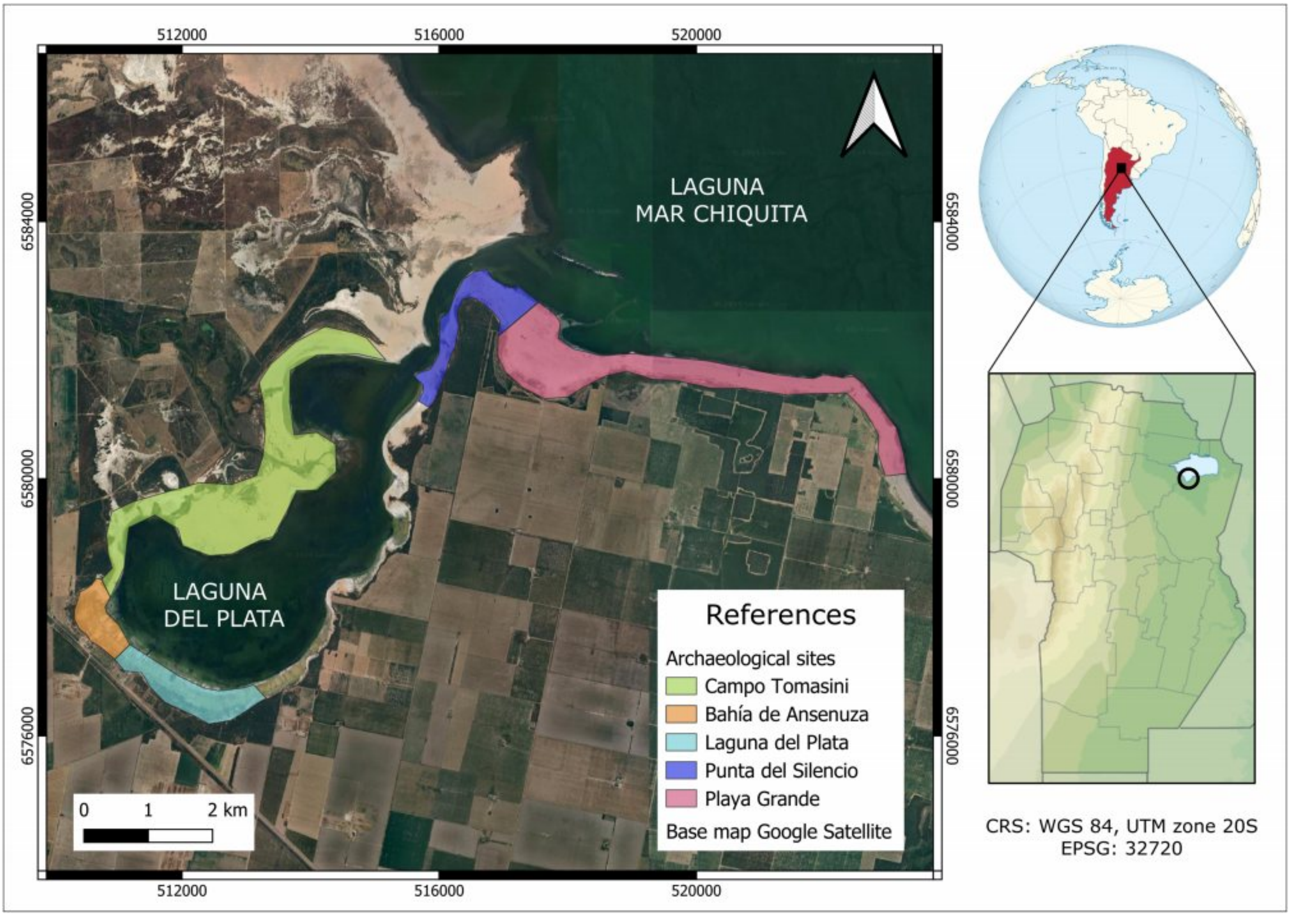

FIGURE 2 | Map of the study area showing the delineation of the surveyed archaeological sites. Coordinate Reference System (CRS): WGS 84/ UTM zone 20S (EPSG: 32720).

TABLE 1 | Information about the archaeological sites prior to the survey conducted in this study.

Archaeological site	Findings	Bibliographic references
Campo Tomasini	Malacological and ceramic fragments	Bonofiglio (2015); Tavarone et al. (2016)
Bahía de Ansenuza	One individual and abundant ceramic material	This work
Laguna del Plata	Two individuals	Fabra and González (2019)
Punta del Silencio	Four individuals, abundant ceramic fragments, lithic material (projectile points and a hand axe) and 16 UFES	Fabra et al. (2019)
Playa Grande	Five individuals, presence of ceramic material	This work; Fabra and Demarchi (2013); Fabra et al. (2019)

2 | Materials and Methods

The methodological design was structured in two stages: desk research and fieldwork. In the first stage, the search and selection of satellite images and a high-resolution Digital Elevation Model (DEM) were carried out with the aim of mapping the different geomorphological features of the lagoon landscape. For this, optical satellite images from the Sentinel-2B sensor (Level 2A) with a spatial resolution of 20 m were used, downloaded from the Copernicus Open Access Hub of the European Space Agency (ESA); and a DEM generated from Synthetic Aperture Radar (SAR) data from Alos-1 Palsar, with a spatial resolution of 12.5 m, obtained from the Alaska SAR Facility (ASF) portal of the University of Alaska Fairbanks. Additionally, QuickBird images provided by Google Earth were used to complement the creation of a detailed base map of the study area. This base map served as a reference for the design of transects, which facilitated the systematic terrestrial survey during the field stage. In this stage, surveys were conducted along transects parallel to the coastline, with a 50-m equidistance. This strategy allowed the complete coverage of a coastal strip between 350 and 400 m, bounded by the current coastline of the lagoon and the boundary of the forested area.

The geolocation of the archaeological finds, which included ceramic fragments, lithic artefacts, bone remains and UFES, was carried out using a Pentax G7 GNSS positioning system (SRC: WGS84, UTM, zone 20S) in RTK (Real-Time Kinematic) mode, allowing for millimetre-accurate locations. The average error margins were 4 mm in the horizontal plane (horizontal root mean square [HRMS]) and 6 mm in the vertical plane (vertical root mean square [VRMS]). Additionally, a Garmin Dakota 20 handheld GPS was used, along with the Geo Tracker application (error margin of 3.35 m), to load the waypoints corresponding to 16 UFES identified in a previous campaign (Fabra et al. 2019), which were then located on the ground and repositioned using the high-precision GNSS system. For measurements of azimuths and diameters of the UFES, a Brunton compass and a 5-m tape measure were used, respectively. A 25-MP digital camera from a Samsung Galaxy A30 smartphone was employed for the photographic documentation of the finds.

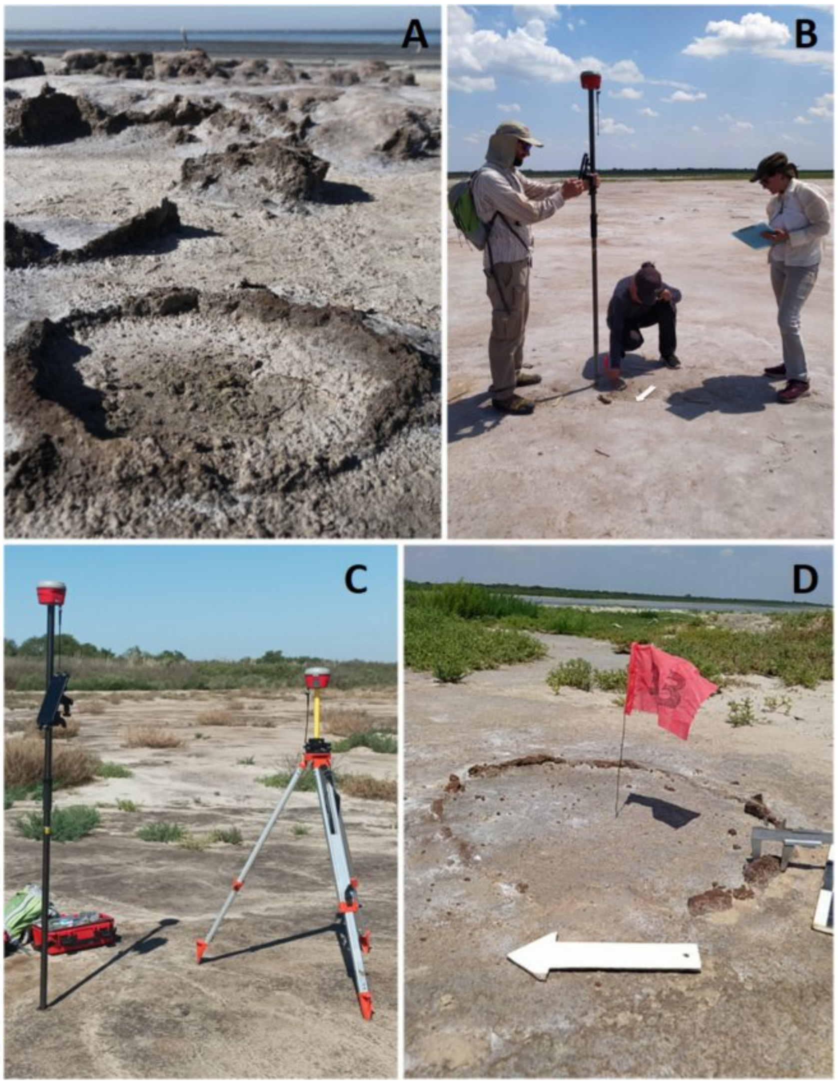

FIGURE 3 | Field images. (A) Panoramic view of a sector with multiple UFES at the Punta del Silencio site. As a reference, the UFES observed has a visible mouth diameter of 45 cm. (B) Data collection activity in the field. (C) GNSS Pentax G7 equipment used during the surveys. (D) Recording and measuring the UFES in the study area.

During the prospections, the characteristics of the UFES were recorded, including their floor plan design, diameter, wall thickness, association with other nearby elements or structures and their relationship to the landscape. The data were systematically collected using ad hoc forms and later digitized into a database organized in an Excel spreadsheet and a Geographic Information System (QGIS software).

In a later desk research stage, the data were processed and analysed to visualize the distribution of UFES across the different geomorphological features of the lagoon landscape, allowing for a more detailed understanding of their spatial configuration and characteristics. To achieve this, multispectral readings of Sentinel-2B satellite images (Level 2A) were conducted, taking advantage of their high resolution through various band combinations in RGB composition to identify physical location patterns. Specific combinations were evaluated to differentiate reflectance sectors on the beach and detect potential variations in the substrate (Chuvieco 1996; Gis and Beers 2017). The combinations evaluated were (i) RGB 4,3,2 (natural colour) (also referred to as true colour or standard false colour composite); (ii) RGB 8,4,3 (infrared colour) (used for vegetation); (iii) RGB 11,8A,2 (agriculture); (iv) RGB 8A,11,4 (land use/water bodies) (also referred to as land/water); (v) RGB 12,11,4 (false colour urban); and (vi) RGB 12,4,1 (lithological discriminator).

It is important to highlight that the Level 2A processing of Sentinel-2B is a surface reflectance product from atmospherically corrected orthophotos, allowing it to be used without the usual atmospheric noise found in images captured by optical sensors (Copernicus n.d.; Gis and Beers 2019). To create the band combinations, the Semi-Automatic Classification Plugin (SCP) tool in QGIS was used, which enables supervised classification of remote sensing images (Zalazar and Equipo de Educación a Distancia Mario Gulich, 2022 [2024]).

Finally, the kernel density estimation (KDE) technique (Chen 2017) was applied in QGIS to estimate the density of spatial distribution and identify areas of UFES concentration.

3 | Results

The systematic prospections conducted on the southern coast of Laguna Mar Chiquita led to the registration of a total of 260 UFES (Figure 3), which are distributed heterogeneously across the sites Campo Tomasini ($n=25$), Bahía de Ansenuza ($n=15$), Laguna del Plata ($n=5$), Punta del Silencio ($n=178$) and Playa Grande ($n=37$) (Figure 4).

These structures are found exclusively in the coastal strip or beach, between the lagoon shore and the forest, at an ellipsoidal height of 91–95 m relative to the WGS84 ellipsoid. It is important to note that, so far, surveys conducted in the shrubland area, located at an ellipsoidal height of 96 m, have found no evidence of UFES. Likewise, according to oral accounts,

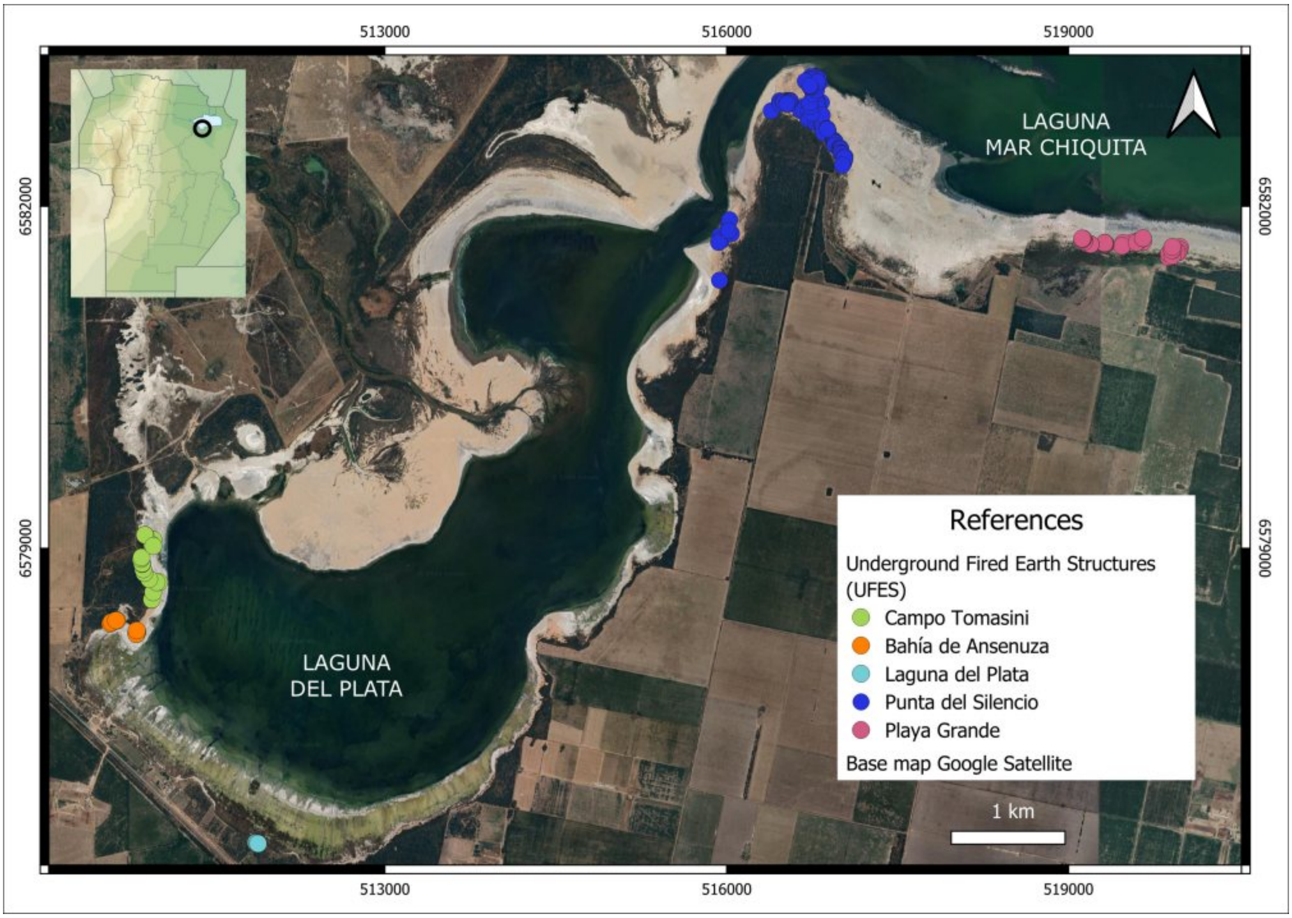

FIGURE 4 | Distribution map of UFES along the southern coast of Laguna Mar Chiquita.

local inhabitants have not observed these structures in that area either (Figure 5). Consequently, the pattern identified in the studied sites suggests a possible regularity in the spatial distribution of UFES.

Regarding the location of the UFES within the beach area, multispectral readings in RGB composition of the Sentinel-2B (Level 2A) satellite images provided satisfactory results. Of the combinations analysed, the RGB 12,4,1 composition proved to be the most optimal for spatially identifying potentially fertile soils from an archaeological perspective, suitable for the construction of these structures.

This band combination is used in geological studies as a lithological discriminator based on reflectance levels (Alonso Fernández-Coppel and Herrero Llorente 2001). For example, Band 12 (short infrared) identifies minerals and soil changes, Band 4 (red edge) detects chlorophyll and vegetation health, and Band 1 (visible blue) highlights water bodies. In this context, it was observed that the UFES, located in the beach area, are situated on a consolidated sedimentary substrate that ranges from light brown to pinkish tones (Figure 6). Although specific studies are needed to determine the exact type of sediment where the UFES are located, the Sunchales 3163-II geological map at a 1:250000 scale (Gaido et al. 2024) suggests that this substrate may correspond to loess-type aeolian deposits, known as Pampas loess.

To analyse the spatial concentration of the UFES, KDE was applied with a 250-m radius. This method allowed for the identification of high-density areas using a colour gradient that represents zones where the structures are located within distances smaller than the specified reach value. As a result, a higher clustering of UFES points was observed at the Punta del Silencio site (Figure 7).

The analysis of the UFES diameters, showed values ranging from 0.17 to 0.90 m. Given the absence of previous techno-typological studies establishing specific size parameters, we classified these structures based on their observed distribution into three categories: small (0.15–0.29 m), medium (0.30–0.69 m) and large (0.70–0.90 m). This classification was defined by the authors as a heuristic tool to facilitate comparison and discussion. Due to preservation conditions, it was not possible to measure all the UFES, but data for 224 structures were recorded. Among them, medium-sized structures predominated significantly, accounting for 87.1% of the total. They were followed by small structures, with 9.8%, and large ones, with 3.1% (Tables 2 and 3). Although no clear sectorization by size was identified, the large-diameter UFES, which are the least frequent ($n = 7$), are located among clusters of medium and small UFES, which could indicate a particular role. Two of these large structures were recorded at the Campo Tomasini site, three at Punta del Silencio and two at Playa Grande (Figure 8).

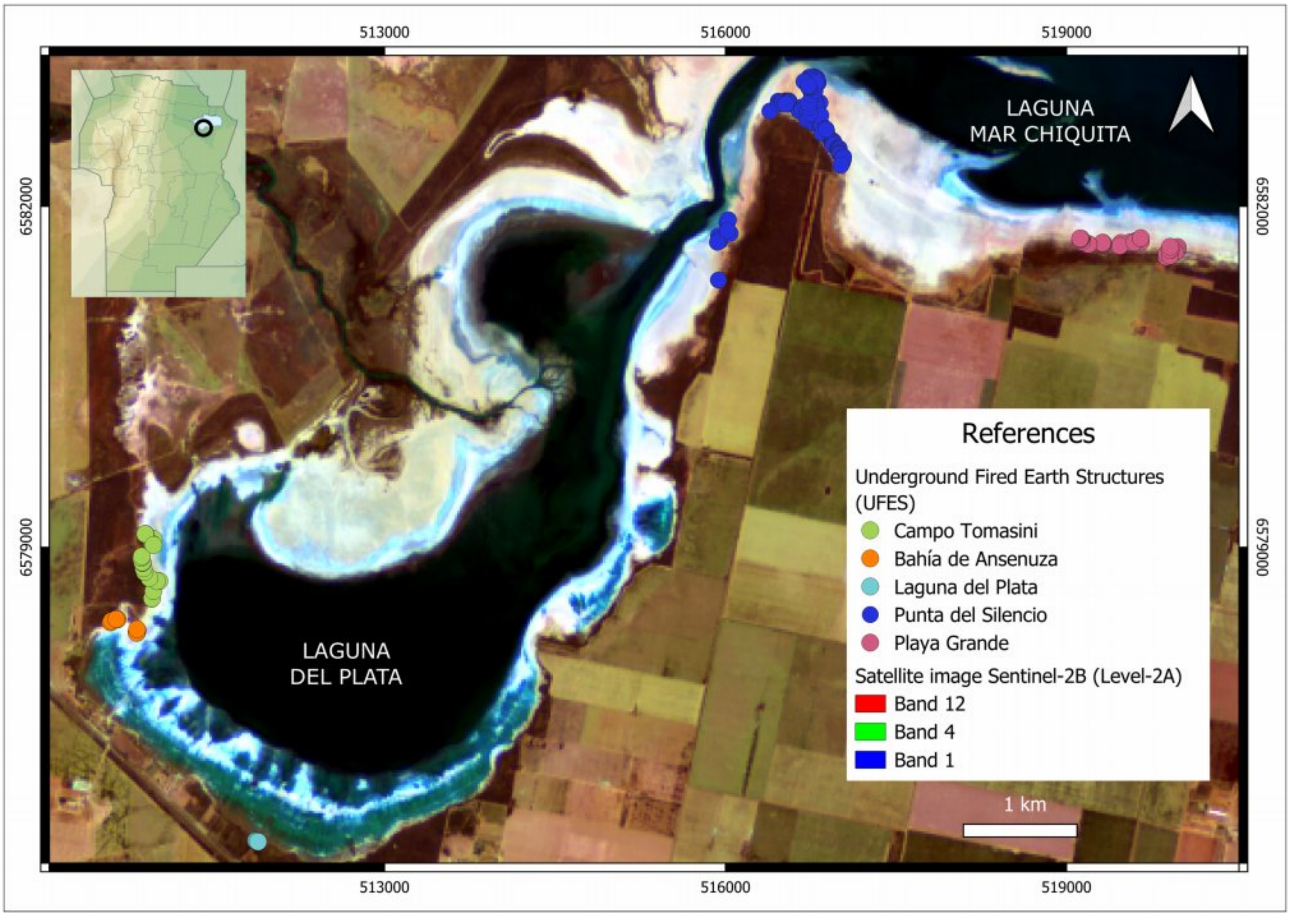

FIGURE 5 | Distribution of UFES along the southern coast of Laguna Mar Chiquita according to their ellipsoidal height, generated from the Alos-1 Palsar Digital Elevation Model (DEM) with a spatial resolution of 12.5 m.

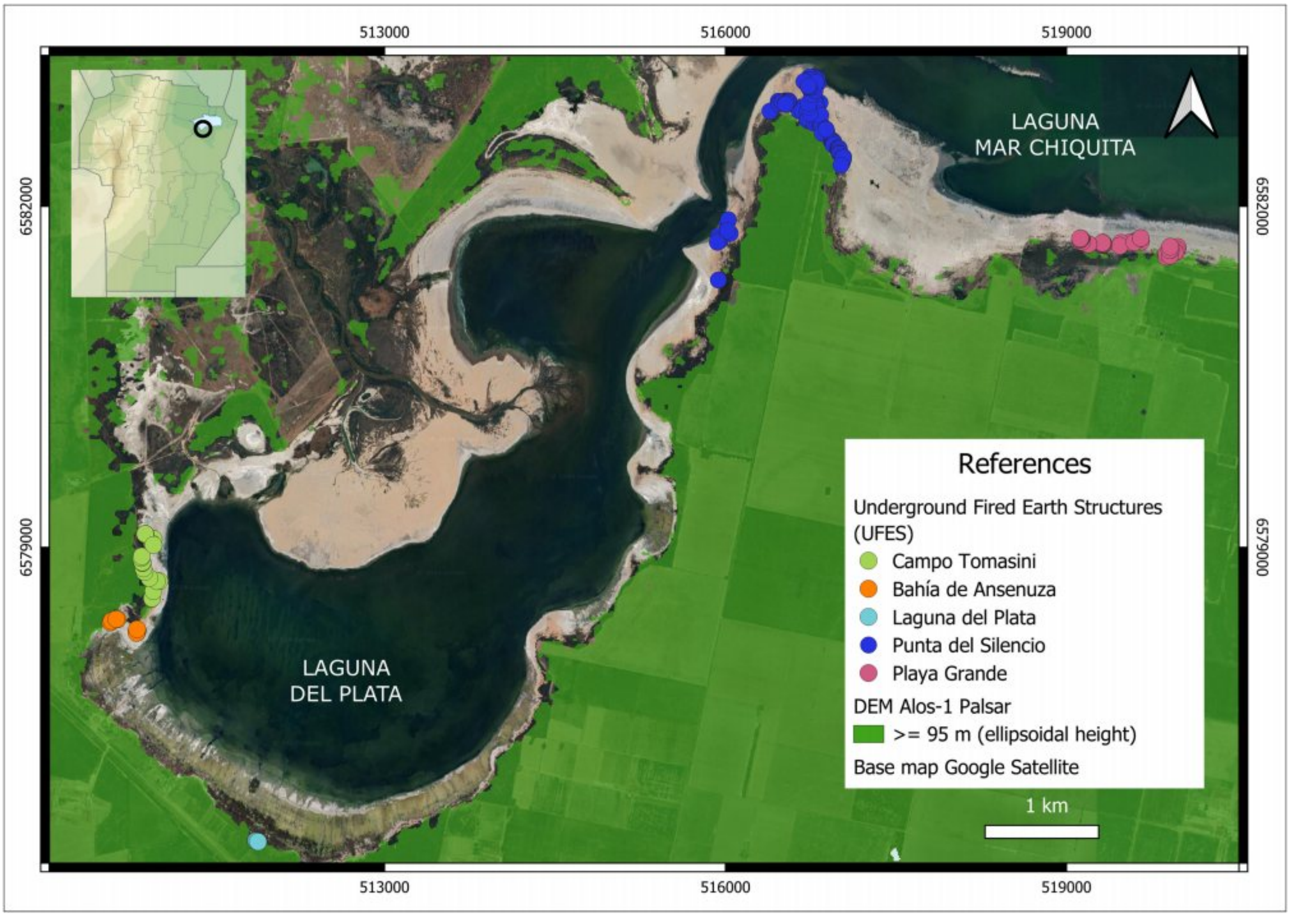

FIGURE 6 | Distribution of UFES over the loessic substrate. A combination of RGB 12-4-1 multispectral bands is presented. The dark elements in the image indicate lower reflectance (higher absorption), whereas the lighter or white areas correspond to regions with higher reflectance (e.g., beach areas with high salt concentration). The blue-toned areas represent wetland sectors.

4 | Discussion

The results of this study have successfully addressed the main objective, which focused on analysing the distribution pattern of UFES, which were found in all the surveyed sectors. According to the kernel distribution analysis, the highest number and frequency of UFES were recorded at the Punta del Silencio site, followed by Playa Grande, Campo Tomasini, Bahía de Ansenuza and Laguna del Plata.

It is important to note that Laguna del Plata has experienced fluctuations in its connection with Laguna Mar Chiquita over time due to hydroclimatic variations. In this regard, the existence of a site such as El Diquecito, located only 1000–1500 m from Punta del Silencio, is worth mentioning. At this site, at least 32 UFES, 12 human burials, and large concentrations of ceramic and lithic material were recorded (Fabra et al. 2012; Fabra and Demarchi 2013). Although El Diquecito is not part of this study, the spatial proximity between both sites is relevant, as it suggests that the communities that inhabited them may have been in contact or maintained some form of relationship, particularly during periods of negative hydroclimatic balance. During cold and dry periods, when decreased rainfall and increased evaporation reduced the levels of the main water body, transit between these areas would have been possible. In contrast, during warmer and wetter periods, increased rainfall could have raised water levels, re-establishing the connection between the two lagoons. Considering these fluctuations in the connection between Laguna del Plata and Laguna Mar Chiquita, it is interesting to note that although the sites of Laguna del Plata, Bahía de Ansenuza and Campo Tomasini are currently located on the southern coast of Laguna Mar Chiquita, their positioning around Laguna del Plata raises the possibility that the UFES could have been constructed in direct relation to this body of water, particularly during periods when it was isolated from Laguna Mar Chiquita due to hydroclimatic changes. However, as there is no direct evidence of the exact timing of UFES construction, this remains a hypothesis that would need to be confirmed through further excavations and analysis of their functionality and chronology.

Although the aim of this study is not to map the associations between UFES and other archaeological materials, it is important to note that these structures are located in sites where primary human burials have previously been recovered, along with a considerable amount of ceramic material, both on the surface and in stratigraphy, as well as various lithic artefacts. Additionally, evidence of domestic and ritual activities has been found at all the surveyed sites (Fabra 2020). Given this contextual association, it is plausible to consider that the construction

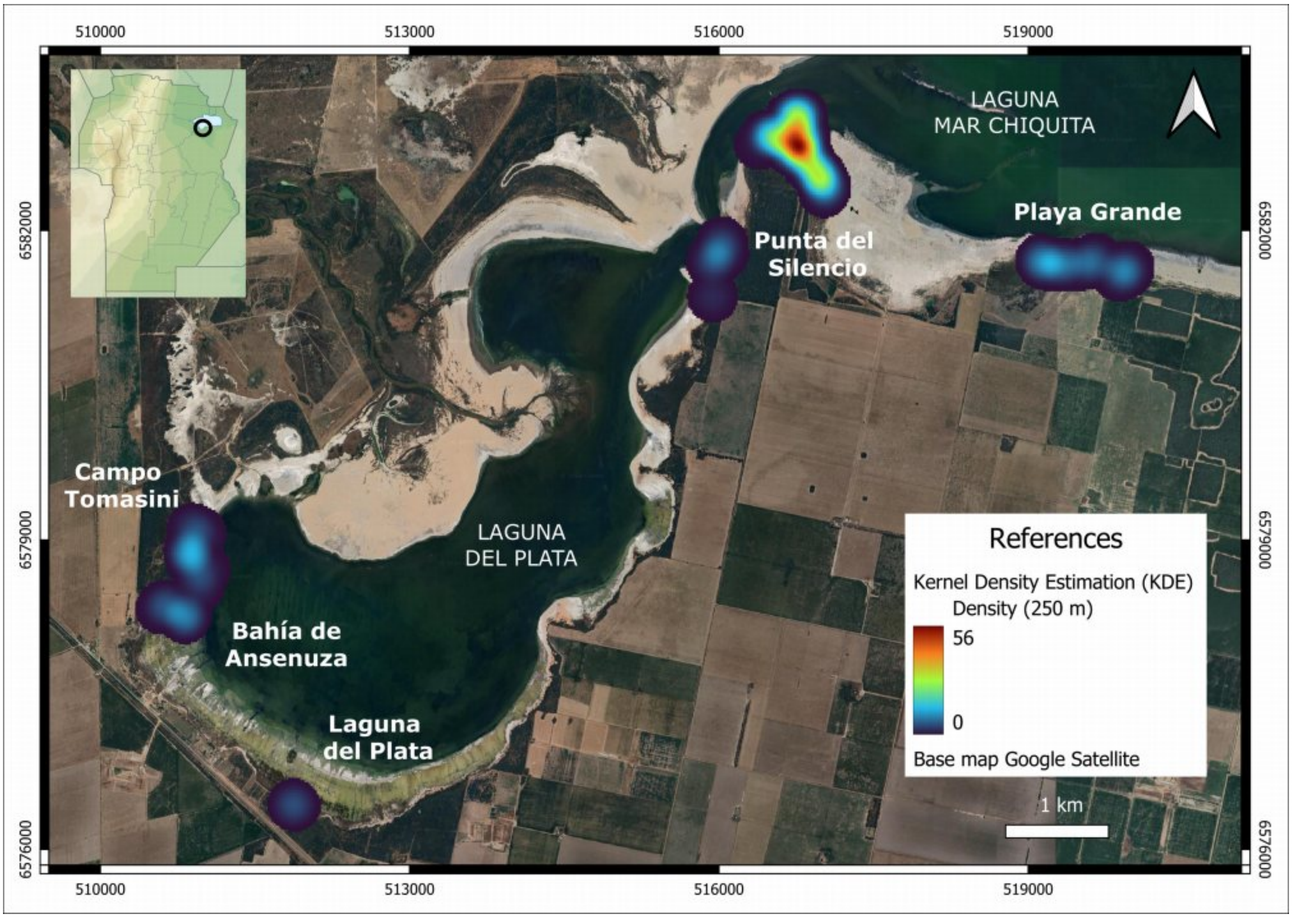

FIGURE 7 | Kernel density estimation of the UFES.

TABLE 2 | Summary of descriptive statistics for the 'diameter' variable.

Statistics	Value
N° UFES	224
N° nulls	36
Mean	0.414 m
Standard deviation	0.112 m
Median	0.4 m
Minimum	0.17 m
Maximum	0.9 m
Range	0.73 m

and use of the UFES were embedded within broader social and symbolic practices of the communities that created them.

This study confirmed that the UFES are predominantly located between the shoreline and the forest or shrubland, positioned below an ellipsoidal height of 95 m. Their placement in the beach zone of the lake, on a consolidated sedimentary substrate that ranges from light brown to pinkish tones (Pampas loess), suggests a selective site choice. These structures are grouped as 'islands' within the beach, reinforcing the hypothesis that their placement was strategically selected based on their relative proximity to both water bodies: Laguna Mar Chiquita and Laguna del Plata. However, the possibility of continuing prospecting in the shrubland areas in the future is not ruled out, with the aim of determining whether UFES are present.

On the other hand, a key aspect to consider is whether the diameters observed today correspond to the original openings of the UFES. If they do, this could suggest that larger structures had a distinct function within the group. Conversely, if post-depositional processes have altered their dimensions, it may indicate that some structures were originally built at a higher elevation than the surrounding ones, with only their central portions remaining due to erosion. Understanding these patterns is relevant for evaluating site formation processes and assessing the potential heights at which these structures were initially constructed.

Distribution studies, such as the one conducted in this work, are rare for this type of structure. Typically, studies mention groupings that vary in number: from hundreds, as in Mendoza (Rusconi 1942) to a few dozen, as in the case of Cornero and del Rio (2015) in the Salado River basin (Santa Fe), and even a few units, such as those documented at the Paradero Laguna de la Sal (Oliva 1947). These studies highlight common characteristics such as similar diameters and general shapes, described as bell-shaped, pear-shaped or elliptical, with varying heights and a layer of charcoal and ash at the base.

TABLE 3 | Observed frequency of UFES by diameter size.

UFES diameter	Campo Tomasini	Bahia de Ansenuza	Laguna del Plata	Punta del Silencio	Playa Grande	Total
Small	0	5	0	15	2	22
Medium	18	8	2	147	20	195
Large	2	0	0	3	2	7
Total	20	13	2	165	24	224

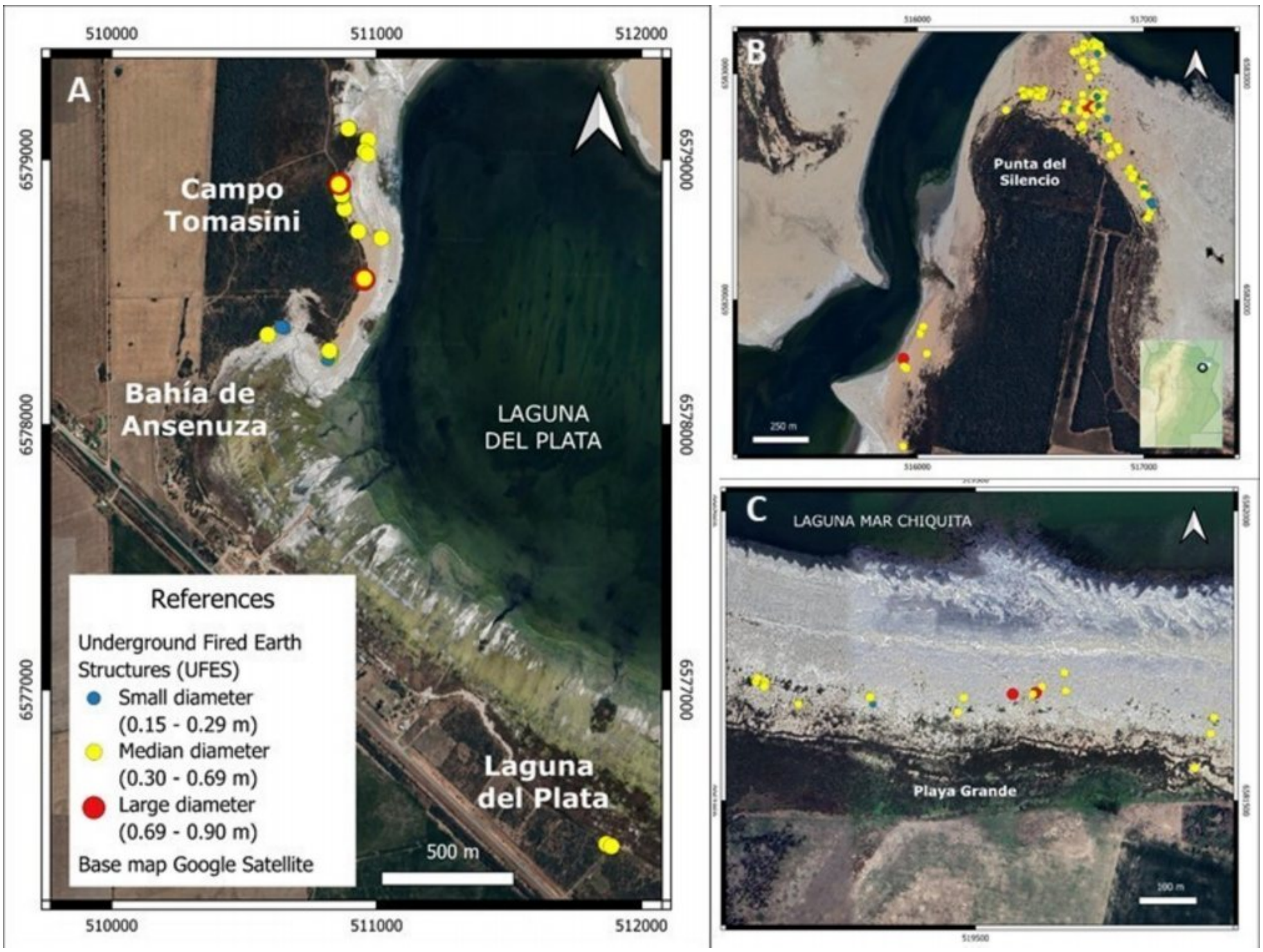

FIGURE 8 | Distribution of UFES according to their diameter.

Additionally, the results of this study partially align with those obtained by Laguens (1993) at another site, El Ranchito, located in the northwest of the Córdoba province. Although this site is not situated on the coast of a lagoon but rather in areas associated with freshwater streams, it is relevant primarily due to its proximity and its location within a semi-arid region with generally similar climatic characteristics. Although there have been previous studies on UFES, this is the first to date that conducts a distributional analysis of UFES, making it a key reference for such approaches. The significance of this comparison lies mainly in the distribution of these structures across the landscape and the patterns associated with it. The similarity lies mainly in the number of structures recorded and their distribution. At the intrasite scale, their overall location is not random, as they are found in specific areas of the beach that share certain environmental characteristics, such as altitude and loessic substrate type. However, within these defined areas, the spatial arrangement of individual structures does not follow a regular or predictable pattern. In some cases, they appear clustered, whereas in others, they are isolated or even overlapping, without a consistent spatial pattern. This suggests that, at this finer scale, their distribution is random. Although this comparison provides valuable insights into spatial patterning, it is important to acknowledge that the different geomorphological settings—coastal lagoon vs. freshwater stream—may have influenced the preservation and visibility of the structures. Future research could further explore how these environmental dynamics impact the integrity and detectability of UFES over time.

In his intrasite study, Laguens identified a non-random clustering of between 100 and 120 units, with diameters ranging from 40 to 90 cm, distributed across three distinct sectors of the site. However, within each sector, their distribution was random, leading the author to suggest that there was no prior planning or design in the allocation of these structures within activity areas. This pattern raises questions about whether the structures were built cumulatively or if they underwent rapid growth over a short period. Additionally, the author proposes that El Ranchito may have been a site with a special purpose, where periodic gatherings of people from different locations took place, associated with ritual or seasonal activities, such as the collection of algarroba and other plant resources. These gatherings, mentioned by early chroniclers (Cabrera 1931), could explain the random aggregation of UFES as a result of the periodic repetition of the same practices. Considering this, our study proposes a primarily residential use of the sites, but the possibility of periodic gatherings for specific activities should not be dismissed. The presence of small and seasonal camps raises the question of whether subtle variations in the elevation of the UFES within the same site could indicate distinct moments of construction, potentially reflecting asynchronous occupations. If such variations can be identified through our methodology, they could provide valuable insights into occupation dynamics, including seasonal or intermittent site use. Therefore, although a residential function remains a central hypothesis, we acknowledge that periodic aggregations for ritual or seasonal activities may have played a complementary role in shaping the spatial distribution of these structures.

However, we consider this similarity to be partial because, unlike El Ranchito, in the sites surveyed on the southern coast of Laguna Mar Chiquita, the UFES are not isolated from other archaeological materials or human burials. On the contrary, they appear to be integrated into more complex spatial dynamics, which may have developed at varying rates and over hundreds of years. Their location was likely strongly influenced by their proximity to a body of water, whose presence probably played a key role in shaping and structuring the use of space by the communities that inhabited its shores. It is important to note, however, that taphonomic dynamics in lagoonal and fluvial environments may differ and, consequently, affect the preservation and alteration of archaeological materials in distinct ways. Whereas lagoonal environments tend to be more stable over the long term, riverbanks are characterized by greater variability. Therefore, comparisons between the sites on the southern coast of Laguna Mar Chiquita and El Ranchito must take these differences into account, particularly regarding abandonment and material preservation. Although our study does not address these taphonomic processes in detail, we recognize that these dynamics could influence the preservation and visibility of archaeological materials. In this regard, future research could delve further into these aspects to provide a more detailed interpretation of the variations observed between the sites.

5 | Conclusion

The results obtained not only deepen our understanding of the UFES on the southern coast of Laguna Mar Chiquita but also provide a framework to compare these structures with similar cases in other regions of Argentina, particularly through the innovative application of surface prospection techniques and differential GPS mapping. This methodological approach stands out as a valuable tool for future surveys and research aiming to identify similar structures in other regions, offering a new way to approach the study of these archaeological features.

The archaeological survey conducted using differential GPS allowed for the precise geolocation of the UFES, which represented a significant improvement in recording their spatial distribution. This methodology was complemented by the analysis of various satellite images, which provided a more detailed view of the structures' locations along the beach, thus facilitating the interpretation of spatial patterns.

During the fieldwork, topographical variations along the coast were identified, revealing a heterogeneous distribution of UFES, especially medium- and small-sized ones, which are located on a specific substrate. This pattern suggests that predetermined locations were selected for their construction, implying deliberate planning and careful site choice. The preference for this loessic substrate could suggest that the UFES were constructed over a relatively short period, considering the significant changes in the coastal morphology due to the hydroclimatic variability of Laguna Mar Chiquita. In the future, it would be essential to conduct more detailed studies to understand the reasons behind the selection of these particular spaces, exploring chronological, climatic, environmental, social and possibly symbolic factors that may have influenced the decision to place them in these specific areas.

In this study, we have worked with the UFES visible today. It is important to highlight the potential use of other geophysical prospection methods to detect UFES, which can be applied non-invasively in large and hard-to-access areas. These methods include magnetic gradiometry, ground-penetrating radar (GPR), electromagnetic induction and geoelectrics (Osella and Lanata 2006; Piro 2009; Bagaloni et al. 2011; Koster 2016; Perdomo et al. 2022; Wilken et al. 2022). In addition, in situ geotechnical research methods that allow for the analysis of subsurface characteristics and the assessment of variations in terrain topography, such as changes in compaction or soil layers, could also be useful (Koster 2016; Wilken et al. 2022).

Although in various sites across the country, UFES are typically associated with freshwater courses or palaeochannels from permanent or temporary rivers, their distribution and association on the southern coast of Mar Chiquita are closely linked to a saline water environment, with no evidence of connection to current freshwater courses or palaeochannels. This particularity raises questions about the interactions between these environments and their influence on the social and economic organization of the communities that built them.

The beach, defined as a space with variable dimensions over time due to the hydroclimatic fluctuations of Laguna Mar

Chiquita and positioned as an intermediary between the forest and the water, may have been perceived as a meeting and communal space. Although its extent may change, the UFES are always found in these areas, regardless of their size or shape during different periods. Furthermore, it likely symbolized a deep connection with natural elements such as water, air and sun within the social framework of these communities. This symbolic and practical relationship with the saline water body seems to have influenced the choice of these spaces, as no UFES have been found within the forested or shrubland areas to date. Although further prospections are needed in this area, which presents challenges due to dense vegetation and fauna, ethnographic and archaeological data suggest that the distribution of UFES is primarily concentrated in the beach zone of the lagoon.

These results highlight the need to continue deepening the study of UFES from various perspectives. In addition to advancing their geolocation, the use of unmanned aerial vehicles (UAVs) becomes essential to obtain high-resolution DEM that allow for further refinement of the UFES locations along the shoreline. At the same time, systematic excavations within the UFES are necessary to identify potential variations in the shapes, sizes and wall thicknesses, as well as to conduct studies of vegetable microremains that could help us understand the different uses these structures might have had over time. It is also crucial to determine whether the different diameters recorded correspond to the original openings of the UFES, which could suggest distinct uses, or if, conversely, the variations in their dimensions result from erosional factors that affected UFES built at a higher elevation. Furthermore, excavations will allow for the correlation of the hydroclimatic changes suggested by the multiproxy model of Piovano et al. (2009) with the chronology of the UFES themselves.

Finally, it is important to highlight that these structures constitute a key component of the local heritage, currently protected within the Ansenuza National Park. Knowing the exact location of these structures and understanding their possible uses is not only crucial for the advancement of archaeological knowledge but also for strengthening strategies for the protection and conservation of these important remnants. Raising public awareness and actively involving the community in the preservation of these sites are essential to ensure their long-term protection, allowing future generations to value and learn from this unique heritage.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data generated and analysed during this study are not publicly available. For further information, please contact the authors.

Endnotes

[1] https://www.casarosada.gob.ar/pdf/HumedalesArgentina.pdf

[2] https://www.boletinoficial.gob.ar/pdf/aviso/primera/266378/20250128

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