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RESEARCH ARTICLE

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Soil use in pre-Hispanic and historical crop fields in the Guatacondo Ravine, northern Chile (2400 years BP): A geoarchaeological and paleobotanic approach

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Abstract

In one of the most arid places on Earth, the Atacama Desert in northern Chile (18–21° S), pre-Hispanic cultures developed different types of tillage and irrigation systems in the Guatacondo Ravine. Their agrarian production, based on a summer precipitation regime, enabled the formative villages of Ramaditas (2300–2600 years BP) and Guatacondo (2400–2800 years BP) to emerge, along with seasonal agriculture. Despite the insight gained into their agricultural technology, we know very little about how this type of soil management affected the soils' plant nutrient status. Thus, our main objective was to determine if the different tillage systems affected the soils' properties. We analyzed the soils and the pollen composition of different tillage systems and carried out direct radiocarbon dating (^{14}C) of sediments. The soils' chemical properties (total nitrogen, phosphorus, and organic carbon contents) indicate greater nutrient retention in the square bed system, associated with a higher silt content and the use of organic fertilizers. Pollen analyses show the presence of crop, weed, and riparian species. In conclusion, the analysis of ancient soils gives us valuable information about the innovations and changes implemented in ancient times in the Guatacondo Ravine.

KEYWORDS

Formative period, land use, pollen composition, pre-Hispanic crop fields, soil properties, tillage system

1 | INTRODUCTION

In one of the most arid places on Earth, the Atacama Desert, in northern Chile's Tarapacá Region (18–21° S), there is evidence of the presence of agriculture since 2500 years BP, particularly inland (Pampa del Tamarugal) and in the Tarapacá, Guatacondo, and Maní Ravines. During the Formative period (2500 years BP), an extraordinary agricultural system was developed by farmers, particularly inland (Pampa del Tamarugal) and in the ravines of the Tarapacá Region. In the Guatacondo Ravine, in particular, farmers built extensive and diverse types of crop fields (Rivera, 2005; Rivera & Dodd, 2013), allowing the production of maize, gourds, and beans (García et al., 2014; Rivera, 2005; Figure 1). These crops fields surrounded the distinctive village-ceremonial complexes of Guatacondo 1 and Ramaditas (Mostny, 1971; Rivera et al. 1995-1996). These villages (ca. 2500–2800 years BP) are conglomerates of circular structures, which have been interpreted as forming a congregational center where the communities who inhabited the coast and valleys of the Tarapacá Region converged, as part of their mobile cyclical desert lifestyle (Adán et al., 2013; Urbina et al., 2015).

Domestic macrobotanical remains similar to those discovered in the Guatacondo Ravine have been found on the coast of the Tarapacá Region, in the Formative archaeological sites of Punta Patache, Cañamo, and Caleta Huelén (García et al., 2014; Nuñez & Moragas, 1977; Rivera, 2005; Urbina et al., 2011; Zlatar, 1983).

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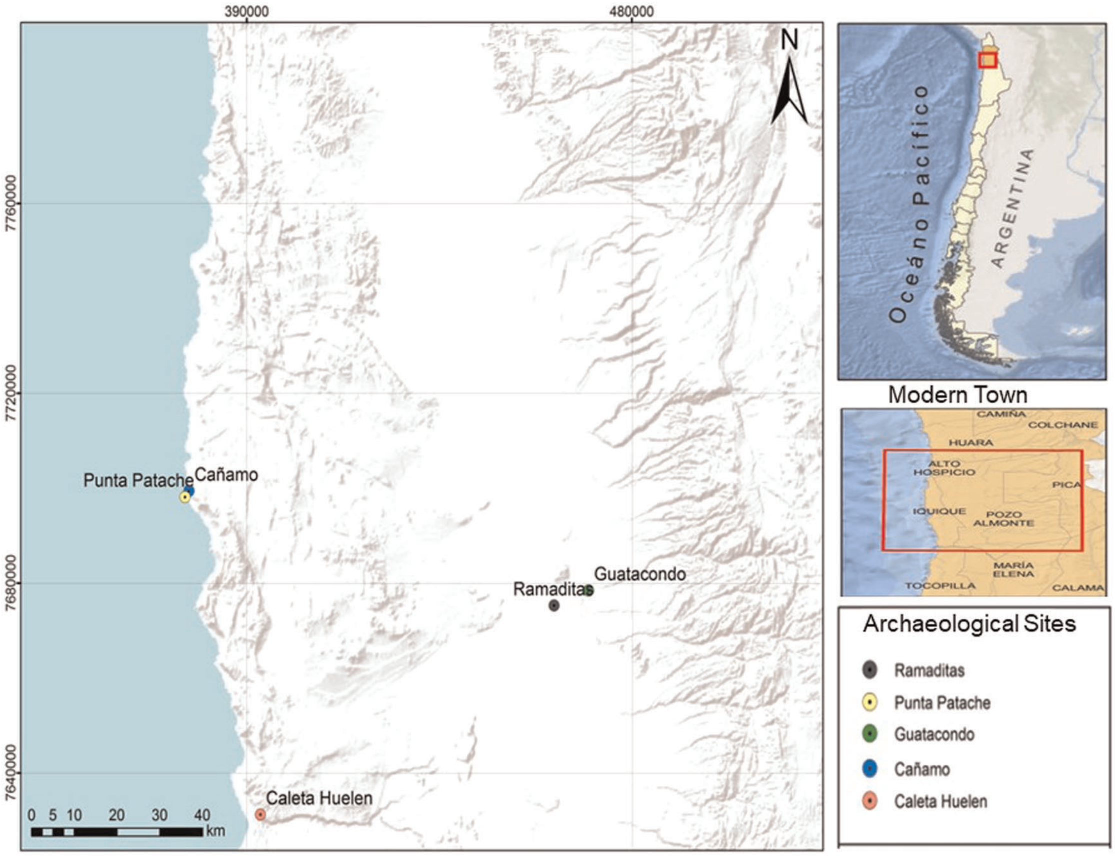

FIGURE 1 Sites in the Tarapacá Region with agricultural botanical remains from the Formative period named in the text [Color figure can be viewed at wileyonlinelibrary.com]

These presumably indicate a long-standing exchange of agricultural resources from inland toward the coast, emphasizing the regional importance of the Guatacondo's field crops in the past.

At the foot of the hill of the Guatacondo Ravine, which takes the form of a plateau over an alluvial fan, there are more than 600 ha of crop fields (Figure 2 and Figure 3). The crop fields were used diachronically for at least 300 years (Vidal, García, et al., 2015; Vidal, Mandakovic, et al., 2015), and different types of tillage systems and irrigation technologies were developed. It has been postulated that seasonal agriculture was developed in the Guatacondo Ravine, based on fast-growing crops, and linked to the summer rainfall (South American Monsoon) that characterized the Andean plateau. The seasonal rainfall topped up the groundwater and surface aquifers, making this seasonal agriculture possible (Gayó et al., 2009; Vidal, García, et al., 2015). The summer rains currently fall at higher elevations of over 3000 m.a.s.l. (Mendonça, 2017). However, during the period 2000–720 years BP, they were more intense even at lower—and currently drier—elevations (Gayó et al., 2012; Jara et al., 2019; Maldonado & Uribe, 2015; Nester et al., 2007). Although the shallow soils of this region would not allow intensive cultivation (Vidal, García, et al., 2015), the nitrate-rich soils and management of the water resources would have permitted high vegetation density (Rivera & Dodd, 2013; Vidal, Mandakovic, et al., 2015).

The irrigation systems used in the crop fields in the Guatacondo Ravine are complex, comprising primary, secondary, and tertiary channels (Rivera & Dodd, 2013; Staller, 2005; Vidal, Mandakovic, et al., 2015). Rivera and Dodd (2013) postulated the existence of a complex irrigation network, where multiple collector channels carried the water to the crop. The water was channeled directly from the river via a primary channel and from the groundwater via a system of wells (Rivera & Dodd, 2013; Vidal, García, et al.,2015).

On the basis of preliminary soil analyses, Rivera (2005) suggested that the crop system at the Ramaditas site was based mainly on annual monoculture crops. However, based on the different types of tillage, the same authors postulated that diverse crops were more intensively cultivated in enclosed spaces. Although there is no clarity about the type of agriculture developed, we do know what types of crops were consumed in the Guatacondo 1 and Ramaditas villages. For example, macrobotanical remains of quinoa (*Chenopodium quinoa*), corn (*Zea mays*), gourds (*Lagenaria* sp.), and beans (*Phaseolus vulgaris* and *Phaseolus lunatus*; García et al., 2014; Ramírez de Bryson, 2005; Rivera et al., 1995–1996, Tartaglia, 1980) have been recovered from the domestic areas of the village of Guatacondo 1. Starch from *Z. mays* and *Solanum tuberosum* was discovered in microremains of coprolites, whereas *Chenopodium* was identified from phytoliths, along with abundant Cheno-Amaranthaceae pollen, all from Ramaditas (Compound 1; Scott et al., 2005). The palynological

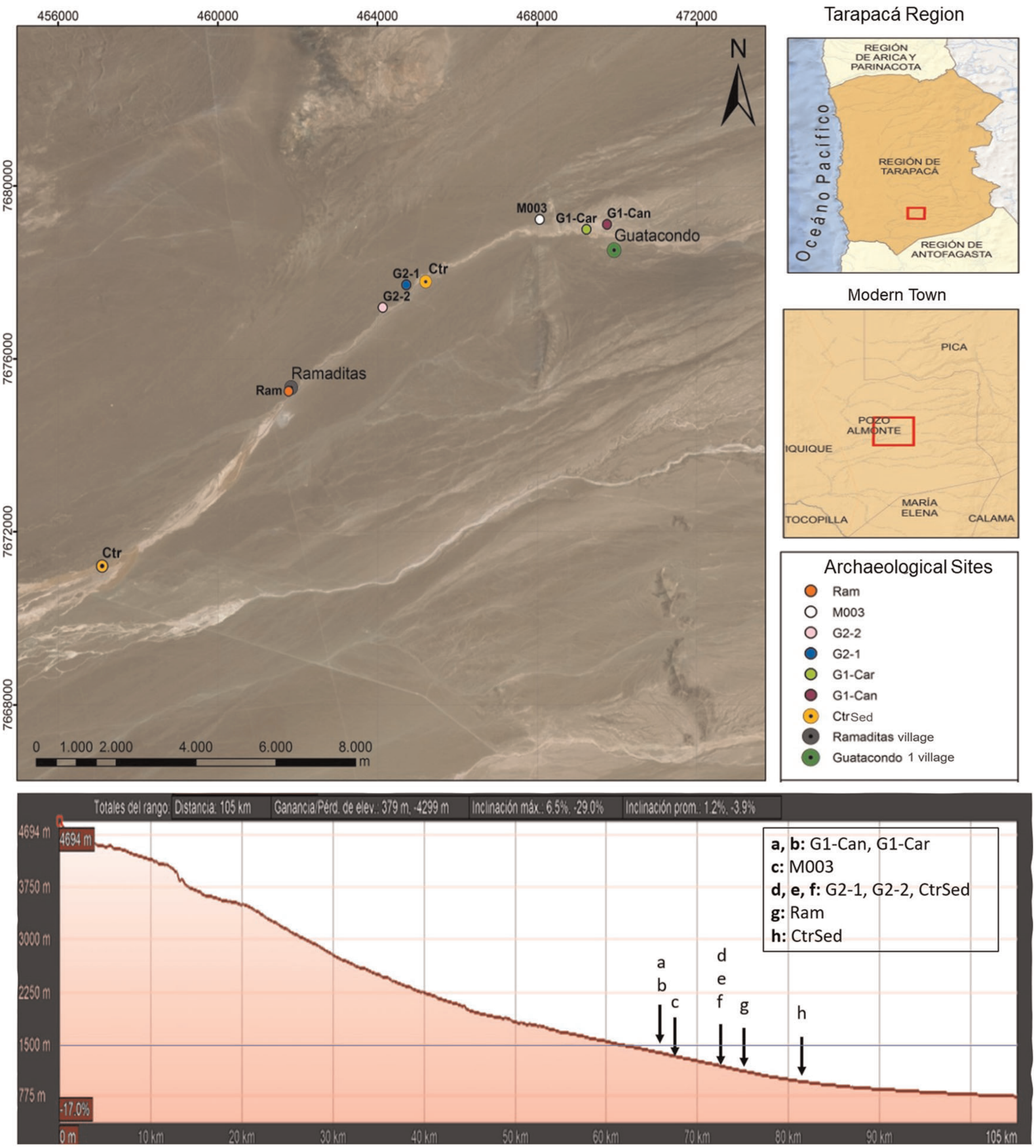

FIGURE 2 A map indicating the location of the study sites in the Guatacondo Ravine including a vertical profile: Ramaditas (Ram), Guatacondo (G2-1, G2-2, G1-Can, G1-Car), M003, and control (CtrSed) sites. The present-day town of Guatacondo is also indicated on the map [Color figure can be viewed at wileyonlinelibrary.com]

analysis of the domestic areas of Guatacondo 1 village demonstrates a predominance of wild plants, such as *Prosopis* sp., *Carex* sp., *Calandrinia* sp., probably *Opuntia* sp., *Chenopodium* sp. (*quinoa* or *amaranto*), and corn grains, with the genus *Prosopis* (Williams, 1980) predominating.

Several authors have documented that deliberate soil management techniques in arid regions of the world, such as runoff agriculture, terracing, and surface rock sorting, may have an indirect effect on the accumulation of soil nutrients by changing the physical properties of the soil, for instance, thickening the uppermost soil horizons and improving the soil texture through the accumulation of fine sediments (Homburg & Sandor, 2011 and references therein). However, less evidence has been documented about direct changes in the chemical and biological properties of soils through the deliberate soil management of crops in ancient times (Del Árbol Moro, 2005; Goodman, 2002; Homburg & Sandor, 2011; Homburg et al., 2005; Roldán et al., 2008; Sullivan, 2000).

The agricultural production in the Guatacondo Ravine has been studied using the morphology of the fields (Figure 3), macrobotanical remains in the domestic areas, the irrigation systems, and paleoenvironmental analysis (García et al., 2014; Rivera & Dodd, 2013; Staller, 2005; Vidal, García, et al., 2015; Vidal, Mandakovic, et al., 2015). However, there is no record of how the different soil management practices affected the chemical elements that are essential

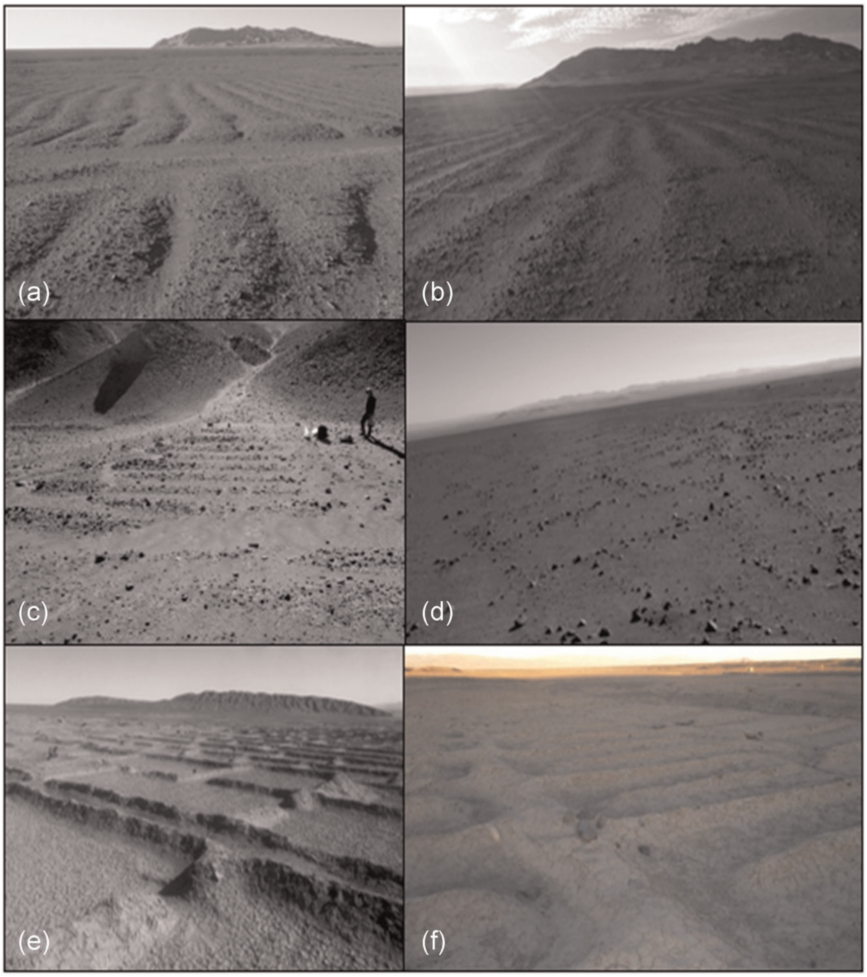

FIGURE 3 Photos of ancient crop fields in the Guatacondo Ravine: (a) extended beds (*melgas*) tillage system of Ramaditas; (b) extended beds (*melgas*) tillage system of Guatacondo 2: G2-1; (c) shallow terrace system of M003; (d) *canchones* (square beds) tillage system of Guatacondo 2: G2-2; (e) square beds (*canchones*) tillage system of Guatacondo 1: G1-Can; (f) spiral-shaped beds (*caracol*) tillage system of Guatacondo 1: G1-Car [Color figure can be viewed at wileyonlinelibrary.com]

for or that limit plant growth. This question is fundamental to understand the kinds of practices that were developed by pre-Hispanic cultures for sustaining agriculture in one of the world's driest deserts. This information can also help us to evaluate the different technologies used in agriculture long ago, including water management, the use of landscape resources, and the associated social organization. Thus, this study attempts to determine how the different tillage systems affected the soil properties and whether differences in soil properties could be related to agricultural practices, such as the type of fertilizer applied and the intensity of agriculture. The central questions are as follows: (a) Did the different tillage methods affect the physical and chemical properties and pollen composition of the soil? (b) Was some kind of fertilizer used for agriculture in ancient times in Guatacondo? (c) What type of fertilizer was used? (d) Are the temporal differences among the study sites expressed in the chemical properties and pollen composition of the agricultural soils?

To answer these questions, we evaluated the chemical properties, texture, and pollen composition of soil samples. We also carried out an exploratory analysis of the natural abundance of stable nitrogen isotopes ($\delta^{15}N$) in agricultural soils. This technique was used to assess the source of the fertilizer used.

Recognizing the variation in the chemical elements of the soils provides us with the basis for interpreting the soil management, application of fertilizers, and the recurrence of agrarian use, mainly because anthropic alteration of the medium distorts the soil components by increasing, decreasing, or having a neutral effect on the soils' chemical properties (Sandor & Homburg, 2017). The enrichment of phosphorous (P), carbon (C), and nitrogen (N) has been related to an increase in the amount of organic material in the soil. In agricultural soils, this has been interpreted as fertilizer use and adequate soil management (Del Árbol Moro, 2005; Goodman, 2002; Homburg & Sandor, 2011; Homburg et al., 2005; Mejía & Barba, 1988; Roldán et al., 2005, 2008, 2014). Conversely, an impoverishment in C, P, and N has been attributed to intensive agriculture without allowing time for the properties of the soils to regenerate (Homburg & Sandor, 2011; Homburg et al. 2005).

Additionally, P is the main element for interpreting traces of human activity, due to its stable character and low presence in the Earth's cortex. However, the evidence provided by the set of chemical elements of the soil offers the most convincing interpretation of the data. It is, therefore, fundamental to recognize the origin of the soil elements. For example, the organic C, a large part of total N, and a smaller proportion of the total P come from the organic matter deposited by the senescent plant cover and all the associated fauna (Julca-Otiniano et al., 2006; Martínez et al., 2008; Munera & Meza, 2012; Perdomo & Barbazán, 2001).

The quantification of the soil elements includes the mineral and organic fractions that are available (in soil solution) and fixed (bonded to clay). The available P and exchangeable cations (e.g., Na, K, and Mg) have their origin in the parent substrate and, to a lesser proportion, in the soluble organic matter that has deposited and mineralized. Their importance in geoarchaeological study lies in the fact that they are elements that either limit (P and N) the development of plants or are essential to it (K, Mg); their relation to organic C will help to determine if some of the total and exchangeable elements have their origin in the decomposition of organic matter (Chapin et al., 2002; Zarin et al., 1998).

2 | STUDY AREA

The Guatacondo Valley (20°59′43″S, 69°18′37″W) lies in the southern part of the Pampa del Tamarugal. This area is a vast alluvial plain between the Coastal Mountain Range and the Andean foothills, and it is a part of the Atacama Desert. Currently, the climate is hyperarid, with negligible precipitation in the low-lying areas and up to 200 mm per year in higher areas during summer as a result of the South American Monsoon (Mendonça, 2017; Rojas & Dassargues, 2006). There was more intense precipitation ca. 2000 years BP (Gayó et al., 2012; Maldonado & Uribe, 2015; Nester et al., 2007). Although this seasonal rain did not change the arid landscape of the Pampa del Tamarugal, it topped up the subterranean aquifers that maintained the dense *Prosopis* spp. forests (Houston, 2001). At present, as in the past, the permanent flow of water means that riparian xerophytic vegetation can prosper in the valleys (Gayó et al., 2012).

The soils are described as little-developed Entisols with almost no organic material (Rovira, 1984). The underlying substrate is reddish sandstone and siltstone (Servicio Nacional de Geología y Minería, 2003). The valley's stratigraphy is an alluvial fan valley composed of fluvial and alluvial successions over which the archaeological remains of agricultural fields are usually found (Antinao, 2015).

3 | MATERIALS AND METHODS

3.1 | Sample sites

We selected six archaeological types of ancient crop fields plus a control sample site over an area of 13.5 km on the plateau of the Guatacondo Ravine. The archaeological crop fields of Ram, G2-1, G2-2, M003, G1-Can, and G1-Car represent different forms of tillage and irrigation systems developed during the Formative, Colonial (ca. 200 years BP), and Republican periods (ca. 100 years BP; Table 1, Figures 2 and 3). The control site (CtrSed) did not show any alteration resulting from human activities and it was within the same geological substrate and environmental setting as the archaeological agricultural crop sites. The archaeological tillage systems are as follows:

TABLE 1 The characteristics of study sites: site name/abbreviation, Spanish name of the tillage type, tillage type, irrigation system in the area studied, archaeological period, presence of nearby domestic spaces, date in radiocarbon years BPs (see Table 2 for details)

Site	Spanish names	Tillage type	Irrigation	Area of sampled field (m^2)	Period	Presence of archaeological domestic spaces	Radiocarbon dates of the fields (years BP)
Ramaditas	Melgas	Extended bed	Surface	82,500	Formative	Yes	2300–2600[a]; Rivera (2005), Uribe & Vidal (2012)
G2-1	Melgas	Extended bed	Surface	10,000	Formative	Yes	2151 ± 22
G2-2	Canchón	Square bed	Flood	150	Formative	Yes	2080 ± 20
M003	Terrazas	Terracing	Flood	100	Formative	No	2060 ± 20
G1-Car	Caracol	Spiral-shaped bedding	Surface	10,000	Colonial	No	180 ± 20
G1-Can	Canchón	Square bed	Flood	416,000	Repub-lican	No	100 ± 20
Control (CtrSed)	None	None	None	-	Current	No	Unknown

[a]Corresponds to Ramaditas village.

(a) Ram (Figure 3a and Table 1) is located within the village and has an undefined area of beds or *melgas* irrigated by reticular channels (Rivera, 2005). The specific sample site is located in the Ramaditas village (Compound 1).
(b) G2-1 (Figure 3a and Table 1) is located 150 m to the west of the archaeological housing described as Guatacondo 2 (Vidal, García, et al., 2015). This site presents rows of extended beds or *melgas* and furrow irrigation.
(c) G2-2 is located 900 m to the southwest of housing Guatacondo and it is defined by square beds (*canchones*), which are described as beds encased by aligning stones (Rivera, 2005; Figure 3b,d and Table 1).
(d) M003 is a shallow terrace and is part of a broader terrace system located on a mountain foothill that crosses the Guatacondo Ravine (Figure 3c).
(e) G1-Can is described as a square bed and is located on the northern bank of the Guatacondo Ravine, opposite the main village of Guatacondo 1 (sensu Mostny, 1970). Mostny (1970) suggested that it was constructed through clearance and accumulating clay to form the bounding walls of the beds (Figure 3e).
(f) G1-Car is located 350 m to the west of the fields described above, where the soil for cultivation is organized into spiral-shaped beds (*caracoles*; Figure 3f). The irrigation type is surface, counteracting the erosive effect produced by the extended beds (Vidal, Mandakovic, et al., 2015). Both sites (G1-Can and G1-Car) were reoccupied in the Colonial and Republican periods.
(g) CtrSed is the control site. It showed no evidence of human occupation and the soils originate in alluvial fans and colluvium, similar to those at the agricultural sites. For this purpose, control samples were taken in two sectors, on the southern slope against G2-1 and 8 km southwest of Ramaditas village.

3.2 | Soil sampling and analysis

We extracted five soil samples from each study site, at least 10 m apart, within the area of each ancient crop field. We selected the crop fields that had already been sampled for radiocarbon dating. The soil samples for radiocarbon dating were collected from under the rocks that were used in the channels as gates to control the flow of water and from a circular structure (G1-1-E4) in the G1-Car system (Table 2).

Soil samples were extracted to a depth of 20 cm. We excavated two levels of 10 cm each. Each horizon was visually recognized by the higher silt content of the subsurface soil. Samples were randomly located within an area, representing the state of conservation of the agricultural structure and proximity to the domestic contexts. The good state of preservation in terms of the morphology of the different tillage types allowed us to discard any postdepositional disturbance (e.g., precipitation and alluviums) that would have obscured our interpretation of the results.

We determined the concentration of the following chemical elements in the soil: available phosphorous (P_a), total phosphorous (P_t), total nitrogen (N_t), organic carbon (C_{org}), and exchangeable potassium (K), magnesium (Mg), and sodium (Na). The extraction and determination of the elements were performed in the Biogeochemistry Laboratory of the Pontificia Universidad Católica de Chile, Santiago. The total content of organic C and N were determined in ground-acidified soil samples through flash combustion in a Carlo Erba NA 2500 Elemental Analyzer (Robertson et al., 1999). Total P was extracted from ground soil samples using a concentrated sulfuric acid/water peroxide solution in a Hach Digesdahl digestor and determined by colorimetry through the molybdenum blue method (Thomas et al., 1999). Exchangeable cations were extracted using a 1-M ammonium acetate solution (1:10) and determined using a PerkinElmer 2380 AAS (Robertson et al., 1999). Available P was obtained by lactation through the calcium acetate–lactate method (CAL) and determined by colorimetry using the molybdenum blue method (Steubing et al., 2002). The pH level and electrical conductivity were determined from a soil–water suspension with a 1:5 ratio and the specific electrometric determination (Steubing et al., 2002). The presence of carbonates in the soil was evaluated by adding 1-M HCl and visually assessing the effervescence class (United States Department of Agriculture, 2017). The three soil fractions (sand, loam, and clay) were separated using the decantation method to determine the soil texture using the textural triangle method (United States Department of Agriculture, 2017). The natural abundance of the stable isotope of N, expressed as $\delta^{15}N$ (‰), was determined from five pulverized soil samples in a Delta Advantage IRMS (isotope ratio mass spectrometer) connected to an EA

TABLE 2 Results of radiocarbon dating in tillage systems of Guatacondo Ravine

Lab code	Sample	Associated tillage system	Material	^{14}C age without calibration (years BP)	Error (±)	^{14}C age-calibrated 2-sigma (years BP)
UGAMS-20242	Z2-002-E6	G2-2	Sediment	2080	20	1998
UGAMS-20243	M-020-198	M003	Sediment	2060	20	1964
D-AMS 009020	GUAT 382	G2-1	Plant macro	2151	22	2086
UGAMS-20246	G1-1-E4	G1-Car	Sediment	180	20	172
UGAMS-20246	G1-1-E4	G1-Car	Sediment	180	20	183
UGAMS-20245	G1-1/194	G1-Can	Sediment	100	20	111

2000 Flash Element Analyzer in the LABASI Laboratory of the Pontificia Universidad Católica de Chile. These samples came from the surface horizon of the RAM, G2-2, G1-Car, and G1-Can tillage sites, and we also analyzed a control sample from the area of alluvial and fluvial flows. This type of analysis give us insights about the source of the fertilizers applied to the crop fields, by comparing published data on the isotopic signal of δ^{15}N of the enriched guano of sea birds (Gagnon et al., 2013) and depleted both camelid guano and plant tissue from the Atacama Desert (Díaz et al., 2016)

The pollen analysis was performed in the Paleoclimate Laboratory in the Center for Advanced Studies in Arid Zones (CEAZA) using the standard procedure designed by Faegri and Iverson (1989). The taxonomy was determined using reference collections and literature (Heusser, 1971; Marjfraf & D'antoni, 1978). One bulk soil sample from the 10–20-cm level was analyzed per site. For each sample, we analyzed three plates of subsamples extracted from the bulk soil samples, except for the G1-Can and G1-Car sites, for which only one subsample was analyzed.

3.3 | Statistical analysis

We used analysis of variance to evaluate the significantly statistical differences and similarities in the soil chemical elements between (1) the ancient crop fields and the control site, (2) the various tillage systems, and (3) the different periods of use. We also used the Pearson correlation analysis to evaluate the degree of association between organic C, N_t, P_t, P_a, and base cations. The analyses were performed using permutation (Quinn & Keough, 2002) of pairs in the R-Crane program for ANOVA and correlations. A value of $p \leq .05$ was considered to be statistically significant.

4 | RESULTS

4.1 | Radiocarbon dates of tillage systems

The results of radiocarbon dating indicate that the RAM, G2-1, G2-2, and M003 systems date back to the Early Formative period (2086–1876 years BP), whereas the G1-Can tillage systems showed dates associated with the Colonial–Republican period—specifically 100 years BP. The organic remains of the circular structure named G1-1-E4 give a date of 180 years BP (Table 2). This structure, part of the G1-Car system, was probably used as a storage area (see below).

4.2 | Chemical and physical properties of the soil

All soil samples showed electric conductivity ranging from 1400 to 8570 µS/cm, indicating that the soils are nonsaline to moderately saline (saline ≥ 4000 µs/cm; United States Department of Agriculture, 2017). The pH indicated moderately alkaline soils (8–8.6) and the effervescence classes showed that all sites can be classified as highly carbonated. The lowest silt content is presented in the soil of the shallow terraced system M003 at 7%, whereas the highest silt content is up to 61% in G1-Can. The square bed (*canchones*) tillage systems G2-2 and G1-Can presented twice as much silt content as the extended bed (*melgas*) in G2-1 and the spiral-shaped bed (*caracoles*) in the G1-Car tillage systems (Figure S1). The tillage system of RAM presented a silt content of 20.4% and the control sample showed 35.3% silt content (Figure S1). The other sediments in these samples were sand, which indicates a range of soil textures from silty to sandy-silty and sandy soils.

4.3 | Differences between the tillage systems versus the control samples

There were significant differences between the agricultural and control samples in the chemical element contents of the soils (Figure 4), except for the pH values of the soils. The G1-Car, G1-Can, Ram, and G2-2 tillage system had higher content of total organic C than the control site (Figure 4a). The soils of Ram, G1-Can, and G2-2 presented higher total N contents than those of the CtrSed (Figure 4a). Meanwhile, the soils from G1-Car, G1-Can, G2-1, and G2-2 presented higher available P than those from the control site (Figure 4b). The soils from the G1-Car, G1-Can, and G2-2 sites presented higher total P contents than those from the control site (Figure 4b). The soils of all the tillage systems, except M003, presented a higher Mg content than those of the control site (Figure 4b). By contrast, there were less exchangeable K and Na in the soils from all the agricultural fields, except for G1-Can, where the K content was similar to that of the control site (Figure 4c).

4.4 | Differences between tillage systems: Extended beds (*melgas*), square beds (*canchones*), and spiral-shaped beds (*caracoles*)

When comparing the sites from the Formative period (Ram, G2-1, G2-2), we noticed statistically significant differences between Ram and G2-1 and G2-2; the soils of the former had higher concentrations of total N (378.3 vs. 326.5 mg/kg) and organic C (4235.3 vs. 3270.7 mg/kg), but the concentration of total P (223.75 vs. 296.9 mg/kg) was lower than that of G2-2 (Figure 5a) and similar to that of the G2-1 tillage systems. In relation to the tillage systems, the soils of G2-2 (square bed) had higher nutrient concentrations than those of G2-1 (extended bed), which was significant for total P (296.9 vs. 222.6 mg/kg) and total N (326.5 vs. 276.9 mg/kg; Figure 5b). The available P, total organic C, and exchangeable K, Na, and Mg contents of the soils were similar in the soils of all the tillage systems from the Formative period. When comparing the sites of the Colonial–Republican period, the soils of the G1-Can fields had higher nutrient concentrations than those of G1-Car, and these were significant for total N (421.8 vs. 306.9 mg/kg), exchangeable K (474.7 vs. 328.1 mg/kg), and Mg (80.3 vs. 67.9 mg/kg; Figure 5c). The total organic C, Pa, Pt, and exchangeable Na in the soils were similar in the tillage systems of the Colonial and Republican periods.

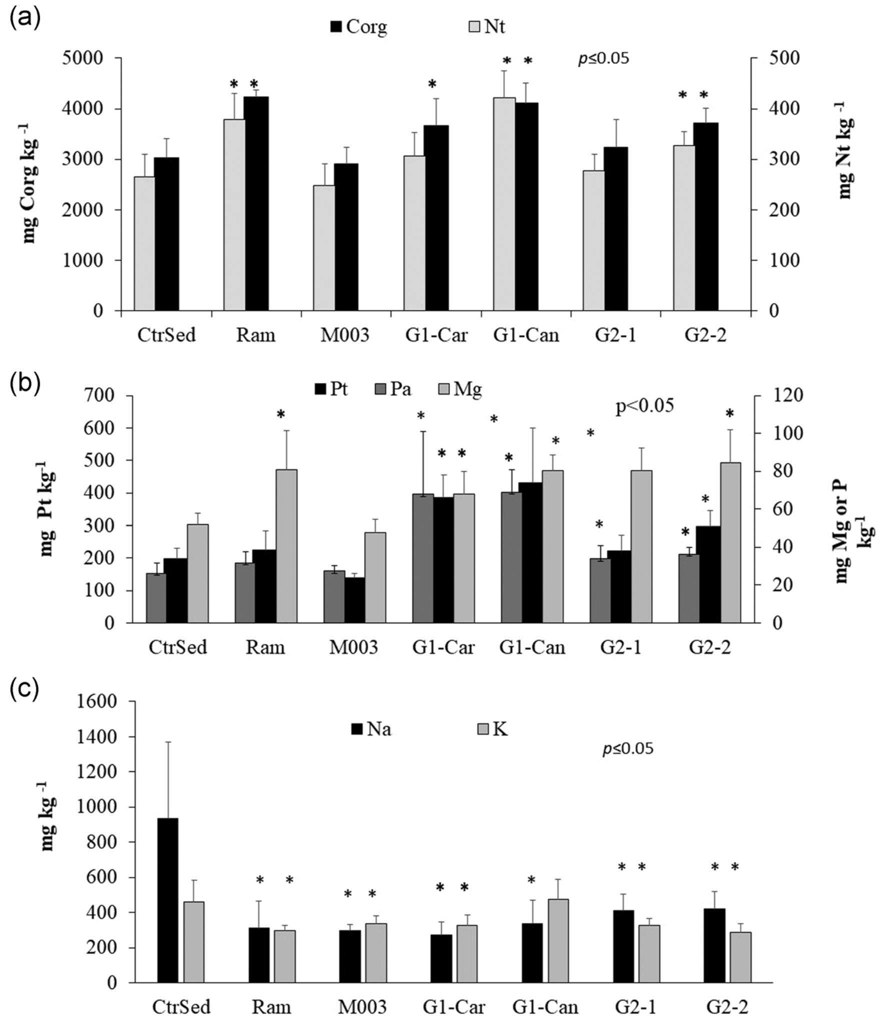

FIGURE 4 The mean element contents ($n = 5 \pm SD$) of the topsoil of the study sites in the Guatacondo Ravine: (a) total organic C and N; (b) total and available P and exchangeable Mg; and (c) exchangeable Na and K. *Significant differences between the agricultural fields and the control site ($p \leq .05$)

4.5 | Differences between the Formative period and the Colonial and Republican periods

Only P (total and available) showed a clear difference between two periods: Formative versus Colonial–Republican; both the G1 tillage systems (G1-Car and G1-Can) of the Colonial–Republic period had higher concentrations than all the fields of the Formative period (Figure 6a). Moreover, the soils from the G1-Can crop field from the Republican period had higher contents of organic C and total N than G2-1 and a higher content of total N than G2-2 from the Formative period (Figure 6b). The soils from Ram had higher organic C (4235.3 vs. 3664 mg/kg) and total N (378.3 vs. 306.9 mg/kg) than G1-Car from the Colonial period, despite being 2000 years older (Figure 6b).

4.6 | Natural abundance of $\delta^{15}N$

The results for the $\delta^{15}N$ found in the topsoils were as follows: G1-Car: 3.76‰ ($\delta^{15}N$), G1-Can: 2.93‰ ($\delta^{15}N$), Ram: 1.75‰ ($\delta^{15}N$), and G2-2: 1.41‰ ($\delta^{15}N$). The mean value of $\delta^{15}N$ was 2.46‰ (Figure S2), whereas the control sample showed a value of 4.08‰ ($\delta^{15}N$).

4.7 | Correlation analyses of organic C and the other chemical elements

The correlation analyses of the soils of all the tillage systems show positive and significant correlations between organic C and N_t, P_t, P_a, and exchangeable Mg (Figure 7). There was no significant correlation with the other cations, such as K and Na.

4.8 | Pollen analysis

The cultivated fields had significantly higher quantities of pollen and varieties of taxa than the uncultivated soil (Figures 8 and 9). The most represented family was Asteraceae, with the pollen type *Senecio*, *Baccharis*, and *Tessaria*. The genus *Myrica*, probably *Myrica pavonis*, was also found in significant quantities. *M. pavonis* grows in valleys that have a permanent flow of water and is native to the area (Gatica-Castro et al. 2015; Riedemann et al. 2016). This species is currently absent from the study area, which suggests that the environmental conditions were more humid in the past, as has previously been indicated by Maldonado and Uribe (2015), Betancourt et al. (2000), and Gayó et al. (2012). Cucurbita pollen was only found

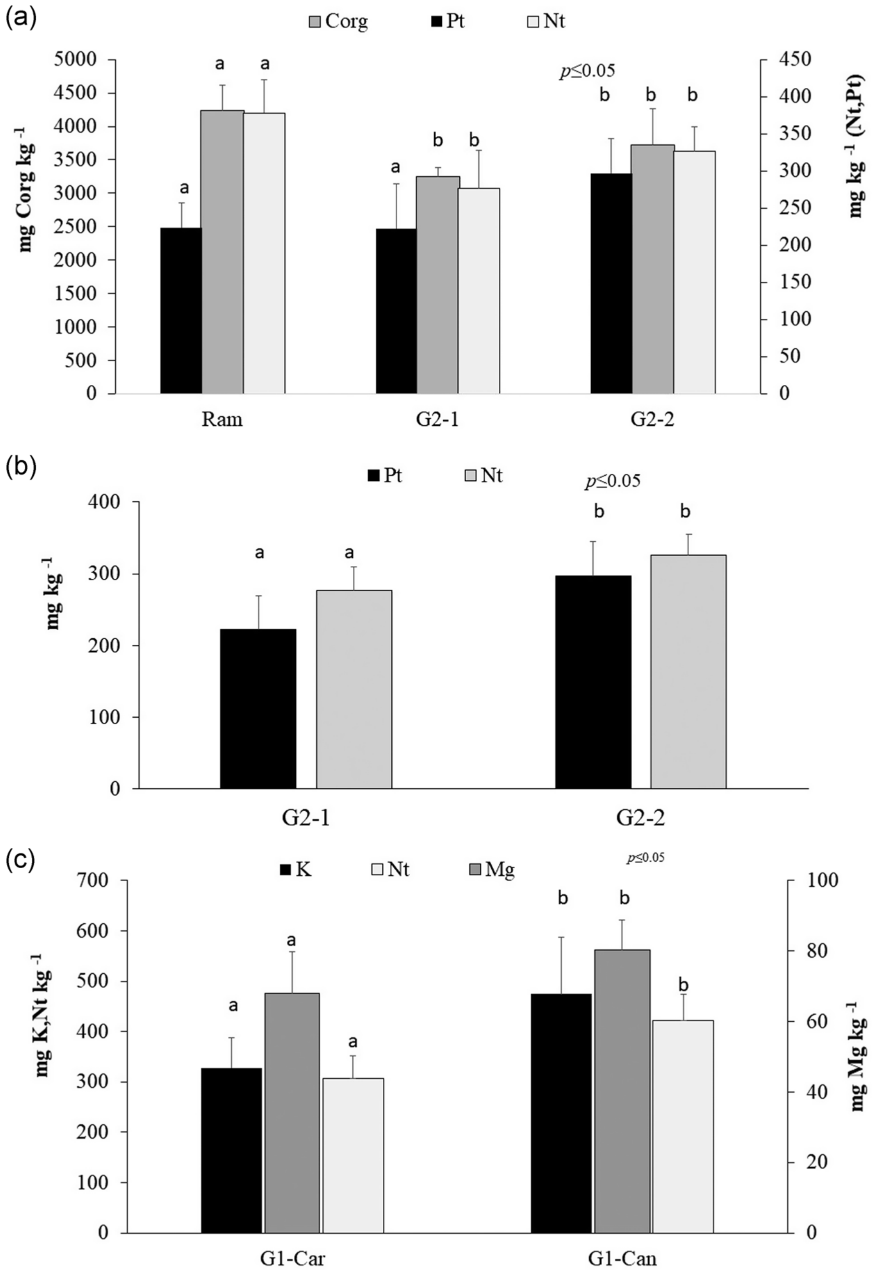

FIGURE 5 The contents of chemical elements in the topsoils ($n = 5 \pm SD$): (a) total organic C and total P and N of Ramaditas and the two sites at G2; (b) total P and N, comparing two tillage systems in G2, extended beds (*melgas*) of G2-1 and square beds (*canchones*) of G2-2; and (c) exchangeable K and Mg and total N, comparing two tillage systems in G1 (spiral-shaped: *caracoles* and square beds: *canchones*). Different letters indicate statistically significant differences among (a) sites and (b, c) tillage systems ($p \le .05$)

in Ram. It is important to note that the Cucurbitaceae pollen found in this study resembles the *Cucurbita* type rather than the *Lagenaria* type. *Solanum* pollen is present exclusively at the M003 site. All the pollen grain families found in this study are native to the area (Riedemann et al. 2016; Teillier, 1998; Villagrán et al., 1999).

The Ram and G2-2 fields have similar abundance and taxonomic variability: 11 and 10 taxa and 150 and 110 pollen grains, respectively. The G2-1 and M003 fields have seven taxa, whereas, in terms of abundance, G2-1 has slightly more pollen grains than the M003 system: 50 versus 33 pollen grains (Figure 9). We noted a difference in the abundance of pollen grains and the taxonomic richness between the two Formative period tillage systems: G2-1 and G2-2. G2-2 (square bed) has higher abundance and taxonomic richness than G2-1 (extended bed). Meanwhile, the Colonial–Republican period sites G1-Can and G1-Car show some difference, as the G1-Car (snail-shaped bed) has higher abundance and taxonomic richness than G1-Can (square bed).

The Chenopodiaceae–Amaranthaceae family is the most abundant in all fields, except Ram. There were two morphometric varieties of Chenopodiaceae–Amaranthaceae pollen. One type, with a diameter of <20 μm, may correspond to *Amaranthus* (Franssen et al., 2001) or to a wild variety of *Chenopodium* (García et al., 2011). Both species may have been cultivated or used as forage and are present in all the tillage types studied. The second type belongs to *Atriplex* sp., with a pollen diameter of 25 μm (Collao-Alvarado et al., 2015; Figure 9). This is from a type of native local flora that still grows near the Guatacondo River. *Atriplex* is only present in the tillage systems G2-1, G2-2, and G1-Car.

We found a large quantity of *Z. mays* pollen concentrated in a medium-sized circular structure (G1-1-E4) located in the area

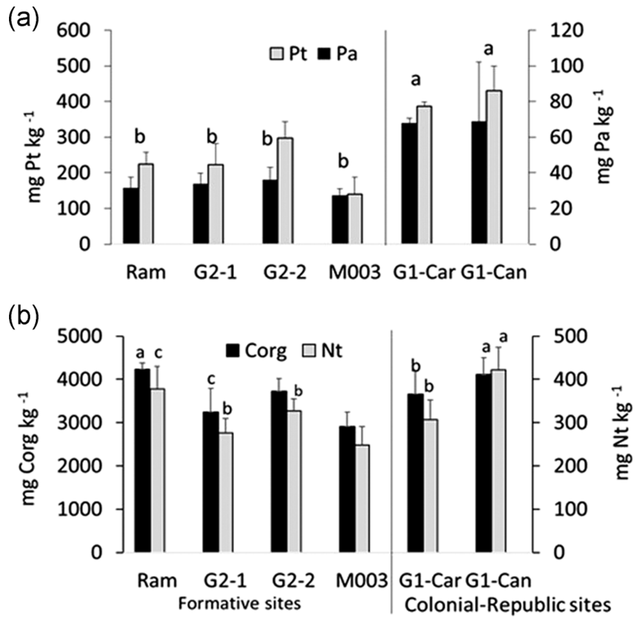

FIGURE 6 The contents of chemical elements in the topsoils (n = 5 ± SD): (a) total and available P and (b) organic C and total N iof Guatacondo Ravine, comparing different periods: Formative (RAM, G2-1, G2-2, M003) and Colonial–Republican context (G1-Car, G1-Can). Different letters indicate significant differences among periods ($p \leq .05$)

surrounding the G1-Car fields, but it was absent in the sample area for this tillage type (Segura, 2017).

Finally, the control sample had only 23 grains and the taxa corresponding to Chenopodiaceae–Amaranthaceae and Asteraceae. It is not possible to state whether the pollen ascribable to Chenopodiaceae–Amaranthaceae family corresponds to a domestic or wild variety.

These preliminary and exploratory results from palynological evidence give us some insights into the diversity of crops cultivated in the different tillage systems during the Formative period.

5 | DISCUSSION

5.1 | Evidence of agricultural practices and the use of fertilizers: Crop fields versus control sites

Compared with the control site, significant enrichment of organic C was observed in four tillage systems (Ram, G1-Car, G1-Ca, and G2-2), of total N (Ram, G1-Can, and G2-2) and P in three tillage systems (G1-Car, G1-Can, and G2-2), and of Mg in five ancient agricultural fields of the Guatacondo Ravine (Ram, G2-1, G2-2, G1-Can, and G1-Car). According to previous studies (Del Árbol Moro, 2005; Goodman, 2002; Homburg & Sandor, 2011; Homburg et al., 2005; Mejía & Barba, 1988; Roldán et al., 2005, 2008, 2014; Sandor & Homburg, 2017), this may result from the intentional incorporation of organic fertilizer to maintain an optimum soil nutrient status. This is also supported by the significant positive correlations found between soil organic C and the corresponding elements that are incorporated into mineral topsoils through the decomposition of senescent organic matter (Zarin et al., 1998). So far, there is no evidence that organic matter was burnt to accelerate decomposition.

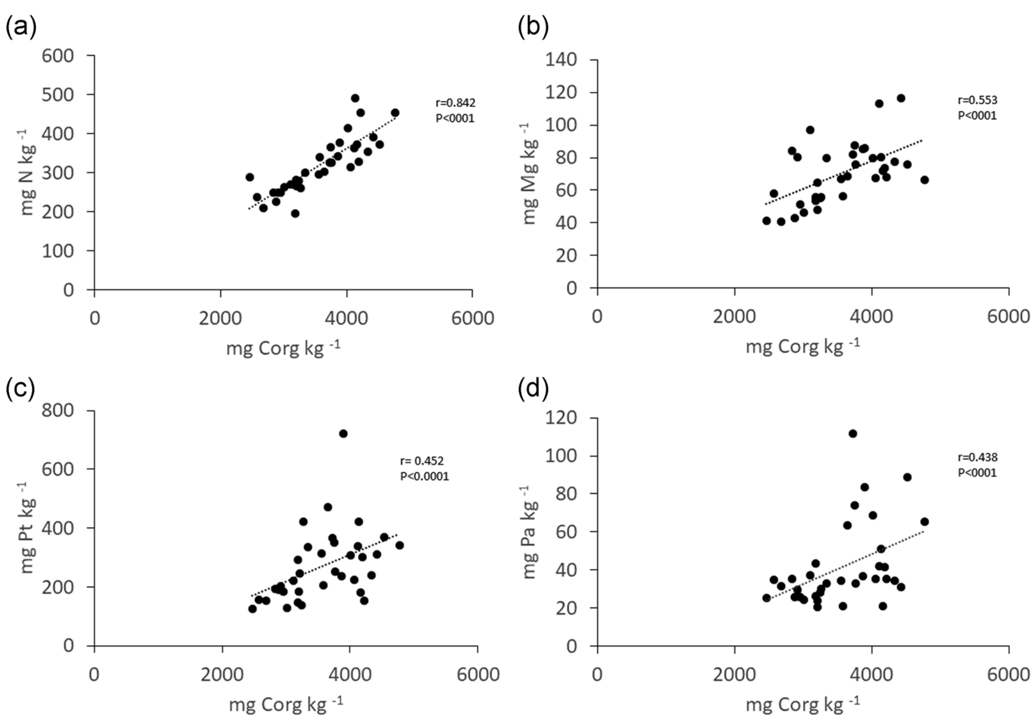

FIGURE 7 Pearson correlations between the contents of organic C and (a) total N, (b) exchangeable Mg, (c) total P, and (d) available P in the topsoil of the study sites ($n = 35$) in the Guatacondo Ravine

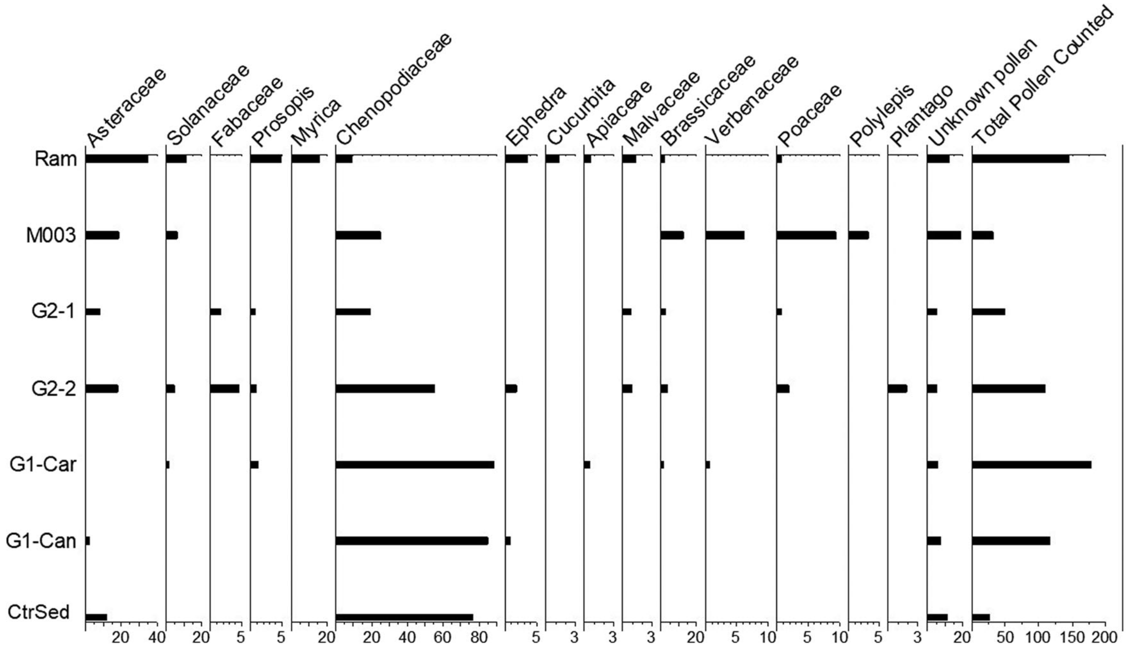

FIGURE 8 A pollen diagram showing the percentages and totals at each site and the control site. Axis *X* represents the percentage for each taxa and total sum of all pollen grains, whereas axis *Y* shows the study site of the Guatacondo Ravine

There is little research to provide data on how the chemical properties of soils were affected by pre-Hispanic agriculture in the ancient soils of arid regions around the world. In the Colca Valley of Peru, uncultivated land had a P content of 800 versus 1300 mg/kg in ancient cultivated soils on terraces (Sandor & Homburg, 2017). The authors attributed this enrichment to fertilization with marine guano or other type of animal manure, which had been well preserved in the terracing system.

From pre-Hispanic times onward, marine guano was used in agricultural fields in the high ravines of the Arica and Parinacota

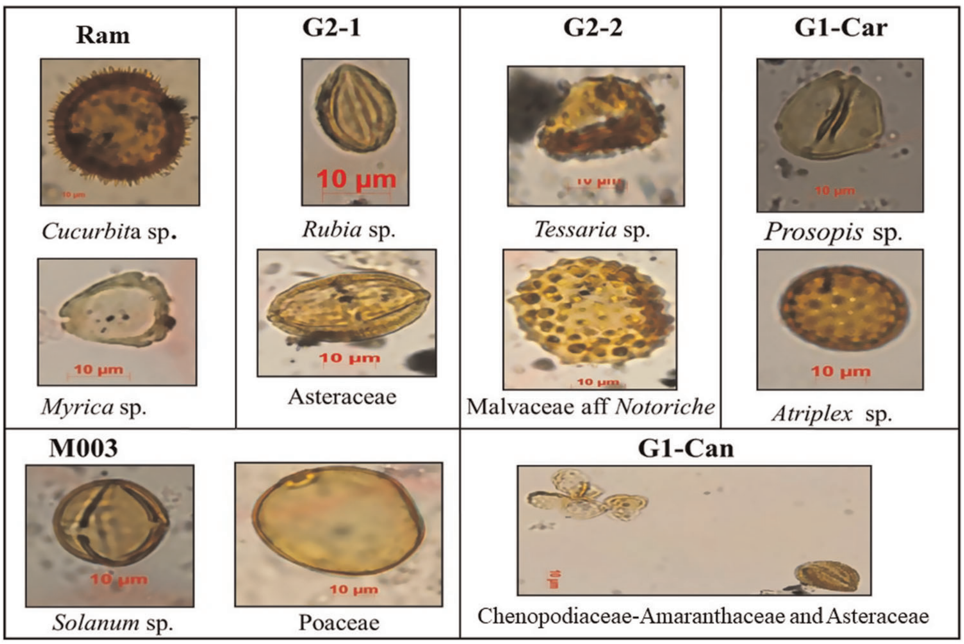

FIGURE 9 Examples of pollen grains found in the crop fields studied in the Guatacondo Ravine [Color figure can be viewed at wileyonlinelibrary.com]

Region (Méndez-Quirós & Sánchez, 2012; Platt, 1975), whose main productive center was the coast, some 100 km to the west of the study area. However, the isotopic analysis of our soils indicates a signal that is much more depleted in ^{15}N ($\delta^{15}N$ = 2.46‰) than that from sea bird guano ($\delta^{15}N$ = 20‰; Gagnon et al., 2013; Figure S2). The mean value for the ancient agricultural soils in the Guatacondo Ravine is closer to the values for the leaf tissue of native vegetation ($\delta^{15}N$ = 4.1‰) and camelid coprolite ($\delta^{15}N$ = 5.6‰) in the region (2700 m.a.s.l.; Díaz et al., 2016; Figure S2). This comparison suggests that the N in the soils of ancient crops comes from the decomposition of depleted organic matter applied by fertilizing with stubble, either from weeds (Masalles, 2004) or from parts of the cultivated plants. So far, we cannot discard the possibility that some type of guano other than sea birds (i.e., camelids) may have been used as a fertilizer, either alone or mixed with the plant tissue. This explanatory analysis gives insight into areas for further research exploring alternative sources of fertilizers for crop fields.

5.2 | Variability among tillage systems and sites

Our results indicate differences in the chemical elements and physical properties (texture) of soils between diverse tillage systems. We found significant differences between the square beds (G2-2, G1-Can), seed bedding (G2-1), and spiral-shaped beds (G1-Car), because the square beds had a higher proportion of silt than the extended beds or spiral-shaped beds (Figure S1). Thus, the square bed fields of G2-2 and G1-Can retained more of the fine fraction due to the flood irrigation system, which decants the fine fraction. This process would help to retain the plant-limiting elements N and P, as observed in G2-2, as well as exchangeable K and Mg and total N, as observed in both G1-Can and G2-2. Furthermore, based on ethnographical observations, Platt (1975) described how the square beds of the Azapa Valley, located about 280 km to the north of the study site, retained more sediment than the spiral-shaped bed tillage system, showing a greater accumulation of sediments as a result of the flooding of the plots of crops and resulting decantation of the suspended sediments, thereby retaining the nutrients in the fields. Descriptions of the irrigation systems currently used in Colombia indicate that surface irrigation (extended beds and spiral-shaped tillage), especially in furrows, is more prone to erosion and fertilizer loss due to washing and dragging, and encourages salts to flourish in systems with low water (Arango, 2002). Therefore, the differences that we observed in the fine and chemical fractions may be due to the nature of each tillage system. When comparing different sites that have the same tillage system (extended beds) and are from the same period (Formative), as is the case of Ram and G2-1, the differences in the chemical elements may be explained by differences in the source of fertilizer and the type of crops developed. Current studies in Mexico (Durango) show slight differences between the P content of various organic fertilizers, such as compost versus manure (López–Martínez et al., 2001).

Ethnographic studies in Tarapacá Region document that tillage systems were selected to respond to the need to develop the crop in a better way, so specific crops were cultivated in specific tillage systems (Platt, 1975). For example, corn, wheat, and onion seem to have been grown in square beds, whereas squash, beans, and different grains tended to be planted in extended beds (Platt, 1975; Urrutia, 2011, 2020). The spiral-shaped and seed beds, which generally provided a slow rate of irrigation, are described as appropriate for those plants with surface irrigation, such as squash. In short, these studies demonstrate the in-depth knowledge of the requirements of plants developed through constant experimentation by current (and past) populations living in the foothills and highlands of the Tarapacan streams and western desert valleys of Atacama.

In relation to the pollen analysis, given the large differences in pollen composition between the ancient crop fields and the control samples, the greater diversity presented by the flora in the Guatacondo fields is best explained as the product of farming. The pollen analysis showed riparian taxa (*Myrica*) and wide diversity of taxa in the crop fields, meaning that diverse wild weed flora developed in association with crops such as squash, maize, beans, and maybe quinoa and potatoes. These results are concordant with the previous reports on macrobotanical remains found in the Guatacondo and Ramaditas villages. Only the M003 site (terraces) shows the presence of Solanaceae pollen, probably *Solanum* (potato). This result is satisfying, as starch grains for *Solanum* sp. were reported from coprolites from Ramaditas villages and lithic agricultural shovels found in the fields (Albornóz & Carrasco, 2016; Scott 2005). Berlin et al. (1977) suggested that due to the pollination mechanism, the *Cucurbita* type of pollen appears where the plants were grown or stored, suggesting that squash was cultivated in these fields, a suggestion that is confirmed by the findings of squash consumption from the macro remains found in Ramaditas village (Ramírez de Bryson, 2005).

5.3 | Temporal variability: Formative and Colonial–Republican periods

Phosphorous (P total and available) is the only element that showed a clear difference between periods. G1-Can and G1-Car from the Colonial–Republican period had higher concentrations than those in all of the Formative fields. This element, which is essential to plants, is recognized as being among the most stable (without gaseous or hydrological losses as in N and C), and thus it reflects differences in the agricultural production in the valley over time, with more fertilizer use during the Colonial–Republican periods and/or diverse harvesting methods. Whereas it might be expected that the historical fields (G1-Can and G1-Car) would have higher element concentrations than the Formative fields, due to the reduced chance of nutrient losses from soil erosion over time, other diagnostic indicators of organic matter (total N and organic C) show the opposite. For example, G1-Car (Colonial–Republican field) had lower concentrations of total N and organic C than Ram (Formative field). This suggests that the enrichment or impoverishment is due to the nature of the work practiced at each site. Thus, different fertilization, husbandry, and harvesting methods, together with the nature of each tillage method would have produced a greater difference in chemical concentrations than the temporal distance.

5.4 | The social implications of the use of agricultural soils in the Guatacondo Valley

This study provides evidence that the different tillage systems are associated with different chemical signals in the topsoils, which may reflect variability in social practices, such as the following: the different types of crops, diversity of fertilization elements, and different crop husbandry and harvesting systems used during the Formative and the Colonial–Republic periods. This high diversity in social practices is also supported by previous findings from different forms of settlements, mortuary practices, architecture, textile goods, lithics, and archaeobotanical remains among Guatacondo's archaeological sites (Uribe, 2008; Uribe & Adán, 2012). Diverse family groups congregated in the Guatacondo Ravine (Adán et al., 2013; Muñoz et al., 2017; Urbina et al., 2015; Uribe & Adán, 2012), with diverse soil management practices in the desert environment. The efficient use of both water and fertilizers in the hyperarid conditions made it possible for agriculture to be sustained for at least 300 years during the Formative period (Vidal, García, et al., 2015; Vidal, Mandakovic, et al., 2015).

The higher concentration and retention of chemical elements in Guatacondo crop fields suggest beneficial soil management and small-scale use (Homburg & Sandor, 2011; Sullivan, 2000). Although the deficiency of K indicates depletion of this nutrient, we observed it in the surface horizon, but not in the subsurface horizon (Segura, 2017), and so it was not enough to call it soil degradation. Where soil degradation has been observed (Arizona Desert), it has manifested in the reduction of N, total P, and organic C, even at deeper levels (Homburg & Sandor, 2011). In the Guatacondo Ravine, by contrast, we found enrichment of these elements as compared to the control site with similar environmental conditions to the agricultural fields. Furthermore, we did not find soil acidification or a loss of edaphic structure, as would be expected from intensive use (Del Árbol Moro, 2005; Goodman, 2002; Homburg et al., 2005). Moreover, the lower concentration of Na found in crop fields in relation to control site suggests that the diverse cultivation systems would have decreased the chances of a detrimental effect of Na accumulation in soils. Rather, we observed that the crops had a mostly beneficial effect on the soil in the retention of elements (Homburg & Sandor, 2011), which indicates adequate, seasonal management rather than intensive use, as was also proposed by Rivera (2005). The chemical evidence of the soil supports the hypothesis of extensive, seasonal agriculture suggested by Vidal, García, et al. (2015) and Vidal, Mandakovic, et al. (2015), which is inserted within a cycle of regional mobility (Adán et al., 2013; Urbina et al., 2015; Uribe & Adán, 2012). Fertilization with stubble/nonmarine guano and fallow seasons would be very useful in a residential mobility system.

Pollen analysis showed that the crops in the Formative period developed in association with weed flora growing within the field and most probably in the surrounding areas as well, resulting in diverse species growing in the fields, which may have been used for construction, food, medicine, stubble, or forage. The consumption and use of wild species in the valley has been documented, which was apparently greater than that of domestic plants (García et al., 2014; Williams, 1980). There is no evidence of corn cultivation during the Formative periods from the pollen analysis presented here. We, therefore, suggest that the lack of evidence of *Z. mays* in the fields maybe due to restricted use of the crop. This was previously postulated by Santana-Sagredo et al. (2015) and Vidal et al. (2019), and supported again by our findings. However, we did find pollen grains concentrated in a small structure outside the sampled fields of G1-Car, which may correspond to a medium-sized storage facility from the Colonial period.

6 | CONCLUSIONS

In the most arid desert of the world, ca. 2200 years BP, the pre-Hispanic cultures developed diverse systems of agricultural practices, which were adapted to use the limited supply of water from a seasonal precipitation regime. These agricultural practices led to the main nutrients being conserved in the soils, such as N, P, and Mg, which mainly came from organic matter deposited on the soils when fallow. The practice that best preserved the soil nutrient status was the square bed (*canchones*) tillage system, which was flood-irrigated, thereby increasing the possibility of the soils retaining nutrients, avoiding leaching and soil erosion. The square bed tillage system is used nowadays by the current population that inhabits the Guatacondo Ravine. Similar soil conservation practices developed by pre-Hispanic cultures have been documented for other arid and semiarid regions of America, indicating expanded empirical knowledge about sustainable land use for providing food.

Seasonal agriculture was linked to the mobility systems suggested by the occupation of this valley, in which fertilizing with stubble and using fallow seasons were the means most often used to avoid transporting fertilizers. This phase saw the development of a greater diversity of tasks to those previously observed, which represent beneficial soil management that implied a level of knowledge and know-how among the collectives who lived in the area, as a result of knowing their environment (climate, soil, and vegetation). Our study showed that the variability in the chemical, physical, and paleobotanical properties of the soil, linked to different tillage systems, may be a consequence of the diversity of human groups who arrived in the area and the experimental phase of early agriculture in these environments. This, in turn, reflects a period of articulation among diverse collectives who established the foundations for the agricultural development during the Late phase of the Formative period in the Tarapacá Region.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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