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RESEARCH ARTICLE

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Soils in ancient irrigated agricultural terraces in the Atacama Desert, Chile

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Abstract

The Atacama Desert is among the driest places on Earth, yet ancient agricultural systems are present in the region. Here, we present a study of terraced agricultural soils in the high-altitude eastern margin of the Atacama Desert in northern Chile, mainly dating to the Late Intermediate Period (ca. 950–1400 AD) and Inka period (ca. 1400–1536 AD). Terraced fields were compartmentalized to distribute limited irrigation water originating mainly from springs. Natural soils used for agriculture are mostly Aridisols developed on Pleistocene alluvial fan terraces and hillslopes underlain by volcanic bedrock. One research objective is to evaluate long-term soil change from agriculture. In this hyperarid climate, agriculture is only possible with irrigation, so natural soils on the same geomorphic surface adjacent to irrigated soils provide baseline data for assessing anthropogenic soil change. Data from soil profiles and surface transects indicate intentional soil change through terracing, removal of soil rock fragments, and probable fertilization. Agricultural soils have anthropogenic horizons ranging from 16 to 54 cm thick. Most agricultural soils have higher phosphorus levels, suggesting enrichment from fertilization. Changes in soil organic carbon and nitrogen are also evident. Unintentional anthropogenic soil change resulted from $CaCO_3$ input through irrigation with calcareous spring water. Initial studies suggest that agriculture here was sustainable in the sense of conserving soils, and maintaining and possibly improving soil productivity over centuries.

KEYWORDS

ancient agriculture, anthropogenic soil, anthrosol, Atacama Desert, irrigation agriculture, terrace agriculture

1 | INTRODUCTION

Agriculture has profoundly altered its underlying soil resources worldwide over thousands of years, both through deliberate management, and unintentionally (Kuzyakov & Zamanian, 2019; Sandor & Homburg, 2017). Ancient cultivated soils are long-term sources of data on anthropogenic soil change and processes, as well as agricultural management strategies across a wide range of environmental and climate conditions. Ancient cultivation and soil modification on sloping terrain commonly incorporated terracing (Quirós-Castillo & Nicosia, 2019; Sandor, 2006; Stanchi et al., 2012; Wei et al., 2016). Terracing and terraced soils represent an intensive investment in landscape modification and management to improve agricultural productivity and conserve land and water resources. The Andes and neighboring highlands are well-known for their remarkable terracing systems, examples of landesque capital (Håkansson & Widgren, 2014) linked to larger social and political dynamics, spanning many centuries (Denevan, 2001; Donkin, 1979).

We investigated soils as part of an interdisciplinary archaeological project to study ancient irrigated terrace agriculture in the high-altitude part of the Atacama Desert in northern Chile. The overall purpose of the project is to understand land use and society before and during Inka rule, including how agriculture functioned in this hyperarid environment (Parcero-Oubiña et al., 2017). Pre-Columbian irrigated agriculture dates from the Late Intermediate Period (LIP, ca. 950–1400 AD) through the Inka or Late Period (ca. 1400–1536 AD). Some terraced fields have continued to be farmed from historic times to the present. However, most of the ancient terraces are abandoned, as they are elsewhere in the region and throughout the Americas (Denevan, 2001; Donkin, 1979; Wright, 1963). Water sources for canal irrigation of agricultural terrace systems within the study area were primarily springs. Some terraced irrigated field systems elsewhere in the region relied more on streams from the Andes.

The objectives of our soil investigations are to characterize soils used for irrigation agriculture, to infer soil management practices, and to assess anthropogenic soil change resulting from agriculture. Research questions about natural soils used for farming are: did farmers select certain soils overall or for certain crops, or were other factors more important? Also, are the natural soils favorable for agriculture, and to what degree was soil modification through management needed to improve their productivity? In testing for and measuring soil change from agriculture, in what ways were soils deliberately altered through management practices such as terracing, irrigation, and fertilization? Do the agricultural soils show signs of unintentional anthropogenic change?

Terraced fields and irrigation canals were studied in two areas, Paniri and Topaín, located in the Turi Basin on the piedmont at the eastern edge of the Calama Basin and north of the Rio Salado (Figures 1 and 2). Much of the landscape was transformed for irrigation agriculture through the construction of remarkable canal systems, bench terraces on hillslopes, and other terraced fields on less sloping landforms (Figures 3 and 4). Parcero-Oubiña et al. (2017) measured 25 ha of prehistoric fields at Paniri, although their original extent could have been greater. Malim (2009) estimated 150 ha of fields at Paniri, but this much larger estimate is not supported by the evidence seen in satellite images or on the ground (Parcero-Oubiña et al., 2017). The fields at Topaín comprise about 35 ha (Parcero-Oubiña et al., 2017). Prehispanic and historic terraced irrigated fields

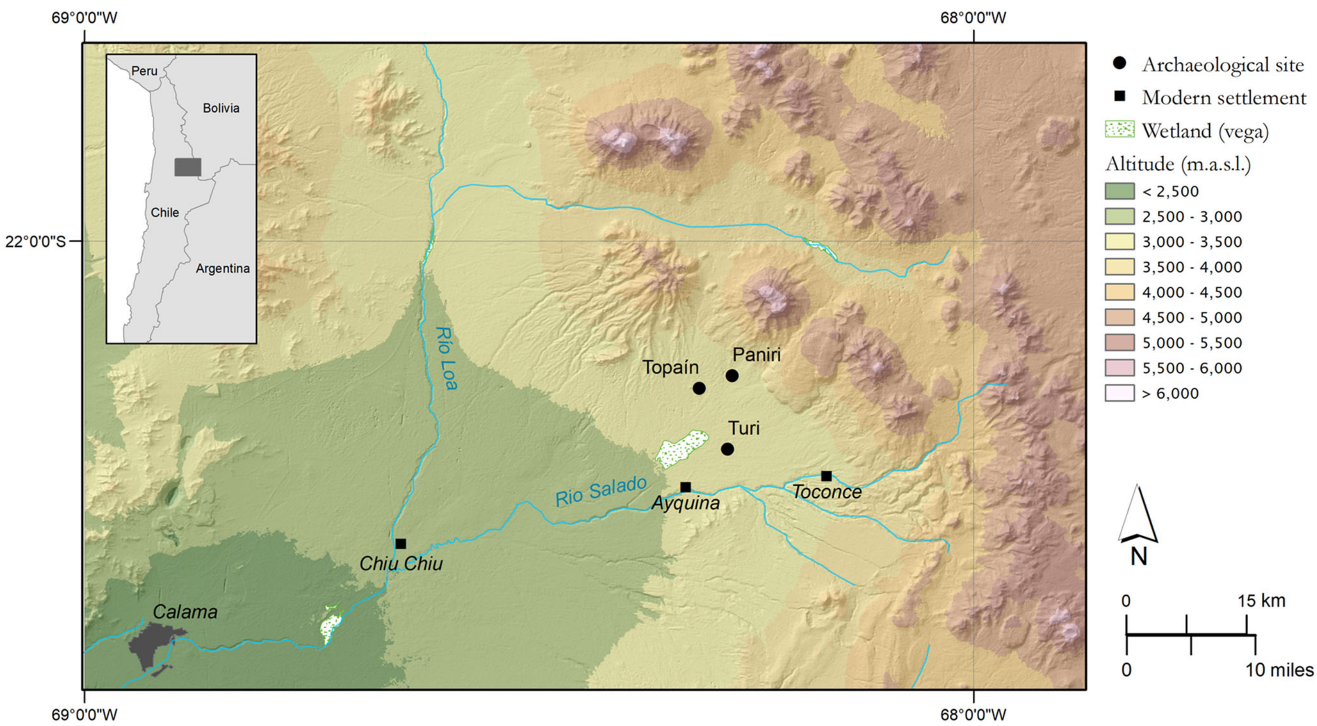
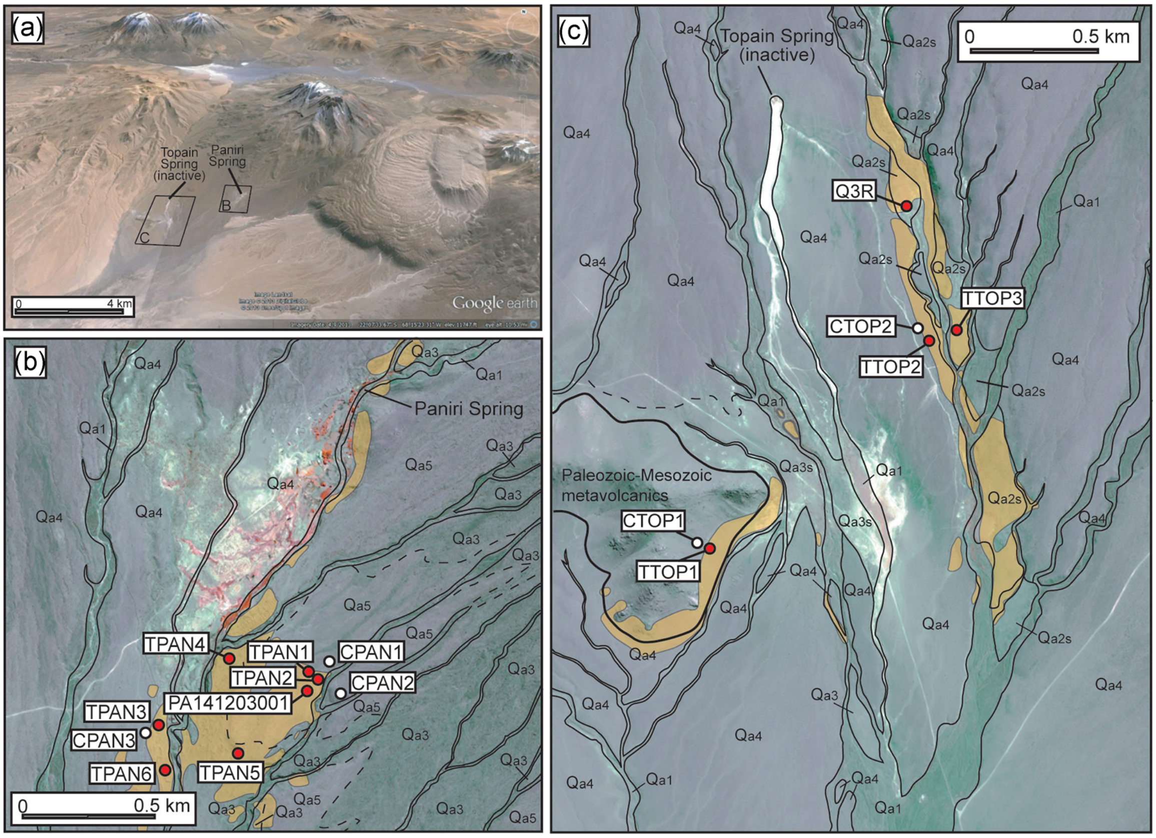


FIGURE 1 Study area [Color figure can be viewed at wileyonlinelibrary.com]



Mapping Unit	Description	Estimated Age (yr B.P.)
Qa1	Active alluvial fan channels; distributary drainage; no soil development	< 1000
Qa2s	Holocene alluvial terraces; sandy facies; dendritic drainage; weak soil development (A, Bw, Bk)	<10,000
Qa3	Late Pleistocene alluvial fans and terraces; distributary drainage; weak rock varnish and soil development (Bw?, Bk?, Bq)	~10,000–125,000
Qa3s	Late Pleistocene alluvial terraces; sandy facies; dendritic drainage; weak rock varnish and soil development (Bw?, Bk?, Bq)	~10,000–125,000
Qa4	Middle Pleistocene alluvial fans; dendritic drainage; highly dissected; cobble-armored surfaces; strong rock varnish and soil development (Bt, Btq, Bqm)	~125,000–500,000
Qa5	Middle Pleistocene alluvial fans; dendritic drainage; highly dissected; cobble-armored surfaces; strong rock varnish and soil development (Bt, Btq, Bqm)	~500,000–750,000

FIGURE 2 (a) Oblique Google Earth image of Topaín and Paniri study areas within the Turi Basin. (b) Surficial geologic map and sampled soil locations at Paniri. (c) Surficial geologic map and sampled soil locations at Topaín. Soil sample locations TTOP 1-CTOP 1 are on Cerro Topaín, and TTOP 2-CTOP 2, TTOP 3, and Q3R are in Lower Topaín. Shaded areas are terraced fields (adapted from Parcero-Oubiña et al., 2017). Soil horizons in the legend indicate maximum B horizon development in each map unit. CPAN, control Paniri; CTOP, control Topaín; TPAN, terraced Paniri; TTOP, terraced Topaín [Color figure can be viewed at wileyonlinelibrary.com]

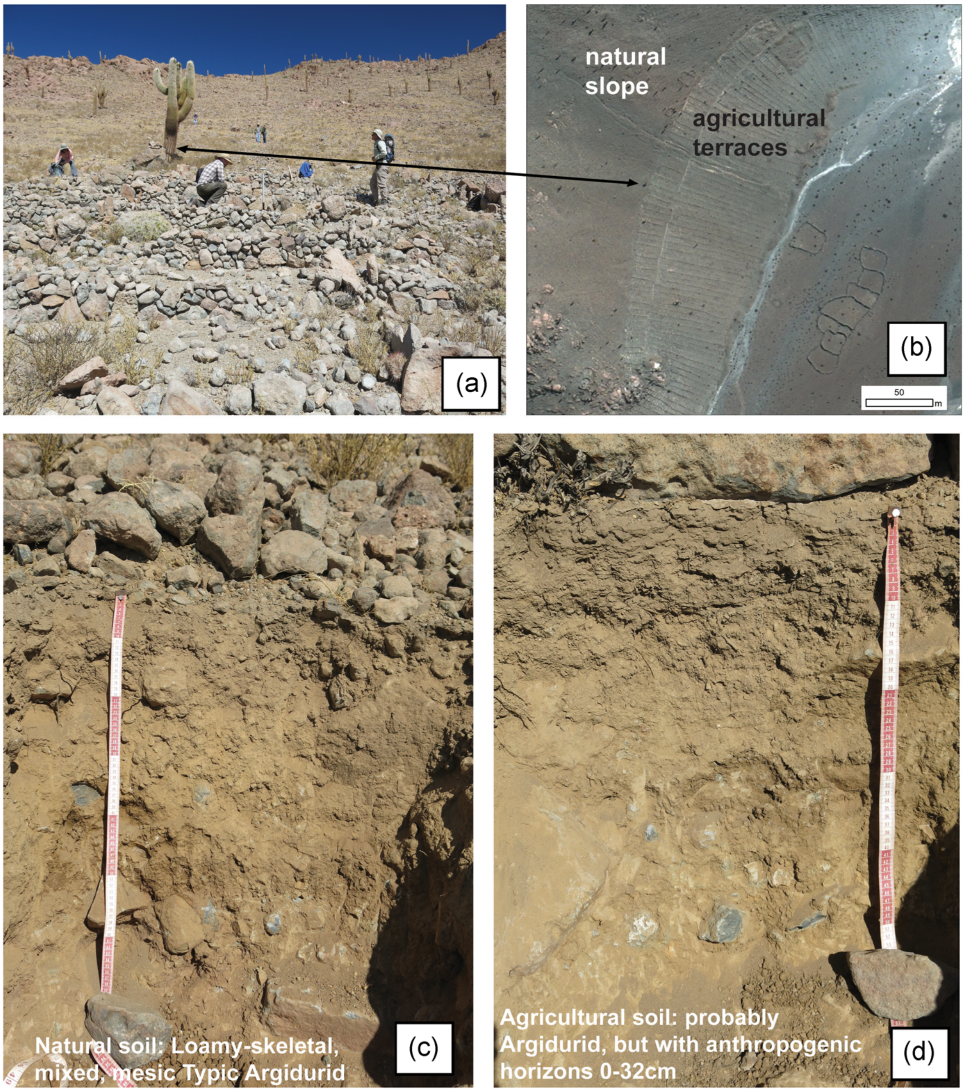


FIGURE 3 Photos of landscape and soils at Cerro Topaín. (a) Agricultural terraces downslope and natural area upslope from the highest irrigation canal. (b) GeoEye satellite image. The same cactus in (a) and (b) marks the position of the highest canal. The linear features oriented parallel to slope are lateral canals and field borders. For a closer aerial view of the agricultural terraces, see Figure S3b. (c) Natural (control CTOP 1) and (d) agricultural terrace (TTOP 1) soil profiles at Cerro Topaín. Horizons and depth function for these soils shown in Figure 6. Scale divisions of each red and white band 10 cm. CTOP, control Topaín; TTOP, terraced Topaín [Color figure can be viewed at wileyonlinelibrary.com]

are also extensive elsewhere in the high Atacama Desert (Donkin, 1979; Field, 1966; Gayo et al., 2019; Ugalde et al., 2020).

2 | GEOMORPHIC, ENVIRONMENTAL, AND CULTURAL SETTING

The agricultural terraces and soils studied are on piedmont surfaces in the Turi Basin, a structural basin located near the southwestern base of Cerro Paniri (5960 m), a stratovolcano within the Central Andean Volcanic Zone (Figures 1 and 2). Local geology is strongly influenced by plate subduction and dominated by Pleistocene lava flows, tuffs, and ignimbrites (de Silva et al., 1994; Godoy et al., 2018; Houston, 2007). Much of the Turi Basin piedmont contains coalesced Quaternary alluvial fans derived from volcanic hillslopes. A small inselberg within the piedmont, here referred to as Cerro Topaín, is composed of Paleozoic-Mesozoic metavolcanics (Houston, 2007). Thin discontinuous eolian sand deposits occur in a few areas. A normally dry lake bed, the Salar de Turi located approximately 6 km south-southwest of Topain, is an ostensible source of eolian dust to the piedmont.

Carbonate-rich springs at Paniri and Topaín serve as the main sources of irrigation. Water from the inactive spring at Topaín was especially rich in carbonate, evidenced by travertine-encased canals (Parcero-Oubiña et al., 2017; Figure S4i). Springs in the Turi Basin are fed by water from melting snow in the volcanic uplands that infiltrates into the subsurface and emerges on the piedmont. The source of carbonate is believed to be buried Miocene freshwater limestones and calcareous sandstones and conglomerates that serve as an important aquifer within the Turi Basin (Houston, 2007).

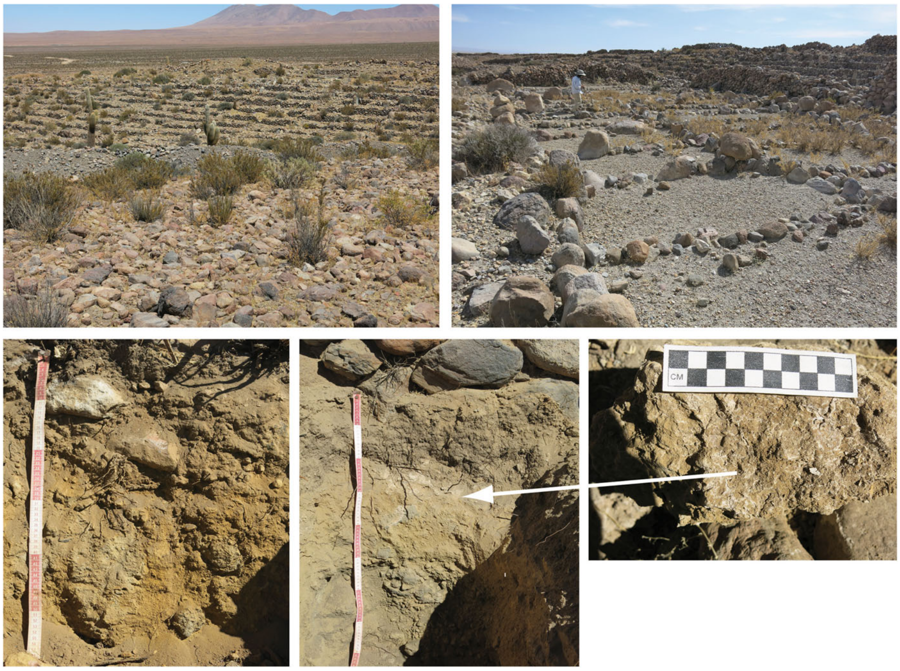


FIGURE 4 Photos of landscape and soils at Paniri. Upper photos: examples of agricultural terraces at Paniri. Left: View from the natural area near soil sample CPAN 2 to agricultural terraces near soil sample TPAN 1. Right: Example of compartmentalized terraces, with *rumimoqos* (polygonal stone mounds with retaining walls) in the middle ground. Lower photos: Natural (control) soils are nearly noncalcareous (e.g., soil CPAN 2 at left), whereas agricultural soils have $CaCO_3$ from irrigation water inputs (e.g., soil TPAN 1 with visible carbonate at right). Scale divisions of each red and white band in soil profiles 10 cm. CPAN, control Paniri; TPAN, terraced Paniri [Color figure can be viewed at wileyonlinelibrary.com]

A hallmark of the Atacama Desert environment is its hyperarid climate; it is among the driest regions in the world. The study area is located in the higher, colder part of the Atacama, which receives more precipitation than farther west, though it is still hyperarid. The Paniri and Topaín fields are located at elevations ranging from about 3150–3250 m. On the basis of limited meteorological data from weather stations in the surrounding region, the mean annual precipitation (MAP) is estimated at approximately 50 mm, and the mean annual temperature (MAT) is about 10°C (Houston & Hartley, 2003; Latorre et al., 2006; Villagrán et al., 1981). The lower part of the Atacama Desert to the west receives very little moisture (e.g., MAP about 4 mm in Chiu Chiu at 2524 m), and precipitation increases with elevation towards the Andes to the east (e.g., MAP roughly 100 mm at Toconce at 3350 m). Likewise, MAT ranges from about 13°C at Calama (2260 m) to 11°C at Ayquina (3031 m) to 7°C at Ollagüe (3700 m). Precipitation also increases to the east with increased proximity to moisture associated with the South American summer monsoon (Houston & Hartley, 2003; Olson et al., 2020). On the basis of current precipitation and temperature and their seasonal distribution, the soils have an aridic moisture regime and mesic temperature regime (Soil Survey Staff, 2014).

Paleoclimate proxy records from the central Andean region, including lake sediments, groundwater discharge deposits, speleothems, packrat middens, and tree rings, all suggest that the strength of the monsoon has varied in the past (Pabón-Caicedo et al., 2020; Vuille et al., 2012). Undoubtedly, these decadal to multidecadal fluctuations influenced spring activity in the Turi Basin. Whereas reconstructions of late Holocene precipitation vary regionally, rodent middens and in-stream wetland deposits from low elevation sites west and northwest of the Turi Basin suggest relatively moist conditions—though still hyperarid—during the LIP (Gayo et al., 2012; Tully et al., 2019; Ugalde et al., 2020), and peat cores from the Altiplano suggest that favorable conditions for spring-fed farming continued during the brief Inka period (Engel et al., 2014; Kock et al., 2019). We presume that fluctuations in monsoon strength influenced spring productivity in the Turi Basin, but more local paleoclimate proxy records are needed to better understand the timing and magnitude of past moisture changes during the LIP and Inka period in our study area.

Unlike lower areas to the west where vegetation is absent or very sparse (below about 3100 m), the study area has sparse grasses, shrubs, cacti, and other plants and falls within the upper end of the Pre-Puna and Puna Belts (Latorre et al., 2006; Villagrán et al., 1981). Estimated vegetation cover within terraced fields ranges from about 7%–20% and 15%–40% in natural areas near fields, within the range reported by Villagrán et al. (1981).

Near the study sites, residents today continue to farm at Ayquina (along the terraced slopes of the Rio Salado canyon), Cupo, Turi, and within a section of the Paniri *quebrada* (stream channel). Fields are irrigated by spring-fed canals as they were in the past and fertilized with manure from llama, sheep, and other livestock. Major crops today and in living memory include maize, wheat, barley, alfalfa, potatoes, and quinoa; other crops include oca, fava beans, onions, garlic, cactus fruit, and, in the microclimate of the Paniri *quebrada*, a variety of tree fruits (Club de Adultos Mayores de Ayquina-Turi and Manríquez, 2017).

The archaeological sites of Topaín and Paniri are characterized by small ridgetop settlements adjacent to extensive irrigated agricultural fields (Ayán Vila & García Rodríguez, 2016; Urbina, 2010). Both are associated with Turi, a partially walled residential settlement or *pukara* adjacent to the Turi *vega* (irrigated pastureland and fields) that was occupied during the LIP and Inka period (Aldunate, 1993). Together, the three sites formed one of several similar farming/pastoral/residential site clusters in the upper Rio Loa and Salado region (Figure 1), centered around the land that could be farmed and grazed. Before the LIP, the economy centered on herding and populations were much smaller. With irrigation agriculture, the population expanded and aggregated at sites like Turi (Castro et al., 2016; Pollard, 1971; Salazar et al., in press). When the Inka conquered this region beginning in ca. 1400 AD, they expanded copper mineral mining at sites in the Loa and Salado drainages, built roads and way stations, and a portion of Turi was reorganized as an Inka administrative sector (Adán & Uribe, 2005; Aldunate, 1993; Berenguer & Salazar, 2017; Castro et al., 1993; Cornejo, 1999; Gallardo et al., 1995; Salazar et al., in press; Uribe & Urbina, 2009).

In addition to examining evidence for soil management, our work at Topaín and Paniri has focused on mapping and dating canal and field systems (Parcero-Oubiña et al., 2017). There are two areas of cultivation at Topaín, each fed by a different canal system originating in the same spring. One canal system irrigated terraces on the slopes of Cerro Topaín, while the other irrigated fields on alluvial fan and stream terraces at Lower Topaín to the east (Figure 2c). Results to date indicate that Topaín was farmed from the LIP into the Inka period, with the Cerro Topaín terraces in use until roughly the early 14th to the mid-15th centuries, and Lower Topaín fields for a shorter duration between the late 14th to mid 15th centuries (Figure 5; Supporting Information Radiocarbon Dates). Farming at Paniri began in the early 15th century, coinciding with the incorporation of the region into the Inka Empire, and continued throughout Inka rule. A section of the Paniri fields continues to be farmed today. Possible reasons for the abandonment of the Topaín fields in the 15th century include a decrease in water flow from the now dry Topaín spring, and/or the decision by the Inka to permanently move Topaín residents as part of a general state policy of relocating people to serve state interests (D'Altroy, 2015). More in-depth discussion of changes in land use during Inka rule at the study sites and regionally can be found in Parcero-Oubiña et al. (2017) and Salazar et al. (in press).

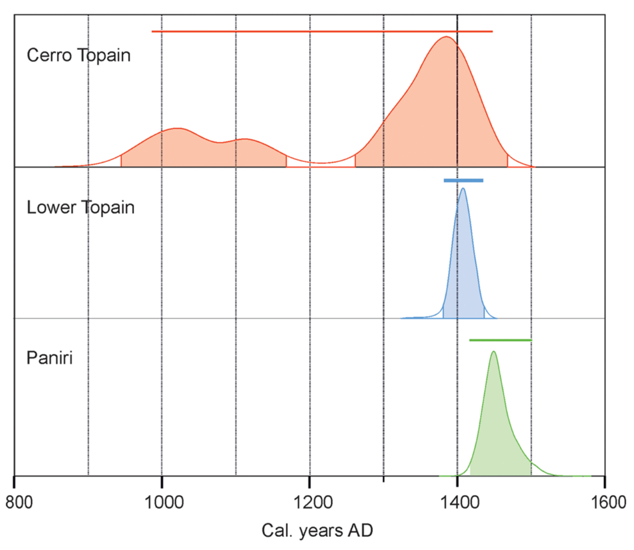


FIGURE 5 Radiocarbon dates (see Supporting Information Radiocarbon Dates for details and methods) [Color figure can be viewed at wileyonlinelibrary.com]

3 | METHODS

3.1 | Field work and sample design

Soil study and sampling were designed to include a range of geomorphic positions, emphasizing the most common settings for terrace agriculture on the shoulder, backslope and footslope positions of alluvial fan terraces, and more gently sloping alluvial surfaces (Figure 2). A prominent area of irrigated terraced fields on the slopes of Cerro Topaín was also sampled (Figures 3 and 6).

A major goal of these soil studies is to test for anthropogenic soil change resulting from agriculture. The limitations imposed by the hyperarid climate make it possible to identify unfarmed locations with natural soils that can be used as "references" or "controls" to provide baseline data for assessing anthropogenic soil change. Farming was only possible where irrigation water could be supplied. On the slopes of Cerro Topaín, for example, there is a clear boundary between unirrigated natural soils upslope of the uppermost irrigation canal and terraced agricultural soils downslope that received irrigation (Figure 3). Four sets of paired agricultural and natural control soils were described and sampled, with each pair located as close to each other as possible in similar soil-geomorphic settings. The method and validity of comparing agricultural soils with natural soils to test for anthropogenic soil change are reviewed in Sandor and Homburg (2017). We think that the control soils identified in this study are valid because they are near the agricultural soils in the same geomorphic positions, and the morphology of natural subsurface horizons underlying anthropogenic parts of the terraced agricultural soils are similar to those in control soils. Control soils were probably not farmed because either they were less accessible to gravitational water flow in irrigation canals or that limited irrigation water supply from springs limited the land that could be farmed.

Sixteen soil profiles in hand-excavated pits were described and sampled by horizon, mainly to naturally cemented sediments that could not be further excavated: 10 at Paniri and six at Topaín (Figure 2). In three soils where cemented sediment was not

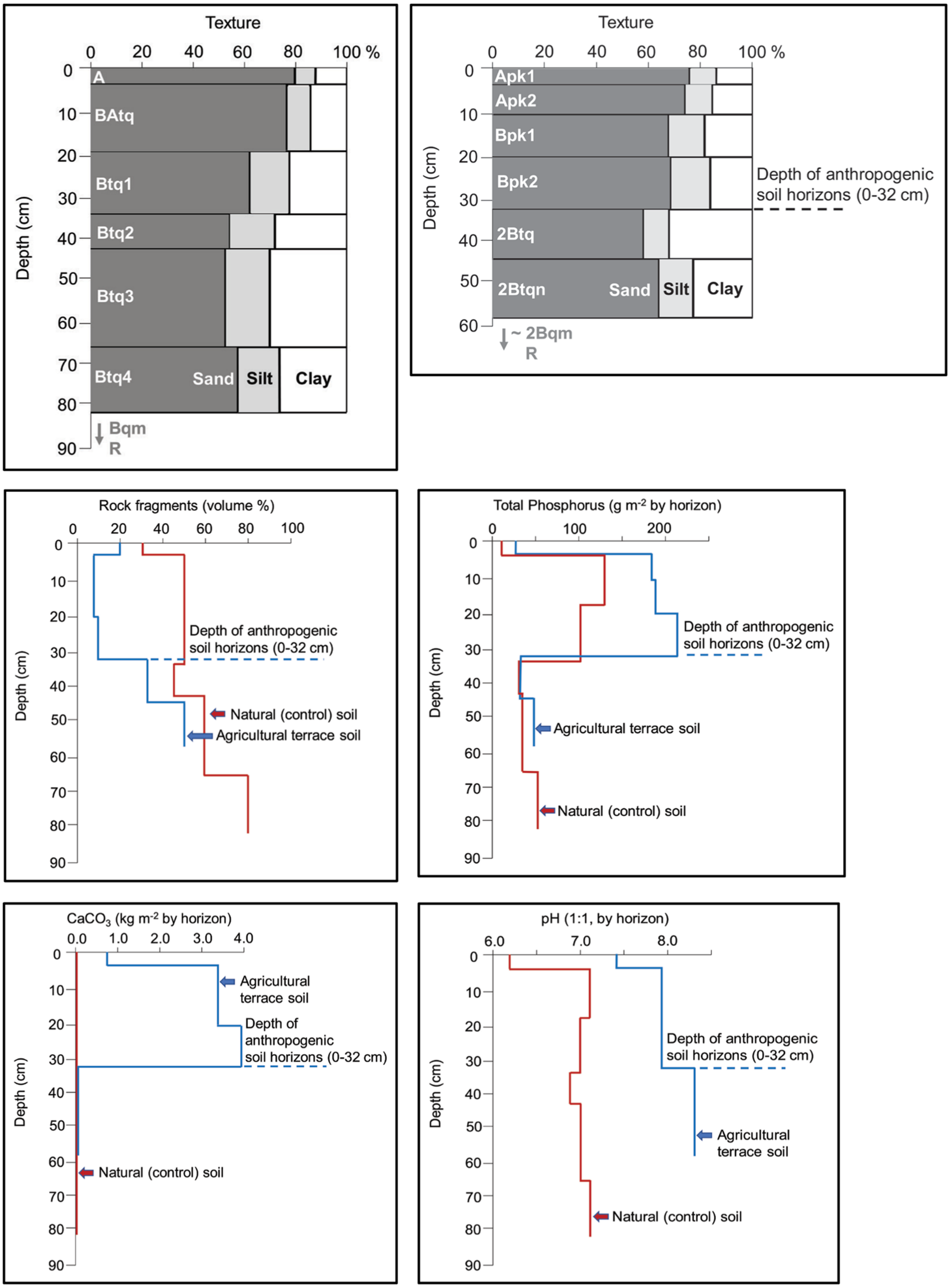


FIGURE 6 Depth functions of soil texture, rock fragment volume, total phosphorus, calcium carbonate ($CaCO_3$), and pH in natural (control) soil (CTOP 1) and nearby paired terraced agricultural soil (TTOP 1) at Cerro Topaín. The agricultural soil has 32-cm-thick anthropogenic horizons overlying the natural argillic horizon. Photos of these soils in Figure 3. CTOP, control Topaín; TTOP, terraced Topaín [Color figure can be viewed at wileyonlinelibrary.com]

encountered, pits were excavated as deeply as safety permitted. Soil profiles included 11 in agricultural terraces and five in natural control soils. Data for all soils sampled are given in Tables S1–S3.

Soil morphology was described and horizons identified using standard methods (Schoeneberger et al., 2012). Descriptions of the 16 soil profiles are summarized in Table S3. Soil rock fragment content was estimated by volume in the field. Approximately 0.5–1 kg of soil was collected from each noncemented horizon for lab analyses and air-dried. During sampling, larger rock fragments and roots were removed, or, in sandy soils with large amounts of rock fragments, soil samples were sieved less than 2 mm in the field. Peds or clods for bulk density determination were collected where possible. In some sandy horizons with little or no soil cohesion, samples for bulk density were collected with a 60-cm^3 metal cylinder. Locations (UTM zone 19S, WGS1984 datum) of soil profiles were determined using a global positioning system. Geomorphic positions and slope aspects were recorded, and slope angles were measured with a clinometer. Dimensions of terraced fields and walls were measured. In 2013, plant species and vegetation cover around each soil profile were described by Virginia McRostie.

Soil profiles are labeled "TPAN," "CPAN," "TTOP," and "CTOP": first letters T or C refer to terraced or control, followed by PAN (Paniri) or TOP (Topaín). Matched sets of agricultural and natural (control) soils include: TPAN 1/CPAN 1 and 2 (i.e., two control soils sampled corresponding to TPAN 1, with lab analyses only on CPAN 2), TPAN 3/CPAN 3, TTOP 1/CTOP 1 (Cerro Topaín), and TTOP 2/CTOP 2 (Lower Topaín). For these soil profile sets, additional surface soil samples (0–15 cm depth) were collected at 5-m intervals from two transects located 5 m upslope and downslope from soil profiles. These give a larger sample size helpful in statistically evaluating the agriculturally important topsoil and comparing agricultural and control soils. These transects were centered around each soil profile, and oriented perpendicular to the natural slope. Within agricultural terraces, the transects were placed along terrace treads. At TTOP/CTOP 1, 10 surface soil samples were collected, and 6 surface samples were collected from the other matched sets.

One-way analysis of variance was used to test for differences in soil properties between agricultural and control soils (0–15 cm depth). In Tables 2 and 3, results are shown for each of the four transects matched pairs ($n = 6$ for each agricultural and control transect), and for combined transects in Figure 7 ($n = 24$ each for agricultural and control samples) to test for overall differences. Significant differences at $p < .05$, .01, and .001 are shown, and actual p values are also reported in Tables 2 and 3. All individual sample data are available in Tables S1 and S2.

3.2 | Laboratory analyses of soils

Lab tests on soil samples were conducted to characterize soil properties critical to understanding productivity, and to assess anthropogenic soil change. Analyses were conducted at the University of Kansas, Colorado State University, New Mexico Bureau of Geology and Mineral Resources, University of New Mexico, and the USDA-NRCS Kellogg Soil Survey Laboratory (see Acknowledgments). Physical soil properties measured were particle-size distribution (total mass of sand, silt, and clay, as well as sand and silt fractions) and bulk density. Chemical properties measured were soil organic carbon (SOC), total nitrogen, available N (nitrate and ammonium), total phosphorus, available P, pH, carbonate, electrical conductivity (EC), and sodium adsorption ratio (SAR). Due to financial limitations, lab tests were mainly run on the four sets of paired terraced and control soil profiles and surface soil transects, plus on two other terraced soil profiles. Particle-size distribution was analyzed by pipette or hydrometer, and USDA sand fractions by wet sieving (Soil Survey Staff, 2011). Bulk density was determined by three-dimensional-laser scanning on air-dried peds or clods (Rossi et al., 2008), or from cores collected in the field for noncoherent samples. Soil water content at 1500 kPa (permanent wilting percentage) was determined by pressure-membrane extraction on less than 2 mm air-dry samples. Total and inorganic carbon were determined by coulometric titration (Hirmas et al., 2012). Organic carbon was calculated as the difference between total and inorganic carbon. Inorganic C was reported as the calcium carbonate equivalent, and as $CaCO_3$ in this paper. Calcite was identified by X-ray diffraction (XRD) in two sediment samples from alluvial fans. Total N was determined by combustion with a LECO TruSpec CN furnace, nitrate-N and ammonium-N following 2 M KCl extraction, total P by inductively coupled plasma mass spectrometry (ICP-MS) after acid digestion, available P by the Olsen test (and ammonium bicarbonate diethylenetriaminepentaacetic acid (AB-DTPA) for Cerro Topaín), pH in 1:1 soil-to-water mixtures, and EC, SAR, and base cations (Ca, Mg, Na, and K) in saturated pastes. Soil transect lab data were statistically analyzed using JMP Pro 14 (SAS Institute, Inc.).

Soil chemical property (SOC, total N, NO_3-N, NH_4-N, total and available P, $CaCO_3$) values were converted from mass basis (g or mg per kg of less than 2 mm soil) to volume basis (kg or g m^{-2} for a specified soil thickness) using the general formula:

$$\text{Soil property on volume basis} = (\text{soil property on mass basis})\\ (\text{bulk density of} < 2\text{mm fraction})(\text{soil thickness})\\ (\text{proportion of soil volume} < 2\text{mm})$$

This was done for surface soils (0–15 cm depth), inferred anthropogenic horizons, and horizons of whole soil profiles. To present data on anthropogenic horizons, soil properties on a volume basis were weight averaged by individual soil horizon thickness. For control soils, soil properties on a volume basis were calculated by weight averaging their horizons to the same depth as their agricultural soil counterparts. In those horizons or 0–15 cm samples where bulk density was not measured, volume-basis properties were estimated using measured bulk densities from the nearest comparable soil horizons.

Mineralogical and chemical composition analyses of a few samples of alluvial fan sediment and its cementing agents were conducted on mineral powders using X-ray fluorescence (XRF), XRD, and ICP-MS. A few samples of soil clay fractions were analyzed by XRD.

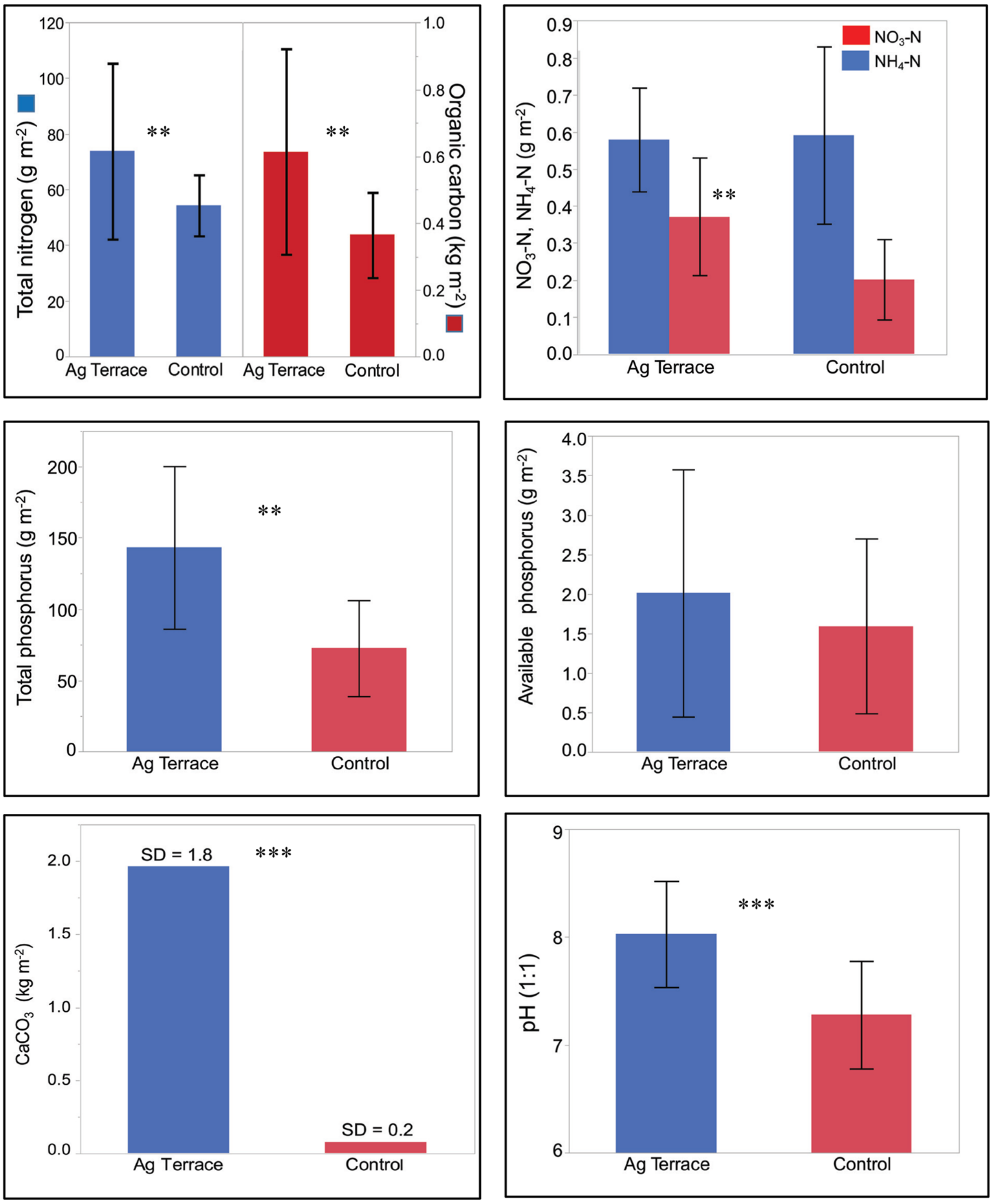


FIGURE 7 Comparison of organic carbon, total and available nitrogen and phosphorus, calcium carbonate, and pH between natural (control) soils and anthropogenic horizons of agricultural soils (0–15 cm depth shown here). Data are means (error bars are standard deviations [*SD*]), with all four paired transects combined (*N* = 48). Mean differences significant at $^{**}p < .01$ for organic C, total N and P, and NO_3-N, and at $^{***}p < .001$ for $CaCO_3$ and pH. No significant differences for NH_4-N and available P [Color figure can be viewed at wileyonlinelibrary.com]

3.3 | Chronometry

Chronology for the terraced agricultural fields at Topaín and Paniri is based on Bayesian modeling of 20 accelerator MS ^{14}C ages on organic sediment and charcoal from fields and adjacent habitation structures (see Supporting Information Radiocarbon Dates for details).

4 | RESULTS AND INTERPRETATION

Observations and data about natural soils and geomorphic locations used for farming are presented first. Next, evidence for anthropogenic soil change is presented based on comparison with matched natural soils, emphasizing that most soil changes resulted from deliberate management, while other change was unintentional.

4.1 | Natural soils and landscape settings for farming

4.1.1 | Soil-geomorphic setting

Natural soils used for terrace agriculture occur mainly on alluvial surfaces and their eroded slopes. Several alluvial surfaces are distinguished on the piedmont based on morphostratigraphy and weathering properties (Figure 2). Holocene active channels (Qa1) and low Holocene alluvial fans and stream terraces (Qa2s) are inset into higher and more dissected Middle and Late Pleistocene alluvial fans and stream terraces (Qa3, Qa3s, Qa4, and Qa5). Qa4 and Qa5 alluvial fan terrace treads are commonly eroded into rounded ridge and ravine (*ballena*) topography. Alluvial deposits interfinger with Quaternary andesitic-to-basaltic lavas and andesitic-to-dacitic-to-rhyolitic tuffs and ashes. Approximate ages for these surfaces are based on correlations to soil-geomorphic mapping by Noller (1993) in Peru, soil-geomorphic studies in the semiarid western Andes (Eash & Sandor, 1995), and recent cosmogenic dating of alluvial fans 140 km south of the study area by Cesta and Ward (2016); maximum ages are constrained by radiometric dating of Cerro Paniri volcanics (Godoy et al., 2018).

The Paniri fields are on hillslopes and treads of dissected alluvial fan terraces (Qa4 and Qa5) underlain by volcaniclastic alluvium or alluvium reworked as colluvium (Figure 2b). Soils on Qa4 were sampled at Topaín, as well on a lower sandy alluvial terrace (Qa2s) (Figure 2c). Topaín soils were also sampled in volcanic-derived colluvium on slopes of the piedmont inselberg Cerro Topaín. The age of the colluvium is probably Pleistocene given the development of soils with argillic horizons (subsurface clay accumulation). There are also eolian sand and dust inputs to these soils, especially noticeable as fine sand at soil surfaces.

A common feature of the piedmont alluvium is that it is deeply cemented. The cementing agent is not $CaCO_3$ except near springs and seeps, and XRF, XRD, and ICP-MS data indicate that this noncalcareous cement is likely amorphous silica. The prevalent silica-rich volcanic rocks and volcaniclastic sediment are probably major sources for the silica cement (Schaetzl & Thompson, 2015, p. 396). The broad extent of this cementation on Pleistocene-age surfaces is remarkable and has not been previously reported in this area. Given that the cementation observed is so widespread and greater than 10 m thick in some areas, it is probably hydrogeologic rather than pedogenic in origin as groundwater in the Atacama Desert is relatively rich in silica (Pigati et al., 2014).

4.1.2 | Natural soils

Natural soils used for irrigated terrace farming at Paniri and Topaín vary substantially in thickness and horizon development. Twelve of the 16 described soils are underlain by laminated silica-cemented soil horizons and/or silica-cemented fanglomerate (Table S3). Cemented layers occur at or near the surface in some positions, such as high alluvial fan terraces and in some locations where slopes were cut during agricultural terrace construction. In soil profiles and transect points examined at Paniri, depth to silica-cemented layers varies from as little as 9 cm to greater than 1.4 m. At Topaín, depth to cemented layers in soil profiles varies from 58 cm to greater than 1 m. Cemented layers are absent within excavated depths of a few soil profiles examined (TPAN 5 and TTOP 3). At TPAN 5, the cemented layer was not encountered within 1.44 m, yet it occurs at or near the surface on nearby hillslopes. On Cerro Topaín, metavolcanic bedrock underlies silica-cemented layers. Overall, natural soils on hillslopes used for terrace agriculture commonly are moderately thin to moderately thick, about 50–100 cm thick to cemented layers. A pattern to this spatial variability of soil depth to cemented layers below summit positions has not been discerned yet, so soil thickness is difficult to predict.

Morphological development of natural soils also varies substantially; however, most of the soils examined have significant subsurface (B horizon) development. This includes soils on slopes of 20 to greater than 35%. Of the five natural soils described, three have weakly to moderately developed subsurface horizons of clay accumulation (Bt or argillic horizons) ranging from 29 to 79 cm thick. Two others have cambic (Bw) horizons, and four soils show probable silica translocation. Natural subsurface horizons underlying anthropogenic horizons in agricultural terraces are also commonly cambic or argillic horizons. Clay translocation to argillic horizons is mostly shown by clay bridging sand grains in these sandy soils, but clay films coating peds and lining pores also occur. The two soil profiles at Cerro Topaín (CTOP 1 and TTOP 1) have stronger argillic horizon development than those on alluvial fan terraces at Lower Topaín (CTOP 2) and Paniri (CPAN 2), with more significant clay accumulation and thicker, more continuous clay films. A comparison of argillic horizons in control (CTOP 1) and terraced (TTOP 1) soils at Cerro Topaín indicates that they are very similar in texture and morphology (Figure 6; Tables S1a and S3). The main variation is that the control soil argillic horizon is thicker, likely due to the mixing of the upper argillic horizon during agricultural terrace construction. Clear glossy coatings on sand grains (e.g., CTOP 2), noncalcareous white masses, and coatings in some B horizons (CPAN 1 and 3, CTOP 1, TTOP 1), and noncalcareous coatings and lamination observed in cemented layers (CPAN 3, CTOP 1) provide evidence of silica translocation and accumulation (Bq, Btq, or Bqm horizons).

Natural soils, especially those on higher alluvial fan and stream terraces (Qa3, Qa4, and Qa5) mostly lack $CaCO_3$, in contrast to agricultural soils on the same geomorphic surfaces that have substantial $CaCO_3$ through inputs of carbonate-enriched spring water during irrigation. None of the five natural soils described in these geomorphic positions have $CaCO_3$ in the soil matrix, but two have discontinuous carbonate coatings on subsurface rock fragments (CPAN 2, CTOP 2). However, $CaCO_3$ is common in natural soils in areas receiving water flow from springs or seeps (Figure 2). In natural soils without $CaCO_3$, pH is mostly slightly acid to neutral in their upper horizons and mostly below 8 in lower horizons (Table S2). The studied natural soils are nonsaline, with most EC values below 1 dS m^{-1}. They also are nonsodic, with most SAR values in upper horizons less than 1 and less than 1–2 in lower horizons.

At their surfaces, natural soils have a high proportion of rock fragment cover (gravel to boulders) ranging from 50% to 80% (Figures 3 and 4; Table S3). They have thin (2–6 cm) sandy surface A or AC horizons underlain by B horizons that are also dominantly sandy, with mostly fine sandy loams in cambic horizons and fine sandy loams to sandy clay loams in argillic horizons. Soil horizons usually contain a high volume of rock fragments in a range of sizes (gravel, cobble, stone, and boulder). B horizons have weak to moderate subangular blocky structure. Below abrupt basal unconsolidated soil boundaries are the silica-cemented layers, designated either as Rqm if interpreted as cemented fanglomerate unaltered by soil formation, or Bqm (duripans) if soil-formed silica-cemented laminae overlie cemented layers.

Dark colors with moist Munsell color values of 1–3 are common in both surface and deepest (C, BC) horizons (Table S3). The dark color is not due to organic matter, which is low in most soils, but rather due to their lithology of dark sands derived mostly from mafic to intermediate volcanic rocks. B horizons (Bt, Bw, and Bq) in most soils have been oxidized to brown colors.

Roots from sparse shrubs, grasses, and cactus are present in all soils, mostly few to common in abundance and very fine to fine in size, with some larger roots. No unconsolidated soil horizons, even those with high rock fragment content, exclude roots. However, roots are unable to penetrate cemented-to-indurated Rqm or Bqm layers.

On the basis of field morphology and lab data, the five natural soils described on higher surfaces on Qa3, Qa4, and Qa5 and Cerro Topaín are classified as various Aridisols (Soil Survey Staff, 2014). Aridisols are soils in arid climates that have subsurface development, though many soils in deserts lack such development and are classified as Entisols (Casanova et al., 2013; Schaetzl & Thompson, 2015). Three of the five described natural soils have argillic horizons, indicating long-term geomorphic (Pleistocene) stability on slopes of alluvial fan terraces and Cerro Topaín. Duripans (silica-cemented hardpans) are likely present in two of the five soils as pedogenically altered uppermost parts of silica-cemented alluvial sediments.

Volcanic glass influence on soils could be expected given that tephra is common in the area (de Silva et al., 1994; Godoy et al., 2018; Houston, 2007). However, only one of the 16 described soils (TTOP 3), located on a lower stream terrace (Qa2s), appears to have some properties indicative of volcanic glass: smeary consistence, possible thixotropy, low bulk density ($<1\ g\ cm^{-3}$), and high 1500 kPa water content/clay (Tables S1a and S3). Volcanic glass influence may also be a reason why soil clay in four soils tested by XRD is mainly amorphous. More field and lab studies are needed on possible volcanic glass effects on these soils. A large area southeast of Paniri dominated by dacitic ash was not farmed, even though it appears canals could have been routed there. Possibly soils in this area are too coarse to retain enough water for crops.

The main natural soils used for agriculture in the study area differ significantly from soils in lower landscape positions (valley floors and *salars*), and from soils in lower parts of the Atacama Desert in lacking carbonate, gypsum, and more soluble salt accumulation, and in commonly having argillic horizons. Soils in the core of the Atacama Desert are well-known for being enriched in salts (Amundson et al., 2012; Casanova et al., 2013; Ewing et al., 2006; Finstad et al., 2014; Rech et al., 2006). The threshold for soil chemical weathering (leaching and clay formation) is thought to be about 100 mm MAP (Ewing et al., 2006), yet these pedogenic processes seem evident here with an estimated 50 mm MAP. Soils with subsurface development such as argillic horizons have generally not been reported or well-recognized in the region (Casanova et al., 2013, p. 25; Diaz Vial & Wright, 1965; Finstad et al., 2014; but see Quade et al., 2007, p. 3777). It is possible that the translocated clay and silica are partly or mostly derived from atmospheric dust, but the lack of carbonate and salt suggests chemical weathering and colloid movement are important soil processes here.

Given the likely Middle to Late Pleistocene-age of these soils, and other research indicating hyperaridity since at least the Late Pliocene to Early Pleistocene (Amundson et al., 2012), these results seem surprising. Climate conditions in the study area located adjacent to the Andes and in a steep precipitation gradient with elevation (Houston, 2007), and also moister conditions during the Pleistocene and early Holocene (Latorre et al., 2006; Olson et al., 2020), may explain the soil development differences. More research on natural pedogenesis and soil spatial distribution in the higher Atacama Desert is needed.

4.2 | Anthropogenic soil change through irrigated terrace agriculture

Natural soils and topography at Topaín and Paniri were significantly altered by long-term agriculture that began approximately a millennium ago. Some change was deliberately accomplished through terracing, irrigation canal infrastructure, and other field construction and management practices, while other soil changes resulting from agriculture were unintentional. The main deliberate physical soil-geomorphic changes resulted from the construction of agricultural terraces with stone walls and nearly level field treads on sloping landscapes (Sandor, 2006). Internally, soils were deliberately altered for agricultural production by removing larger rock fragments and thickened by rearranging and possibly adding soil (fine earth). A major unintentional soil change was the input of $CaCO_3$ from irrigation water supplied from carbonate-enriched springs. These changes from irrigated terrace agriculture have resulted in the development of anthropic epipedons and other altered soil classification (IUSS Working Group WRB, 2015; Soil Survey Staff, 2014).

Terraced fields emplaced in series on hillslopes consist of stone walls up to about 1 m high, bounding nearly level terraced field treads spaced every one to a few meters (Figures 3 and 4; Tables S3 and S4). Measured wall heights around described soils range from 20 to 79 cm, and terraced field width (parallel to the slope, from wall to wall) varies from 1.4 to 2.8 m. Overall terraced field size measured at Paniri and Topaín is relatively uniform (mean 6.5 m^2, standard deviation 1.1 m^2), based on a sample of 111 fields (Parcero-Oubiña et al., 2017). Terrace stone walls constructed mainly of cobbles, stones, and boulders range from one to six courses. Terracing has reduced natural hillslope angles from about 20%–37% to nearly level or very slight slopes on field platforms. Terraced fields on gently sloping areas have lower walls 9–30 cm in height, commonly with only one stone course. In most observed cases, terrace wall stones seem to have been placed on original soil surfaces, rather than embedded into soils. Some walls rest directly on cemented fanglomerate. In other areas of the Andes, it is more common for wall stones to be set inside the soil (e.g., Sandor & Eash, 1995; Treacy, 1989; Wright, 1963).

4.2.1 | Soil morphology and physical properties

Upper horizons of terraced soils have distinctive anthropogenic morphological, physical, and chemical traits, mainly imparted by terrace construction and irrigation, that distinguish them from natural (control) soils (Figures 3, 4, 6, 7; Tables 1–4 and S1–S3). However, some anthropogenic soil change is subtle, and terraced and natural soils also have some similar properties. For example, both terraced and natural soils commonly have thin (2–6 cm thick), loose, sandy surface horizons (usually designated AC), which likely have a significant component of eolian sand. The main anthropogenic soil horizons range in thickness from about 5–50 cm, 24–48 cm in seven of nine terraced soils observed on hillslopes (Table S3). These horizons, mainly designated as Apk or Bpk, are usually calcareous and contain only fine gravel-size rock fragments, in contrast to natural soils that are largely noncalcareous and contain a greater volume and size-range of rock fragments. Artifacts were found in some anthropogenic terraced horizons; for example, ceramic sherds at TPAN 6 and a copper awl and dried manure (probably camelid) in test pit PA141203O01 (Table S4). Horizons underlying anthropogenic horizons are inferred to be natural because they are similar to subsurface horizons in nearby control soils in morphology and development. For example, at terraced soil TTOP 1, a natural argillic horizon with 40%–50% rock fragments of various sizes comparable to the control soil CTOP 1, abruptly underlies 32 cm of inferred anthropogenic soil, which is calcareous and contains about 10% fine gravel (Figures 3 and 6).

A major change with terrace construction and management was the removal of large rock fragments. Rock fragments at soil surfaces are greatly reduced in amount and size on terrace treads from those on natural hillslopes. Whereas natural hillslopes commonly have 50%–80% cover of gravel, cobble, and some stones and boulders, terraced field surfaces mostly have only some fine gravel, except where wall stones have fallen on to terrace treads (Figures 3 and 4). Inferred anthropogenic terraced soil horizons have much lower rock fragment content and size, mostly containing only fine gravel compared with natural soils that commonly have gravels of all sizes, cobbles, stones, and boulders. In hillslope positions at Paniri and Topaín, average rock fragment volume in terraced upper soils ranges from 10%–20% and 10%–14% respectively, in contrast to 38%–79% and 19%–48% in upper parts of natural soils. Comparing the four sets of terraced soils to their specific control counterparts at Paniri and Topaín, rock fragments are lower by 5%–69% (absolute), with a mean reduction of 32% (Table 1). Below altered horizons, terraced and natural soils have similarly high rock fragment volumes (Table S3).

Like natural soils, terraced soils are also dominated by sand, with textures of sand, loamy sand, and sandy loam. Within anthropogenic horizons, lower parts tend to have more silt and clay (Table S1). Whereas most control soils have Bt or argillic horizons that begin fairly close to the surface, terraced soil counterparts mostly lack the clay bridging or clay film morphology of Bt horizons, probably because of disruption of these horizons during terraced soil construction and cultivation. Soil bulk densities mostly range from 1.1 to 1.7 g cm^{-3}, and are not different between agricultural and natural soils. This indicates that agricultural soils have not been compacted, and most bulk densities in anthropogenic soil horizons are 1.1–1.5 g cm^{-3}, a favorable range for crop root growth (Soil Quality Institute, 2001).

4.2.2 | Soil chemical properties

Soil chemical property data for SOC, N, P, and $CaCO_3$ were calculated on both a mass basis (gram or milligram per kilogram of < 2 mm

TABLE 1 Rock fragment content (volume % of soil) comparison between agricultural and natural (control) soils

Control soil profile	Thickness (cm)	Control soil rock fragments (%)	Agricultural soil profile	Agricultural soil rock fragments (%)	Rock fragment mean difference (%)
CPAN 1	54	79	TPAN 1	10	69
CPAN 2	54	38	TPAN 1	10	28
CPAN 3	24	40	TPAN 3	20	20
CTOP 1	32	48	TTOP 1	10	38
CTOP 2	28	19	TTOP 2	14	5

Note: 1. Thickness refers to depth from surface corresponding to inferred thickness of the anthropogenic part of the terraced agricultural soil.
2. Rock fragment % refers to mean volume % of rock fragments (gravels, cobbles, stones, and boulders) of the soil estimated in the field, weighted by soil horizon thickness.
3. Rock fragment mean difference % = control soil mean % − agricultural soil mean %.
Abbreviations: CPAN, control Paniri; CTOP, control Topaín; TPAN, terraced Paniri; TTOP, terraced Topaín.

TABLE 2 Statistical comparison of surface soil (0–15 cm depth) chemical properties between agricultural and natural (control) soils at Paniri and Topaín, with organic carbon, nitrogen, phosphorus, and $CaCO_3$ on a mass basis

	Agricultural soil		Control soil			
Variable	Mean	*SD*	Mean	*SD*	*p*	Significance
Paniri transects 1-2 (TPAN 1–CPAN 2 sample pair)						
Organic carbon (g kg^{-1})	4.2	0.6	4.5	1.7	.68	
Total nitrogen (g kg^{-1})	0.47	0.08	0.51	0.11	.48	
Organic carbon:nitrogen ratio	9.0	0.45	8.6	1.94	.69	
Nitrate-nitrogen (mg kg^{-1})	2.6	1.3	2.9	2.0	.80	
Ammonium-nitrogen (mg kg^{-1})	3.5	0.7	6.5	2.6	.02	*
Available nitrogen ($NO_3 + NH_4$) (mg kg^{-1})	6.1	1.5	9.3	4.1	.10	
Total phosphorus (mg kg^{-1})	745	177	430	47	.002	**
Available phosphorus (Olsen) (mg kg^{-1})	20.5	13.1	17.7	4.1	.62	
pH (1:1 soil:water)	8.0	0.2	7.0	0.2	<.001	***
$CaCO_3$ (g kg^{-1})	7.04	3.68	0.07	0.02	<.001	***
Electrical conductivity (EC) (dS m^{-1})	0.62	0.10	0.72	0.60	.70	
Sodium adsorption ratio (SAR)	0.53	0.11	0.57	0.21	.72	
Paniri transect 3 (TPAN 3–CPAN 3 sample pair)						
Organic carbon (g kg^{-1})	3.3	0.9	3.5	1.0	.69	
Total nitrogen (g kg^{-1})	0.36	0.08	0.46	0.09	.09	
Organic carbon:nitrogen ratio	9.0	2.0	7.6	0.7	.12	
Nitrate-nitrogen (mg kg^{-1})	2.1	0.7	1.1	0.4	.007	**
Ammonium-nitrogen (mg kg^{-1})	3.7	0.6	3.6	0.7	.77	
Available nitrogen ($NO_3 + NH_4$) (mg kg^{-1})	5.8	1.0	4.7	1.0	.10	
Total phosphorus (mg kg^{-1})	694	60	369	41	<.001	***
Available phosphorus (Olsen) (mg kg^{-1})	12.9	5.2	9.0	3.8	.16	
pH (1:1 soil:water)	8.3	0.1	7.6	0.5	.009	**
$CaCO_3$ equivalent (g kg^{-1})	22.7	9.6	2.1	3.1	<.001	***
EC (dS m^{-1})	0.93	0.43	0.48	0.10	.03	*
SAR	0.72	0.40	0.72	0.22	.98	
Cerro Topaín (Topaín transect 1: TTOP 1–CTOP 1 sample pair)						
Organic carbon (g kg^{-1})	4.2	1.9	2.2	0.5	.005	**
Total nitrogen (g kg^{-1})	0.57	0.17	0.44	0.07	.03	*
Organic carbon:nitrogen ratio	7.3	2.0	5.1	1.0	.006	**
Nitrate-nitrogen (mg kg^{-1})	1.8	0.6	1.8	0.5	.93	
Ammonium-nitrogen (mg kg^{-1})	3.3	0.6	6.3	2.5	.002	**
Available nitrogen ($NO_3 + NH_4$) (mg kg^{-1})	5.1	0.9	8.1	2.7	.004	**
Total phosphorus (mg kg^{-1})	1071	201	1001	259	.51	
Available phosphorus (Olsen) (mg kg^{-1})	3.2	1.0	4.7	1.0	.004	**
Available phosphorus (DTPA) (mg kg^{-1})	10.4	2.5	11.6	1.9	.25	
pH (1:1 soil:water)	8.0	0.1	6.9	0.2	<.001	***
$CaCO_3$ equivalent (g kg^{-1})	14.6	9.8	0.0	0.0	<.001	***
EC (dS m^{-1})	0.30	0.00	0.21	0.03	<.001	***
SAR	0.20	0.02	0.23	0.03	.012	*
Lower Topaín (Topaín transect 2: TTOP 2–CTOP 2 sample pair)						
Organic carbon (g kg^{-1})	1.7	0.4	1.8	0.4	.94	
Total nitrogen (g kg^{-1})	0.23	0.05	0.31	0.03	.007	**
Organic carbon:nitrogen ratio	7.6	0.8	5.7	1.5	.02	*
Nitrate-nitrogen (mg kg^{-1})	1.7	1.0	1.1	0.6	.19	
Ammonium-nitrogen (mg kg^{-1})	2.6	0.8	2.9	0.8	.41	
Available nitrogen ($NO_3 + NH_4$) (mg kg^{-1})	4.3	1.7	4.0	1.3	.77	
Total phosphorus (mg kg^{-1})	565	127	479	33	.14	

(Continues)

TABLE 2 (Continued)

Variable	Agricultural soil		Control soil			
	Mean	*SD*	Mean	*SD*	*p*	Significance
Available phosphorus (Olsen) (mg kg^{-1})	9.2	2.8	15.5	5.7	.04	*
pH (1:1 soil:water)	7.7	0.9	7.6	0.4	.81	
$CaCO_3$ equivalent (g kg^{-1})	1.04	0.5	0.08	0.04	.001	**
EC (dS m^{-1})	0.45	0.14	0.43	0.12	.83	
SAR	1.02	0.44	0.99	0.27	.90	

Note: A total of 6 (Paniri transects and Lower Topaín transect sample pairs) to 10 Cerro Topaín (TTOP 1–CTOP 1 sample pair) samples of each kind of soil collected from transects.

See Table S2b for individual data.

Probability values (*p*-values) refer to the statistical comparison between paired transects using one-way analysis of variance. Significance of *p*: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Abbreviations: CPAN, control Paniri; CTOP, control Topaín; TPAN, terraced Paniri; TTOP, terraced Topaín.

soil) and volume basis (gram or kilogram per square meter to a depth of 15 cm for surface transects, or to the depth of inferred anthropogenic horizons). Because differences in these soil properties from anthropogenic soil change are most evident on a volume basis (mainly due to deliberate removal of rock fragments), and the volume basis more accurately reflects amounts of N and P accessible to crops, volume basis data are emphasized here. Examples of SOC, N, P, and $CaCO_3$ distribution by soil horizon through entire soil depths on a volume basis for agricultural and control soils are shown in Figure 6 for Cerro Topaín because that area had the clearest distinction between agricultural and control soils in the same geomorphic context. Data on both a mass and volume basis for the four paired samples are summarized for 0–15 cm depths in Tables 2 and 3, on a volume basis for anthropogenic horizon depths in Table 4, and for all individual samples in Table S2.

Agricultural soils at two of the four paired sample areas (Paniri Transect 1-2 [TPAN 1–CPAN 2], and Cerro Topaín [TTOP 1–CTOP 1]) have significantly more SOC and total N on a volume basis relative to control soils (Tables 3 and 4). Paniri Transect 3 (TPAN 3–CPAN 3) and Lower Topaín Transect (TTOP 2–CTOP 2) data do not show this trend (see later Section 5). Combining all four paired samples, this trend holds for both surface soils (0–15 cm depth), where SOC and total N average 614 and 74 g m^{-2} in agricultural soils and 364 and 54 g m^{-2} in control soils (Figure 7), and to the depth of anthropogenic horizons. Nearly all N in both agricultural and control soils is organic, ranging from about 95%–99% of total N (Tables 2–4, and S2). Higher proportions of inorganic N (nitrate) have been found deep in some desert soils (Walvoord et al., 2003), and abundant nitrate occurs in lower areas of the Atacama Desert that mainly originates from atmospheric deposition (Casanova et al., 2013; Finstad et al., 2014). However, that is not the case for the higher elevation piedmont soils in this study area.

A plausible reason for the higher total N in some agricultural soils is past fertilizer application. Fertilization of soils with camelid manure and other materials is a long-standing practice in this area, as it is elsewhere in the Andean region (Denevan, 2001; Latcham, 1936). From an overall perspective, however, total N in these soils is relatively low, reflecting low soil organic matter typical in deserts. Abandoned terraced soils in the semiarid Colca Valley, Peru with loam textures have mean total N values much higher than these soils, although sandy soils have comparable total N values (Sandor & Eash, 1995; Sandor & Furbee, 1996).

Combining all paired sites, plant-available N as nitrate (NO_3-N) is higher in agricultural soils, but overall at low levels (Figure 7; Table 4). These data suggest that farmers did not use nitrate from the Atacama Desert as a fertilizer. The nitrate levels here are considered very low (<3 mg kg^{-1} on mass basis, Table 2) by current agricultural testing standards (Flynn, 2012), so N additions would be needed in these soils to achieve productive crop yields. Plant-available N as ammonium (NH_4-N) is not different between agricultural and control soils for the combined paired samples (Figure 7).

Phosphorus, second only to nitrogen as an essential soil macronutrient for plants, is present in greater amounts in agricultural soils. Total P levels in surface soils and to the depth of anthropogenic horizons are significantly higher ($p < .001$) than in control soils for both Paniri paired samples and Cerro Topaín, and for all paired samples combined (Figures 6 and 7; Tables 3 and 4). Below anthropogenic horizons, P levels in agricultural and control soils are similar. Phosphorus enrichment in agricultural soils is also evident on a mass basis for both Paniri paired samples (Table 2). The higher P in agricultural soils probably results from long-term accumulation from fertilization. A trait of most soils tested is that total P is greater than total N. This is due to the low organic matter in hyperarid desert soils as well as possible residual P from long-term fertilization in agricultural soils.

Plant-available forms of P tend to be slightly higher in agricultural soils but differences are more subdued than for total P. The minimal differences in available P between agricultural and control soils relative to greater amounts of total P in agricultural soils are likely due to pH differences. Phosphorus is most available at slightly

TABLE 3 Statistical comparison of surface soil (0–15 cm depth) chemical properties between agricultural and natural (control) soils at Paniri and Topaín, with organic carbon, nitrogen, phosphorus, and $CaCO_3$ on a volume basis

	Agricultural soil		Control soil			
Variable	Mean	*SD*	Mean	*SD*	*p*	Significance
Paniri transects 1–2 (TPAN 1–CPAN 2 sample pair)						
Organic carbon (kg m^{-2})	0.73	0.11	0.39	0.15	.001	**
Total nitrogen (g m^{-2})	82	14	44	9	<.001	***
Nitrate-nitrogen (g m^{-2})	0.45	0.22	0.25	0.17	.10	
Ammonium-nitrogen (g m^{-2})	0.60	0.12	0.56	0.23	.68	
Available nitrogen ($NO_3 + NH_4$) (g m^{-2})	1.05	0.27	0.81	0.36	.21	
Total phosphorus (g m^{-2})	130	31	37	4	<.001	***
Available phosphorus (Olsen) (g m^{-2})	3.57	2.28	1.53	0.36	.06	
$CaCO_3$ equivalent (kg m^{-2})	1.23	0.64	0.01	0.01	<.001	***
Paniri transect 3 (TPAN 3–CPAN 3 sample pair)						
Organic carbon (kg m^{-2})	0.57	0.14	0.47	0.13	.57	
Total nitrogen (g m^{-2})	57	13	61	13	.63	
Nitrate-nitrogen (g m^{-2})	0.34	0.10	0.15	0.05	.002	**
Ammonium-nitrogen (g m^{-2})	0.58	0.10	0.48	0.10	.10	
Available nitrogen ($NO_3 + NH_4$) (g m^{-2})	0.92	0.16	0.63	0.14	.009	**
Total phosphorus (g m^{-2})	109	10	49	5	<.001	***
Available phosphorus (Olsen) (g m^{-2})	2.04	0.82	1.19	0.51	.06	
$CaCO_3$ equivalent (kg m^{-2})	3.58	1.51	0.27	0.41	<.001	***
Cerro Topaín (Topaín transect 1: TTOP 1–CTOP 1 sample pair)						
Organic carbon (kg m^{-2})	0.83	0.37	0.26	0.06	<.001	***
Total nitrogen (g m^{-2})	113	33	52	8	<.001	***
Nitrate-nitrogen (g m^{-2})	0.36	0.11	0.21	0.06	.002	**
Ammonium-nitrogen (g m^{-2})	0.65	0.13	0.75	0.30	.33	
Available nitrogen ($NO_3 + NH_4$) (g m^{-2})	1.00	0.17	0.96	0.32	.72	
Total phosphorus (g m^{-2})	211	40	119	31	<.001	***
Available phosphorus (Olsen) (g m^{-2})	0.63	0.20	0.56	0.12	.39	
Available phosphorus (DTPA) (g m^{-2})	2.04	0.50	1.38	0.23	.001	**
$CaCO_3$ equivalent (kg m^{-2})	2.88	1.93	0.00	0.00	<.001	***
Lower Topaín (Topaín transect 2: TTOP 2–CTOP 2 sample pair)						
Organic carbon (kg m^{-2})	0.33	0.08	0.35	0.07	.66	
Total nitrogen (g m^{-2})	43	9	61	6	.002	**
Nitrate-nitrogen (g m^{-2})	0.32	0.18	0.21	0.12	.23	
Ammonium-nitrogen (g m^{-2})	0.48	0.14	0.57	0.16	.31	
Available nitrogen ($NO_3 + NH_4$) (g m^{-2})	0.80	0.31	0.79	0.25	.91	
Total phosphorus (g m^{-2})	106	24	94	6	.25	
Available phosphorus (Olsen) (g m^{-2})	1.72	0.53	3.05	1.13	.03	*
$CaCO_3$ equivalent (kg m^{-2})	0.20	0.10	0.02	0.01	.001	**

Note: A total of 6 (Paniri transects and Lower Topaín transect sample pairs) to 10 Cerro Topaín (TTOP 1–CTOP 1 sample pair) samples of each kind of soil collected from transects.

See Table S2b for individual data.

Probability values (*p*-values) refer to the statistical comparison between paired transects using one-way analysis of variance. Significance of *p*: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Abbreviations: CPAN, control Paniri; CTOP, control Topaín; TPAN, terraced Paniri; TTOP, terraced Topaín.

acid to neutral pH and availability decreases at higher pH because P becomes bound in calcium-P compounds of low solubility (Brady & Weil, 2008). While most control soil upper horizons have pH in the optimal range of 6–7 for P availability, the pH of terraced soils is more alkaline (about pH 8) because of carbonate from irrigation water (Figure 7; Table 2). Low available phosphorus can also be a problem in soils derived from volcanic ash (Casanova et al., 2013, p. 104). Interpretation of available P data for fertility levels in agricultural soils in the 0–15 cm and anthropogenic horizon depths varies by location and soil test reference (e.g., Flynn, 2012; Shaver,

TABLE 4 Comparison of chemical properties (organic carbon, nitrogen, phosphorus, and $CaCO_3$) on volume basis between paired agricultural terraced and natural (control) soil profiles at Paniri and Topaín to the depth of the anthropogenic layer identified in each agricultural soil

Soil profile	Context	Depth (cm)	Organic C (kg m^{-2})	Total N (g m^{-2})	NO_3-N (g m^{-2})	NH_4-N (g m^{-2})	Available N (NO_3 + NH_4) (g m^{-2})	Total P (g m^{-2})	Available P (g m^{-2})	$CaCO_3$ (kg m^{-2})
TPAN 1	Agriculture	0–54	2.24	233	0.42	1.38	1.80	256	6.7	9.46
CPAN 2	Control	0–54	1.46	181	0.29	1.31	1.60	130	4.8	0.03
TPAN 3	Agriculture	0–24	0.69	91	0.61	0.81	1.42	173	5.4	3.60
CPAN 3	Control	0–24	0.44	71	0.14	0.55	0.69	61	0.9	0.05
TTOP 1	Agriculture	0–32	1.86	215	0.46	1.09	1.55	610	1.2	8.31
CTOP 1	Control	0–32	0.43	87	0.30	1.51	1.81	229	1.1	0.00
TTOP 2	Agriculture	0–28	0.48	90	0.35	0.54	0.89	149	2.6	0.11
CTOP 2	Control	0–28	0.43	94	0.15	0.79	0.94	140	4.8	0.02

Note: See Table S2a for individual data.
Abbreviations: CPAN, control Paniri; CTOP, control Topaín; TPAN, terraced Paniri; TTOP, terraced Topaín.

2014). Paniri soils (0–15 cm) mostly test in the medium/optimal range and TTOP 2 nearly so. Available P in Cerro Topaín soils test very low with the Olsen method, but mostly medium with the AB-DTPA test (Self, 2010).

4.2.3 | Soil change from carbonate in irrigation water

Although much anthropogenic soil change resulted from deliberate management practices such as terracing, rock fragment removal, and fertilization, significant differences between agricultural and control soils in carbonate content and pH are attributed to unintentional long-term input of carbonate-rich irrigation water in the agricultural soils.

A major difference between agricultural and natural soils is that agricultural soils are calcareous, whereas natural soils outside of areas receiving spring water or seepage are mostly noncalcareous. This pattern is consistent at both Paniri and Topaín for all four sets of terraced soils and their control counterparts. Terraced soils have disseminated $CaCO_3$, and visible $CaCO_3$ especially in middle to lower parts of anthropogenic horizons (Table S3). Carbonate morphology includes filaments, powdery forms, masses, and coatings on peds, rock fragments, and tops of silica-cemented layers (Figure 4). Tufa fragments, commonly of gravel size, are visible on some terraced surfaces and soils (e.g., TTOP 3). Carbonates also coat stones used to line canals, in aqueducts constructed across *quebrada*s, and bases of terrace wall stones (Supporting Information Figures). In contrast, rock fragments at surfaces and in soils in unirrigated areas have very little if any carbonate coatings. Control soils lack carbonate in the soil matrix, with small amounts observed as rock fragment coatings at CPAN 2 and CTOP 2. Carbonate was detected in two of six control soil transect points at CPAN 3, but these points are located a few meters downslope from a canal that conveyed irrigation water to agricultural terraces downslope.

A comparison of field morphology between agricultural and control soils indicates color differences (Table S3). Colors of most agricultural soils tend to either be slightly yellower in hue (10YR) than upper control soils (7.5–10YR), or have slightly lower chromas. These differences likely result from $CaCO_3$ in terraced soils.

Reflecting soil morphology, chemical data confirm inputs of $CaCO_3$ into agricultural soils (Figures 6 and 7; Tables 2–4). Anthropogenic horizons and surface horizons in agricultural soils have $CaCO_3$ accumulation, whereas control soils have either no or low amounts of $CaCO_3$. Significant $CaCO_3$ has been added to agricultural soils in irrigation water to produce Bk horizons, but not to levels that define calcic horizons (Soil Survey Staff, 2014). Below anthropogenic horizons, $CaCO_3$ is absent or low in agricultural soils, as they are in control soils, supporting the inference of very little or no $CaCO_3$ in the original soils.

Carbonate input from irrigation caused pH increase in agricultural soils (Figures 6 and 7; Tables 2 and S2). $CaCO_3$ tends to buffer soil pH at about 8. For paired surface soils at Paniri and Topaín, mean pH in agricultural soils is 7.7–8.3, and 6.9–7.6 in control soils. Whereas pH in calcareous anthropogenic horizons of agricultural soils is slightly to moderately alkaline (pH high 7 to low 8 range), most pH in control soil horizons to the same depth is slightly acid to neutral to slightly alkaline. pH mostly remains around 8–8.5 in agricultural soils throughout their observed depth, even when $CaCO_3$ declines below anthropogenic horizons (e.g., Figure 6).

Salinity (EC) and sodium (SAR) are mostly low in surface soils of both agricultural and control soils, with mean values ≤1 for all four paired samples (Tables 2 and S2). Salinity remains low throughout all agricultural and control soil profiles at Paniri and Cerro Topaín. SAR values at Paniri are low for all three agricultural soil profiles but are higher in the lowest two horizons at Paniri Control 3 (SAR 5–10). At Cerro Topaín, SAR rises to 5–7 in the lowest horizons of the agricultural soil, to levels higher than the control soil (SAR 1–2). This suggests some deeper translocation of soluble salt (sodium) during long-term irrigation, which goes along with higher pH and slightly higher EC in the agricultural soil. This may also be the case for the agricultural soil TTOP 2, where SAR reaches 30 in the lowest horizon. Keeley (1988) reported some high pH (9.2) in terraced soil at Paniri, above pH 8.5 considered the threshold for possible sodic conditions.

High levels of both salt and sodium were measured starting at about 30 cm depth at the nonpaired agricultural soil TTOP 3, located on a low alluvial fan terrace where salts are more likely to accumulate in this hyperarid environment (Table S2a). Another probable sodic soil (QR3) was observed in an agricultural field in a lower landscape position at Topaín associated with a saline seep that is likely natural. This soil has a hard, dark surface crust, salt efflorescence, and a field pH > 8.5, suggesting a sodic "black alkali" soil (Schaetzl & Thompson, 2015, p. 403).

5 | DISCUSSION

5.1 | Soil-geomorphic settings for agriculture

Soil-geomorphic settings used for agriculture here are mostly higher alluvial fan and ephemeral stream terraces, and on Cerro Topaín. Although reasons for farming these piedmont areas are not fully known, they likely relate to the agronomic advantages of these geomorphic positions and soil quality. Compared with more alkaline lower areas of the Turi Basin, the higher eastern areas nearer to the mountains have nonsaline, nonsodic soils with favorable sandy to loamy textures. Management practices such as terracing and removal of large rock fragments further improved soils for crop production. These areas are also closest to springs that served as primary water sources for the irrigation essential in this hyperarid climate. Nevertheless, great engineering skill was required to route canals from springs to fields in these higher locations, and lower areas could have been irrigated if there had been a desire to farm them. Farming is practiced today in some nearby lower areas. A microclimatic advantage of farming hillslopes at this high altitude is that they are less prone to freezes by cold air drainage than flatter lower areas. Inactive alluvial fan and stream terraces are also not subject to rare episodic floods.

Cemented horizons and sediments that underlie many of the terraced fields and canals have significantly influenced soil thickness and development, soil water movement and retention, and agriculture. Although a disadvantage of silica-cemented layers is that they make for shallower soils, an advantage is that their low permeability allows applied irrigation water to be held in crop rooting zones. In addition, water movement and downward loss are slowed by the presence of finer-textured argillic horizons found in some of these soils, or by other textural discontinuities. The optimal condition of rapid water infiltration into soils and water retention within rooting zones occurs when sandy surface horizons overlie less permeable soil horizons or other layers, as is the case in many of the soils used for agriculture at Paniri and Topaín. Soils with such horizons have been deliberately used for farming in other arid regions because of this water-retaining ability (Sandor, 2006).

5.2 | Agricultural terrace construction and soils

A common purpose in building bench terraces on slopes in arid lands is to create relatively level, stable fields that facilitate irrigation, and enhance conditions for crop productivity. In this hyperarid area of Chile, strategies to conserve limited water resources are essential. At Paniri and Topaín, many terraced fields were segmented into small areas of a few square meters (Figures 3 and 4). This compartmentalization of fields within terraces likely enabled farmers to judiciously distribute precious irrigation water from springs in space and time.

Soils in these agricultural terraces are expected to be thicker than the original soil thickness because of filling upslope of terrace walls, which is the case in many terraced soils in the Andes and other world regions (Frederick & Krahtopoulou, 2000; Sandor, 2006; Sandor & Eash, 1995). However, it is not clear in this study area how much extra soil was emplaced upslope of terrace walls, partly because natural soil thickness varies so much. In fact, overall soil thickness is greater in three control soil profiles compared with adjacent terraced agricultural soils (Table S3). Also, soil modification involved removing larger rock fragments (larger than fine gravel), which constitute a significant volume of natural soils. The mean estimated rock fragment volume in the inferred anthropogenic upper part of terraced soils is 13%, compared with 45% in corresponding depths of control soils (Table 1). Overall, while extra soil possibly was emplaced in terraces, it may also be that existing upper soils were just changed by removing large rock fragments, without any or much incorporation of new soil material.

Observing terraced soils elsewhere in northern Chile, Wright (1963) thought that denser subsurface horizons with more clay and stones were part of the constructed soil or at least due to cultivation. In our study area, the subsurface argillic horizons with more clay and rock fragments of various sizes and orientation (i.e., without a pattern suggesting human construction) indicate that these subsurface horizons are natural.

The specific methods by which larger rock fragments were removed in constructing these terraced soils, whether by hand removal and/or sieving, is unknown, though there is a historical reference that rock removal from state agricultural fields was one of the labor tribute duties imposed by the Inka on conquered subjects (Cabeza de Vaca, 1885 [1586]). Many larger rock fragments removed from upper soil horizons were used in constructing terrace walls and *rumimoqos*, which are polygonal walled mounds and ridges of varying sizes and orientations at Paniri made with cobbles and other rock fragments (Figure 4 and Supporting Information Figures; Alliende et al., 1993; Malim, 2009; Parcero-Oubiña et al., 2017).

An exception to the removal of rock fragments in terraced soils is the emplacement of gravel and cobble pockets near the downslope walls of terraces. These rock fragment pockets are a common construction feature in agricultural terraces in the Colca Valley, Peru, and elsewhere in the Andes to facilitate drainage and reduce pressure on terrace walls (Londoño et al., 2017; Sandor & Eash, 1995; Treacy, 1989). Only two possible examples were observed at Paniri (e.g., TPAN 1, Table S4). Most terrace walls in the study area are shorter than those in the Colca Valley, and most soils are sandy, so perhaps this feature was not always needed.

Other questions about soil emplacement and filling upslope of terrace walls in the study area remain unresolved. In other regions, wedge-shaped soils between bench terrace walls are commonly observed, with soils thicker toward front (downslope) walls and thinning toward back (upslope) walls (Frederick & Krahtopoulou, 2000; Sandor, 2006; Treacy & Denevan, 1994). This pattern was observed at Paniri by Keeley (1988), but we only saw a few examples at Paniri and Topaín (TPAN 1, TPAN 5, and TPAN 6). In the case of TPAN 1, the soil steeply deepens near the downslope terrace wall, suggesting excavation into the slope to emplace the wall.

Natural subsurface horizons underlying terraced soil horizons commonly have slopes that parallel natural hillslope gradients (e.g., Sandor & Eash, 1995). In this study area, we have not consistently observed this parallel relationship. At TPAN 5, for example, subsurface horizons slant at about 18%, less than the overall 37% backslope, and at TTOP 1 the natural argillic horizon slope is about 12%, less than the 25% overall backslope. Some possible reasons are that overall measured slopes (taken several terraces apart) may overestimate natural slopes at any given terrace, subsurface natural soils may have been cut out of slopes in some terraces so soil fill between terrace walls is more level, and slopes in some areas possibly were steepened by erosion relative to older developed soil horizons and strata before terracing. Horizon slopes in natural soils generally seem to parallel natural slopes, though more careful measurements are required. Overall, more specific study of surface topography and subsurface soil horizon slopes on successive terraces is needed.

An important question about terrace construction here is whether soil materials were imported as terrace fill (see Denevan, 2001, p. 38). If so, were sources local or more distant? There is evidence of local soil import to terraces in some cases. At Paniri, terraced soils near the main valley floor have sandy gray fills that resemble *quebrada* alluvium, possibly indicating fill was brought in. Keeley (1988) reported that soils still farmed at Paniri "…are almost completely remade periodically and soil is brought in from nearby uncultivated areas, if needed, to maintain the level in relation to the field walls." The terraced fields that are still farmed are located close to the current settlement and adjacent to the main *quebrada*. She does not specify fill source, whether it is from adjacent hillslopes and/or the *quebrada*. Keeley (1988) thought that many Paniri soils are severely eroded, which she apparently saw as the main reason why farmers needed to periodically add more soil fill (see Section 5.3).

However, most agricultural terraces are located farther from *quebradas*, on alluvial fan interfluves, and Cerro Topaín, and it would take enormous labor to transport soil fill to these areas. The capability of prehispanic societies in the region for monumental construction works is well known, but was it necessary in the case of these terraced soils? On the basis of our observations and data, we think that importing soil from a distance to terraces was mostly unnecessary and that it would not make sense from a soil quality perspective. For example, soil textures of terraced and control soils at Cerro Topaín are very similar (Table S1a). The anthropogenic soil layer (upper 32 cm) of the terraced soil has nearly the same texture as the control soil to the same depth (both sandy loam with weighted means of 70% sand, 12%–13% silt, and 16%–18% clay). Silt and sand fraction indices (coarse/fine silt, and percent sand that is coarse, medium, and fine) show no statistical differences. In other words, the observed texture of the anthropogenic part of the terraced soil is nearly equivalent to mixing the same soil thickness in the control soil. The underlying natural argillic horizon is also similar to that of the control soil: both sandy clay loams averaging 27% clay. The data from Cerro Topaín suggest that terraced soils are mostly developed in situ, and that any added fill could come from immediately local sources. At Lower Topaín and Paniri, there are minor but statistically significant differences in texture between terraced and control soils (Table S1). Considering that both agricultural and control soils are sandy, attributing relatively subtle textural differences to deliberate import of soil into agricultural soils that would serve a purpose is doubtful.

Adjacent natural soils are mostly deep enough to provide fill for downslope terraces if needed. In most cases, terraced soils seem to consist of in-place soil with stones removed rather than imported soil fill. Although some terraced areas with soils that are very shallow to cemented layers or bedrock may have required added soil material from local sources, bringing in soil fill from a distance would not be necessary for most locations.

Another argument against the widespread import of soil fill from lower areas is that soils on the immediate hillslopes are higher in quality for crop production. For example, lower areas at Paniri are *quebradas* with commonly coarse sandy alluvium with low water-holding capacities, and lower areas south of the terraced slopes of Cerro Topaín have high pH, and contain carbonates and possibly other salts.

5.3 | Accelerated soil erosion

An important kind of anthropogenic soil degradation common in the history of agriculture is accelerated soil erosion (Bell & Boardman, 1992; Dotterweich, 2013; Sandor, 2006). Examples of both soil degradation by erosion and soil conservation in ancient abandoned agricultural terraces have been reported elsewhere in the Andes (Branch et al., 2007; Field, 1966; Goodman-Elgar, 2008; Inbar & Llerena, 2000; Keeley, 1985; Londoño et al., 2017; Sampietro-Vattuone et al., 2019, 2011; Sandor & Eash, 1995; Zaro and Umire Alvarez, 2005; Zaro et al., 2008). Have the soils of the study area been seriously eroded, and if so, to what degree? Keeley (1988) concluded that all agricultural soils at Paniri have been eroded, especially on gently sloping land. She states these soils "…appeared to be extremely eroded by wind and water action, no doubt due to lack of a vegetation cover, with perhaps 30 to 60 cm lost. This was deduced by looking at the present soil surface in relation to the tops of the stone walls and canals to which, in the past, the soil would have reached." However, this reasoning may not be correct because (1) the tops of intact walls, especially with vertically-oriented oblong stones, were commonly placed to extend higher than soil level (e.g., Figure 4), and (2) $CaCO_3$ deposits from carbonate-rich spring irrigation water have built up canal levels above the ground surface—this is especially seen at Topaín (e.g., Parcero-Oubiña et al., 2017; Figure S4i).

We have not observed such widespread accelerated erosion of hillslope terraces described by Keeley. Although there are areas of breached and eroded terraces, many terraces and soils seem relatively intact (e.g., Figures 3 and 4). The terraced soils we observed in several locations have anthropogenic soil horizons level with nearly level terrace treads not truncated by erosion. We also think that interfluve summits of alluvial fan terraces that Keeley viewed as extremely eroded are natural and predate agriculture. Most soils in interfluve summit positions, including those well outside of agricultural field areas, are shallow to cemented fanglomerate.

5.4 | Soils and agricultural productivity

5.4.1 | Soil thickness for crop production

Many natural soils used for agriculture are shallow to moderately deep. Some agricultural soils are as shallow as 10–30 cm over natural cemented layers, and their occurrence among intact terrace walls indicates that the shallowness is not due to anthropogenic erosion. Examples of such thin terraced soils are TPAN 3 and TPAN 4 (Table S3) and soils observed in transect points around TPAN 3. What crops could be grown in these soils and how? Local people familiar with farming say that certain crops such as quinoa, wheat, or *tunas* (prickly pear cactus grown for its fruit) are adapted and can be grown successfully in these shallow soils. They point out that management practices such as soil mounding or hilling, and fertilization with manure or other materials, would improve productivity. In our studies, we did not observe evidence of mounding in the ancient, abandoned terraces. Anthropogenic soil horizons seem fairly level and uniform, with most agricultural and control soil horizon boundaries similarly smooth to wavy (Table S3). An advantage of these soils is that underlying cemented layers would retain irrigation water in the crop rooting zone. Local people also said that other crops such as maize, potatoes, and other tubers can be grown in somewhat thicker but still fairly shallow soils (about 40–50 cm). In a preliminary study of stone hoe fragments, McRostie (2015) noted the similarity of starch granules adhered to the hoes to starch from a variety of tubers, including oca (*Oxalis tuberosum*), mashua (*Tropaeolum tuberosum*), ulluco (*Ullucus tuberosum*), and/or potential varieties of potato (*Solanum tuberosum*), but a more definitive study remains to be carried out.

5.4.2 | Soil nutrients and fertility

Increases in major crop nutrients nitrogen and especially phosphorus in agricultural soils relative to natural soils are evident, but not to high levels (Figures 6 and 7; Tables 2–4 and S2). This raises the issue of nutrient management and the use of fertilizers by farmers. In some other areas of the Andes, greater amounts of N and P in ancient and traditional agricultural soils reflect long-term fertilization with camelid and other manures and other fertilizer materials (Denevan, 2001, pp. 35–38, 168; Goland, 1993; Keeley, 1985; Salminci et al., 2014; Sampietro-Vattuone et al., 2011; Sandor & Eash, 1995; Winterhalder et al., 1974). For example, N and P levels measured in Colca Valley terraced soils are far higher than in control soils (Sandor & Eash, 1995). Some extraordinarily high soil P levels measured there were attributed not just to regular animal manure and hearth ashes, but also to sea-bird guano from Peruvian coastal islands, which was commonly applied in the Andes (Denevan, 2001, p. 35; Donkin, 1979, pp. 1–2; Julien, 1985; Santana-Sagredo et al., 2017). Traditional farmers in the study area are known to have used, and still use, manure to fertilize soils. Although fertilizer use may not have been as high as in some areas of the Andes, the significantly higher levels of total P in agricultural soils compared with control soils at Cerro Topaín and especially Paniri likely reflect accumulation from long-term fertilization. Phosphorus is a particularly useful marker of ancient agriculture and fertilization because of its relatively low mobility and long-term stability and persistence in soils (Holliday & Gartner, 2007; Homburg et al., 2005; McLauchlan, 2006).

Would $CaCO_3$ inputs into agricultural soils from irrigation water have altered soil productivity for crops? Most crops are not directly affected by $CaCO_3$, but resulting higher pH reduces the availability of some essential plant nutrients such as P, Fe, Mn, and Zn (Brady & Weil, 2008, p. 385; Casanova et al., 2013, p. 106), which could be a problem for sensitive crops. Agricultural soils mostly have lower available P/total P ratios compared with control soils probably because of $CaCO_3$ and higher pH in agricultural soils. However, a possible benefit of this $CaCO_3$ for crops is increased soil water-holding capacity (Duniway et al., 2010; Georgen et al., 1991). $CaCO_3$ inputs would also counter the negative effects of high sodium on crops and soils (Brady & Weil, 2008).

All EC and SAR values measured at Paniri are well below levels considered potentially detrimental for even the most sensitive crops (Flynn & Ulery, 2011). SAR values of 5–7 at Cerro Topaín are below the sodic soil minimum of 13, but still represent a significant increase, approaching levels high enough to begin causing agricultural problems (Sumner & Naidu, 1998, p. 17; Flynn & Ulery, 2011). The high SAR at 50 cm depth for TTOP 2, and high EC and SAR for TTOP 3, would be detrimental for crops. Salinity does pose problems for irrigated agriculture along rivers in lower areas of the Atacama Desert (Casanova et al., 2013, p. 138; Prieto, 2015). Some native crops such as quinoa are relatively salt-tolerant, and there is evidence that over long time periods, farmers in the Atacama Desert have developed relatively salt-tolerant cultivars of maize and other crops (Casanova et al., 2013, p. 138).

5.5 | Relation of agricultural soils to cultural context and age

Are there differences among agricultural soils at Topaín and Paniri that may relate to their cultural and chronological context? Archaeological evidence and radiocarbon dates (Figure 5, Supporting Information Radiocarbon Dates; Parcero-Oubiña et al., 2017) indicate that Cerro Topaín fields were farmed first and for the longest time, from the LIP (as early as the 10th century AD) into the Inka period in the mid-15th century. Lower Topaín fields span a shorter time between the late 14th to mid-15th centuries. Farming at Paniri coincided with the period of Inka rule and continued in some locations historically to the present. It is uncertain why agriculture ceased at Topaín and switched to Paniri during the time of the Inka rule. Possible factors such as drying of the Topaín Spring and Inka political strategy were briefly discussed in Section 2.

Current data do not indicate major differences between Cerro Topaín and Paniri in terms of irrigated terracing systems, natural soil quality, or anthropogenic soil change that could help explain the change in farming location. Terraced soils in both areas exhibit removal of large rock fragments, enrichment in total P attributed to fertilization, and inputs of $CaCO_3$ and increased pH due to irrigation with calcareous spring water. There are signs of increased sodium (SAR) in the lower horizons of the Cerro Topaín agricultural soil (Tables S2a and S3), but not at high enough levels to be a causal factor in abandoning Cerro Topaín for Paniri.

However, Lower Topaín stands out as different from Cerro Topaín and Paniri in terms of soil quality and change resulting from agriculture. Among the four paired soil samples, Lower Topaín (Topaín Transect 2: TTOP 2-CTOP 2 sample pair) is consistently an exception to trends in chemical property differences between agricultural and control soils measured in the other three paired soils (Tables 2–4). For example, the clearly higher levels of total P (volume basis) in surface and anthropogenic horizons in agricultural soils compared with control soils at Cerro Topaín and Paniri are not present at Lower Topaín. The same is true for pH differences. Although the significantly higher $CaCO_3$ in agricultural versus control soils holds for all four paired soils, there is much less $CaCO_3$ at Lower Topaín. These soil findings fit with radiocarbon dates indicating that Lower Topaín was farmed for a relatively short time and perhaps less intensively, and with archaeological findings that Lower Topaín has a much lower density of pottery sherds and a higher proportion of fields lacking surface sherds compared with Cerro Topaín and Paniri (Figure 5, Supporting Information Radiocarbon Dates; Parcero-Oubiña et al., 2017).

Another finding at Lower Topaín is that its lowest areas (e.g., TTOP 3) contain naturally higher levels of salinity and sodium considered detrimental for most crops (Tables S2a and S3). This, along with possible drying of Topaín Spring that would have curtailed irrigation on the slopes of Cerro Topaín, may have been an additional impetus to move the farming to Paniri, which had more reliable spring flow for irrigation, and suitable soil quality on piedmont alluvial fan surfaces comparable to Cerro Topaín.

6 | CONCLUSIONS

Soils used for terrace agriculture commonly have significant natural subsurface development, including cambic and argillic horizons, and duripans. More work is needed to investigate processes that produce significant pedogenesis in this area and the extensive silica cementation of piedmont alluvium. Due to silica cementation, many soils used for agriculture are shallow to moderately deep. Natural soils on hillslopes in higher geomorphic positions not reached by spring water flow or groundwater do not have carbonate or other salt accumulation, even though the current climate is hyperarid. This contrasts with soils in the core of the Atacama Desert.

Soil physical and chemical properties have been significantly altered during ancient and traditional agriculture through deliberate management and unintentional anthropogenic change. Soils were deliberately modified for agriculture by terracing, irrigation, removal of large rock fragments, and fertilization. On the basis of soil texture data and field observations, we infer that terraced soils (1) mostly consist of the same local natural soil with large rock fragments removed and (2) any added fill is probably from immediately local soils. Although fertilizer use may not have been as intense or as long-term as in some areas of the Andes, significantly higher levels of total phosphorus in agricultural soils compared with control soils at Cerro Topaín and especially Paniri likely reflect accumulation from long-term fertilization.

A major anthropogenic soil change observed throughout the study area is that agricultural soils have received significant inputs of $CaCO_3$ from irrigation with spring water that is naturally rich in carbonate. Corresponding control soils contain either no or little $CaCO_3$. Except in low geomorphic positions, most agricultural soils are nonsaline and nonsodic. However, there is evidence of sodium (SAR) increase below physically modified terraced soil horizons at Topaín, possibly from irrigation water.

Natural soils used for agriculture mostly have favorable properties, suggesting that they were important factors in originally selecting areas for farming. These properties include (1) permeable sandy surface horizons and slowly permeable to impermeable subsurface horizons and layers that would facilitate water infiltration and retention within crop rooting zones and water distribution in canal systems, and (2) soils without salinity or sodium problems that are common in soils in lower landscape settings in the Atacama Desert.

Terracing, removal of large rock fragments, possible soil additions and thickening, and other management practices such as fertilization and mounding, would have enhanced the productivity of natural soils. These management practices would have helped farmers overcome shortcomings in natural soils such as shallowness (problems with low water- and nutrient-holding capacity and physical support for crops), and naturally low levels of organic matter and nitrogen.

Unintentional additions of $CaCO_3$ from irrigation water may have lowered soil productivity somewhat, for example, because associated higher pH decreases the availability of nutrients such as phosphorus. However, $CaCO_3$ may have helped increase available water retention in these sandy soils.

Continued studies of terraced soils and comparison with natural soils are needed to learn more about how agricultural terraces and their soils were constructed, and to better understand long-term soil management; for example, to assess fertilization practices to maintain supplies of nutrients such as nitrogen and phosphorus for crops. Current data are insufficient to definitively explain why farming ceased at Topaín and switched to Paniri during the Inka period. Further chronological precision, and archaeological, hydrologic, and soil-geomorphic studies, will be needed to better understand the agricultural history.

Research results suggest that agriculture here was sustainable in the sense of conserving soils over centuries through terracing, irrigation, nutrient inputs, and other management. Evidence of soil conservation includes thickened anthropogenic surface horizons with fewer rock fragments, favorable bulk density and no compaction, and higher levels of organic carbon, nitrogen, and phosphorus relative to natural soils.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are mostly available in the supporting information files of this paper. Other data are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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