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RESEARCH ARTICLE

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# Erosion control in Prehispanic agrarian landscapes from Northwestern Argentina: El Alto-Ancasti Highlands case study (Catamarca, Argentina)

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## Abstract

Recent research in the El Alto-Ancasti Highlands (Northwestern Argentina) has identified an extensive agricultural system distributed in between residential sites. This agricultural system seems to have been vulnerable to a gullying system that caused erosion and soil surface loss. The existence of check dams along the inside of these gullies places the beginning of this erosion process at least during its Prehispanic occupation, between 600 and 1000 AD when the agricultural system was active. Here, we characterise the Prehispanic construction of the agricultural landscape, its impact on soil formation and the interaction established by Prehispanic farmers in the area with the local erosive dynamics along the eastern frontier of Northwestern Argentina. Our study indicates the need to pursue further research into runoff agriculture in these environments and its potential contribution for the mitigation of long-term erosive processes and risks, as well as elucidating strategies towards sustainable soil management by modern-day local communities.

KEYWORDS
check dam, erosion dynamics, landscape management, runoff agriculture

## 1 | INTRODUCTION

The aim of this article is to characterise the construction of an extensive agricultural landscape near the site of El Taco (Catamarca Province, Northwest Argentina) in relation to the ongoing advance of erosion processes and concomitant soil loss. In so doing, we seek to understand the specific local adaptations by agrarian systems to these threats in a little-studied area, in this case, the Neotropical highland region along the eastern boundary of Northwest Argentina.

Interactions between past populations and the environment are an increasingly researched topic within archaeology. The initial questions within this larger theme are aimed at explaining how the environment influenced decision-making and the future of past populations. In recent decades, and given greater impetus by the current environmental crisis, the question has shifted in the opposite direction, aiming to understand the impact of past populations on the environment and the causes behind degradation processes, especially after the emergence of agro-pastoralist societies around the world (Buntgen et al., 2011; Holling et al., 2002; Kirch, 2004; Latorre et al., 2001; Rick & Sandweiss, 2020; Stephens et al., 2019). Agrarian systems provide a physical record towards understanding human intervention of natural spaces. In this sense, analytical concepts such as *Capital Landesque* (Doolittle, 1984) or Landscape Legacy (Arroyo-Kalin, 2016) were developed where the agricultural landscape forms a human working capital, built over long periods of time by different generations working in an area. This deployment results in long-term engineering work that requires little daily labour demand, while delivering higher performance over time.

  

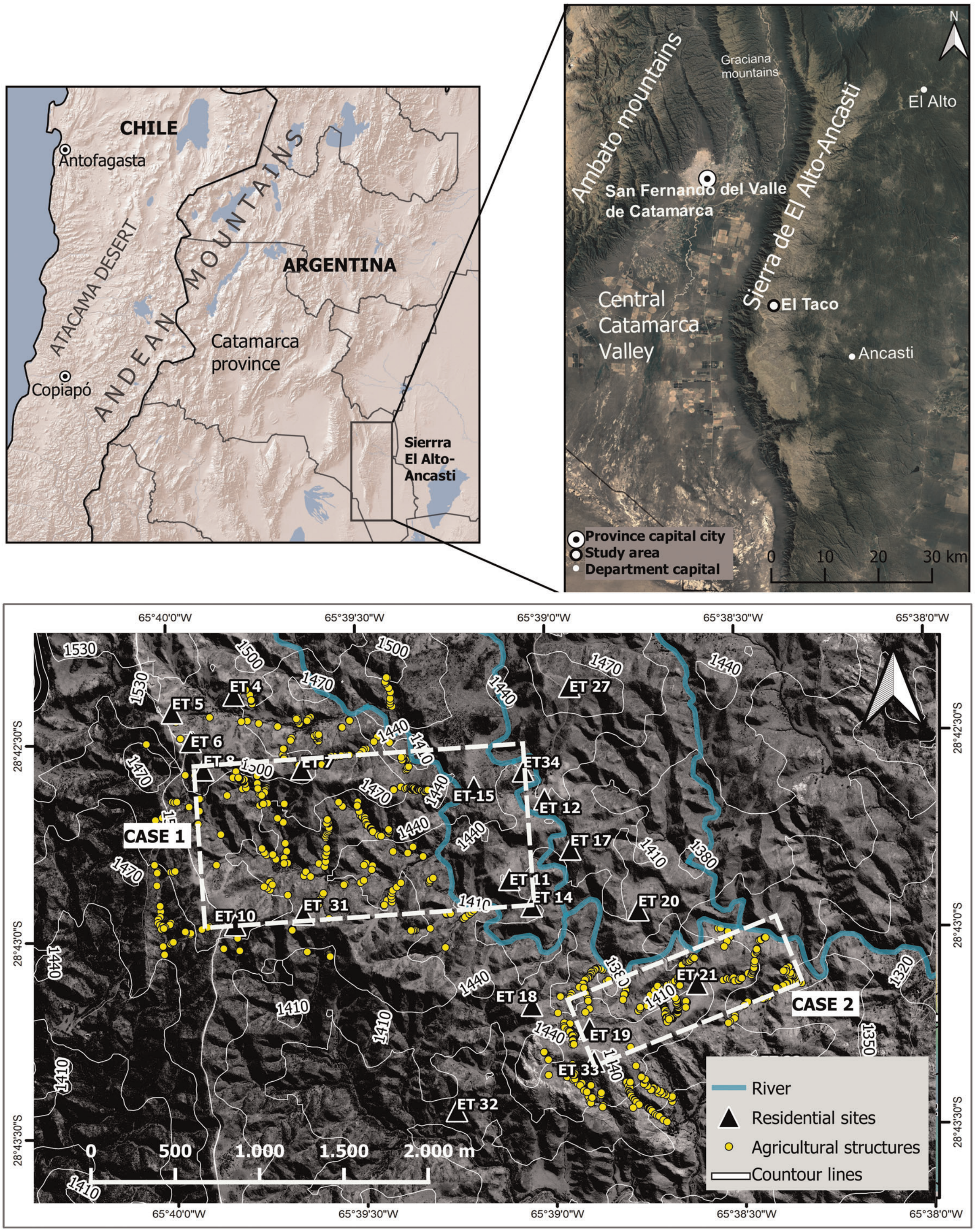


**FIGURE 1** The geographical location of the study area and distributional map of the registered residential complexes. This study focused on the areas marked as Case 1 and 2 [Color figure can be viewed at wileyonlinelibrary.com]

On the basis of an analysis of archaeological and ethnohistorical data from Mesoamerica and the Mediterranean, Butzer (1996) observed that, in the management of agrarian systems, situations of internal or external stress may require a change of priorities towards survival in the short term, which, in turn, may cause long-term ecological damage. Butzer (1996) concluded that the development of agrarian systems in different places at different times involved trial and error which also generated varying degrees of ecological damage.

The abandonment and lack of maintenance of the agrarian landscapes were also identified as a cause behind the emergence of soil erosion; in this sense, the processes of environmental degradation were understood as the result of the dynamics between people and the environment rather than the result of a purely ecological process (Fisher, 2005). Soil degradation is a relevant issue today, understood as a social and environmental problem that entails a decrease in the productive capacity of agricultural spaces and grazing areas, which become a threat to local economies. Numerous researchers have highlighted the need to study the dynamics involved in specific anthropized landscapes from an archaeological point of view, recognising that some environmental problems in the present, such as soil degradation, were similar, and therefore familiar to those faced by societies in the past. Therefore, an understanding of current environments with a long occupational history acquires relevance for present-day and future environmental management (Butzer, 1996; Doolittle, 1985; Endfield, 2012; Fisher, 2005; Gómez Ortiz, 2001; Kolb, 2013; Lane, 2017; Pabón et al., 2013; Reese, 2020; among others).

In Northwestern Argentina, paleoenvironmental research has focused on establishing correlations between climate and cultural change at different spatial and temporal scales. In respect to the paleoenvironmental evolution during the Holocene, a significant amount of data was gathered, showing general regional trends and local particularities. The co-occurrence of more favourable climate interludes has been noted during the appearance of the first hunter–gatherer occupations and subsequent developments of agro-pastoralist communities (Grana et al., 2016; Olivera, 2001).

Regarding the environmental impacts caused by past communities, regionally it was noted that ca. 1000 years BP, a process of increasing aridity began, at a time when the valleys of Northwest Argentina were occupied by agro-pastoralist populations (Lindskoug, 2013; Oxman et al., 2016; Peña-Monné & Sampietro-Vattuone, 2019). Although some researchers maintain that during this period, anthropic activity must have exerted pressure and overexploitation of the environment, causing the abandonment of large areas (Peña-Monné & Sampietro-Vattuone, 2019), other studies suggest that while during this period there were important environmental changes that led to landscape modifications, they did not mark the abandonment of these areas by local populations (Meléndez et al., 2018; M. Quesada & Maloberti, 2015; Ratto et al., 2013).

In this sense, the impact on the environment by Prehispanic populations and its relationship with events of environmental degradation is a growing line of research in Argentina, especially in high Andean or circum-*puna* areas. (Lupo et al., 2016; Meléndez et al., 2018). This type of research is still in the early stages of explaining the complex dynamics behind the lightly studied environments of the ecotonal humid eastern highlands of Northwestern Argentina. Yet, it is relevant towards understanding the wider regional climate and/or human driven impact on ecosystems.

## 2 | THE STUDY AREA

The El Alto-Ancasti Highlands extends longitudinally across the south-central area of the Catamarca Province in Northwestern Argentina (Figure 1). Its elevation has been impacted by Andean orogeny (Quaternary), thus generating an asymmetric profile with steep slopes to the west rising a maximum height of 2000 m above sea level and smooth and undulating slopes to the east which reach 300 m above sea level. The geology of the mountains is formed by a crystalline basement composed of metamorphic and granitic rocks from the Precambrian to Lower Palaeozoic age. At the foot of the mountain range are ancient quaternary fanglomerates and sandstones. The sedimentary cover that completes the stratigraphic sequence of the mountain range is composed of loessic deposits in the upper reaches of the highlands. These loessic deposits have distinctive characteristics: a variable grain size between sandy and sandy silt, and a low content of calcium carbonate and quartz, with the generalised presence of volcanic glass. The intermontane depressions are filled with silts and sands of fluvial and aeolian origin (Blasco et al., 1994; Sayago, 1995) (Supporting Information S1, Figure S1).

Regional soil taxonomy includes three main soil types (Panigatti, 2010; Vargas Gil, 1990): (1) Ustortents (steep slopes and riverbeds; A, C, R horizons, regolite or agglomerates of variable granulometry. Climatic conditions favour the formation of surface mulch); (2) Argiustols (smooth relief areas, including hilltop peneplain, >70 cm deep; A1, B2, R horizons); (3) Haplustols (eolic, medium-coarse texture widely distributed, A1–B2 cambic-R horizons.) The phytogeography of the highlands includes hilltop grasslands, located between 1500 and 2000 m.a.s.l., and forests along the eastern slope located between 1500 and 1700 m.a.s.l.

Northwestern Argentina is characterised by arid climates on its Andean side, although the El Alto-Ancasti Highlands is at the eastern edge of this macroregion, located in a transitional zone towards more humid climates with marked seasonality. Its geological structure has an impact on microclimatic factors, with the eastern side being more humid (Mórlans, 2007). Rainfalls mainly occur between December and May, averaging between 700 and 1200 mm annually. This is then followed by a dry season during spring and winter. The dry season affects both the grasslands and the forests lasting from June until November. Wider climatic phenomena also have an impact on the area (e.g., ENSO—'El Niño'), causing dry spells followed by highly humid periods. ENSO also affects the water volume in highland rivers that flow towards the forests. These higher humidity conditions provoke flooding events which weaken the soil's structure through erosion (Karlin, 2012).

In summary, the study area does not constitute an environmentally homogeneous space. On the contrary, one of its main features is an important altitudinal gradient (ca. 400–2000 m.a.s.l.) and an irregular topography (deep ravines, undulated terrains, elevated geoforms, among others). Likewise, rainfalls vary due to the particular structural configuration of the area which shift from south to north (Mórlans, 2007). The area's paleoenvironmental data, obtained from the Hindcasting Ecosystems Model (HEMO) application, cover a chronological framework that extends from AD 442 to 1980 CE. During this period, between AD 500 and 900, extreme fluctuations of dry and wet periods were identified, and after AD 1000, stable drier conditions prevailed, coinciding with the abandonment of some sites in the area; these conditions lasted until AD 1500 (Burry et al., 2018).

### 2.1 | The archaeological landscape

The archaeological landscape of El Taco is located within the highland grasslands of the El Alto-Ancasti Highlands (Figure 1). The geography is dominated by ravines set in between hills of loessic soil and rocky outcrops. Current evidence suggests that significant human occupation begun during the first millennium AD. Settlement areas located on summits in association with terraced ravines were surveyed in a radius of approximately 5 $km^2$ (Ahumada & Moreno, 2015-2016).

These surveys located 19 settlement complexes with a range of architectural features. In general, smaller complexes were quadrangular stone constructions, frequently including one or two enclosures (up to 4 × 4 m) joined together and/or adjoining other larger enclosures (which could be up to 20 m in length). Some of the larger residential complexes, with up to 27 associated enclosures, present stratigraphic evidence suggesting that they were not being used simultaneously; in this sense, they would correspond to the 'casas mocha' recorded by Rivet and Tomasi (2016). This is a frequent phenomenon in the Andes, whereby the houses of the initial inhabitants were not demolished after their death, with descendant families continuing to add residential structures to the complex, meaning that the abandoned buildings would, in turn, both materialise their ancestors and serve as territorial markers. Such is the case of El Taco 19, one of the largest sites, which evidences an occupation history of at least 200 years, with four radiocarbon dates (1240 ± 50, 1270 ± 60, 1340 ± 80 and 1390 ± 70' BP) indicating that the period between AD 600 and 800 was the main period of use (Barot & Gasparotti, 2018; M. N. Quesada et al., 2012; Zuccarelli, 2020). Sites with similar features were registered in the northern and middle subregions of the highlands, demonstrating a continuum of village-type settlement with a strong agro-pastoralist orientation (Zuccarelli, 2020).

From a chronological standpoint, the archaeological sites at El Taco were associated with La Aguada occupations. This was further confirmed by the architectural style and iconographic designs present in the ceramic material recovered from different stratigraphic excavations of residential complexes as well as ground surveys conducted in the area. Typically, La Aguada sites are in the modern-day provinces of Catamarca, La Rioja and San Juan with a chronology ranging from the 6th to 11th century AD (Laguens et al., 2013; Lindskoug, 2018; Marconetto et al., 2015).

Nevertheless, given regional variability and a distinctiveness in the management of symbolic resources, it has been argued that La Aguada was the manifestation of a regional integration resulting from the interaction of different social groups during the Early Period, otherwise known as the South-Andean Formative (500 BC–AD 650). Once it appeared, La Aguada culture had a lasting presence and interacted with populations from other neighbouring geographical areas, each one with their own features, eventually partaking of the supraregional sphere, establishing nexus beyond their local area, during a period known in the Andean region as the Middle Period (650–850 AD) (Laguens et al., 2013).

Under La Aguada, a transformation of the agrarian landscape occurred, recorded across a number of different valleys. In these, there is a proliferation of agricultural technologies which included the extensive construction of agricultural terraces and hydraulic structures, as well as camelid herding (Rodriguez Oviedo, 2018; Zucol et al., 2012).

Constructive features both at residential sites and in productive structures recorded in our study region depict similarities in both formal and emplacement strategies to those present in the valleys located within the mountainous region surrounding El Alto-Ancasti (Figure 1, Catamarca valley and Ambato mountains). By the end of the 10th century AD, these Middle Period societies suffered a combination of social and environmental stresses—currently under study—that led to the abandonment of sites at a regional scale with no evidence of reoccupation, until the Spanish colonial period, in several valleys (Gordillo, 2007; Laguens et al., 2013; Marconetto et al., 2015).

This situation is replicated in El Taco, where there are two well-defined occupational periods represented: a Prehispanic occupation, briefly outlined above, and a more recent Spanish colonial occupation related to ecclesiastical settlements. During the latter period, the residential and production pattern changed, with settlements placed in the lower sectors of the ravines next to watercourses, whereas Prehispanic spaces and agricultural practices were abandoned. The historical documents and archaeological records show that there was an economical reorientation of the area towards animal husbandry from the 17th century AD onwards (Nagel, 2018).

## 3 | MATERIALS AND METHODS

Agrarian landscape study in the El Alto-Ancasti Highlands integrated a number of different field approaches set at varying scales based around geo-archaeologically informed systematic surveys involving (1) the use of spatial models and surveys to characterise the past erosion control across a set of gullies, (2) architectural surveys to characterise the agrarian landscape's construction methods and (3) the use of sedimentological proxies (soil chemistry and microremains analysis) from cultivation plots to characterise soil management and crop production.

In seeking to portray the complexity of the construction process involved in this agrarian landscape and the different factors interacting in its formation and evolutionary history, this study followed a double scale of analysis: the area's agrarian landscape, in general, and a more detailed survey of two ravines with similar landforms that are part of the same basin.

These examples are described as Case 1 and Case 2 (Figure 1). Both cases are part of the typical regional settlement pattern, with residential sites in loessic plains located on the summits, incorporating adjoining ravines replete with extensive agricultural structures (Section 4, Figure 3). Case 1 focused on a sector of the agricultural system linked to residential sites ET6, 10 and 20. This area had been impacted to varying degrees by erosion and active gully formation processes. In this sense, they served as a test case regarding interactions between Prehispanic populations and local erosive dynamics. Furthermore, we believed it could provide a useful case study highlighting viable technological solutions to modern-day processes potentially inducing soil loss. On the contrary, Case 2 was selected due to its proximity and functional links to the ET19 site. Site ET19 has well-documented chronostratigraphic evidence. Excavations targeted field areas with little erosional disturbance, which presented well-preserved contexts for plant microremain sampling.

## 3.1 | Regional-scale dynamics using geographical information systems (GIS) and remote sensing

To record and understand erosive dynamics and the anthropic impact over past and present landscapes in Case 1, we used digital elevation models (Conolly & Lake, 2006; Parcero Oubiña, 2002) and Qgis 3.0.2 open-source software for GIS modelling. Hydrology tools were applied to produce flow direction models within the hydrographical basin and drainage structure. The result was presented in a raster layer showing a local model of those places in the landscape from lowest to highest accumulated flow, deposit basins and areas more prone to sediment removal in a bid to link erosive factors and the location of Prehispanic agrarian architecture.

In addition, the use of remote sensing imagery in the study region (including Case 1 and 2) allowed us to generate an ecological variability model of the fields through analysing vegetation phenological changes. We used the normalised difference vegetation index (NDVI) for analysing the response of vegetation to environmental conditions in dry and humid seasons, to demonstrate the functioning of the agrarian structures. The values of this index, which measured the amount of photosynthetic biomass, oscillated between −1 and 1 (Tucker, 1979). Finally, we selected dry season analyses to estimate microclimatic differences, given that during these periods, those places in the landscape where vegetation remained effervescent were more easily recognised, allowing us to infer particular hydric and/or humidity conditions. The data generated were synthesised graphically through use of cluster and outlier geostatistical analysis,

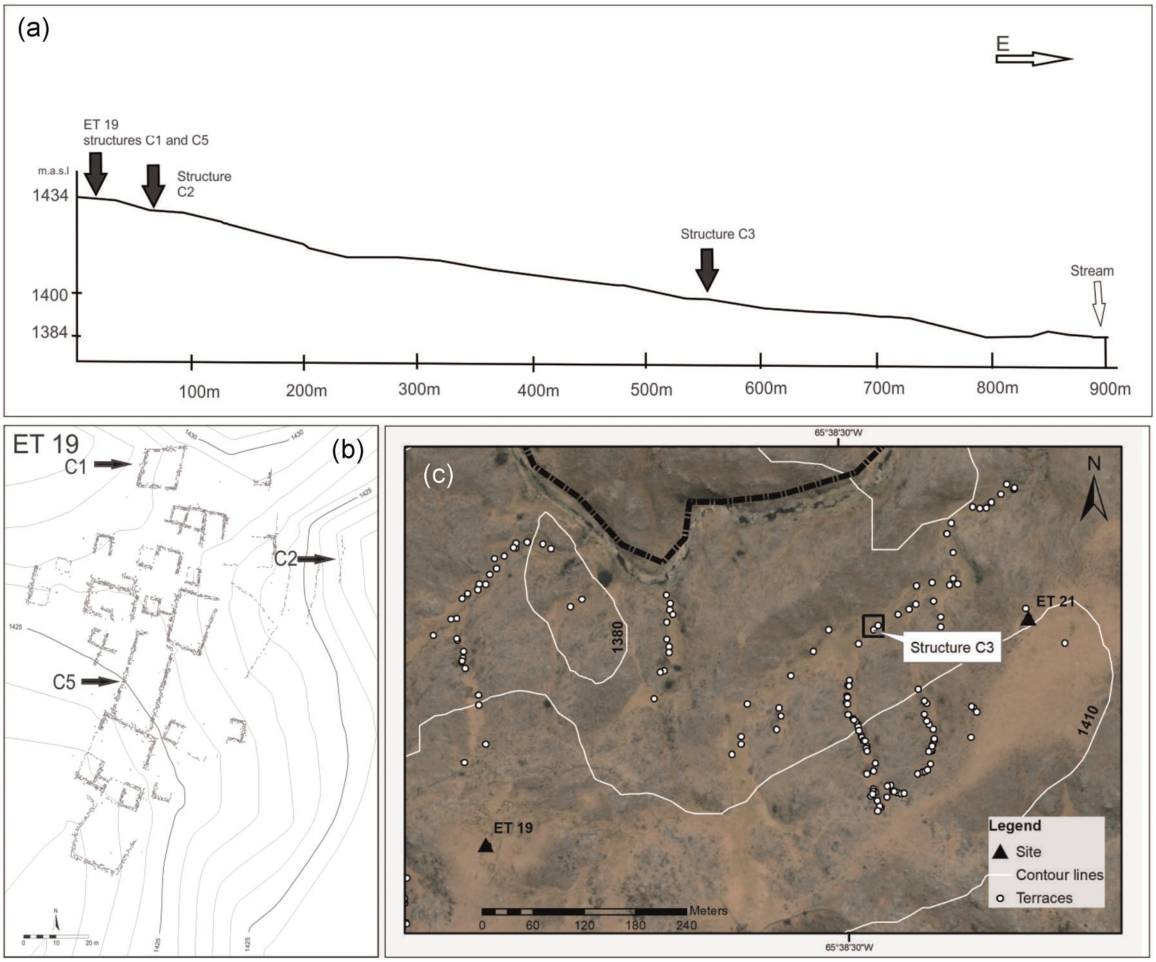


**FIGURE 2** Sample profile scheme from Case 2, ET 19 site. (a) Topographical profile of the sampled ravine and general sample pit location. (b) ET 19 site planimetry with C1, C2 and C5 sample pits location. (c) C3 sample location [Color figure can be viewed at wileyonlinelibrary.com]

differentiating the values from different terraced areas. The Anselin Local Moran's algorithm indicated whether the apparent similarity (a spatial clustering of high or low values) or the lack of similitude (an atypical spatial value) was more noticeable than expected across a random distribution.

### 3.2 | Survey of gully systems and check dams

Physical surveys were carried throughout the gully systems to record relevant in situ geological, morphological and topographic characteristics of the gully systems in the different sectors of sediment erosion or accumulation that had been pre-located through spatial modelling. The locations of cultivation terraces and check dams were GPS-georeferenced and added to our digital cartographies. The check dams were architecturally surveyed; in each case, we documented their state of preservation and their relationship with the erosive processes recorded for the immediate area. To understand the processes related to gully advance in the present day, we analysed panchromatic vertical aerial photographs, available for this area since 1969. These images were corrected and georeferenced using the spline algorithm, providing greater local precision, and then overlapped with ArcGis WMS free high-resolution images to visualise the evolution of erosion in these gullies over the last 50 years.

### 3.3 | Excavations, soil chemistry and phytolith analysis

To assess work processes and land-use dynamics in a typical agrarian system in El Taco, we sampled select structures at different locations within a system comprising a residential site, ET19, and an ancillary collector ravine which descended to rejoin the permanent watercourse downstream. This we labelled as Case 2. Three test pits and a trench were excavated at the archaeological site of El Taco (ET) 19: two on the summit area (C1 and C5) directly associated with housing structures and another on a crop terrace in the upper portion of the ravine (C2), and finally a trench on a terrace located in the lower section of the same ravine (Figure 2—sample profile scheme). The objective was to obtain data regarding the construction techniques of cross-channel terraces, the presence of erosive and degradation processes, the pedological characteristics of the terraces and the crops present in them.

Soils analyses were undertaken in the Department of Agrarian Sciences and Agrarian Chemistry, University of Catamarca. In each profile, the succession of soil layers or horizons was determined by describing their morphological properties: colour, texture, structure, consistency and presence of carbonates, roots, humidity, cementation and others. Samples from each horizon were taken for laboratory analyses using standard methods. The evaluated soil chemical variables were the content of oxidable carbon, nitrogen, extractable phosphorus (Olsen et al., 1954), electric conductivity, pH, sodium absorption relation and carbonates.

Phytoliths were extracted using standardised techniques of wet oxidation and heavy flotation (Coil et al., 2003; Piperno, 2006). The classification and quantification of phytolith morphology was made following IPCN (2005), Twiss (1992) and Zucol et al. (2012) to establish botanical affinity. Furthermore, this classification included cross-referencing with reference collections for phytoliths from South American crops and wild taxa published by M. A. Korstanje and Babot (2007), Babot et al. (2007) and Del Puerto (2015). The phytoliths were mounted on microscope slides in both wet (oil immersion) and dry (Canada balsam) media and analysed under a Nikon Eclipse E200 optical microscope with an incorporated camera. A minimum of 250 short cells was classified. Topsoil samples in each structure were used to compare modern phytolith assemblages with past assemblages (Petö et al., 2008).

## 4 | RESULTS

### 4.1 | Field surveys: General distribution and formal characteristics of agrarian architecture

At the locality of El Taco, we surveyed 623 agricultural structures emplaced in ravines of different sizes in association with settlement sites in the upper sectors of the ravines (Figure 1). These were 19 residential complexes with similar constructive features arranged in an area of approximately 5 $km^2$. In each ravine, the walls from agricultural structures were constructed contouring the microtopography, with check dam walls perpendicular to the ravines, in some instances, curved in the direction of the slope and/or reinforced with lateral walls placed to contain alluvium.

The terracing technology employed was not that of slope terraces, rather it focused on cross-channel terraces within the different ravines systems. These systems varied from narrow ravines to permanent watercourses to systems including narrow tributary streams connected to wider ravines. In the latter, the fields were extensive, located over thick sedimentary deposits, and they presented strong, solid walls (for an example of these systems, see Figure 3 and the constructive record of structure C3 in Section 4.1.2). In all cases, rocky outcrops from the slope flanks and the basal section of the ravines were used to support the walls from one end of the ravine to the other. This ancient type of agriculture has typically functioned without irrigation and has been characterised as 'runoff agriculture' (Treacy & Denevan, 1994; Sandor et al., 2007). In this sort of system, fields were placed in ravines to intercept runoff and associated sediment and organic debris transported from the neighbouring uplands.

#### 4.1.1 | Spatial models

The application of runoff modelling (Figure 4) and the analysis of aerial images (Figure 8) focused on the area affected by erosive processes concentrated in Case 1, where 164 structures were

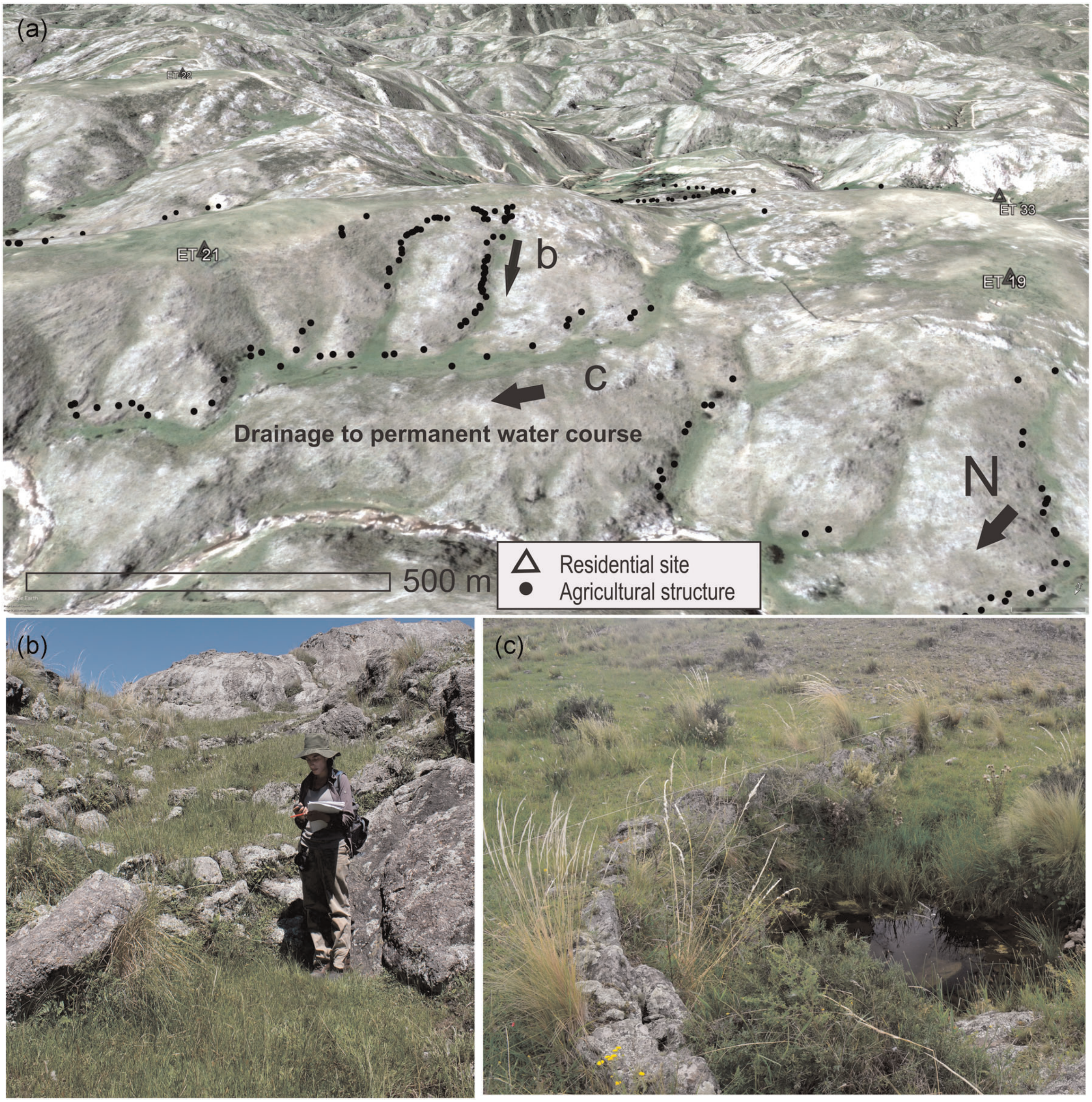


**FIGURE 3** (a) Agricultural landscape general organization and settlement pattern, arrows indicate flow direction (Google Earth Pro, image from 2012). (b) Example of structures located in steep ravines (also signalled in (a)). (c) Structures located in the lower reaches (also signalled in (a)) [Color figure can be viewed at wileyonlinelibrary.com]

recorded. This area was the subject of different ongoing types of interventions to preserve approximately 14 ha of cultivable soils.

This model distinguished between accumulation and sediment removal areas to contrast these processes in the field and its relationship with the current state of the agrarian architecture. Headward erosion exposed deep profiles in those areas with higher sediment accumulation located in the lower basin of Case 1. These sediments had two origins according to the regional soil chart (Vargas Gil, 1990): one being the oldest material formed by remnants of dissected peneplain from the hilltop summits distributed throughout the El Alto-Ancasti Highlands and the other type of material being eolic sediment deposits.

The depth of the walls in areas of high accumulation and headward erosion indicated that there was already a thick sedimentary basin by the time cross-channel terraces were built in this area. Therefore, terraces built in removal areas were constructed within narrower and steeper ravines, over less developed (or inexistent) soils. This had an impact on the natural removal processes exposed by the model, favouring the formation of new soils and affecting their natural distribution (where deep and well-developed soils could only be found on hilltop summit or low and shallow areas). This 'runoff farming' (Treacy & Denevan, 1994) was designed to receive sediments from adjacent slopes into natural catchment basins reinforced by a system of check dams. The runoff model allowed us to observe the drainage catchment and to interpret the agrarian landscape, landscape that involved water retention by capillarity across the whole system. The system also included differential hydric retention gradients according to the position of the structure within

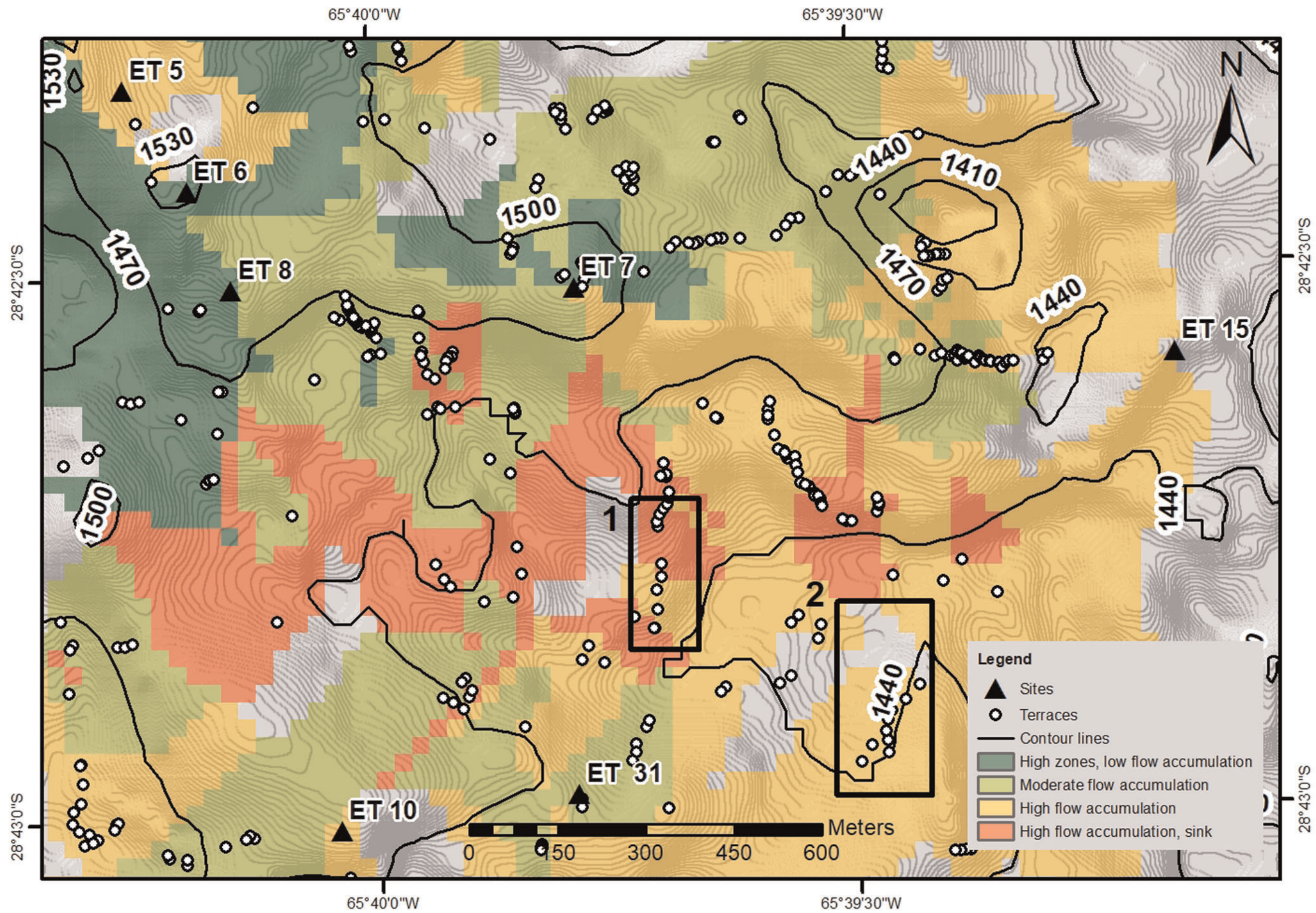


**FIGURE 4** Runoff modelling (areas 1 and 2 refer to Gullies I and II studied in Case 1) [Color figure can be viewed at wileyonlinelibrary.com]

the general system (noted in the model as high accumulation areas) (Figure 4).

Furthermore, at a larger scale encompassing the locality of El Taco, we implemented the NDVI model for the detection of microclimatic differences. As an example, we observed that the ravine descending from the ET19 site (Case 2, Figure 5, also images shown in Figure 3) demonstrated a wide variability regarding vegetation indicators within different sections of the system. Areas with northwestern orientation had low values (low vegetation indicators), whereas the portion of the inferior section presented comparatively higher values (higher vegetation indicators), precisely where the large wall structures were located and where the humid-retention characteristics observed in the field were also high (e.g., vegetated and humid, or wet soils in the area) (structure C3, Section 4.1.2).

### 4.1.2 | System of gully and check dams

We analysed two continuous gullies (Gully I and Gully II), located in the area identified as Case 1 (Figure 1); here, the spatial model highlighted a predominance of sediment accumulation zones with the presence of active erosion (Figure 4). In the area, we identified that cultivation terraces were arranged within ravines that descended towards a permanent stream that run eastward, spatially linked to the El Taco 10 and 21 settlement sites. During the field surveys, we discovered that the evolution of the gullies occurred in the opposite direction to the runoff, advancing towards the upper sectors due to headwater or backward erosion. Geomorphological observations distinguished two predominant factors in the evolution of gullies in the sector: soil removal and subsidence. Soil removal was caused by a flow that generated, in the first instance, incisions in the form of narrow crevices through which a constant flow of water run during and/or after a storm. The subsidence caused surface collapse due to the weakening of the gully structure and the formation of tunnels and galleries in underground areas.

*Gully I*

The first case, as detailed in the Figure 6a, was a large-sized gully, which following the characterisation of Thomas et al. (2004), extended for more than 200 m along a narrow ravine with a general north–south orientation before ending at a permanent stream. This gully had a main channel and two ancillary branches, a longer one heading north and a smaller north-eastern one. The gully had a transversal U-shape, with straight profiles along both sides, and it reached a depth of up to 5 m. The exposed profiles did not show any signs of stratification.

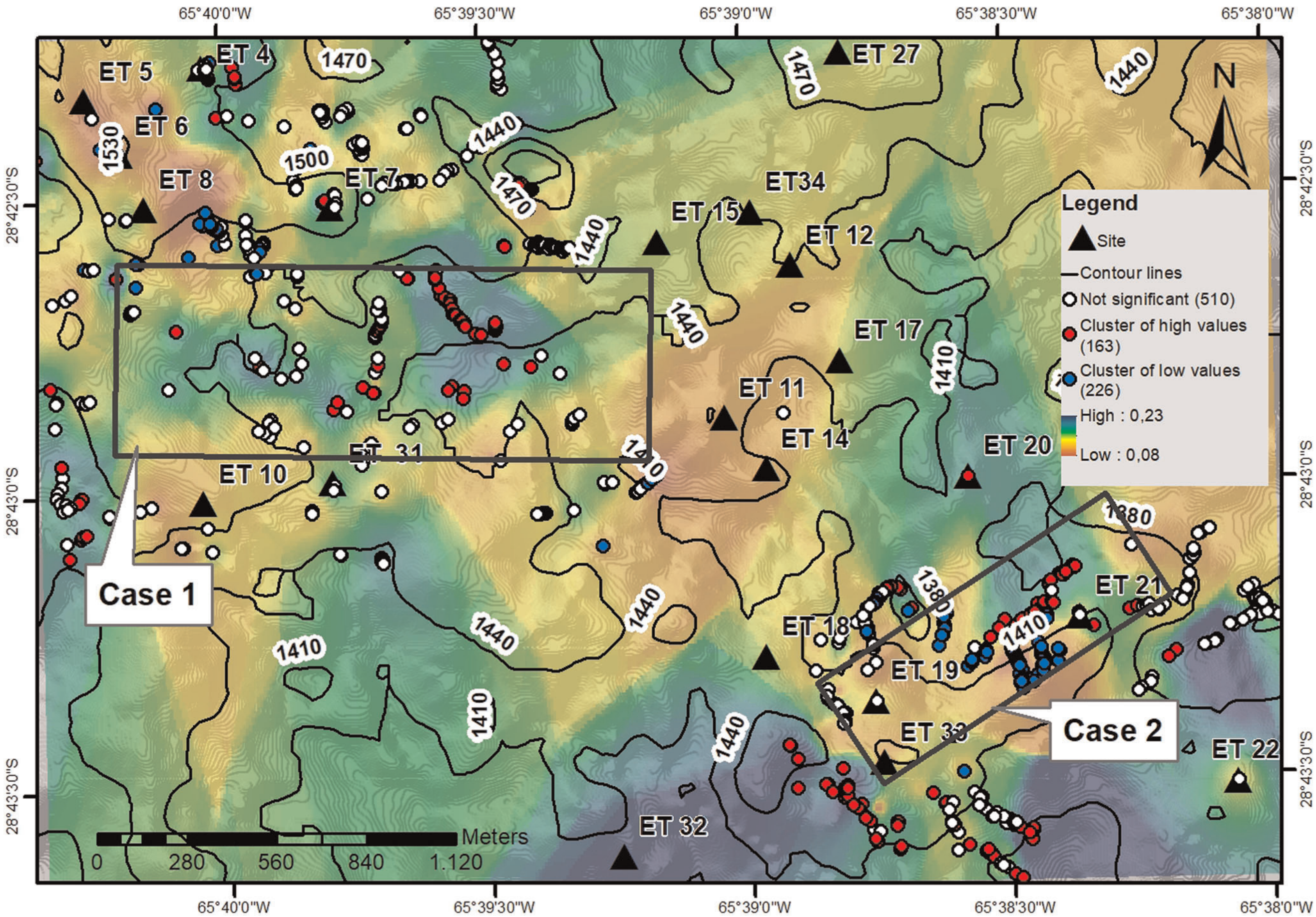


**FIGURE 5** Microclimates in El Taco systems inferred using normalised difference vegetation index [Color figure can be viewed at wileyonlinelibrary.com]

Along the non-eroded surface of the ravine, on both sides of the gully, we identified 16 crop terraces, which in some cases occupied the total width of the ravine of approximately 25 m. The altitudinal difference in the affected sector, from summit areas to the lower portions of the current stream, was 16 m. Aside from crop terraces that had been cut by erosion, along the gully flanks, we identified seven structures, composed of the remains of stone walls constructed from rocks of different sizes (between 0.50 and 1 m), transversally disposed to the gully's channel. These structures were identified as check dams 001 to 007 (CD001) and were in different states of preservation. The best-preserved structures were those located near the upper portions of the gully, whereas those surrounding the current course were less well-preserved. Figure 6b represents the location of the registered structures including their relationship with the erosion cut terraces.

The control structures or check dams designated as CD001 and 002 were in a bad state of preservation. Both were in the lower sector, near the permanent stream, at the base of the main channel before the branch separation of the gully.

Structure CD001 was situated 15 m to the north of the current stream course, resting on the eastern flank, 2 m below the non-eroded surface or topsoil of the gully. It had a length of approximately 2.50 m and was placed perpendicular to the main channel. At this juncture, the width of the main channel was 13 m. Along the exposed profile or western flank of the gully, we did not observe rocks that would evidence the continuation of this stone wall. Two metres to the north of this first structure, on the non-eroded surface and upper limit of the gully flank, we identified the remains of an eroded terrace. Structure CD002 was located 17 m to the north of CD001, embedded on the western flank, 2 m below the non-eroded surface. Both structures were under 0.70 m in height. Rocks belonging to the collapsed walls were not present in situ, a matter further discussed in Section 5.1.

The northern branch of the gully was 145 m long. Here, we registered three structures: two with similar characteristics to the check dams considered above (CD003 and 004) and a well-preserved one (CD005). CD003 was located on the eastern flank of the gully, whereas CD004 was embedded on a sediment island between the eastern and north-western margins of this gully branch. In both cases, these structures had an extension of 2 m in length and a height of below 0.50 m. The best-preserved structure along this branch of the gully, CD005, was a stone wall measuring 7 m in length with a width of 5 m (Figure 6c,d).

The northern branch of the gully is 50 m long, and the head section presented recent erosive advance. Here, we registered two

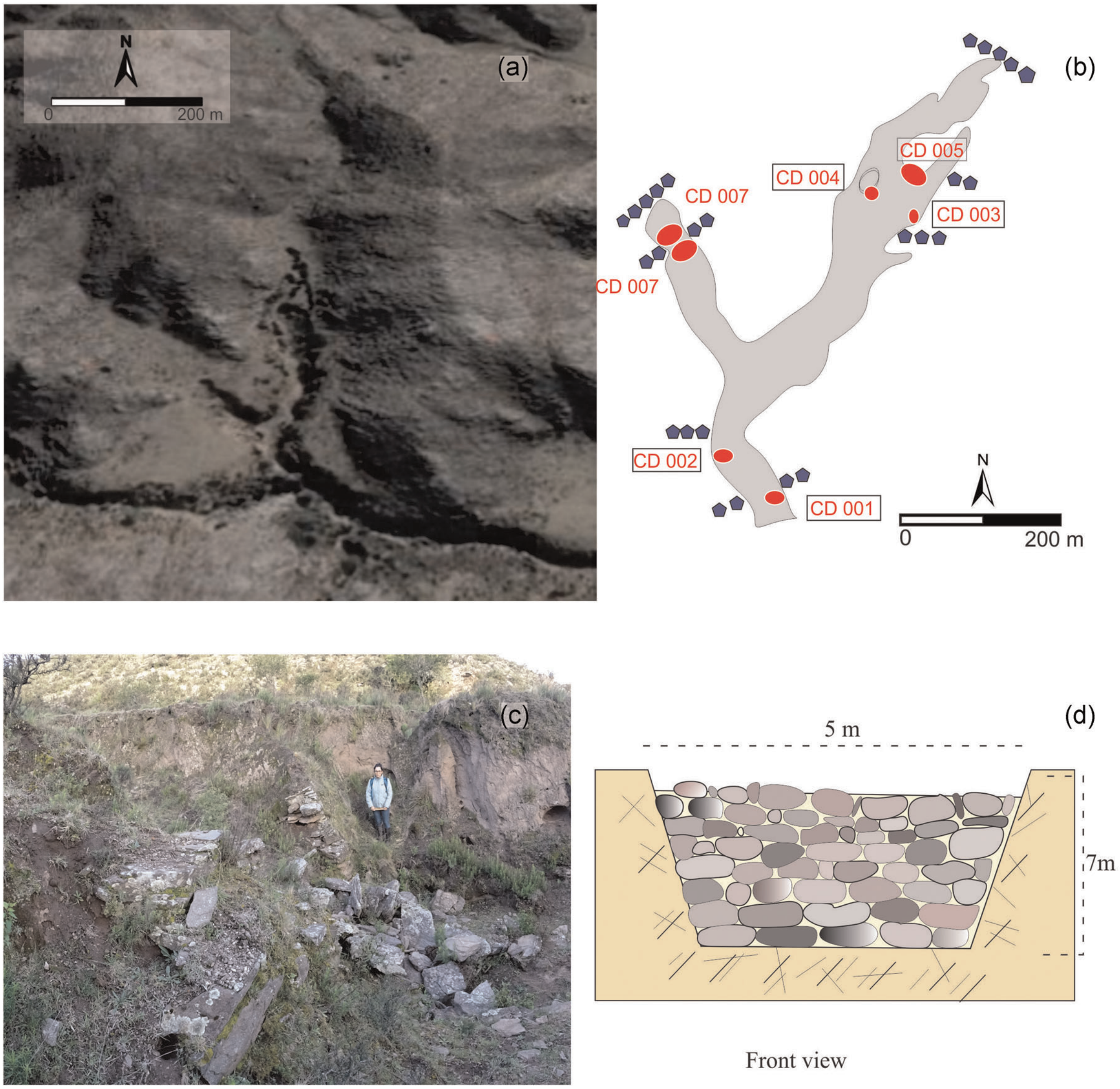


**FIGURE 6** (a) The current state of the observed gully through a satellite image (Google Earth). (b) The current situation of the surveyed structures within the gully. (c) A photograph with a well-preserved check dam (5). (d) A simplified scheme of the ancient check dams [Color figure can be viewed at wileyonlinelibrary.com]

well-preserved stone structures (CD006 and 007). The first one, CD006, was located 15 m apart from the head section and consisted of a stone wall extending from one side of the gully to the other. It had an extension of 4.30 m and a height of approximately 3 m. The middle section had partially collapsed with some blocks from the central area still visible on the ground. The last registered structure (CD007) was a stone wall with a width of 1.50 m and a length of 4 m, stretching from one side of the gully to the other, with a maximum height of 3 m. CD007 uses an ignimbrite outcrop as its foundations. The structure, in this case, had collapsed along the middle section. In front of this structure, there was a column 2 m long and 1.50 m high, which we registered as part of the same overall construction.

*Gully II*

The second sector of terraces affected by erosive processes was located 400 m south-east of Gully I, in the lower sector of the hydrographic basin (Figure 7a). In this case, the existence of the gully was down to two factors: the formation of a crevice due to an intermittent flow of water and its subsequent widening due to soil subsidence as a consequence of subsoil weakening.

Gully II formed a continuous gully with a well-defined surface drainage system. There was a main gully in which secondary gullies converged, forming a drainage system or several drainage systems that are currently inactive (Figure 7b).

The main U-shaped gully extended from the permanent stream for 500 m in length, towards the higher sectors. From the current head of the gully to base level by the permanent stream, there was a difference in level of 25 m. Secondary U-shaped gullies with heavily eroded walls completed the dendritic shape of Gully II. The area is currently used for cattle grazing, whose movement from the top to the bottom of the gully causes landslides and surface subsidence. Large uneroded columns of sediment can be found inside the gully,

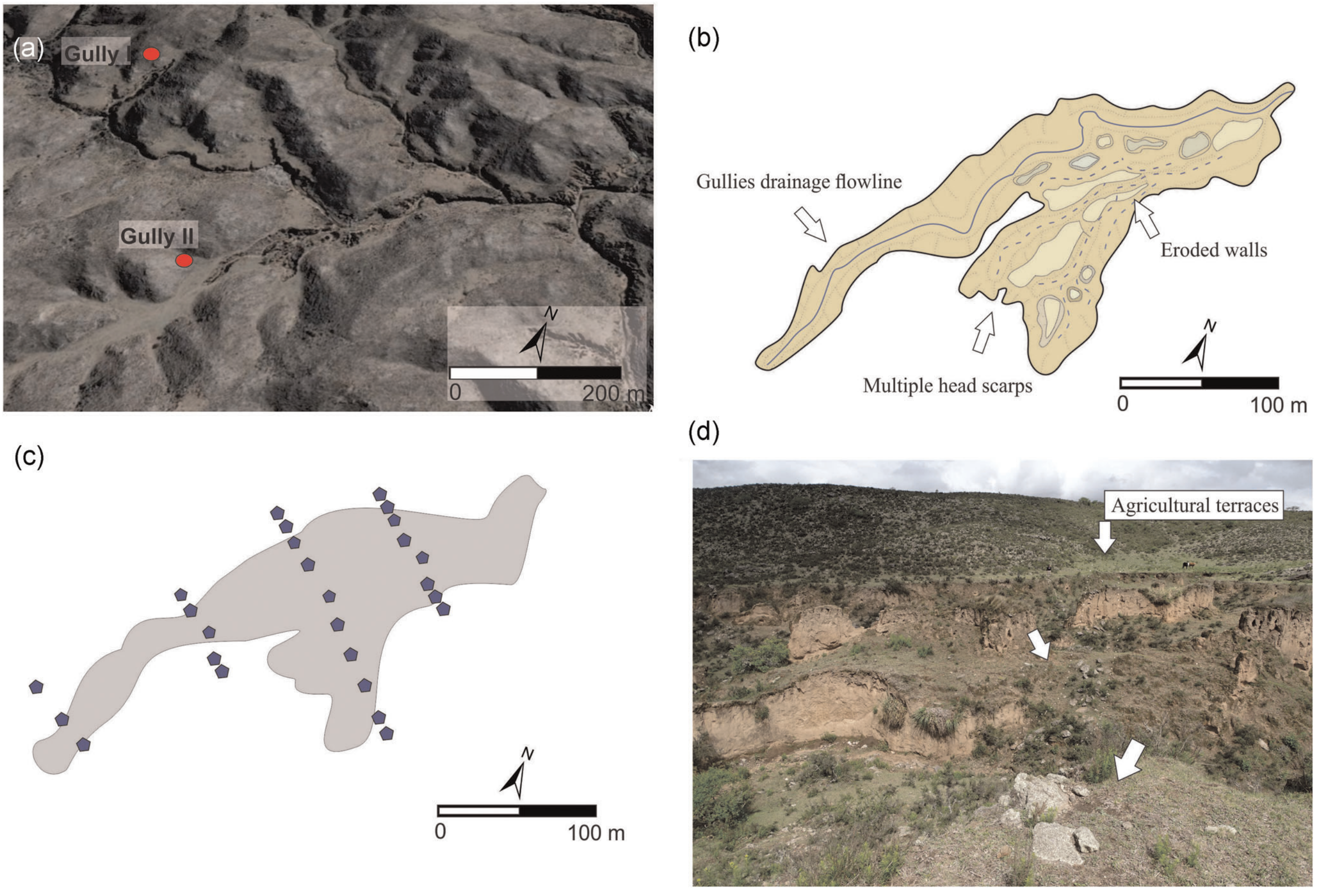


**FIGURE 7** (a) The location of Gully II in relation to the Gully I and the current condition of the gully observed through a satellite image (Google Earth). (b) The main channel with active erosion and the eroded branches with inactive erosion. (c) The current situation of the gully where the blue dots indicate the remains of cultivation terraces that are located on the margins and at the bottom of the ravine. (d) A photograph of the current gully is observed and the alignments of rocks that made up the archaeological cultivation terraces are indicated with arrows [Color figure can be viewed at wileyonlinelibrary.com]

giving the interior a labyrinthine shape. The subsidence processes occurred mainly due to soil dissolution at subsurface levels.

Unlike Gully I, there was no evidence for massive control structures or check dams. Along the edge of the gully bank, we observed the wall remains of at least three agricultural terraces, which are also visible outside the gully (Figure 7c,d). At the gully base and in the sediment columns, terrace stone alignments were visible. These had not been dragged downslope and remained as witnesses to soil subsidence. The process of retrograde (or remontant) erosion at the head of the main gully was still active; during our fieldwork, we recorded recent removals of soil in the upper sections that exposed new buried terraces that were not visible on the surface. Therefore, we suspect that terraces are under-represented in this sector.

Our analysis of the 1969 aerial photographs and Google Earth and Bing satellite images for 2003, 2010, 2012 and 2019 along both gullies (Gully I and II) show that advancing headwater erosion has been slow. There were no changes between 1969 and 2010, whereas during the period between 2012 and 2019, there was erosion in the higher areas of at least 5 m in at least four different sectors. Although the widening of the gullies is a progressive process, it is a process that has accelerated during the last few decades (Figure 8). The reasons for gully growth are addressed in the discussion below.

#### 4.1.3 | Excavations, soil chemistry and phytolith analyses

These analyses sought to characterise the use of agricultural spaces in different locations across an agricultural system associated with the El Taco 19 site. In particular, we wanted to compare the use of residential plots in fields with terraced structures from the ravine summits downwards (see Figure 2).

*C1 and C5 pit samples: Loessic plain with residential sites*

The agricultural plot C1 was constructed a few metres away from a housing unit in the upper portion of the ET19 site, with a double-row wall, 12 m long and 60 cm width (Figure 9).

Sediments associated with the terrace walls were fairly homogeneous and contacts between sedimentary deposits were

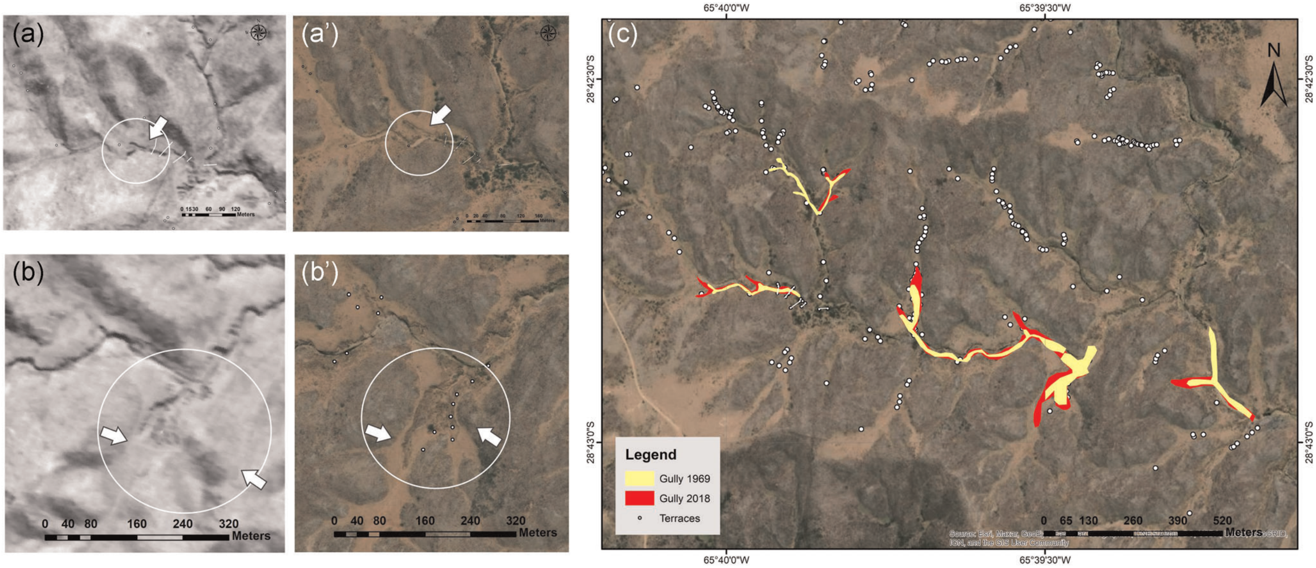


**FIGURE 8** Aerial photographs (a) from 1969 compared with year 2018 satellite images (a′) show Gully I erosion advance. (b) Year 1969 and (b′) year 2018 show the main channel erosive process in Gully II. (c) A general comparative view of the area comprised in Case I with gully erosion detected in different zones [Color figure can be viewed at wileyonlinelibrary.com]

gradational, with only minor differences in compaction. Field characteristics and laboratory analyses allowed us to divide this profile into four overlying units. Unit 4 (up to 20 cm) consisted of fallen rocks from the wall. The excavation was carried out down to the bedrock. Textural analyses demonstrated that this profile was composed of loam across all the separate strata. This was loam with low salinity (<2.0 dS/m) and slightly acidic pH. This changed in Unit 3. Alkalinity increased from moderate to extremely alkaline in the basal levels. High levels of phosphorus and total organic matter throughout the profile indicated that the structure was intensively used. Phosphorus values were the highest of the three samples collected in Case 2. In the lower unit, several ceramic fragments were recovered, and these were similar to the ceramic styles recovered in the residential units (Barot & Gasparotti, 2018) (Supporting Information S2, Figure S4a).

In Unit 4, phytolith assemblages were mainly grasses with no crop remains (Figure 12). Within Unit 3, maize phytoliths, microcharcoal and burnt microremains were identified. Although we found no evidence to suggest the use of hand-filled sediments, it is highly probable that this was the case considering the location of the structure on top of the hill, over a natural outcrop.

The C5 structure, also located within the residential assemblage on the loessic plain (see Figure 2), was a 20-m single-row rectangle without filling. Unlike structure C1, the soil texture had a higher clay component (clay-loam), tending to silty clay towards the lower level, and there was a tendency to alkalinity, presence of carbonates and a marked impoverishment of organic matter towards the lower levels (Table 1). This test pit was characterised by slow runoff, indicated by the carbonates found up to a depth of 28 cm and the increase in alkalinity across the whole profile. Unfortunately, high alkalinity values (up to 9.5) were detrimental for the preservation of siliceous microremains (Piperno, 2006) that would have given an indication as to its agricultural function. Higher phosphorus values in Unit 3

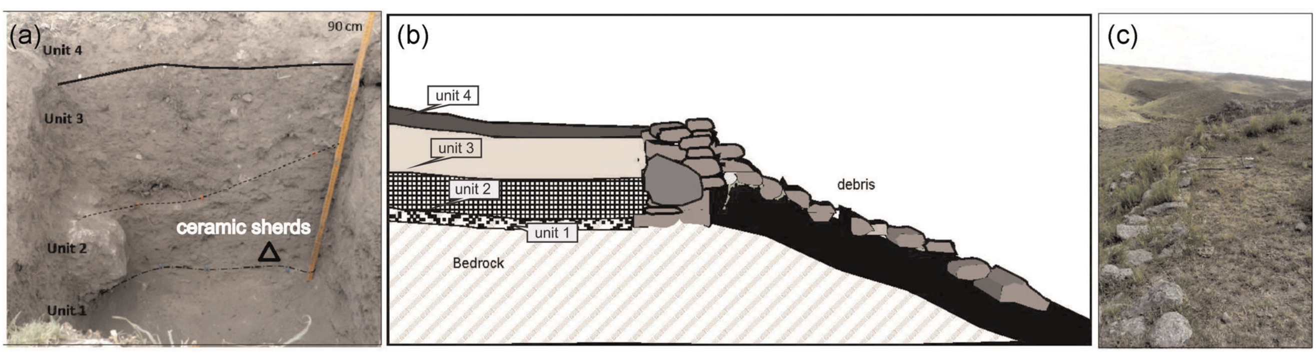


**FIGURE 9** Structure C1. (a) Strata classification. (b) Structure profile and architectural characterisation and strata units. (c) General view of the structure [Color figure can be viewed at wileyonlinelibrary.com]

**TABLE 1** Soil analyses from structures C1, C2, C5

| Sample ID | Depth (cm) | Strata | pH | Conductivity (dS/m) | Texture class | Sand (%) | Clay (%) | Silt (%) | Organic carbon (%) (C) | Organic matter (%) (OM) | Phosphorus (ppm) (P) | Observations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C1 | 0–5 | Sup. | 6.6 | 0.47 | Loam | 51.8 | 12.2 | 36 | 1.65 | 2.84 | 59.08 | |
| C1 | 5–10 | 4 | 6.7 | 0.37 | Loam | 0 | 0 | 0 | 2.54 | 4.37 | 43.15 | Microcharcoal |
| C1 | 10–40 | 3 | 7.2 | 0.46 | Loam | 49.8 | 16.8 | 33.4 | 1.29 | 2.22 | 94.47 | Crop phytoliths microcharcoal |
| C1 | 40–50 | 3 | 8.3 | 0.42 | Loam | 45.4 | 16.8 | 37.8 | 1.55 | 2.6 | 102.06 | |
| C1 | 50–80 | 2 | 8.7 | 0.39 | Loam | 45 | 19 | 36 | 1.48 | 2.55 | 104.08 | |
| C1 | 80–90 | 1 | 8.8 | 0.39 | Loam | 45.4 | 14.4 | 40.2 | 0.66 | 1.14 | 46.95 | |
| C2 | 0–5 | Sup. | 7.2 | 0.64 | Silt-loam | 31.4 | 14.2 | 54.4 | 2.96 | 5.11 | 38.89 | |
| C2 | 0–10 | 4 | 7.1 | 0.64 | Silt-loam | 31 | 19.2 | 49.8 | 2.3 | 3.97 | 28.5 | |
| C2 | 10–20 | 4 | 7.3 | 0.56 | Silt-loam | 28.6 | 17.6 | 53.8 | 2.03 | 3.5 | 11 | |
| C2 | 20–30 | 3 | 8.3 | 0.64 | Silt-loam | 31 | 19.6 | 49.4 | 1.32 | 2.27 | 7.77 | Crop phytoliths microcharcoal |
| C2 | 30–40 | 3 | 8.5 | 0.58 | Silt-loam | 27 | 21.6 | 51.4 | 0.71 | 1.23 | 10.36 | Crop phytoliths microcharcoal |
| C2 | 40–50 | 2/3 | 8.5 | 0.55 | Silt-loam | 23.2 | 23.4 | 53.4 | 0.69 | 1.18 | 7.77 | Crop phytoliths microcharcoal |
| C2 | 50–60 | 2 | 8.6 | 0.58 | Silt-loam | 25.8 | 22.8 | 51.4 | 0.49 | 0.85 | 9.5 | Crop phytoliths microcharcoal |
| C2 | 60–70 | 1 | 8.7 | 0.61 | Silt-loam | 21.4 | 20.4 | 58.4 | 0.14 | 0.24 | 5.75 | |
| C5 | 0–8 | 1 (sup) | 8.1 | 0.55 | Loam | 52 | 10 | 38,2 | 2.69 | 4.64 | 15.39 | |
| C5 | 8–28 | 2 | 8.8 | 0.43 | Silt-loam | 26.6 | 19.6 | 53.8 | 1.73 | 2.98 | 6.61 | Bones and pottery |
| C5 | 28–79 | 3 | 9.3 | 0.43 | Silt-loam | 24.6 | 17.6 | 57.8 | 0.8 | 1.37 | 16.85 | Bones and pottery |
| C5 | 79–84 | 4 | 9.5 | 0.45 | Silt-loam | 25.6 | 20.6 | 53.8 | 0.16 | 0.28 | | Bones and pottery |

(28–79 cm) could be explained by the presence of bones and archaeological materials in this strata. Further extensive excavations in this structure will be necessary to define its purpose within the domestic context, but the abundance of materials could imply an alternative use rather than agriculture.

*Sample pit C2: Upstream terrace*

This 20-m long structure was located in the top section of a terraced ravine, near the residential area. The construction technique involved the use of flat gneiss rocks placed at an inclination angle to compensate for the slope, with smaller rocks placed inside the structure to support the angle of the wall (Figure 10). Within this structure, we identified four units. As with C1, the sediments were fairly homogenous. The excavation was carried out down to the stratum below the level of the wall, which appeared as friable weathered bedrock, consistent with a C soil horizon.

Unit 4 presents a clay-loam texture, slightly acidic pH with a high percentage of organic matter, high levels of phosphorus decreasing towards the base of the unit, as well as a progressive change from a clay-loam to silt-loam texture. Unit 3 was formed by a series of fallen rocks from the wall and inclusions (25–50 mm). This unit presented fluctuations in total phosphorus values and increasing alkalinity towards the base. The same pattern was repeated in Unit 2; however, it had significantly less total organic matter. Finally, Unit 1 at the base of the terrace was highly alkaline with poor levels of organic matter and total phosphorus values in comparison with the upper levels.

With regard to phytolith analysis, this structure presented evidence of crop production. Maize remains were identified in the samples sealed by the wall debris, with the presence of cucurbits, legumes and rhizomes (*Canna* sp.) (Figure 12) (see phytolith assemblages in Supporting Information S2, Figure S2).

When considering the distribution profile, phytolith analyses showed morphotypes related to *Zea mays* (maize) and cucurbits (squash/gourd) in samples #14 (−30 cm, Unit 3, below wall remains), #13 (−40 cm, Unit 3) and #12 (−60 cm, Unit 2). Sample #13 had the strongest evidence for the presence of burning or charcoal when compared with the lower (#12) and upper sample (#14). Sample #14 presented morphotypes compatible with maize and others related to a rhizome, *Canna edulis*.

In Unit 2, #12 (basal), we found morphotypes likely corresponding to legume and maize. Botanic affinity exhibited a greater percentage of panicoid shapes in sample #13 (−40 cm), followed by sample #12 (−60 cm) and sample #14 (−30 cm). This was the group of botanic affinity associated mainly with grasses of C4 photosynthetic patterns (such as maize and other grasses from temperate to warm climates). However, cultivated soils present a higher variability in botanical association (different types of grasses) than the topsoil sample (modern vegetation assemblage), where panicoid forms associated with bilobate morphotypes predominated, a situation that might be related to the impact of modern animal husbandry within the current plant assemblage (Del Puerto, 2015). When analysing the different microremains, sample #13 presented a higher amount of microcharcoal particles, diatoms and sponge spicules, compared with the rest of the profile (Figure 12).

In relation to the structures located on the summit, this test pit showed lower concentrations of organic matter towards the base levels and phosphorus fluctuations produced by crop assimilation; however, the total values of the latter indicated a lower incorporation of domestic residues in comparison with structure C1. According to edaphic studies, these soils had finer textures than those located in the fields, being classified as silty loam, with silt levels providing a high water retention capacity. Due to the homogenous nature of the profile, it was not possible to distinguish whether soil had been artificially added to this upstream structure alongside natural accumulation. The main feature that distinguished the strata used during Prehispanic times from post-abandonment was fallen rocks from the walls. This collapse sealed the profile which we sampled for phytoliths and soil analyses, as well as the ceramic material recovered.

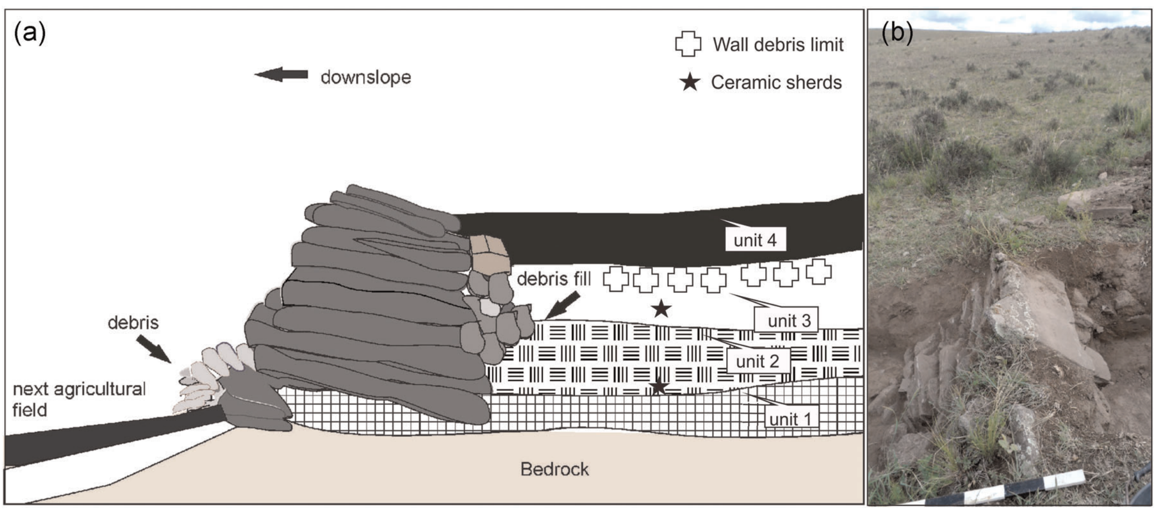


**FIGURE 10** Sample pit C2. (a) Stratigraphy and architectural survey. (b) General view of the wall [Color figure can be viewed at wileyonlinelibrary.com]

The soil chemistry and phytolith analysis also support the fact that Unit 3 was the last cultivated strata. In this case, we do have some evidence to suggest self-filling of this strata; the evidence is that of the ceramic material. The ceramic's degree of fragmentation and erosion suggests that it was redeposited here from living areas located above (<10 m from C2) and subsequently mixed with other sediments.

These ceramic sherds also provide a relative chronology for the structure. Beneath the wall rocks, in strata 3, which would have been the last cultivated stratum before abandonment, a small diagnostic fragment was recovered (Supporting Information S2, Figure S4b)—the 'Negro Grabado' style (Gordillo, 2007)—dating to the first millennia AD. As such, this ceramic is similar to that recovered from the excavated dwellings (Barot & Gasparotti, 2018). In the basal stratum of the structure, a ceramic fragment corresponding to the same style was also recovered (Supporting Information S2, Figure S4c).

### Trench C3: Downslope structure

This thick, 15-m long wall is located downstream in the same ravine as C2. It was constructed at a point where the ravine becomes narrower and the slope is much more uneven. Excavations showed that this wall was set into the hillside flank, just above the bedrock (Figure 11). Our excavation revealed that construction of the wall was through the positioning of gneiss and schist slabs between 0.5 and 1 m in length, forming a supporting wall oriented towards the slope, with a reinforced trapezoidal base. The interior face of the wall had two types of fill: one at the wall base composed of variably sized stone debris and soil and the second, located in the upper section of the wall, composed of angular rocks of different sizes (Figure 11). Ceramic sherds were recovered from the wall filling (Supporting Information S2, Figure S5). Although the sherds lack diagnostic decorative features, their macroscopic characteristics resemble the styles found in the ET19 structures.

Further analyses focused on field observations of soil structure and phytoliths. The soil structure was composed of three units. Unit 3 was humic, with the presence of roots, whereas Unit 2 soil had a clay-loam texture with agricultural debris. Both units had a dark brown colour. Unit 1 had a lighter tone of dark yellowish-brown clay-loam texture with carbonate concretions, which had concentrated in the basal strata through lixiviation.

Regarding the phytolith assemblages, Unit 2 was cultivated and exhibited differences between the deepest (Sample 5) and the highest (Sample 3) segment of the unit. Sample 5 (basal strata) had more microcharcoal particles and dicot platelets, which generally

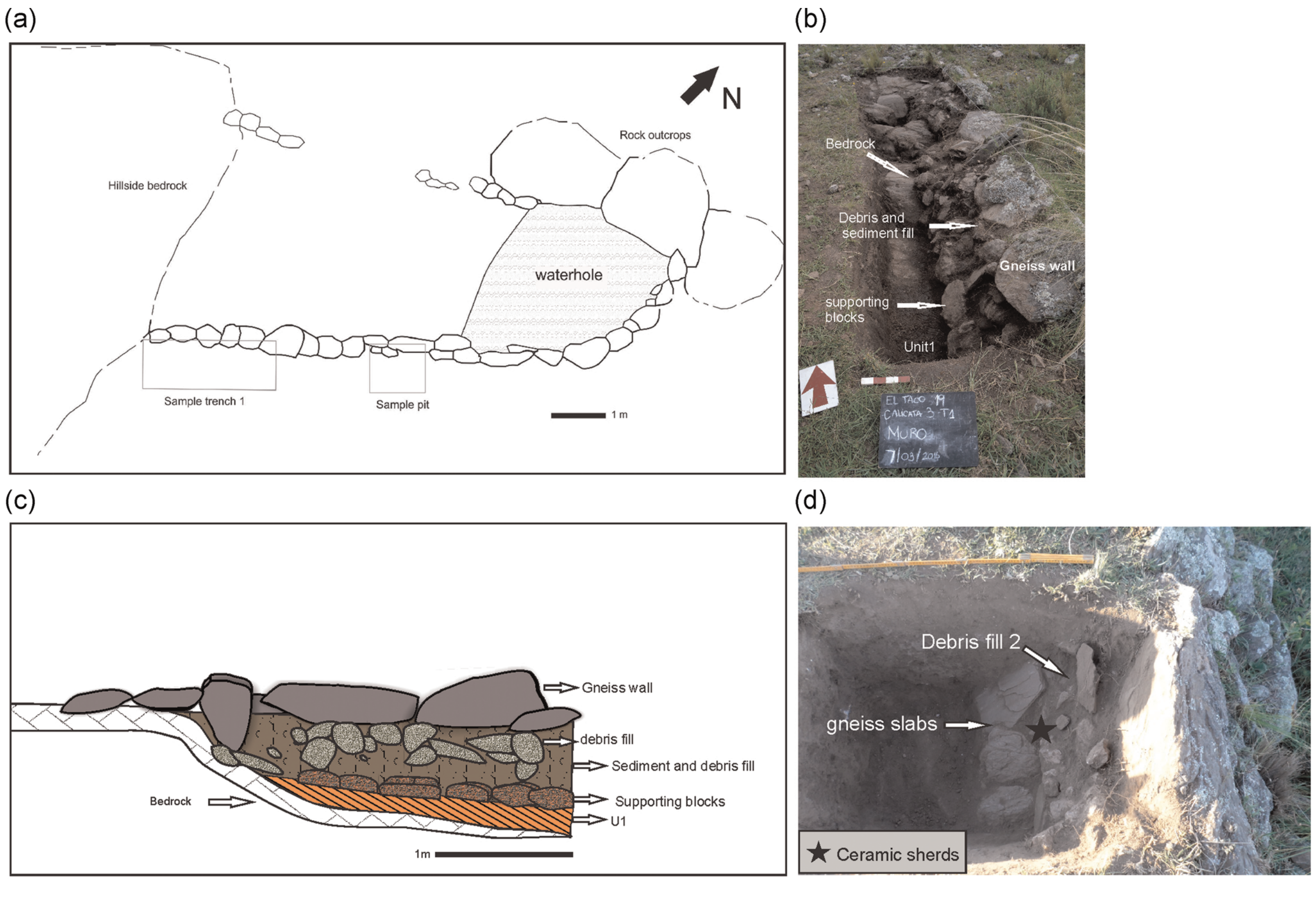


**FIGURE 11** (a) Structure C3 general planimetry with locations of the sample pit in the central section and sample trench in the western section. (b) Picture of sample trench showing different wall components, (c) frontal profile sample trench 1 and architectural survey. (d) Picture of sample pit in the central section and different wall components [Color figure can be viewed at wileyonlinelibrary.com]

grow in places contexts after the harvest. In addition, at this level, we found maize and cucurbits phytoliths. The main botanic associations included grasses such as short panicoid, arundinoid, chloroid and pooid cells (see Figure 12 and phytolith assemblages in Supporting Information S2).

To a lesser extent, we also found other morphotypes, such as dicot and Arecaceae. Sample 3 had a different distribution of botanic associations, with a predominance of phytoliths assemblages associated with warm temperature conditions (40% of chloroid phytoliths), followed by panicoid, arundinoid and pooid. Among the panicoid assemblages, there were maize phytoliths (cob and leaves). Those phytoliths not belonging to grasses were dicot morphotypes including globular phytoliths of cucurbits and rhizomes, for example *Canna edulis*, and indeterminate seed phytoliths from rhizomes that resembled those present in the Marantaceae family (Piperno, 2006). Tuberous roots were also present in the assemblages (Supporting Information S2, Figure S3g). Sample 3 presented the least number of charcoal particles but the highest level of diatoms. A higher number of diatoms in this stratum could imply a greater input of water or moisture concentration associated with crops. Likewise, in both Samples 3 and 5, we found sedge (Cyperaceae family) and spore morphotypes and spores, both common to wet conditions. The topsoil phytoliths lacked charcoal particles and diatoms.

This structure was typical of the wall filling type found in the lower catchment areas of this 'runoff farming' system (Treacy & Denevan, 1994). These structures allowed for the preservation of humidity in the soil and favoured the drainage of excess water through the base of the wall. At present, the exterior side of the structure had a cavity created by hydric erosion, where water drainage during humid periods could be observed. The retention of humidity was a built-in architectural strategy. In this sense, the two types of wall filling could have different origins. One of them might have been due to the cut produced to build the wall, subsequently filled with soil and debris to allow water drainage and a strengthening of the foundations. The second debris accumulation—located over the slabs—was caused by stone removal during agricultural tasks and/or stones tumbling down from higher up.

This structure is an example of the human investment expended in tackling the slope and of its construction process, including the use of bedrock as solid foundations for structures, a commonality across the gullies in the study area (Figure 11).

## 5 | DISCUSSION

### 5.1 | Erosion mitigation dynamics in rainfed runoff agriculture

In this article, our focus has been to characterise the agrarian landscape of El Taco towards understanding its formation history in relation with local environmental dynamics and to document the technical solutions employed during the Prehispanic period to face-off active erosive processes. These involved decision-making regarding local environmental management. The construction of this agrarian landscape also involved the creation of agricultural soils and labour investment towards the building of complex structures which were, in turn, maintained and managed across different generations.

This study was the first to document the processes of soil degradation that agro-pastoralist communities faced on the eastern Andean boundary Northwestern Argentina. Recording this extensive agricultural landscape allowed us to evaluate how erosion affected it. In this sense, Case 1 allowed us to argue that the structures identified within Gully I were similar to present-day check dams, a technology type recommended by the FAO (1986) to mitigate erosion in gullies systems around the world. Other similar archaeological examples have been identified in North America and the Central Andes, where different authors have emphasised the need to understand and deepen our knowledge concerning these environmental management technologies and how, aside from their heritage value, they can provide a solution to present-day problems (Doolittle, 1985; Lane, 2017; Reese, 2020).

The location of the surveyed architecture in these gullies shows that the erosive process increased during the first phase of agricultural construction—the typical ravine cross-channels were found in association with residential sites in high areas. This increased erosion dug into the creek's base level, producing in its wake different moments of collapse of the cross-channels, leading, in turn, to renewed attempts to alleviate this ongoing erosion through the construction of new robust walls across the erosion front.

Once the erosion destroys the walls and negatively impacts the agricultural terraces, the remaining rock blocks are not kept in situ. Rather, they are recovered and reused in the construction of a new wall meant towards stopping or redirecting the gully formation, thus protecting those terraces in the upper sectors. This activity meant a constant maintenance of the structures. The long-term success of these structures can be seen in the fact that the last containment walls (currently well-preserved) still protect the upper sector agricultural terraces, after almost a millennium of post-abandonment of this agrarian landscape.

Nonetheless, erosive processes are ongoing and will still cause soil loss if these check dams are not maintained. Furthermore, the successive construction of these structures to mitigate erosion demonstrates that erosive processes did not act progressively, but rather were discontinuous events. This implies that check dam construction was effective, at least for a time. The evolution of the ravines observed in satellite imagery revealed that the gullies remained stable between 1965 and 2003, whereas the images from 2012 showed a progressive advance towards the upper sectors. The HEMO model showed negative values of NDVI or drought between the years 2005 and 2009. In the study area, the combination of drought and overgrazing produced a rapid weakening of the soils, which were then more susceptible to erosion during the rainy season occurring between November and March (INTA, 1995). In this sense, the absence of check dams and the remains of destroyed terraces at Barranco II indicated that no recent effort was made to mitigate erosion in this area.

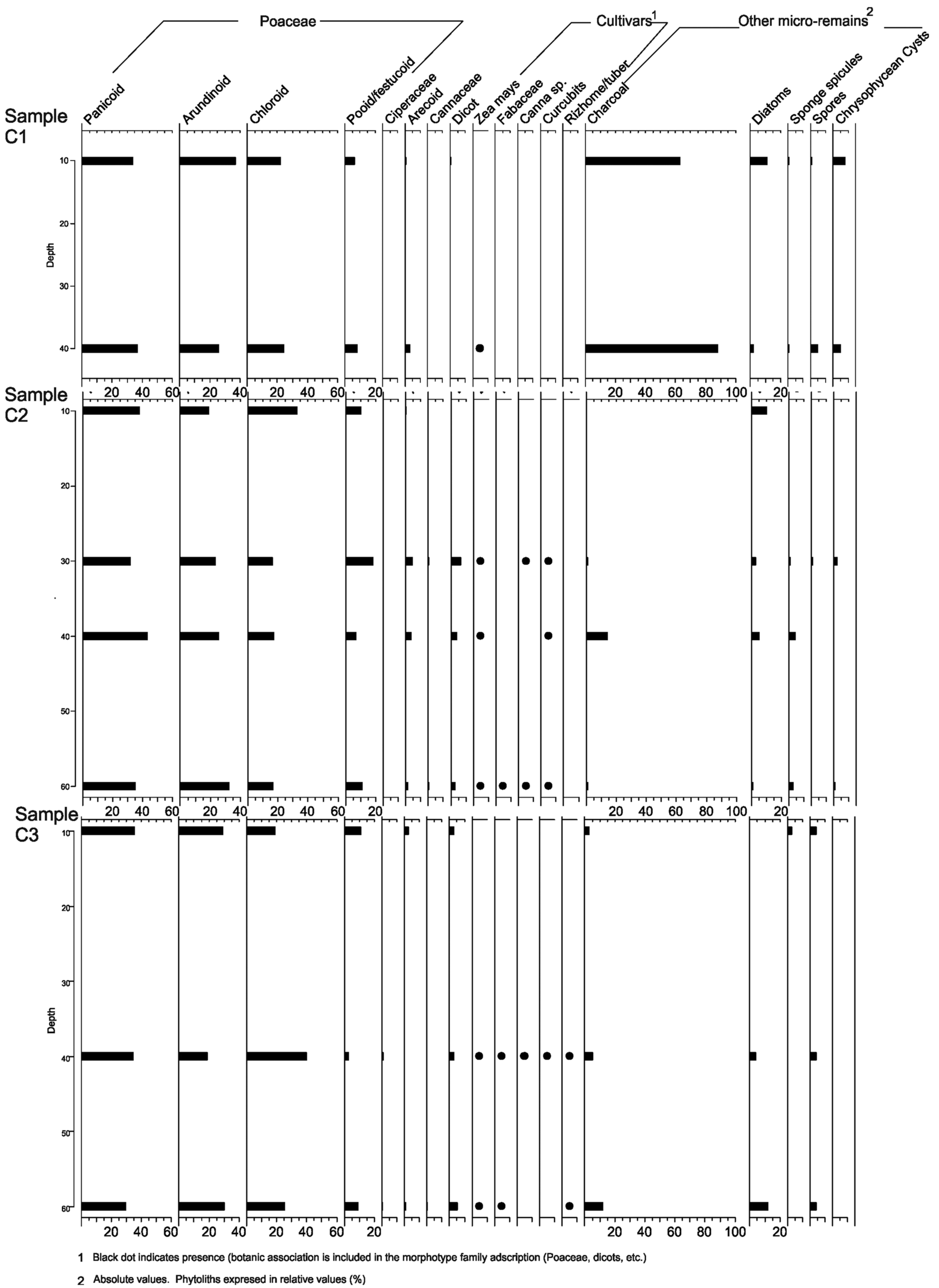


**FIGURE 12** Microremain charts from samples C1, C2 and C3

The present shape of Gully II was the result of a crevice that started eroding the gully leading to different episodes of soil subsidence which occurred post-abandonment of the agricultural fields; this erosive process is still active. Therefore, we identified two erosive processes occurring in the gully providing a relative chronology of this erosion. First, the erosion process of the creek began while the agricultural structures were still in use; this erosion was primarily caused by a combination of land-use strategies, climatic events, as well as due to the physical properties of loessic deposits and seasonal fluctuations in this environment.

Second, the highly eroded process with little evidence of containment or mitigation structures seen within Gully II started after the abandonment of the agricultural terraces. Following the concept of *landesque capital* (Doolittle, 1984), both processes could have been the result of the abandonment of the agrarian system as a whole or an unintended consequence of land use. In both cases, current use of the land for grazing accentuates existing erosive processes and generates new ones, such as embankments or cattle terraces and cattle tracks. The failure of containment structures and the concomitant advance of erosive processes have been shown by different studies to be the consequence of multiple factors such as ravine drainage, lack of maintenance (which may also be the original factor) or deepening and active widening of the ravine, which once formed act as a conduit for water (Gellis et al., 2005; Getaneh et al., 2016, and the Jalda Project (2011) in the Bolivian highlands).

## 5.2 | Modelling past landscape variability in agrarian systems

Concerning the general functioning of the El Taco society and its agrarian system, the spatial models we undertook allowed us to complement our interpretations. In El Taco, specifically in the structures located on the loessic plains and along the ravines, water catchment by capillarity could vary in availability between higher and lower altitudes throughout the seasonal cycles. In addition, our hydrological models made it possible to identify sediment removal and deposition areas and may in the future guide our surveys of other sectors of the highlands, thereby revealing other places along the water basin which have been impacted by human action and construction.

The plant model allowed us to generate hypothetical scenarios during the dry season, when differential patterns could be detected before being erased during the wet seasons. The lower portions of the ravines and specific sectors in the landscape concentrated the most humidity. Following the paleo-environmental NDVI modes (Burry et al., 2018), between 600 and 1000 AD, there were cycles of positive anomalies—excessive rains—and cycles of negative anomalies—droughts—which were related to wider climatic processes such as regional volcanic eruptions, among others. A possible implication is that, in this fluctuating scenario, the generation of a productive mosaic that favoured the systems' flexibility was a key factor behind its emergence.

An analysis of microclimatic differences, measured through the vegetation across this extensive terrace system, suggests that populations in the past had access to different microclimates according to annual seasonal fluctuation and during more lasting environmental changes. In this scenario, it was crucial to preserve these productive areas, given the variable climatic context, allowing for risk reduction and the rotation of plots through fallowing. In this manner, the construction of agricultural structures across different environmental mosaics and the predominance of the cross-channel terrace dryland farming technology were the selected strategies to face frost, droughts and even excessive rainfall hazards. This demonstrates a flexible territorial pattern in the face of climatic fluctuations, particularly considering that this technology also predominated in contemporaneous agricultural sites in different environmental contexts, such as the forests located in the nearby eastern slopes of this mountain range (M. Quesada et al., 2017).

## 5.3 | Characterisation of agricultural soils through sedimentological studies and architectural surveys of construction techniques

Finally, the use of sedimentological studies allowed us to characterise anthropogenic soil use. In this sense, researchers studying the functionality of these terraces have highlighted that erosion control was an important focus of this technology; other authors consider that water retention was the main function, given that these structures permitted water percolation through the homogenisation of the slope and the reduction of soil runoffs (Treacy & Denevan, 1994). Likewise, thicker soils allowed plant roots to seek humidity from the basal levels, while water retention was accompanied by the construction of permeable walls filled with pebbles that prevented waterlogging (Denevan, 2001; Treacy, 1994, among others).

More recently, other authors (Sandor et al., 2007) have highlighted that a crucial, though not-often studied, aspect of runoff agriculture is that it is not only a technique to manage water supply but that it also replenishes soil fertility through transportation of nutrient-rich organic matter and sediments from watershed to field. This deposition of sediment and organic debris is crucial for sustained agricultural productivity.

In our study, microremain analyses revealed the types of cultivars produced within the system as well as the additional input of organic matter through burned material. In Case 2, through excavation and analysis of sediments from agricultural terraces, we were able to verify the highly productive potential of these areas even today. We established that the identified cultivated species were mostly the same ones across all the locations (maize, cucurbits, cannas and legumes), except for a variety of rhizomes in structure C3, which was coherent with the greater humidity concentration produced in the structures located in these lower areas. This was supported by our field surveys and was also detected via satellite imagery, showing a greater vegetation development in these areas during the dry season due to the higher humidity retention.

Another implication of the presence of this cultivar combination in all our samples was that soil management probably involved crop rotation to balance soil nutrients. Soil enrichment involved variable practices in the structures located on the summits, more strongly associated with the incorporation of domestic residues (charcoal, bones, etc.) noticeable by the elevated total phosphorus values and complemented by the incorporation (both in field structures and in cross-channel terraces at different altitudes) of carbonaceous particles in the matrix. In downstream terraced structures, this incorporation was likely caused by periodic controlled fires of field stubble, which allowed nutrients to be released as well as runoff from higher placed domestic areas.

In agricultural fields associated with dwellings, the presence of microcharcoal could be more related to residues from domestic fires. Moreover, the frequent incorporation of ashes into the soils favours their alkalinisation, a fact that might have influenced their chemical values (Steiner et al., 2009). Finally, the differences shared between the phytolith assemblages from topsoil samples above wall collapse with the cultivated soils beneath indicate that post-Hispanic landscape management, mainly cattle herding, had an impact on vegetation composition, alongside the erosion processes discussed above. This interplay of dynamics could have been part of different maintenance strategies. Future research will aim to study these further through increased comparative sampling.

Finally, architectural surveys in the ET19 ravine allowed us to characterise the constructive techniques employed in the different areas of the system. Wall construction presented similar characteristics including foundations over basal and/or lateral bedrock flanks, stonework formed by the use of flagstones of variable size and deposits and/or fill. Moreover, structures located at the base of ravines where flow accumulated presented stronger walls (as the excavated structure C3 demonstrates), used bedrock as the foundation, employed 1-m long flagstones, base reinforcements, and were infilled with a great volume of stones, allowing capillary water flow in these ravines.

## 6 | CONCLUSIONS

It is important to highlight that although substantial data on components and linkages in runoff systems in the study region have been collected and evaluated during this study, more study is required on many aspects, such as further comparative soil surveys and finer grained chronology. Nevertheless, the evidence presented here allows us to approach the relative temporality of the practices developed by Prehispanic farmers and the techniques employed by them in their interaction with the processes occurring in the El Alto-Ancasti Highlands.

As previously mentioned, this area of Northwestern Argentina encompassing the central valleys of Catamarca and the El Alto-Ancasti Highlands do not present dated events and/or material culture suggesting a reoccupation during the second millennia of the present era. The nature of this abandonment occurring between the 10th and 11th century AD—due to environmental and/or social causes—is a much-debated topic in local archaeology (Cruz, 2006; Gordillo, 2007; Gordillo & Vindrola-Padrós, 2017; Marconetto et al., 2015), especially considering that the surrounding areas (such as the western Andean region) present an occupational sequence lasting until the moments of indigenous–Hispanic contact.

The radiocarbon dates obtained from residential sites such as El Taco 19 and their association with terraces, the type of architecture, as well as the material culture recovered, place this agrarian landscape between the 7th and 8th century AD. A persistent pattern identified through field surveys and intensive study of Case 1 and 2 show an occupation characterised by residential sites with cultivation plots that were in the naturally fertile loessic fields on the summits and the construction of cross-channel systems in ravines of different order descending downstream from these elevations.

The hierarchical organization of ecological zones in El Taco may have been a negotiation and management strategy among the area's social groups. Microclimatic and topographic characteristics of the agricultural locations discussed demonstrate that heterogeneous conditions for the development of different crops and/or the generation of deep soils in humid areas may have been vital in the face of climatic fluctuations. The erosion, we identified, was not homogeneously present across the whole study region, rather it was in some ravines with terraces systems such as Case 1, where it has remained active from the Prehispanic period up to the present.

This indicates that the onset of erosion was not exclusively the product of climatic or environmental conditions but responded to transformations of the landscape due to land use, periods of inactivity in that sector of terraces and/or lack of maintenance of the structures. In turn, this caused the advance of erosion that was controlled or mitigated, at least for a time, through the construction of check dams. As suggested by Fisher (2005), gully advance over the terraced sectors can be understood as an unintended consequence of landscape management. Nowadays, soil erosion is one of the greatest threats to local communities, given that this active erosive process compromises large areas of the surface terrain, limiting soil productivity.

The agrarian landscape in El Taco must be understood as the result of an accumulation of work processes, leading us to a better understanding of the present-day environmental dynamics. It is worth noting that the technological solutions employed by past populations in the face of potential soil loss were effective in the short term. This makes it critical for us to study these systems and their maintenance as a technology for the control and mitigation of long-term erosive processes, thereby providing useful data regarding sustainable soil management and mitigation of risks for modern-day local communities.

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## DATA ACCESSIBILITY STATEMENT

Free access image source: AsterGdem, https://asterweb.jpl.nasa.gov/gdem.asp

Free access Landsat 5$^{TM}$. Source: https://earthexplorer.usgs.gov/. Years 2010–2011 (LT05_L1TP_230080_20101008_20161012_01/LT05_L1TP_231080_20110425_20161209_01).

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