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RESEARCH ARTICLE

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Human-driven geomorphological processes and soil degradation in Northwest Argentina: A geoarchaeological view

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Abstract

The study of human-driven processes is useful to gain a better understanding of the long-term evolution of land degradation, soil erosion, and geomorphology as well as resource availability for human settlement. The objective of this paper is to identify the long-term results of human impact on the vulnerable dryland ecosystems in Northwest Argentina, specifically to analyze the consequences of the spread and consolidation of the agricultural way of life on the landscape. To reach this objective, a multiproxy interdisciplinary geoarchaeological study was conducted to link an evolutionary geomorphological model with the soil development and degradation, peopling, and land use change during the Upper Holocene and integrate distinct areas of the Tafí Valley region, which is the most studied area, other neighbouring valleys, and the Puna. The analyses identified positive human-driven impacts that led to a general degradation of the landscape during the agricultural Prehispanic Period, dated between ca. 2000 and 500 BP. This degradation is manifested by accelerated morphogenesis, mainly fine-grained accumulated sediments, thick deposits, and the presence of human debris interbedded with the natural sediments. The success of the productive agricultural systems that expanded during the Formative Period led to a gradual increase in the demographic density, resulting in extensive environmental degradation due to overexploitation of the drylands of Northwest Argentina, in some cases increased by adverse climatic changes.

KEYWORDS

drylands, erosion, Holocene, land degradation, Prehispanic settlements

1 | INTRODUCTION

The surface of the Earth is being extensively transformed by human activities. This is related to the triggering of the degradation of soils, vegetation, and hydrological systems by several factors. The rise of the anthropic force is due to the demographic increases, technological changes, and human efforts satisfying their needs. This research focus has received increasing attention in the last decades and is important in the study of past societies that had triggered major changes in various environments across the world (Butzer, 2005; Goudie, 1993; Wright, 1993, among others).

Three main technical-cultural eras of humankind have been recognized as important to demographic growth and economic development: (a) the fabrication of tools, (b) the rise of agriculture, and (c) the industrial revolution. Over time, these eras had an increasing impact on the landscape, and they were related to changes in the demographic and environmental dynamics (Rózsa, 2007). The rise of agriculture is most relevant to the study of early agricultural societies. It is linked to several activities that introduced changes in the relatively steady and stable geomorphological systems (Knox, 2000), especially in the drylands that are highly sensitive areas less able to adjust to these changes (Miles et al., 2001). Direct environmental impacts are produced by intentional activities (such as tilling, grazing, plowing, forest clearance, and terracing), and indirect environmental impacts are a consequence of those actions (such as compaction by trampling, overgrazing, and increasing erosion; Montgomery, 2007; Wilkinson & McElroy, 2007). Sedentary settlements create an intense change in natural resources. Environmental responses, such as feedback mechanisms, could act to positively reinforcing the processes triggered by human actions (producing more degradation) or negatively allowing the system to reach a new balance (Chin, Florsheim, & Wohl, 2014). In terms of agricultural processes, the adoption of technologies to adapt landscapes and plant production, the use of wood for fuel and construction, the clearance of forested areas for grazing, the growth and complexity of the human population, and the increasing size of flocks are among the most determinant factors involved in environmental changes. The global changes in the landscape, with different agricultural and livestock choices made according to each region, may have been the preindustrial antecedent of the concentration process of certain atmospheric gases (CH_4 and CO_2) and caused the current Global Climate Change (Ruddiman, Ellis, Kaplan, & Fuller, 2015).

The aim of this paper is to focus on the long-term results of the human impact across the vulnerable dryland ecosystems in Northwest Argentina, especially to analyze the consequences of the spread and consolidation of the agricultural way of life on the landscape. To reach this objective, a multiproxy interdisciplinary geoarchaeological study was conducted, which links the evolutionary geomorphological model with soil development and degradation, peopling, and land use changes during the Upper Holocene and integrates the distant areas of the region such as the Tafí Valley, which is the best known study area, other neighboring valleys, and the Puna.

This is the first approximation on this subject in Northwest Argentina in a wide perspective including the well-studied features of the Tafí Valley in a regional and even global framework.

2 | STUDY AREA

Tafí Valley is a tectonic basin located in the northwest Subandean Ranges of Northwest Argentina. Its altitude ranges between 1,800 and 3,000 m asl. The valley is bordered by mountains that exceed

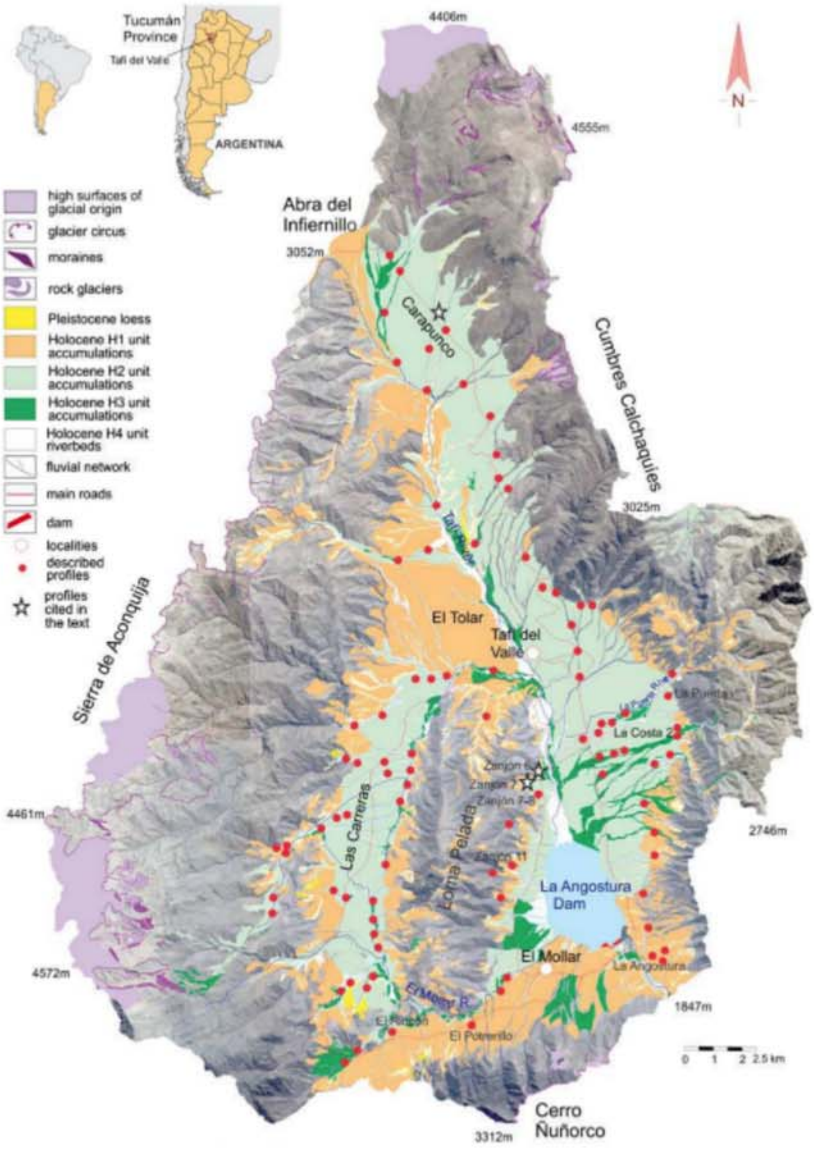

FIGURE 1 Geomorphological map of Tafí Valley and recorded profiles [Colour figure can be viewed at wileyonlinelibrary.com]

3,000 m asl. In the center of the valley, there is an isolate relief (Loma Pelada, 2,680 m) that separates the western basins from the Tafí River and the eastern tributaries (Figure 1). The climate in the Tafí Valley is semiarid, reaching an average rainfall per year of 400 to 550 mm, and the average annual temperature is 13.1°C. The plant cover is dominated by grasslands with small forests on slopes in areas of higher humidity.

The valley basement is Precambrian and Cambrian in age and includes metamorphic rocks with granitic intrusions. This basement is covered by Quaternary deposits of various ages and some Tertiary remnants. The Pleistocene is represented mainly by loess accumulations dated to ca. 1.5 Ma. Other Pleistocene deposits are relicts of alluvial fans that are exposed by thrust faults. In the lower areas, most deposits are of Holocene age (Figure 1; Sampietro-Vattuone & Peña-Monné, 2016).

The evolutionary Holocene regional model establishes that during the Holocene, the valley experienced four main aggradation/incision cycles (Sampietro-Vattuone & Peña-Monné, 2016). These cycles created the sediment accumulations of different ages, separated by the presence of intermediate incision phases. The earliest stage, named H1, was dated to ca. 13000 to 4200 BP and is mainly represented by slope deposits (H1s). H1 was formed under wetter conditions, and a gradual shift to harsher conditions by the end of the period has been interpreted. This stage was followed by the development of an Upper Holocene accumulative unit dated to ca. 4200 to 600 BP and represented by slope (H2s), alluvial terrace (H2t), and alluvial fan (H2f) deposits. These accumulations were formed under wetter conditions and include features that have been interpreted to be a general environmental degradation over time (Sampietro-Vattuone & Peña-Monné, 2016). Smaller deposits from the later H3 and H4 phases are recognizable in the inner sections of the incision that cuts the previous deposits. They were dated to ca. 600 BP until present and include the Little Ice Age Period and the Present Warm Period (Figures 1 and 2a).

3 | ARCHAEOLOGY OF THE AREA

The main archaeological sites from the valley belong to the Formative Period (ca. 500 BC–1000 AD) and are considered among the earliest sedentary settlements in Northwest Argentina. This social entity was named the Tafí Culture (González & Núñez Regueiro, 1960). This

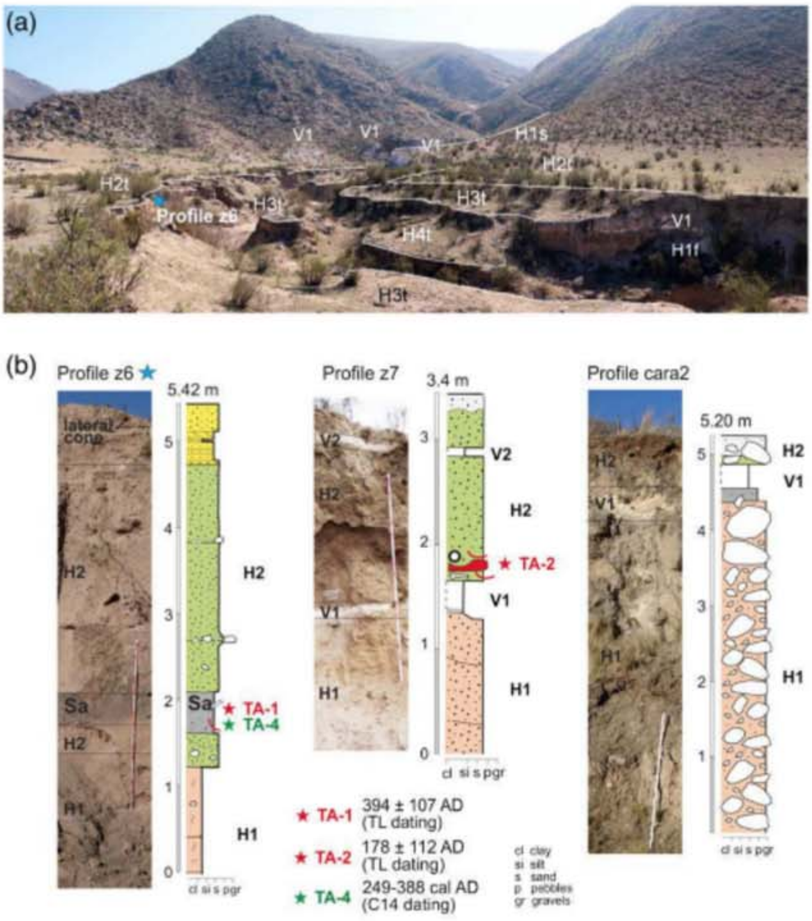

FIGURE 2 (a) General view of the representative accumulation stages recorded in Stream 6 with profile z6 location; (b) representative profiles of H1 and H2 accumulation units (see the paleosoils (Sa), archaeological interbedded occupations, V1 and V2 volcanic ashes, and datings). Loma Pelada profiles mainly composed of fine sediments: (z6) profile from Stream 6; (z7) profile from Stream 7; and (cara2) profile from Carapunco formed by debris flow with volcanic ashes interbeded in debris flow deposits [Colour figure can be viewed at wileyonlinelibrary.com]

entity was defined according to several typical features: lithic sculptures (monoliths and stone masks), a settlement pattern characterized by circular stone structures (isolated, arranged around a large [over 20 m in diameter] central patio, or arranged to form a complex of circular rooms), agricultural structures, and a single ceremonial mound (Sampietro Vattuone, 2010). According to radiocarbon dating, the settlements started ca. 2296 ± 70 BP (González & Núñez Regueiro, 1960) and ended by 990 ± 30 BP (Franco Salvi, Salazar, & Berberián, 2014). Studies of the way of life of the people have suggested an egalitarian society that extensively occupied the valley; the entire valley was colonized with highly persistent domestic residential spaces and continuously occupied throughout the first millennium AD (Sampietro-Vattuone & Peña-Monné, 2016). By the end of that period, deep local and regional environmental changes occurred. A marked drought, contemporary with the Medieval Climatic Anomaly, affected the populations of the Formative Period across Northwest Argentina (Peña-Monné et al., 2015).

At the Tafí Valley, this event is contemporaneous with the appearance of a new sociocultural entity from the Late (or Regional Developments) Period, characterized by *Santa María bicolor*, *Famabalasto black incised*, and *Quilmes red engraved* ceramic types (Sampietro-Vattuone & Peña-Monné, 2016). The dispersed residential units were made of adobe brick and mud walls. They used to include a rectangular patio with one or two circular rooms. The people of the Late Period also had an agricultural subsistence system. The current interpretation is that these people settled at dispersed specific points in the valley, between 656 ± 39 BP and 405 ± 44 BP, forming less visible settlements than the Tafí people (Manasse, 2012). It is probably that the chronological frame of these settlements expands while researches on the subject deepen, especially considering the persistence of the agrarian exploitation (Sampietro-Vattuone & Peña-Monné, 2016). Some Inca (ca. 1490–1535 AD) ceramic types and structures were found but they are still not dated.

The arrival of the Spaniards to the Northwest Argentina (1535 AD) initiated profound changes in the use of space, systems of exploitation, and agricultural technology (introduction of the wheel and plow); these changes, together with the income of sheep, goats, cattle, and horses, constituted a new productive resource of great regional value (Robledo, 1995).

4 | METHODOLOGY

To address our goal, we did a full-coverage survey of the archaeological settlements by using Google Earth images (Google, Landsat/Copernicus, 2013) and aerial photographs from different times (1970, 1987, 1995, and 2000), detailed drone surveys (DJI Phantom 4 and Mavic Pro), and a private flight (2016). The archaeological sites and structures of this area are easily viewable due to the vegetation cover (grassland) and the settlement characteristics (most structures were built with large rock blocks and they are not totally buried at present). The archaeological data were combined with the geomorphological map to identify the areas that were more likely to provide the best naturally exposed profiles. According to previous knowledge of the area and our survey, H2 accumulations were especially targeted for the identification of geoarchaeological evidence (Upper Holocene accumulations contemporary to human intensive occupations, ca. 4200–600 BP). Following the implementation of a geomorphological criterion (distinguishing among slopes, fluvial terraces, and alluvial fans), 168 representative profiles were recorded. The stratigraphic, pedological, chronological, and cultural features were documented, as well as their topographic and geomorphological location.

Next, three agricultural areas (La Costa 2, Río Blanco, and El Potrerillo; Figure 1) were excavated to collect physicochemical soil measurements within the following three main contexts: (a) agricultural terraces, (b) residential units, and (c) unaltered surfaces. To identify the past human agricultural soil modifications, we selected techniques that allowed the establishment of available forms of soil nutrients, focusing on the features related to anthropogenic modifications (as proposed by Sampietro Vattuone, 2010). One hundred seventeen samples were obtained. The apparent density (AD; via the parafined clod method), pH (digital pH meter), texture (densimetric method), and organic matter content (chromic acid titration method; Walkley & Black, 1934) were determined. According to their diagnostic value, the available macronutrients such as phosphates (molybdenum blue method) and calcium (complexiometric method) were also determined (for the specific methodological adaptations to chemical determinations, see Roldán, Sampietro, & Vattuone, 2006).

The sample variability and similarities among the soil profiles were determined with principal component analysis using Xlstat 2009 for Excel. To introduce the data into the system, we calculated the average values for each variable in each profile. Therefore, each component was calculated using such averages. We used biplot graphics that represent the distribution of the profiles together with the considered variables to identify which are the most significant variables of the agricultural system (Jolliffe, 2002).

All the collected information, including the geomorphology, natural outcrop descriptions, pit descriptions at the archaeological sites, statistical interpretation, and regional and local environmental information, was compiled and interpreted to identify the human-driven processes.

5 | RESULTS

During the Holocene, the study area was affected by large landscape changes. The relief suffered an intense remodeling by tectonic forces and especially by climatic and anthropogenic causes. Since ca. 4200 BP, the older Holocene accumulations (unit H1) were partially affected by an incision phase that affected all the river courses of the area (Sampietro-Vattuone & Peña-Monné, 2016). After the incision phase, the alluvial fans and fluvial terraces of the H2 unit accumulated at the lowest areas of the valley, most of which were occupied by human settlements of different ages, as well as the surrounding slopes (Figures 1 and 2a).

The stratigraphic profiles recorded in this study are distributed along the entire valley (Figure 1). Most of those documented in the southern central area of the valley are composed of sandy-loam and sandy-clay-loam sediments. The main parent materials were the coarse sands from the weathered granite (known as *grus*) and the loess deposits eroded and reworked during Holocene times (Figure 2b, profiles z6 and z7). In the northern sector of the valley, the large alluvial fans were mainly formed by debris flow processes; therefore, the profiles are composed of blocks supported by a sandy-loam matrix (Figure 2b, profile cara2).

In the majority of the documented stratigraphic profiles from the Tafí Valley, most of the sediments of H2 unit overlap the H1 unit. The older unit is the H1 stage, and it is frequently roofed by a volcanic ash layer dated to ca. 4200 BP. This layer was deposited after a Plinian eruption of the Cerro Blanco volcano, located 300 km west to the Tafí Valley (Sampietro Vattuone, Sola, Báez, & Peña Monné, 2017). This layer allows the establishment of a strong stratigraphic correlation, especially considering the textural homogeneity of the profiles that were formed by the reworking of the previous accumulations (Figure 2b, profiles z6 and z7). The interbedded ash, named V1 after Sampietro-Vattuone and Peña-Monné (2016), marks a clear chronological boundary during the sedimentation process in the study area. In the upper section of the profiles that belongs to the H2 unit, archaeological debris including secondary deposits of ceramic potsherds, some lithics, and scarce charcoals are generally observed. In some cases, in situ occupations were found. A new volcanic ash layer (V2) was dated later than 15th/16th centuries (Sampietro Vattuone, Peña Monné, Sancho, Báez, & Sola, 2018).

The earliest occupations generally belong to the Formative Period. We were able to date pottery fragments from an in situ settlement located in the eastern side of the Loma Pelada by the TL

TABLE 1 ^{14}C datings

Field code	Laboratory reference	Material	^{14}C year BP	cal year BP	cal year BC/AD	Cultural period
TA-5	AA100098	Bone	2070 ± 20 BP	1σ: 2010–1933 2σ: 2045–1925	1σ: 61 BC–18 AD 2σ: 96 BC–25 AD	Formative
TA-8	LP3409	Sediment	1750 ± 60 BP	1σ: 1702–1562 2σ: 1805–1434	1σ: 249–388 AD 2σ: 145–517 AD	Formative
TA-7	AA100096	Bone	1040 ± 20 BP	1σ: 935–822 2σ: 957–811	1σ: 1016–1129 AD 2σ: 994–1139 AD	Formative
TA-6	AA100099	Bone	640 ± 20 BP	1σ: 629–554 2σ: 638–546	1σ: 1322–1397 AD 2σ: 1312–1405 AD	Late

Note. Radiocarbon ages were calibrated to 'calendar' ages by using Oxcal v4.2.4 Bronk Ramsey (2013); ShCal13 atmospheric curve.

TABLE 2 Soil profile descriptions from El Tolar archaeological site

Profiles		Hz	Depth (cm)	Texture			Apparent density	pH	P (a) (ppm *100)	OP (ppm *1,000)	OM (%)	Ca (a) (ppm*10^5)
				Sand (%)	Silt (%)	Clay (%)						
Natural	ET-P1	A	0–10	73.6	16.8	9.6	1.4	5.6	1.61	3.8	7.41	8.978
		AB	10–20	55.2	35.6	9.2	1.55	6.5	1.12	9.7	3.96	8.978
		B	20–60	78.2	11.2	10.6	1.52	6.9	1.67	3.6	1.74	8.176
		BC	60–75	77.2	10	12.8	1.48	7	1.05	4.8	1.18	6.814
		2ABb	75–90	77.2	8	14.8	1.5	7	1.3	7.2	0.84	6.132
Agric.	ET-P2	A	0–13	69.4	11.6	19	1.19	5.1	1.61	7.35	9.41	4.489
		2Bb	13–25	71.2	11	17.8	1.54	5.3	1.86	14.74	4.8	3.607
		2BCb	25–50	72.4	12	15.6	1.5	6.3	1.67	4.58	4.46	7.615
Agric.	ET-P3	A	0–19	70	19	11	1.52	5.7	1.49	10.5	7.34	6.012
		2Bb	19–29	72	16	12	1.83	6.4	1.49	7.19	4.53	5.13
		2BCb	29–48	71.2	14.4	14.4	2.2	6.7	2.11	6.05	1.81	5.771
		2Crb	48–70	73.2	12	14.8	1.6	7.1	2.54	2.49	1.25	3.848
Agric.	ET-P4	A	0–18	70.2	17	12.8	1.21	5.8	1.36	20.9	6.18	4.81
		2ABb	18–40	69.2	16	14.8	1.35	6.1	1.3	19.4	4.6	5.771
		2Bb	40–56	69.2	14	16.8	1.47	6.5	1.74	3.8	2.74	5.771
		2Crb	56–70	73.2	9	17.8	1.99	6.9	2.23	11.5	1.43	4.088
Agric.	ET-P5	A	0–16	63.2	18	18.8	1.55	5.8	0.87	4.7	5.63	4.489
		2ABb	16–28	61.6	18.4	20	1.37	6.2	1.2	21.5	4.6	5.771
		2BCb	28–42	61.6	23.6	14.8	1.52	6.7	1.3	13.7	3.01	6.413
		3Bb	42–55	62.6	11.6	26	1.51	6.9	1	7.8	1.24	5.13
Resid.	ET-P6	A	0–5	55.6	18.4	26	1.4	5.7	1.8	17	6.8	7.214
		AC	5–17	55.6	16.4	28	1.37	5.4	1	16.6	4.74	4.97
		2AB	17–27	51.6	13	35.4	1.26	6.2	0.68	16.7	4.46	7.695
Agric.	ET-P7	A	0–21	45.6	14	40.4	1.25	5.6	1.43	26.1	5.39	4.208
		BC	21–40	45.6	12	42.4	1.54	6.4	0.62	19.5	2.53	5.771
		2ABb	40–59	46	12	42	1.36	6.7	0.62	23.9	1.81	6.814
		2Bb	59–90	49	11	40	1.46	7.1	1.24	16.6	0.84	4.489
Resid.	ET-P8	A	0–9	74	18	8	0.88	5.4	1.92	16.1	7.96	8.978
		AC	9–20	76	14.8	9.2	1.37	6.4	1.74	17.9	3.05	7.054
		2AB	20–35	77.6	12	10.4	1.22	7.5	2.42	16	1.43	8.978
		2Bb	35–95	78.6	11	10.4	1.41	7.6	0.87	5	1.05	6.413
		3Bb	95–130	81.6	8	10.4	1.62	6.9	1.98	15.5	0.74	8.176

Note. Hz: horizon; P (a): available phosphate; OP: organic phosphate; OM: organic matter; Ca (a): available calcium.

(thermo-luminiscence) method to 178 ± 112 AD (profile z7) and 394 ± 107 AD (profile z6; Figure 2b; Sampietro-Vattuone & Peña-Monné, 2016). Radiocarbon dating was also performed on the carbonaceous sediments from profile z6, and the occupation was dated to 1750 ± 60 BP (249–388 cal AD; LP3409; Table 1, Figure 2b), contemporaneous with those already obtained by TL. The archaeological materials were crude ceramic potsherds typical of that period. One very relevant feature is that, in all cases, the material from these early

TABLE 3 Soil profile descriptions from La Costa 2 archaeological site

Profiles		Hz.	Depth (cm)	Texture Sand (%)	Silt (%)	Clay (%)	Apparent density	pH	P (a) (ppm *100)	OP (ppm *1,000)	OM (%)	Ca (a) (ppm*10^5)
Natural	LC-P1	A	0–10	8.1	41.6	50.3	1.18	6.5	1.82	2.09	2.31	1.058
		AB	10–27	6.2	73.3	20.5	-	7.8	1.43	1.9	1.32	2.18
		B	27–46	2.5	73.8	23.7	1.93	7.9	1.45	1.99	0.67	1.984
		C	46–87	2.5	89.7	7.8	2.19	8.6	2	1.81	0.21	4.629
Agric	LC-P2	A	0–10	7.5	73.9	18.6	1.42	7	1.15	3.42	1.41	1.587
		B	10–27	12.8	75	12.2	1.87	7.9	1.18	4.45	1.18	1.795
		C	27–40	93.1	4.4	2.5	-	8.3	1.1	3.74	0.77	1.795
Agric.	LC-P3	A	0–3	1.4	75.5	23.1	1.67	6	1.06	4.35	2.38	1.082
		C	3–17	2.9	74.2	22.9	1.34	7.3	0.82	2.71	1.23	1.539
		2Ab	17–34	2.9	74.1	23	1.67	8.4	1.19	5.86	0.93	1.852
		2Bb	34–45	4.5	73.8	21.7	1.54	8.6	1.15	3.92	0.69	1.795
		2BCb	45–68	4.5	73.8	4.7	1.87	8.8	1.03	4.43	0.23	1.455
		2Cb	68–100	93	3.8	3.2	1.81	9.1	1.86	5.53	0.69	1.154
Agric.	LC-P4	A	0–14	9.1	71.7	19.2	1.98	6.9	1.77	7.22	1.37	1.984
		B	14–54	67.8	28.3	3.9	2	8.8	2.51	6.51	0.99	3.703
		2Bb	54–75	57.5	30	12.5	1.35	9.3	1.92	6.27	0.55	3.571
		2Cb	75–93	89.6	8.5	1.9	-	9.6	2.56	5.69	0.65	5.158
Resid.	LC-P5	A	0–16	9.8	70.9	19.3	1.39	6.6	1.53	4.61	1.66	1.19
		BC	16–40	10.5	70.4	19.1	1.98	7.4	1.61	5.21	1.13	1.924
		2ABb	40–45	6.4	87.3	6.3	1.6	7.9	1.77	6.69	1.23	2.777
		2C1	45–96	2.9	74.2	22.9	1.8	8.5	2.1	5.39	0.94	2.89
		3BCb	96–128	69.2	12.6	18.2	1.81	9.2	1.42	6	0.32	1.363
		3Cb	128–140	93	3.8	3.2	1.41	9.5	1.08	4.91	0.56	2.777
Agric.	LC-P6	A	0–12	10.1	71.7	18.2	1.72	6.7	2.15	1.87	2.56	1.771
		B	12–33	9.9	71.4	18.7	1.85	7.3	1.69	2.06	1.46	2.18
		2Bb	33–57	6	89.2	4.8	1.12	9	3.21	2.08	0.28	14.284
		2Crb	57–91	6.1	88.8	5.1	2.35	8.4	3.71	2.75	0.12	12.433
Agric.	LC-P7	A	0–7	1.4	75.5	23.1	1.38	6.8	1.47	2.49	1.66	1.771
		AB	7–23	7.5	73.9	18.6	1.99	6.5	1.02	2.13	1.46	2.044
		B	23–45	7.4	73.5	19.1	1.39	7.9	1.26	2.43	0.99	2.248
		2Bb	45–54	4.2	92	3.8	1.52	8.1	1.56	3.17	0.32	2.317
		2Crb	54–71	4.8	91.3	3.9	2.04	8.6	2.57	3.65	0.26	18.517
Resid.	LC-P8	A	0–6	9.2	68.8	22	1.83	6	1.64	4.61	4.62	2.309
		AB	6–37	9.5	70.1	20.4	1.62	7.1	2.46	4.79	2.26	2.645
		BC	37–69	8.5	69.6	21.9	1.78	7.7	3.57	4.98	2.17	3.042
		2Bb	69–92	8.5	69.5	22	1.56	7.7	2.87	5.14	2.2	3.848
		2BCb	92–125	4.6	91.3	4.1	1.91	8.2	4.52	8.26	0.56	5.687
		2Cb	125–140	4.5	91.5	4	-	8.7	3.14	11.19	0.48	11.583
Resid.	LC-P9	A	0–13	9.7	70.9	19.4	1.18	7	2.74	3.45	2.45	3.174
		AB	13–45	10.9	70.2	18.9	1.79	8.6	4.01	7.72	2.36	5.952
		B	45–73	8.7	71	20.3	1.99	10	3.17	7.16	1.59	7.01
		2Ab	73–88	5.2	88.4	6.4	1.3	10.3	2.98	4.7	1.15	6.745
		2Bb	88–114	68.6	15.3	16.1	2	10.3	3.24	3.69	0.33	4.497
Agric.	LC-P10	A	0–8	9.9	74.2	15.9	1.05	6.3	1.32	3.38	1.97	2.565
		AC	8–23	8.9	74.7	16.4	1.94	7.4	1.17	3.54	0.93	1.635
		2ABb	23–37	11.4	73.8	14.8	2.02	7	0.99	2.93	1.25	1.795
		2Bb	37–55	13	83.2	3.8	1.96	7.9	1	2.23	0.32	1.908
		2Cb	55–75	77.6	16.4	6	1.84	8.3	0.89	10.51	0	2.381
Agric.	LC-P11	A	0–6	9.2	68.8	22	1.8	6	1.21	8.92	2.26	3.848
		AC	6–17	10.1	71.7	18.2	1.3	7.1	1.28	7.76	0.92	1.587
		2ABb	17–36	10.9	70.2	18.9	1.95	7.3	1.03	10.76	0.86	1.771
		2Bb	36–75	4.6	91.1	4.3	1.42	7.6	0.65	11.84	0.62	1.635
		2Cb	75–90	76.3	16.9	6.8	-	7.6	0.73	11.66	0.35	1.499
Resid.	LC-P12	A	0–11	9.3	72.8	17.9	1.19	6.3	1.49	13.44	2.03	1.719
		C	11–24	75.4	17.4	7.2	-	7.2	1.53	12.85	1	1.19
		2C1	72–87	92.6	4.3	3.1	-	8	1.56	12.72	0.07	1.226
		2C2	87–99	12.7	75	12.3	-	8.6	2.37	14.15	0.83	2.822
		3Ab	99–110	1	78.8	20.2	1.53	8.9	1.82	5.59	1.34	3.407
		3Bb	110–159	7.2	73.3	19.5	1.42	8.9	1.75	9.69	1.82	4.629

Note. Hz: horizon; P (a): available phosphate; OP: organic phosphate; OM: organic matter; Ca (a): available calcium.

settlements were located in the base of the lower section of the H2 unit, on top of a paleosoil dated to 2480 ± 110 BP (Sa) by its organic matter content (Sampietro Vattuone, 2010), and developed after the volcanic ashes V1 were sedimented (Figure 2b, profile z6). This paleosoil formed an extended surface across the entire Tafí Valley and was identified in the 26 profiles described in the El Tolar, La Costa, and El Potrerillo archaeological sites (Tables 2, 3, and 4, Figures 3 and 4). In the H2 unit, evidence of an increasing accumulation rate during its formation was observed. As mentioned above, the evidence of the first human settlements were in the base of the profiles, in which the upper sections are composed of silt-clayey sediments with interbedded gravels, or debris flows in the case of the northern area of the valley (Figure 2b). The increasing thickness of the H2 unit, detected in several profiles along the valley, was contemporary with the general erosion detected in the 2A horizon of the paleosoil (Sa), especially in areas intensively used for agricultural purposes (Tables 2, 3, and 4, Figures 3 and 4). This profile section normally contains eroded archaeological remains of rounded ceramic potsherds, eroded camelid bones, and scarce charcoals. The main species used for wood was *Alnus acuminata* Kunth. Other bushes and herbs have been identified as *Baccharis articulata* Lam., *Chuquiraga calchaquina* Cabrera, and *Chusquea lorentziana* Griseb (Aguirre, Peña Monné, & Sampietro Vattuone, in press).

From a physicochemical point of view, it was possible to establish that the three archaeological sites excavated have intrinsic features that allow each group to be identified according to the geomorphological unit and its parent material (Figure 5). In the case of El Tolar, the soils are neutral to lightly acid in the alluvial fan of the Blanco River mainly formed by debris flow processes. The soils described on the apex of the landform were better preserved (e.g., higher organic matter content, less erosion, and more porosity) than those where the agricultural production was higher (compacted soils and low organic matter). The profiles from El Tolar tend to be clayey and have the highest organic matter content from the whole. One residential unit of the El Tolar area was dated to 1560 ± 35 BP (1350–1452 cal BP; Sampietro Vattuone, 2010). The main responses of the paleosoil (Sa) to the human activity was the erosion of the 2A horizon, the loss of porosity, the increase in AD with associated formation of secondary clay coatings in the soil voids, and the loss of organic matter content and quality (Table 2, Figure 3). The La Costa 2 archaeological site is an alluvial fan formed by fluvial processes, where the matrix is mainly composed of the eroded and redeposited Pleistocene loess and blocks from the mountainous river head. These profiles tend to be alkaline, silt is the dominant texture, and porosity and organic matter are low. One residential unit from this archaeological site was dated to 1040 ± 20 BP (1016–1129 cal AD; Table 1). The human-driven features related to agricultural use were the loss of porosity, a loss of fine textured materials on the agricultural surfaces, and a loss of organic matter content (Table 3, Figure 4). Meanwhile, the El Potrerillo archaeological site was settled over a set of coalescent alluvial fans formed by small steep basins. The sedimentary process was dominated by debris flows. The soil profiles in this area have mainly sandy textures and are the richest profiles in terms of phosphate content; in general, the El Potrerillo profiles are similar and show less anthropic impact (Table 4).

Later settlements were also identified in the same H2 sedimentary unit. Among the pits excavated at La Costa 2, one mound of

TABLE 4 Soil profile descriptions from El Potrerillo archaeological site

Profiles		Hz.	Depth (cm)	Texture Sand (%)	Silt (%)	Clay (%)	Apparent density	pH	P (a) (ppm *100)	OP (ppm *1,000)	OM (%)	Ca (a) (ppm*10^5)
Agric	EP-P1	A	0–14	68.2	18.9	12.9	1.93	5.8	1.4	21.48	2.77	1.142
		AB	14–29	68.2	19	12.8	1.97	6.3	1.59	16.05	1.68	1.371
		C	29–34	66.3	19.1	14.6	-	6.5	1.28	17.68	1	0.914
Agric.	EP-P2	A	0–11	67.8	19.3	12.9	1.13	5.7	1.03	19.72	2.38	0.89
		BC	11–26	70.4	18.5	11.1	1.41	5.9	1.22	19.34	1.88	1.218
		2ABb	26–39	69.5	16.7	13.8	1.33	6.1	1.35	17.73	1.43	1.189
		2Bb	39–49	69.7	16.1	14.2	1.14	6.2	1.39	17.71	0.75	1.154
Agric.	EP-P3	A	0–19	68	17.2	14.8	1.58	5.4	1.73	22.53	3.64	1.066
		BC	19–33	68.6	18.3	13.1	-	5.8	1.4	18.7	1.31	1.13
		2ABb	33–55	69.2	17.5	13.3	1.9	6.3	1.52	21.95	0.65	1.34
		2Bb	55–65	46.8	9.5	43.7	1.95	6.3	1.62	15.22	0.55	1.395
		2Cb	65–80	67.9	18.3	13.9	-	6	0.87	17.51	0.46	1.876
Agric.	EP-P4	A	0–10	66.3	19.1	14.6	1.47	5.9	1.14	22.66	2.94	0.954
		AC	10–25	66.8	18.7	14.5	1.63	5.8	1.07	18.19	2.35	1.142
		C	25–42	67.2	18.1	14.7	1.38	5.8	1.4	18.2	1.01	1.096
		2Ab	42–55	67.8	17.7	14.5	-	6.2	1.09	22.09	0.65	0.577
		2BCb	55–65	94.1	3.8	2.1	1.11	6.5	1.45	21.43	0.39	1.154
Agric.	EP-P5	A	0–4	68.2	17.8	14	1.84	5.2	1.3	16.76	1.86	1.09
		BC	4–19	68.7	17.2	14.1	1.9	5.8	2.11	19.73	1.75	1.371
		C	19–27	92.3	4.5	3.2	-	6.3	1.7	23.12	0.59	1.135
		2ABb	27–35	67.9	17.3	14.8	1.33	6.4	1.65	21.9	0.59	1.301
		2Bb	35–59	67.8	17.2	15	1.29	6.8	1.27	24.33	0.46	1.499
Agric.	EP-P6	A	0–4	68	16.9	15.1	1.78	5	1.59	20.89	2.89	0.837
		AB	4–16	67.2	16.7	16.1	1.8	5.2	1.2	15.68	1.96	0.974
		C	16–35	92.5	4.9	2.6	-	6	1.08	16.91	0.8	1.172
		2ABb	35–45	66.8	17.5	15.7	2.11	6.1	1.46	19.68	0.37	1.587
		ABb	45–59	66.9	17.3	15.8	2.05	6.4	1.89	26.39	0.38	1.523

Note. Hz: horizon; P (a): available phosphate; OP: organic phosphate; OM: organic matter; Ca (a): available calcium.

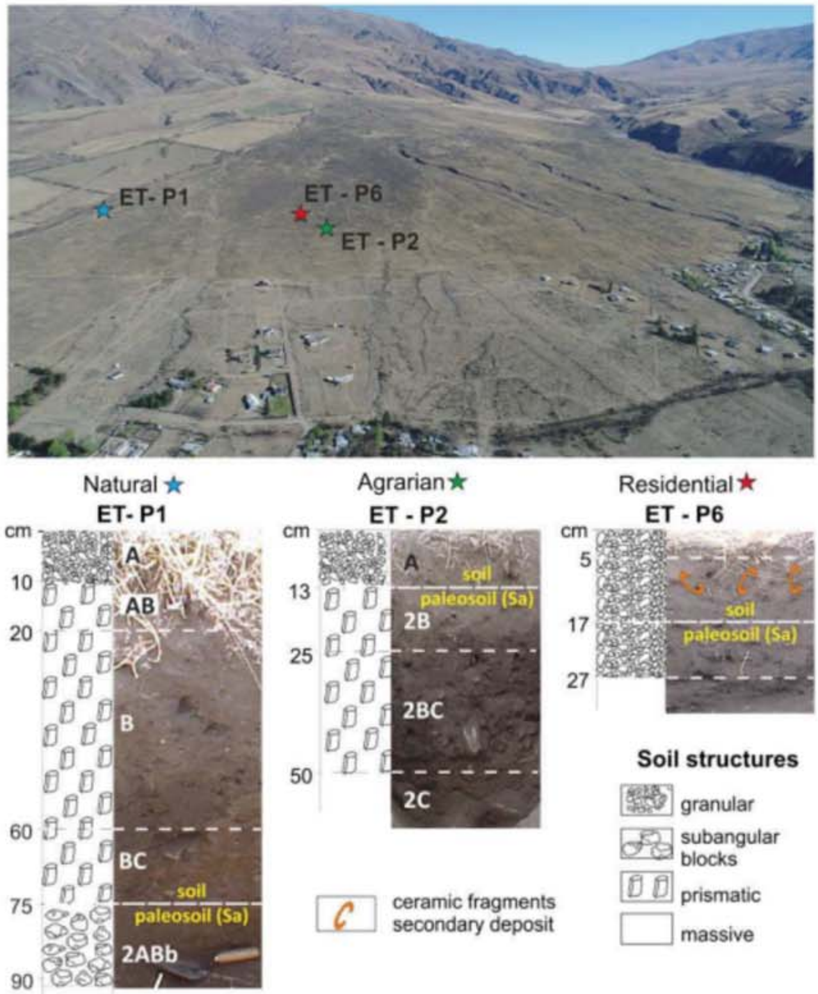

FIGURE 3 General view of El Tolar archaeological site settled over Blanco River alluvial fan, and typical soil profiles in natural, agrarian, and residential contexts (for detailed descriptions, see text and Table 2) [Colour figure can be viewed at wileyonlinelibrary.com]

stones was excavated to gain a better understanding of the inner structure of these kinds of accumulations. Almost no archaeological materials were recovered, but the presence of a few camelid bones allows the base and the top of the accumulation to be dated. The dated ages were 2070 ± 20 BP (2010–1933 cal BP; AA100098) and 640 ± 20 BP (629–554 cal BP; AA100099; Table 1), suggesting that the space was used for a long time. Moreover, a secondary archaeological accumulation sampled from a La Costa 2 H2 slope profile was dated to 630 ± 30 BP (630–547 cal BP; Sampietro-Vattuone & Peña-Monné, 2016).

6 | DISCUSSION

Sedimentary records with similar characteristics to those previously described for the dryland environments of the Tafí Valley provided information for studies focused on discerning the importance of climatic and/or human influence on the sedimentary record. This is the case in the Mediterranean basins, Southwest United States, and South America (Kulemeyer et al., 2013; Onken, Cook, Youberg, Philip, & Pearthree, 2014; Peña-Monné, Julián, Chueca, Echeverría, & Ángeles, 2004; among others).

Our results allow the determination of a set of features related to human-driven processes triggered by land use change in an increasingly populated landscape. The earliest evidence of a human population in the Tafí Valley dates from 2345 to 2159 cal BP (González & Núñez Regueiro, 1960); however, the area could have been previously occupied, since there was an earlier settlement located in a ravine close to our study area, which dated to 7420 ± 25 BP (Martínez, Mauri, Mercuri, Caria, & Oliszewski, 2013). The record of the datings until present shows a consistent continuum in the occupations until 390 ± 40 BP (487–328 cal BP; Manasse, 2012), almost contemporary with the arrival of the Spaniards (Figure 6). However, there is a gap in the radiocarbon datings of about two centuries, which is coincident with the end of the Formative Period settlements and the earliest Late Period. It is possible that this gap corresponds to sampling problems instead of a total abandoning of the area and some residential units may be overly represented in the dating dataset.

During the earliest Formative Period times, the gradual landscape domestication by the families that settled in the valley led to a gradual transformation to agricultural exploitation along the valley bottom, which gradually extended to the valley slopes according to the population pressure growth. There are some interesting data to support this proposition. In several cases, the Formative Period residential units were occupied for centuries. The settlement pattern involves a large circular central patio surrounded by circular rooms, and in some cases, they were very complex and included additional patios. The

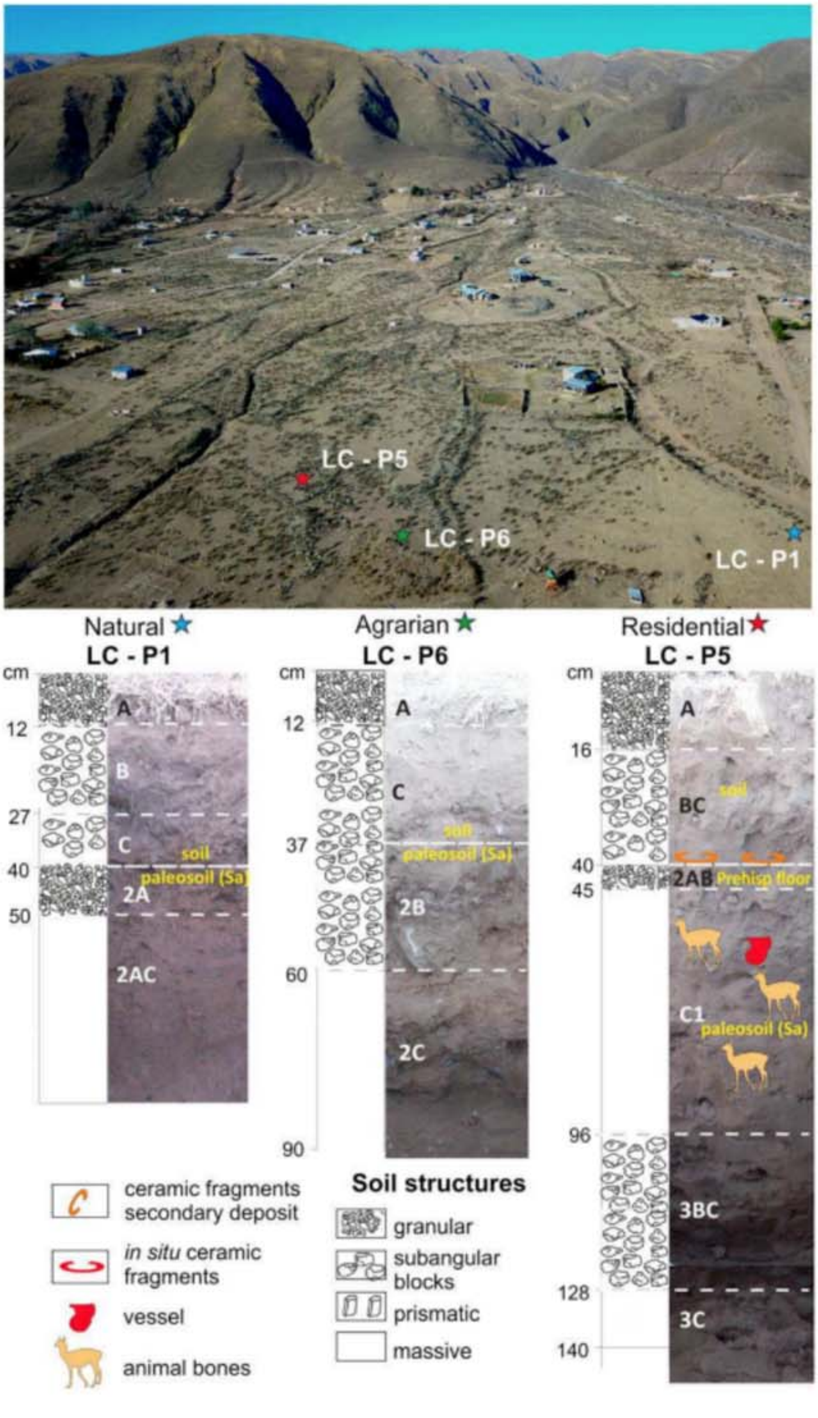

FIGURE 4 General view of La Costa 2 archaeological site settled over La Puerta River alluvial fan, and typical soil profiles in natural, agrarian, and residential contexts (for detailed descriptions, see text and Table 3) [Colour figure can be viewed at wileyonlinelibrary.com]

archaeological findings shows that the addition of rooms was according to the household growth as time went on. In some cases, a residential unit was inhabited for several centuries, as is the case, for example, of Unit 14 at La Bolsa, which was dated to between 1799 ± 37 BP and 1236 ± 37 BP (Salazar & Franco Salvi, 2009), or at El Rincón, which was dated to at least between 1700 ± 40 BP to 1440 ± 40 BP (Cuenya & García Azcárate, 2004). Another interesting example is from a nearby valley named La Ciénega, where the occupation of a residential unit was dated to at least between 1970 ± 120 BP and 1550 ± 80 BP (Cremonte, 1996). Even though there are no demographic studies until now, it was possible that population growth led to a gradual expansion of modified landscapes with a high persistence in the use of previously domesticated spaces; this process was accompanied by an increasing population pressure over the resources. The landscape modification was related to the clearing of forests in the lower sectors of the valley, followed by an intensive agricultural purpose modification by the construction of terraces in the alluvial fans, especially the alluvial fans with smaller gradients in the southern sector of the valley.

The main resource impacted by the agricultural activities was the soil (Sa) that formed at the beginning of the Upper Holocene, under the wet and cold conditions of the 2.8 Bond event (Bond et al., 1997; Figure 6). In general, the systematization of tillage fields by the construction of terraces, as well as plowing and grazing,

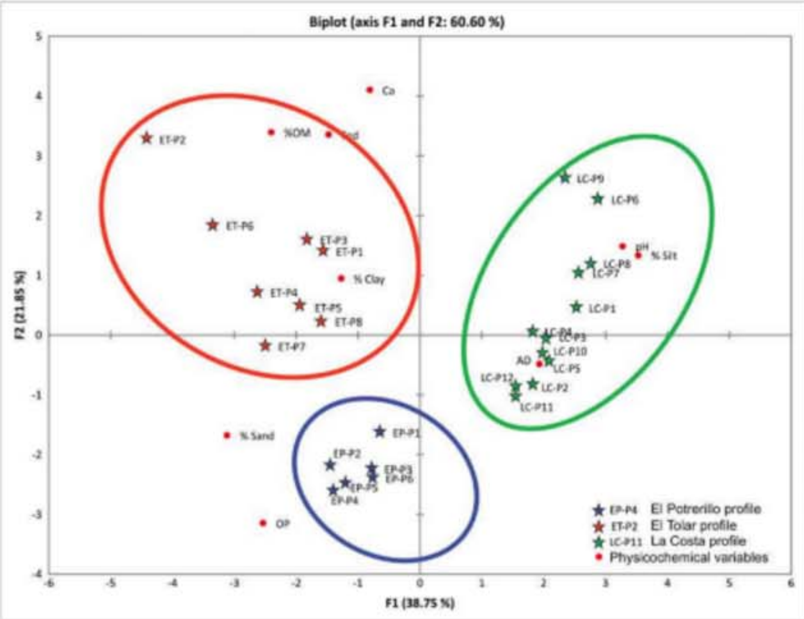

FIGURE 5 Principal components analysis from the physicochemical results obtained from the agrarian archaeological sites of El Tolar, La Costa, and El Potrerillo [Colour figure can be viewed at wileyonlinelibrary.com]

introduces several impacts on the landscape that could be positive, negative, or neutral (Sandor, 2006). The information gathered from all profiles suggests a deficiency in soil management that seems to have severally eroded and degraded the soil during Prehispanic times, increased the accumulation rate of the H2 profile sections (Figure 2), and developed the H2 deposits that created wide and low gradient surfaces across the entire valley (Figure 1). Other outstanding features related to the soil degradation present in this valley are the high nutrient variability among the profiles of each geomorphological unit, compaction, and organic matter loss. Among these variables, continuous tillage and harvesting affected the soil porosity and nutrient availability, respectively.

Other valleys from Northwest Argentina show similar erosional processes and have accumulation units equivalent to the H2 unit defined in this study. This is the case of El Bolsón, located in the eastern border of the Puna. The valley shows Formative Period archaeological settlements since ca. 2000 BP (Meléndez, Kulemeyer, & Quesada, 2017). According to Kulemeyer et al. (2013), the accumulation rate of sediments at Laguna Cotagua has increased up to 10 times since 1420 ± 58 BP. In addition, since that date, pollen records showed anthropic disturbances due to the presence of Chenopodiaceae, Malvaceae, and Gomphrena. These increased rates are also accompanied by the formation of accumulations of fine sediments in several ravines of the valley, dated to 1391 ± 36 BP, 1111 ± 34 BP, and 818 ± 36 BP by the presence of interstratified archaeological remains, contemporary with the formation of the H2 accumulations of the Tafí Valley. These accumulations show accelerated aggradation from ca. 1300 AD (Meléndez et al., 2017). From a paleoenvironmental point of view, the Laguna Cotagua pollen record, which covers a time-span between 5581 ± 40 BP and 345 ± 59 BP, showed that the environment in the region tended to be warm and wet until 1275 AD, coincident with the paleosoil (Sa) development in the Tafí Valley. After 1275 AD, aridity increased until the establishment of the present dry conditions. The northern sector of the El Bolsón Valley was invaded by dunes around ca. 1300–1400 AD, which covered the river heads and slopes. Meanwhile, in the southern section of the valley, an incision phase was established cutting-up the previously deposited accumulations (Meléndez et al., 2017). Closer to our study area, at the Cafayate dune field, Peña-Monné et al. (2015) determined that there was one period of dune activation in the area dated to ca. 1000–1100 AD (Medieval Climatic Anomaly), followed by three intervals during the Little Ice Age: 1300–1420 AD, 1540–1650 AD, and 1740–1830 AD (Figure 6).

Meanwhile, in Antofagasta de la Sierra, located in the Southern Puna of Northwest Argentina, it was established that water availability was highly variable during the Upper Holocene (Grana, Tchilinguirian, Olivera, Laprida, & Maidana, 2016). The period between 3500 and 1600 cal BP was characterized by the development of wetter environments in rivers (3200–1400 cal BP) and peats (2900–1450 cal BP) in this area. During those times, the population tended to be settled in the valley bottom areas, especially after ca. 2100 BP, which was associated with the establishment of productive economies and a mobility system organized around pastoralism, named 'dynamic sedentism' by Olivera (2012). The system was established to take advantage of the several wetlands available in the otherwise harsh region. After 1600 cal BP, erosion, or at least the cessation of soil formation occurred, and previous peat areas were covered by debris flow deposits of more than 1 m thick. In the northern sector of Laguna Colorada, a dune field was developed after 1442 cal BP (Grana et al., 2016). Water availability was restricted, and according to archaeological evidence, it is possible that the population continued to increase and that all microareas of Antofagasta de la Sierra were intensively occupied developing a 'specialized exploitation of space' related to the agropastoral way of life. Intensive incision processes affected the older valley bottom surfaces, exposing up to 3-m-high outcrops (Grana et al., 2016). According to the dating results, the establishment of wetter environments in Antofagasta de la Sierra could be correlated with the paleosoil (Sa) dated ca. 2500 BP in Tafí Valley. The accumulations that were deposited later could be equivalent to the H2 unit of the study area. These aggradational units were also related to the

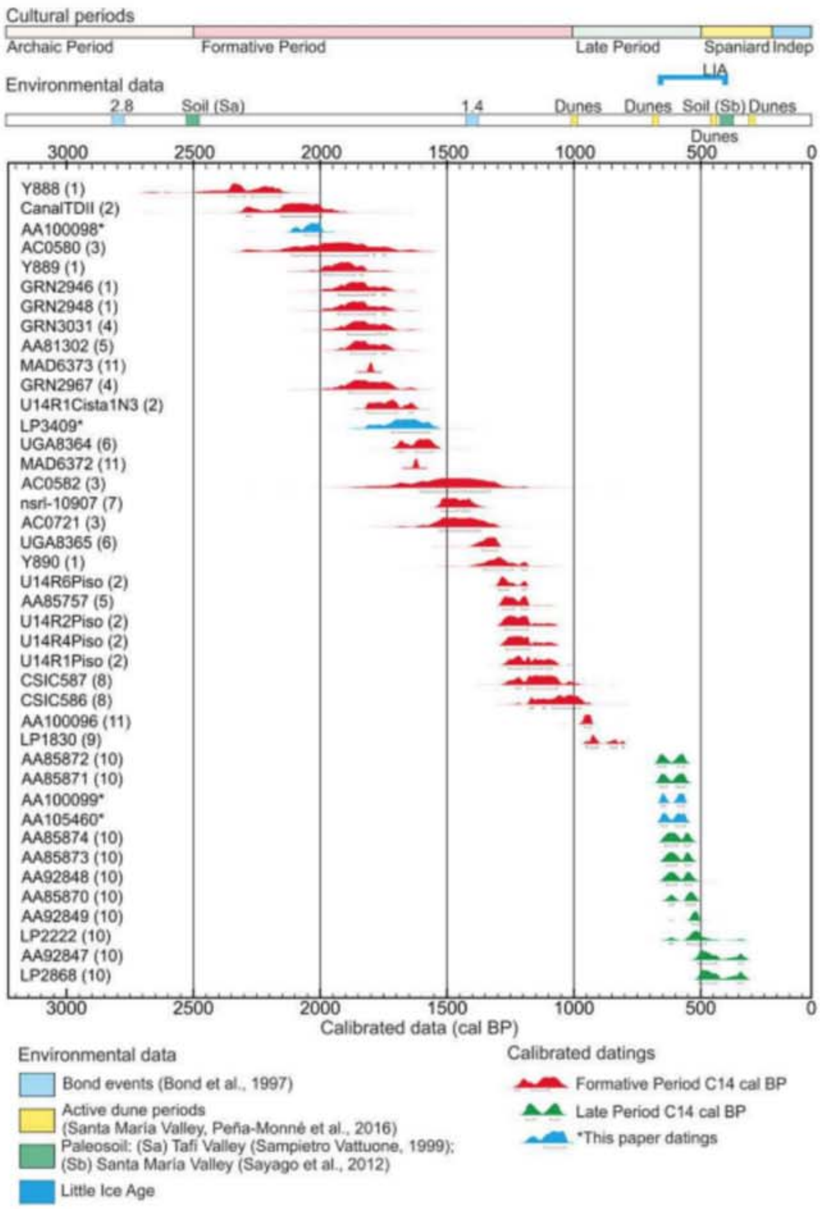

FIGURE 6 Absolute datings obtained from archaeological sites from Tafí valley by several authors and (*) on this paper representing different cultural stages involved in the development of H2 accumulations and related to global and regional environmental changes: (1) González & Núñez Regueiro, 1960; (2) Salazar & Franco Salvi, 2009; (3) Cremonte, 1996; (4) González, 1961–1964; (5) Franco Salvi et al., 2014; (6) Cuenya & García Azcárate; (7) Sampietro Vattuone, 2010; (8) Berberián et al., 1988; (9) Franco Salvi et al., 2014; (10) Manasse, 2012 [Colour figure can be viewed at wileyonlinelibrary.com]

intensive exploitation of the environment under the later drier conditions. It is also suggestive that the dune field of Laguna Colorada developed after 1442 cal BP. Interestingly, at ca.1400 BP in both Antofagasta de la Sierra and El Bolsón, there is a change in the sedimentary process coincident with the global 1.4 Bond event (Bond et al., 1997). Finally, under such dry environmental conditions, between 600 and 300 BP, there was a wetter pulse that enabled the development of a paleosoil. This trend was also present in the Santa María Valley, where the development of a soil (Sb) dated to 435 ± 15 BP (501–340 cal BP) was coincident with a population territorial expansion (Sayago, Collantes, & Niz, 2012).

In a wider geographical framework, studies in the Chaco piedmont (through the eastern piedmont of the Subandean Ranges) and the Amazonian basin have shown the intense human impact on ecosystems by the increasing modification of natural landscapes, especially during the last 2000 years (May, Preusser, Schellenberger, Zech, & Veit, 2010). According to Kulemeyer et al. (2013), the main river migrations by avulsion reflects the riverbed infilling during the Upper Holocene due to the high amount of sediment load produced by human activities from the Andean region.

Considering all the contextual data, the Tafí Valley provides a detailed example of a complex landscape derived from human-driven processes influenced by the Upper Holocene climate oscillations, which could be the most complete study-case analyzed in the region. The success of the agricultural way of life adopted during the Formative triggered a gradual demographic rise followed by increasing landscape domestication. The most impacting activities were likely grazing, tilling, and forest clearing for various purposes. The construction of terraces was not enough to impede soil erosion, which was potentiated by tilling and the extractive effect of agricultural activities continuously performed over centuries. The system probably reached the limit of its charge capacity and environmental deterioration at the same time as the establishment of the Medieval Climatic Anomaly and the consequent loss of environmental sustainability. In the case of the Tafí Valley, it is possible that the sociocultural system collapsed, enabling the entrance of the Santa María people. These few domestic

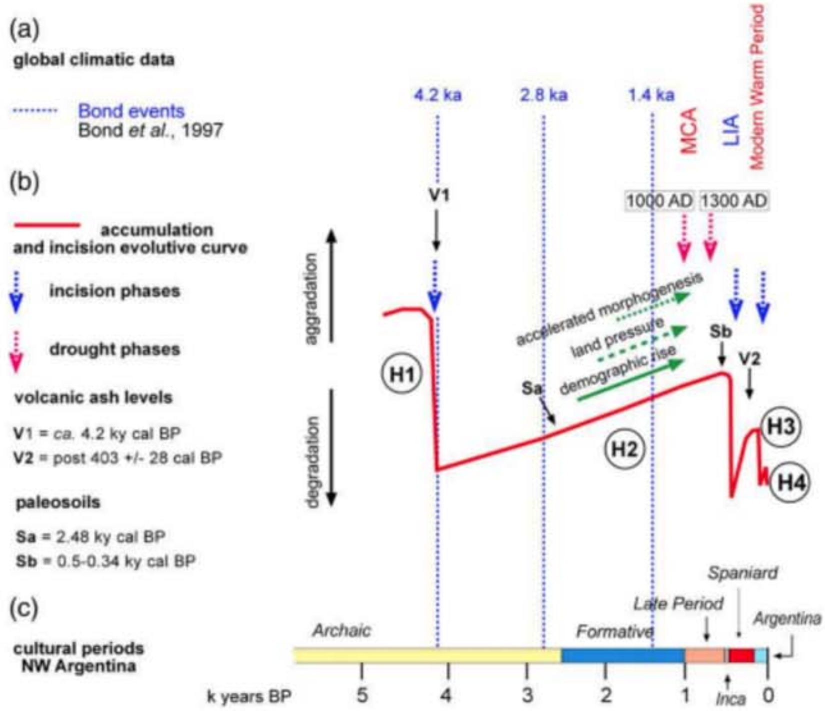

FIGURE 7 Graphical synthesis of the evolutionary degradation process during the Upper Holocene relating: (a) global climatic data; (b) accumulation/incision evolutionary curve, incision and drough phases, volcanic ash levels, and paleosoils; and (c) cultural periods. LIA: Little Ice Age [Colour figure can be viewed at wileyonlinelibrary.com]

units dispersed in the valley were probably dependent from the most populated settlements of the same culture in the Santa María Valley. Archaeological evidence points to a considerably degraded area with a low population density, where at least part of the agricultural spaces continued under exploitation. In general, the same environmental deterioration could be hypothesized in the rest of the drylands of Northwest Argentina.

7 | CONCLUSIONS

The human-driven geomorphological processes identified in Northwest Argentina are a clear example of how the sedentarism of the earliest Formative people and the introduction and adoption of agriculture practices has impacted the landscape. Characteristics of this impact include accelerated morphogenesis, primarily fine-grained accumulation sediments, the increasing thickness of the deposits, and human features interbedded in the profiles, from isolated materials to in situ occupations. These characteristics provide evidence that landscape degradation was a human-driven result that led to a general geomorphological modeling during the agricultural Prehispanic Period in contradiction to the established opinion that Prehispanic people lived in 'harmony' with the environment. It is necessary to include the intensity and persistence of the settlement occupations, especially during the Formative Period, and the features derived from the soil overexploitation recovered, in the case of the Tafí Valley, with the several agricultural profiles analyses showing erosion, compaction, and loss of organic matter and phosphates.

In a general interpretation (Figure 7), the success of the productive agricultural systems that expanded during the Formative led to a gradual increase in the demographic density, resulting in a rising population pressure on the territory, soil, and plant resources and a wide environmental deterioration of the drylands of Northwest Argentina. Activities such as soil and vegetation cover modification as well as overexploitation by tilling and overgrazing increased the erosion and over pressure on the vulnerable ecosystems. There were particularly harsh periods marked by the combination of these positive human-driven processes and climate changes, such as the droughts detected by several proxies at ~1,000 and 1,300 AD. The recognition of H2 accumulations due to wetter conditions in such varied environmental areas as the Puna (Antofagasta de la Sierra) and the intermountain valleys (Tafí and El Bolsón), followed by an increasing accumulation rate and finally an incision and unstable environmental period, has enabled us to propose that climate was not the only triggering factor and that humans had a greater influence on the landscape changes.

This geoarchaeological approach constitutes the first regional research of human-driven processes in the highlands of Northwest Argentina linking evolutionary processes involving human-landscape relationships and that constitutes a promising subject for future investigations.

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