Agricultural suitability and fertility in occidental piedmont of Calchaquíes Summits (Tucumán, Argentina)

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ARTICLE INFO

ABSTRACT

Our study area is located in the piedmont of Calchaquíes Summits (Tucumán Province, Northwest Argentina). The objectives of this paper are to improve the knowledge of Pre-Hispanic agricultural practices on landscape and soils, and to provide new knowledge about land fertility of agricultural areas, taking into account the environmental settings. Physical and chemical features, such as structure, texture, pH, calcium, organic and inorganic phosphorus, and available copper, manganese, and iron were taken into account. After photointerpretation and field surveys, two agricultural terraced geomorphological units were sampled. Samples were made in comparable off-site locations and the archaeological sites. After Principal Component Analysis, physicochemical analysis showed that texture is the most significant difference between the two archaeological sites. Agricultural practices introduced high chemical variations, despite the substantial differences between agricultural and off-site profiles. This is the first approach of this nature in Northwest Argentina.

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1. Introduction

Terrace agriculture has been recognized as one of the most important landscape transformations for crop production in harsh enviroments (Sandor, 2006). Nevertheless, little attention has been paid to soil quality changes, fertility evaluations, and landscape long-term results (Sandor and Eash, 1991). Several positive, negative, and neutral soil changes have been detectected in the drylands of Southwest Indian Agriculture fields in the USA, such as changes in soil landscape, physics and morphology, chemistry, biology, geomorphology, ecosystemic processes, and management of soils (Doolittle, 2000, 2006; Homburg et al., 2005; Norton et al., 2007; Schaafsma and Briggs, 2007; Homburg, 2010).

Northwest Argentina also had a long Pre-Hispanic agricultural tradition that was interrupted when the Spaniards arrived. A significant loss of knowledge and agronomical expertise was the consequence of this disruption in the process of agricultural evolution. As population diminished, due to resistance wars and diseases, and as cultures were destroyed together with social organization, huge areas of productive arid agricultural highlands were abandoned. Less nutritious cultivars such as wheat were introduced, and quinoa, different kinds of potatoes and roots, among other important plants, were abandoned. New species of cattle, which were much more environmentally destructive than camelids, were also introduced, and overgrazing by extensive animal husbandry was the rule. After the discovery of silver mines in Bolivia, the area was intensively used for winter grazing for mules.

In this historical context, our aims were to improve our knowledge of agricultural Pre-Hispanic practices (from Formative to Regional Developments periods, *ca.* 500 BC – 1500 AD), and to provide new knowledge about land fertility of agricultural areas, taking into account the environmental settings.

Our study area, the occidental piedmont of Calchaquíes Summits (Yocavil Valley, Tucumán, NW Argentina) shares the historical process presented above. We will discuss the effects of terrace agriculture on lands and landscape since it was established in one of the sectors with the highest hydric deficit of Yocavil valley.

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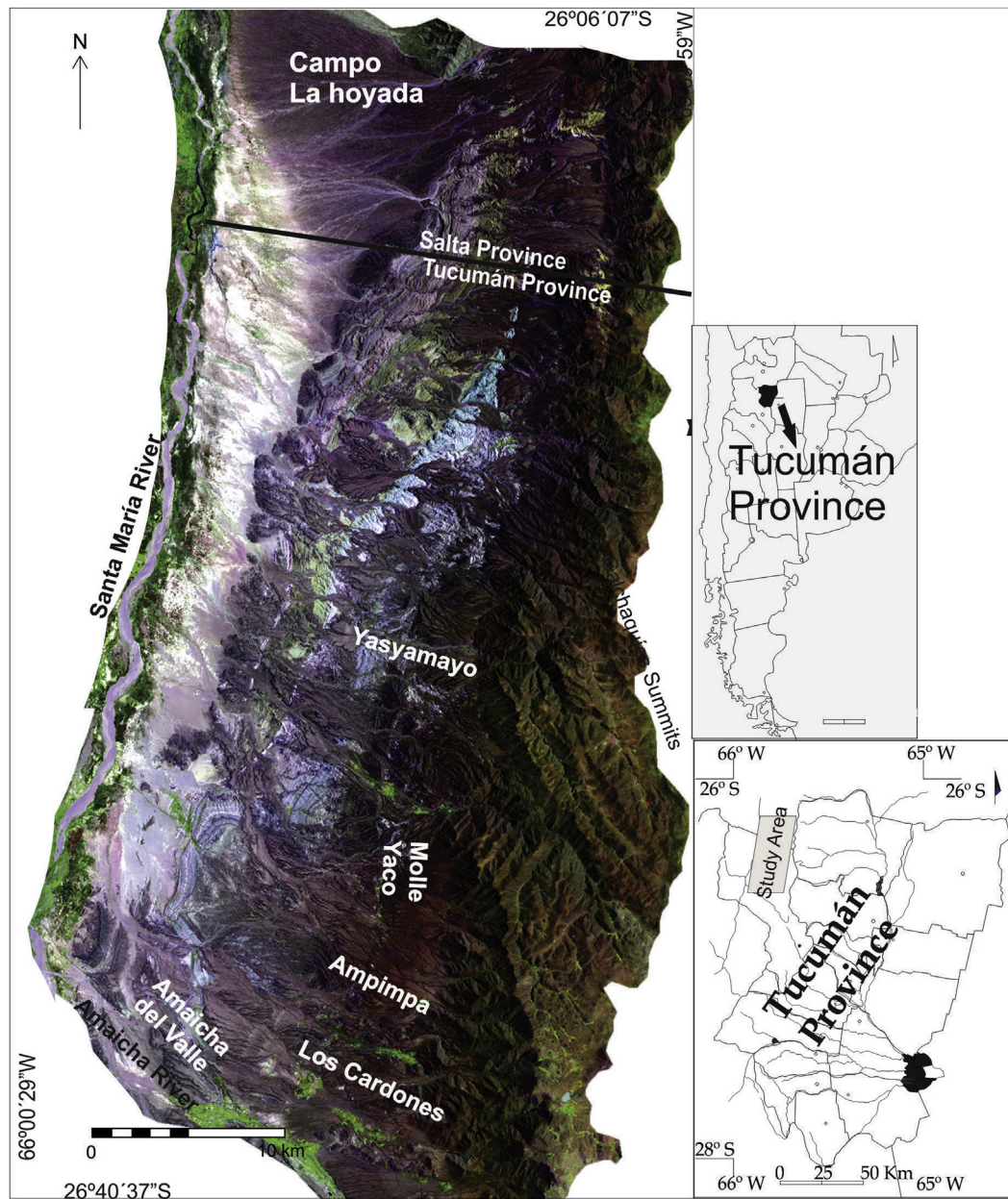
Fig. 1. Study area location.

The reconstruction of Pre-Hispanic agricultural practices developed and applied in these harsh environments over centuries would permit the recovery of agricultural areas that are inactive at present; with the information resulting from this study, it would be possible to propose productive alternatives to pauperized environmentally marginal human settlements. This is the first contribution on this matter for Northwest Argentina, especially considering soil/sediment geochemistry and land fertility reconstruction. In addition, the applied methodology constitutes a good example of the reconstruction of agricultural practices where traditional archaeological evidence is absent. The comparison of physico-chemical characteristics of terraced fields and marginal non-terraced areas makes it possible to reflect the agronomical impact, evaluate agricultural land fertility, and explore the direct and indirect changes caused by long-term agriculture in arid ecosystems.

1.1. Geographical and geological background

Yocavil valley is an elongated south-north oriented basin. In its Tucuman section, it borders on the Aconquija Mountain Range and Calchaquíes Summits to the east, and on the Quilmes Mountain Range to the west. Our study area is located in the southern and central part of the occidental piedmont of Calchaquíes Summits (Fig. 1). Annual rainfall is around 200 mm and potential evapo-transpiration values are more than 700 mm per year. The high water deficit, of around 500 mm per year, makes today's agriculture impossible without irrigation (Pietragalla and Corso, 2008).

The slopes of Calchaquíes Summit are made of metamorphic rocks (Puncoviscana Fm.), characterized by the presence of metamorphic basement of low and medium degree with granitic pluton intrusions. The typical mineral association is quartz, biotite, muscovite, chlorite, and garnets (Toselli and Rossi, 1998). Fluvial

and lacustrine sediments from the Miocene and Pliocene (Santa Maria Group) lie discordant over the piedmont (González et al., 2000).

Pleistocene deposits are of torrential fluvial origin, composed of coarse materials in the upper piedmont and sandy clay in the distal areas and fluvial margins of the central valley of Santa María River (González et al., 2000).

The Early Holocene is represented by debris flow deposits lying over the piedmont. In the bottom valley it is possible to identify sands, and fluvial silts. The presence of petrocalcic horizons in association with dunes is evidence of arid periods. The Middle Holocene, which was wetter at regional level, generated thick clastic sequences associated with alluvial fans or debris flow deposits caused by an increase in glacial and periglacial activity over mountain summits (Sayago et al., 1998a).

Geomorphological studies established that during the Pleistocene three glacis levels were formed. They lie discordant over Tertiary deposits and located in different altitudinal settings, reflecting climatic changes during their formation. More fluid currents formed alluvial fans in different depositional cycles during periods with more availability of solid charges in streams. Contemporaneously, streams coming from the Calchaquíes Summits formed secondary terraces over the Santa María river tributaries, digging old deposits and forming several depositional fluvial fan cycles. Finally, dunes were formed and later fixed by vegetation (Sampietro Vattuone and Neder, 2011).

Quaternary landform soils are Entisols with scarce or non-development of pedogenetic horizons whose properties derive from parent material. They are common in extreme climates. Within this soil order, it is possible to identify Typic Torriorthents whose moisture regime is Torric and where at best it is possible to distinguish a sequence of A-C horizons. Their depth is variable and they are composed of texturally diverse materials with coarse material accumulation (Sayago et al., 1998b).

1.2. Archaeological background

Yocavil valley has presented numerous cultural manifestations since the Pre-Hispanic period. Through the study of such evidence, it was possible to reconstruct the following cultural sequence.

The Earliest discovered settlements belong to hunter-gatherer populations (7000—2500 BP). It is possible to observe these settlements in the Amaicha River basin and adjacent areas, to the south of our study area (Cigliano, 1961, 1968; Hocsman et al., 2003; Somonte, 2007). More representative archaeological materials appear in open-sky sites. These present no stratification and are very difficult to locate chronologically.

Later, Formative Period (FP) settlements (2500—1000 BP) were identified, during which sedentism was established and agricultural practices spread, together with ceramic manufacture and camelid pastoralism. This period was followed by the Regional Developments Period (RDP) (1000—600 BP), characterized by high population growth, the construction of defensive structures in villages and the improvement of agricultural systems. Finally, the Inca Period (IP) (600—500 BP), when the Inca Empire expanded over extensive areas of Northwest Argentina generating changes in power system and space use.

Over the southern part of the occidental piedmont of Calchaquíes Summits, our study area, FP settlements were identified. These constructions are visible on surface, although fragmentary and subjacent to later constructions (Sosa, 1996—97, 1999; Aschero and Ribotta, 2007; Somonte, 2007). The typical settlement pattern is circular rooms constructed with dry stone walls without foundations. Rooms are dispersed on terraced agricultural fields. Radiocarbon data are 1180 ± 40 ^{14}C yr BP (UGA 8360), 1130 ± 40 ^{14}C

yr BP (UGA 8361) y 900 ± 70 ^{14}C yr BP (UGA 8359) (Aschero and Ribotta, 2007). Sosa (1996-97), who made a visual interpretation of aerial photographs of the area, concluded that there exist six FP *loci* located along Amaicha River. However, this work was not field-controlled and it is a non-stereoscopic visual interpretation, so these results are highly speculative and must be taken with caution.

Piedmont photointerpretation made it possible to identify archaeological settlements with different superficial features. They are composed of residential structures dispersed among agricultural areas with different morphologies. It is possible to distinguish between circular and rectangular units. These characteristics, together with collected ceramic fragments, allowed us to establish areas of FP and others, where FP and RDP are superimposed (Sampietro Vattuone and Neder, 2011). The only semi-urban settlement of the sector was studied by Rivolta (2005) and it belongs to RDP.

There exists a differential distribution of settlements by period. Alluvial fans, formed by small basins, were occupied only during FP, while to the south and north of that landform, an area where river basins are bigger, settlements of the two archaeological periods are superimposed. This phenomenon was attributed to water availability changes over time (Sampietro Vattuone and Neder, 2011).

Regarding cultivars identified in the area, Arreguez et al. (2010) recovered archaeobotanic samples of kidney bean (*Phaseolus vulgaris var. vulgaris*), maize (*Zea mays var. oryzaea* and *Z. mays var. indurate*). They also found some botanical debris of amaranth family (*Amarantaceae*), which is in process of identification (Oliszewski, N., personal communication, 2013). These samples were collected in Los Corrales cave, located in the north of Aconquija Range, only 5 km south of our study area, and they are in exceptional conservation conditions. Radiocarbon data of the cave are from 2100 ± 200 ^{14}C yr BP (UGA 01616) to 590 ± 30 ^{14}C yr BP (UGA 06599), comprising FP and RDP (Oliszewski et al., 2008).

Similarly, Cano (2011) identified archaeobotanical remains of maize (*Zea mays*), kidney bean (*Phaseolus vulgaris*), squash (*Cucurbita* sp.), and amaranth and/or quinoa (*Chenopodium* sp. and/or *Amaranthus* sp.) over the piedmont of Quilmes Range, around 10 km to the west of our study area, at El Pichao archaeological site (RDP).

1.3. Geoarchaeology of agricultural terraces, soils, and fertility

There is no doubt that terracing constructed by man modifies soils (Zougmoré et al., 2002; Vancampenohout et al., 2006; Nyssen et al., 2007; among others). However, there are few pedological studies on Pre-Hispanic agricultural terraces of Northwest Argentina (Roldán, 2004; Ogas et al., 2006; Roldán et al., 2008; Williams et al., 2010; Caria et al., 2010; Korstanje and Cuenya, 2008; Sampietro Vattuone et al., 2011).

In this context, and for a better understanding, it is necessary to introduce some preliminary definitions. Sandor (2006) proposed four fundamental types of interventions over landscape with agricultural purposes: a) bench terraces, typical of very steep areas; b) flooded terraces, like those in the Asiatic Southeast; c) run-off terraces, common in arid and semiarid regions; and d) lynchettes and rideaux fields, like those in northwest Europe.

Terrace function is to create a stable topography for agriculture, retain soils and control the erosion, accumulate soils by natural or manual filling sedimentation, control water (from run-off management to irrigation), and modify microclimate (Sandor, 2006). Terrace field construction involves slope segmentation through topographic steps composed of contention walls and fields developed behind the walls. The basic constructive elements of an agricultural terrace are the base of the terrace, the wall, and the soil body (van Breemen et al., 1970, as cited in Sandor, 2006).

Traditional processes to construct soil body could be divided into alluvial/colluvial sedimentation and manual filling. According to Denevan (1980), these two categories make it possible to distinguish between agricultural terraces for the former case and cropping platforms (*andenes* in Spanish) for the latter.

Agricultural terrace construction could have positive and negative effects on landscape. If one considers only run-off terraces, which are typical of our research area, the most characteristic features among geomorphological processes are the episodic deposition of fluvial and colluvial sediments and decreasing slopes. Regarding lands, terraces produce small dams and in some cases laminar erosion of the basins involved; the soil morphology changes, buried horizons appear, and humidity and potential water retention increases. Concerning chemical alterations, it is possible to verify an increase or reduction in organic carbon, nitrogen, phosphorous, and pH. From a biological point of view, there is an increase in organic debris and microbial activity because of sedimentation and humidity (Sandor, 2006).

Among positive physical and morphological soil changes after terrace construction, it is possible to identify a thickening of A horizons and root volume with medium texture, as well as an increase in available water capacity and content; among negative effects, it is possible to identify soil erosion, soil structure degradation and compaction, and even soil crusting (Homburg, 2010; Sandor et al., 1990, 2007).

Changes in soil chemistry are also possible after terracing. Among positive features, it is possible to identify cases of organic carbon, nitrogen, and phosphorous increase or replenishment through runoff or irrigation water and sediment, adequate pH for nutrient availability, and few examples of increase in other nutrients; negative changes included the usual decrease in organic carbon, total and available nitrogen and phosphorous (Homburg, 1992; Sullivan, 2000; Sandor et al., 2007).

The comparison between physicochemical observations of profiles that evolved inside an agricultural runoff terrace system with natural profiles from similar geomorphological settings makes it possible to evaluate soil fertility. Exploring the direct and indirect changes caused inside terraced lands gives an idea of their fertility to produce specific crops, soil fertility meaning the ability of the agricultural land to supply essential elements for plant growth without toxic concentrations of any elements (Foth, 1990).

1.4. Andean crops and agronomical requirements

Among the variety of crops found by diverse methodologies in archaeological contexts, both close to our study area and in similar environments, the following crops stand out because of their recurrence and nutritional value: potato (*Solanum tuberosum*), maize (*Zea mais*), kidney bean (*Phaseolus vulgaris*), amaranth (*Amaranthus caudatus*), and quinoa (*Chenopodium quinoa*).

Each of these crops has specific agronomical requirements. In general terms, potato (*S. tuberosum*) prefers well drained friable soils, with 25–30 cm depth, and pH between 5 and 5.4. Heavy soils with lime and clay are less adequate for this crop (Tapia and Fries, 2007). Maize (*Zea mays*) prefers fertile soils that are neither acid nor too sloped, with no less than 2.5% of organic matter, and with good drainage. According to the surveys made, Maize is one of the few Andean crops that are always fertilized (Tapia and Fries, 2007). Kidney beans (*Phaseolus vulgaris*) prefer loamy soils with good aeration and infiltration. It develops well with around 400 mm of precipitations. Amaranth (*A. caudatus*) prefers loamy soils with good drainage, pH lightly acid up to 8. Under 600 mm of rainfall, it needs irrigation (Tapia, 2000). Quinoa (*C. quinoa*) is a very rustic crop that could be produced in poor soils, with inferior yields. It prefers loamy soils that are not too deep, with high organic matter

concentration and good drainage. The pH must be neutral or lightly alkaline but depending on the variety this crop tolerates pH from 8 to 4.5. In general quinoa does not require fertilizers. Climatic needs are very variable, depending on its variety, and it may grow with 200–2000 mm of rainfall and lightly frozen (Tapia, 2000).

To better understand productive possibilities, it is important to know that, according to surveys conducted in the Peruvian and Bolivian Andes, crop association is normal and pursues different objectives. Maize (*Zea mais*) is a complementary crop of kidney bean (*Phaseolus vulgaris*) because the bacteria growing in the bean roots fix nitrogen, favoring its bioavailability, while the maize straw restores the phosphorous consumed by kidney beans; in addition, the association between maize and quinoa (*C. quinoa*) facilitates pest control. It is common to find several kinds of potatoes planted together and with maize (*Zea mais*), tarwi (*Lupinus mutabilis*) or quinoa (*C. quinoa*). The rotation of crops, even with different intervals of land rest, is also customary (Tapia and Fries, 2007).

1.5. Methodology

We started the photointerpretation of the study area using aerial photographs scale 1:50.000 (SPARTAM AIR SERVICE, 1969). Although this is not the best scale for archaeological purposes, it is the only one available for the region. We constructed our thematic cartography including geomorphological and archaeological maps.

Because of the presence of agricultural terraces, two geomorphological units were selected as samples, a glacis (Yasyamayo site, Y) and an alluvial fan (Molle Yaco site, MY). Two longitudinal transects along the slopes were made over the sites, on each geomorphological unit, to identify diagnostic ceramic fragments from surface and to establish the best sampling points, taking into account the state of preservation and representativeness of the agricultural terraces.

To sample agrarian sectors, we took into consideration that comparing the evolution of the profiles with and without agriculture requires samples sharing the same environmental history. Therefore, we selected locations belonging to the same geomorphological unit and with similar altitudes. Moreover, to obtain highly representative samples of the anthropic impact produced by human practices over agricultural lands, we excavated places immediately upslope behind terrace walls.

We hand-excavated a total of 15 pits, seven in Yasyamayo (three off-site as control profiles, one in a circular unit related to one terrace, and three against terrace walls). We excavated other eight pits in Molle Yaco (three off-site and five against walls).

Profiles were described following Etchevere's rules for soil recognition (Etchevere, 1976). When profiles were not recognizable horizons (typical for Entisols), we sampled the central section of each layer identified. If it was impossible to identify any layer, we sampled every 10 cm. We collected 63 bulk samples.

1.6. Sample physicochemical treatment

Bulk samples were air-dried and sieved. We took into consideration texture (Bouyoucos, 1936) and structure among physical parameters, together with organic matter (%OM), to have an idea of agricultural land quality. According to their diagnostic value, macro-nutrients such as available phosphorus (P_a) and calcium (Ca), together with micronutrients such as available iron (Fe_a), copper (Cu_a), and manganese (Mn_a), were also determined. These elements are also active in geochemical and bioarchaeological processes (Buckman and Brady, 1977). Organic phosphorous (P_o) it has been determined that organic phosphorus is an indicator of human activity as well as the kind of activity, considering that it is a

compound that tends to be quickly associated with other soil elements and it is very stable over centuries (Terry et al., 2000).

Organic matter was determined by adding a specified volume of acidic dichromate solution reacting with 50 mg of each bulk sample in order to oxidize the OM. The oxidation step was then followed by titration of the excess dichromate solution with ferrous sulfate, which gave a volume of ferrous sulfate in mL. The OM was calculated using the difference between the total volumes of dichromate added and the volume titrated after reaction (Walkley and Black, 1934).

Available phosphorus was determined by the molybdenum blue method. Total phosphorus was determined with the same method after sample digestion with sulfuric acid. Organic phosphorus was estimated by the difference between both of them. Calcium was determined by the complexiometric method using EDTA Na_2 (ethylenediaminetetraacetic acid disodium salt) and murexide (Sampietro and Vattuone, 2005). Available micronutrients, like iron, copper, and manganese, not only provide sustenance for plants and are regulators of some of their functions, but also collaborate in plant adaptation to the environment. These micronutrients tend to form chelates, which are considered available to plants (Bohn et al., 1993). Available iron was determined by soil extraction with ammonium acetate-acetic acid and reduction with hydroxylamine chlorhydrate. Optical density was read at 508 nm in a Beckman DU 650 spectrophotometer (Roldán et al., 2005). Available copper was determined by sample extraction with ammonium acetate-acetic acid and treatment with EDTA Na_2 and ammonium citrate. Then, it was titrated with cresol red and ammonium hydroxyde. To separate and eliminate the organic phase, sodium diethyldithiocarbamate and carbon tetrachloride were added. Optical density was read in a spectrophotometer at 440 nm in a Beckman DU 650 spectrophotometer (Roldán et al., 2005). Manganese was determined in samples by treatment with neutral ammonium acetate. After oxidation of the organic matter with hydrogen peroxide, the optical density was read in a spectrophotometer at 540 nm (Roldán et al., 2005).

1.7. Statistical procedure

The pattern recognition of variability and similarities among profiles and variables was done with Principal Component Analysis (PCA) using Xlstat 2009 for Excel. This statistical technique is used for: (a) making an exploratory analysis of data; (b) reducing the number of variables comprised in a dataset while retaining the variability in the data; (c) identifying hidden patterns in the data; and (d) classifying them according to how much of the information, stored in the data, they account for.

The technique serves to intuitively find the causes of the variability of a data set and to sort them according to its relevance. It is very appropriate for this case of study where Pre-Hispanic land treatment is still unknown, and the most important land variables, such as agricultural practice responses, are still not determined (Jolliffe, 2002).

Principal Component Analysis is a powerful, linear, unsupervised, pattern recognition technique used as a mathematical tool for analyzing, classifying and reducing the dimensionality of numerical data sets in a multivariate problem (Brereton, 2003; Jolliffe, 2002; Antonic et al., 2003; Hopke, 2003). In the unsupervised pattern recognition, there is no a priori information of the classification of any of the objects, and the pattern recognition method is used to find the group structure in the data required to find the groups of similar objects. The loading of a single variable indicates how much that variable participates in defining the PC (the squares of the loadings indicate their percentage in the PC). Typically, PCA decomposes the primary data matrix by projecting the multidimensional data set onto a new coordinate base formed by the orthogonal directions with maximum variance in the data. The eigenvectors of the data matrix are called Principal Components (PCs) and they are mutually uncorrelated. The PCs are ordered, so that PC1 displays the greatest amount of variance, followed by the next greatest PC2 and so on. The magnitude of each eigenvector is expressed by its own eigenvalue, which gives a measure of the variance related to that principal component. As a result of the coordinate change, it is possible to achieve a data dimensionality reduction in the most significant principal components and to eliminate the less important ones without any considerable information loss (Dragović and Onjia, 2006). These uncorrelated variables are linear combinations of the original variables and can be used to express the data in a reduced form. The main features of PCA are the coordinates of the data in the new base (score plot) and the contribution to each component of the variable (loading plot). The score plot is usually used for studying the classification of the data clusters, while the loading plots can be used for giving information on the relative importance of the variable to each principal component and their mutual correlation (Penza et al., 2002). The technique has three effects: (a) it orthogonalizes the components of the input vectors (so that they are uncorrelated with each other); (b) it orders the resulting orthogonal components (PCs) so that those with the largest variation come first; (c) and it eliminates those components which contribute least to the variation in the data set (Jolliffe, 2002).

APC is a method based on the correlation of constructed variables (PCs) from original data according to the variance of the original dataset. As a result, this technique could be applied when data are not dimensionally homogeneous or when their magnitude order is not the same (Jolliffe, 2002).

The coordinates of the new data base give the composition of subjacent factors lying under the original data. Previous dataset requirements are (a) variable continuity, and (b) individual number higher than number of variables considered for the analysis (Jolliffe, 2002).

To introduce the data into the software, we calculated the average values for each variable in each profile. We used biplot graphics that represent the distribution of the profiles together with the considered variables to reflect the most significant variables of the agricultural system and the way they grouped.

2. Results

2.1. Archaeology, geomorphology and physicochemistry

Molle Yaco archaeological site is located in an alluvial fan formed during the Early Holocene (Sampietro Vattuone and Neder, 2011), where archaeological settlements belong to the Formative Period (Sampietro Vattuone et al., 2012).

Through the use of a DEM, we determined that dominant slopes are inclined (7–13 %) and moderately abrupt (13–20 %), with west exposition (Fig. 2). Photointerpretation and field survey enabled us to establish that the area was intensively manipulated for agricultural purposes, and that there were also dispersed residential units and other kinds of isolated structures, which are beyond the objectives of this paper.

To date we have identified three types of constructions associated with agriculture: terraces, stone lines, and "*despedres*". The first ones are simple dry stone walls, without additional foundational structures or buttresses; they can reach up to 50 cm high. They are built with boulders, which can be up to 30 cm of A axis. Foundations can have 10 cm under the inferred old planting surface. They are disposed perpendicular to topography forming steps of land of up to 7 m wide. According to field observations, terrace
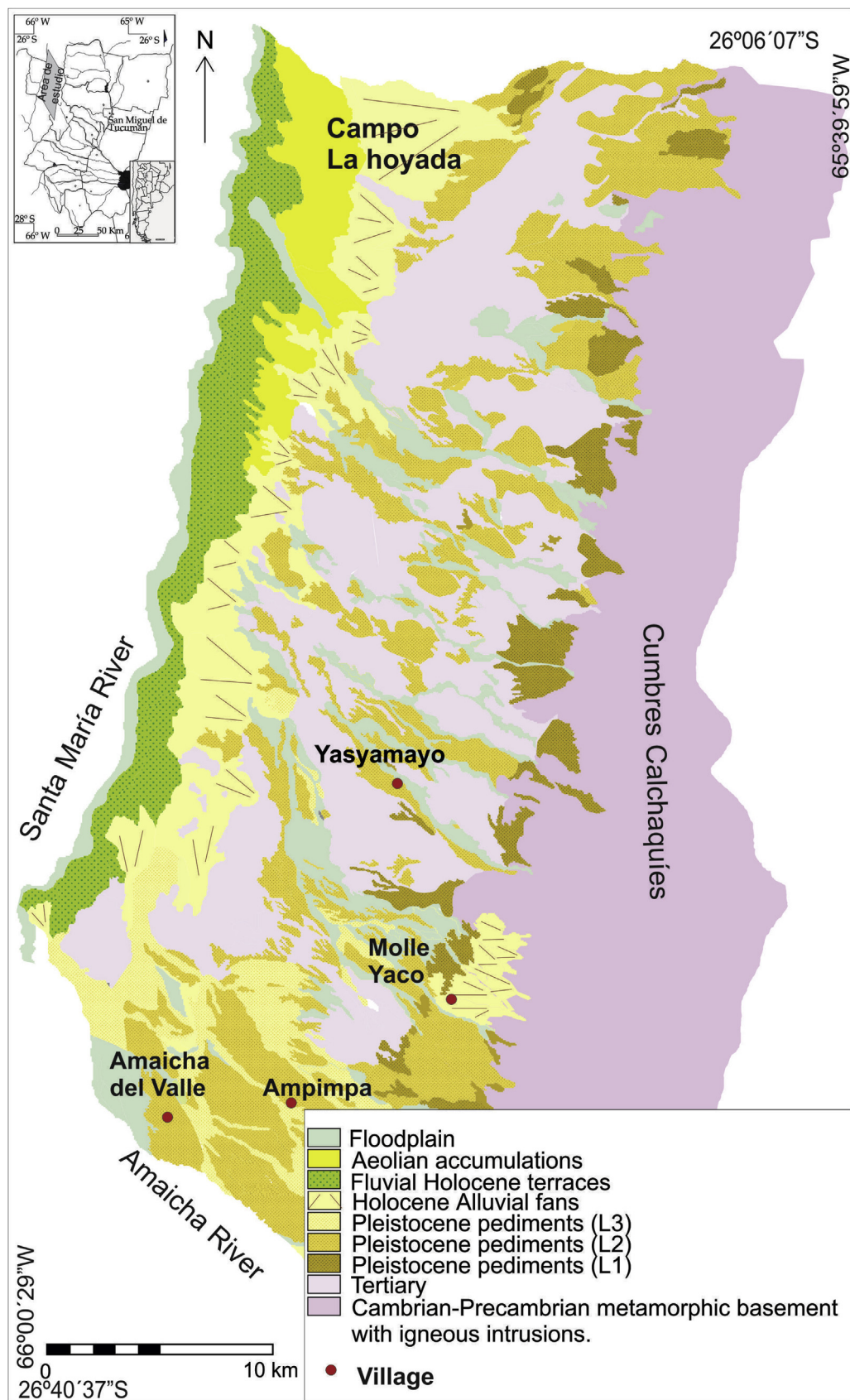
Fig. 2. Detailed geomorphology of Molle Yaco and Yasyamayo.

soil bodies were formed by natural run-off and sedimentation of upslope materials. There are no stratigraphic or physicochemical alterations showing a different formation process. At present, walls are full and they do not exceed soil body level (Fig. 3).

Stone lines are alignments disposed perpendicular to slope in long lines but they are not walls. In some cases they include big stones (A axis of 50 cm), which tend to be separated by 1 and 2 m. They do not generate terraces proper, but rather smooth slopes (Fig. 4).

Finally, "despedres" are round or long lines of unselected stone mounds gradually built by the de-stoning process of the agricultural surfaces (Fig. 5).

On this landform we excavated eight pits, three off-site and five against terrace walls (upslope). Table 1 shows descriptions and physicochemical results. No archaeological findings were made in any of the pits (Table 1).

Yasyamayo archaeological site is at level 2 of a Pleistocene glacis (Sampietro Vattuone and Neder, 2011). Archaeological settlements belong to RDP superposed in some sectors to FP (Sampietro Vattuone et al., 2012).

DEM showed that dominant slope classes are gently inclined (2—7 %) and inclined (7—13 %), with west exposition (Fig. 2). The field survey made it possible to identify big extensions of agricultural terraces with three types of constructions: terraces, "despedres", and isolated circular units.

Terraces consist of simple dry stone walls, 60 cm high from their foundations, and the walls are around 30 cm taller than the soil body upslope the walls. They are settled 10 cm under agricultural level, without foundations of any kind. Soil body was naturally built by alluvial/colluvial sedimentation, favored by lack of vegetation,

Fig. 4. Stone lines from Molle Yaco.

slope and erosive processes. Land between walls is between 2 and 10 m wide (Fig. 6). Despedres have the same characteristics as those of Molle Yaco. Circular isolated units can have up to 3 m diameter, and the walls are scarcely higher than present terrain. Even though we made a pit (Y P2), we did not study them further (Fig. 7).

We excavated seven pits, three off-site, one in a circular unit, and three close to terrace walls. We did not find archaeological materials during excavations. Table 2 lists descriptions and physicochemical results.

2.2. Statistical results

Table 3 presents descriptive statistics of the observed variables. According to Jolliffe (2002), the sample meets the quality standard to be analyzed by PCA. Sample units are not important to this analysis because PCA works with variances generating new non-dimensional variables.

Principal component analysis (PCA) applied to the whole sample showed that it is possible to distinguish between two groups of soil profiles, those belonging to Yasyamayo and those belonging to Molle Yaco (Fig. 8a). The differences are bigger between geomorphological units than those introduced by human manipulation of the areas. Table 4 presents factor loadings of the considered variables. The first five principal components account for 32.51%,

Fig. 3. Agricultural terraces from Molle Yaco.

Fig. 5. Despedres from Molle Yaco.

Table 1
Profile descriptions and physicochemical data from Molle Yaco archaeological site. MY P1 to P3: off-site profiles (control profiles); MYP4 to P8: agricultural profiles. %OM: organic matter percent; ppm: parts per million; X_d: available element; P_o: organic phosphorous.

Sample/depth (cm)		% Sand	% Silt	% Clay	pH	%OM	Ca ppmx10^6	P_a ppm	P_o ppm	Fe_a ppm	Mn_a ppm	Cu_a ppm
MY P1 Control	C1-(0–10)	61.3	10.2	28.5	8.5	0.79	16.5	175	363	0.9	0.05	0.6
	C2-(10–20)	43.7	21.3	35.0	8.7	0.76	69.7	73	560	23.8	0.03	0.4
MY P2 Control	C1-(0–12)	63.8	8.9	27.3	7.9	0.53	1.4	113	512	7.3	0.06	0.6
	C2-(12–24)	62.1	8.1	29.8	8.4	0.7	2.8	101	229	9.3	0.06	1
	C3-(24–26)	62.3	10.5	27.2	8.4	1.09	2.7	106	345	6.4	0.02	0
	C4-(26–30)	52.4	9.6	38.0	8.3	0.63	3.0	70	482	4.3	0.06	0
MY P3 Cont	C1-(0–5)	61.3	8.5	30.2	8.3	1.36	2.0	133	423	3.8	0.13	0.4
	C2-(5–20)	60.5	10.8	28.7	8.6	1.53	8.7	117	263	2.7	0.05	0.7
	C3-(20–40)	38.2	28.3	33.5	8.6	1.04	80.0	114	658	30.8	0	2.1
MY P4 Terrace	C1-(0–10)	59.4	13.6	27.0	8.4	0.48	2.2	125	558	7.5	0	2.9
	C2-(10–20)	60.0	11.6	28.4	8.7	0.42	3.2	121	514	4.5	0.1	0.4
	C3-(20–30)	59.3	2.6	38.1	8.8	0.58	3.6	160	533	8.4	0.01	0.8
	C4-(30–40)	61.2	9.8	29.0	8.8	0.65	4.1	129	677	7.3	0.02	0.8
	C5-(40–50)	64.3	17.6	18.1	8.8	0.53	9.7	107	377	7.3	0.06	0.2
MY P5 Terracee	C1-(0–22)	69.0	9.7	21.3	8.6	1.43	24.7	236	570	6.7	0.04	0
	C2-(22–35)	63.1	16.4	20.5	8.6	1.71	29.0	205	362	6.4	0.01	1.7
	C3-(35–60)	37.3	28.1	34.6	8.7	1.34	67.6	141	556	46.7	0.01	0.2
MY P6 Terrace	C1-(0–10)	67.7	7.8	24.5	8.6	1.34	19.4	171	343	5.6	0	10
	C2-(10–20)	65.6	9.2	25.2	8.6	1.41	22.0	156	407	4.6	0.01	0.4
	C3-(20–35)	51.6	7.6	40.8	8.6	1.52	24.0	150	406	7.3	0	0.6
MY P7 Terrace	C1-(0–10)	48.9	5.7	45.4	8.7	0.85	5.4	291	779	0.9	0.13	0
	C2-(10–20)	50.5	8.8	40.7	8.7	0.37	7.4	113	414	2.9	0.15	2.6
	C3-(20–30)	51.0	9.8	39.2	8.8	0.51	5.6	131	504	4.8	0.08	0.4
	C4-(30–40)	52.1	7.5	40.4	8.8	0.49	6.3	131	533	2.9	0.15	0.5
	C5-(40–50)	66.2	8.7	25.1	8.8	0.62	9.1	121	457	4.6	0.14	0.6
	C6-(50–60)	69.5	15.2	15.3	8.8	0.35	20.4	78	423	3.6	0.14	4.3
MY P8 Terrace	C1-(0–10)	63.9	13.3	22.8	8.5	0.35	1.5	82	528	3.8	0	0.4
	C2-(10–28)	62.6	10.8	26.6	8.2	0.55	2.1	68	204	3.6	0.06	0.4
	C3-(28–40)	52.5	9.6	37.9	8.3	0.48	2.0	79	392	3.7	0.02	0.6
	C4-(40–50)	50.8	9.2	40.0	8.2	0.65	1.7	91	245	8.6	0.01	0.8

18.67%, 15.41%, 11.65%, and 8.05% of total variation of data, respectively, with cumulative variance of 86.28%.

The first PC (F1) shows high loadings of silt, sand, calcium and organic phosphorous (shown by bold numbers in Table 4), showing that the above variables are significant contributions to the first PC. The obtained plot groups 51.17% of the observations. Because the sample has high dispersion, we will return to this subject.

By applying PCA only over textures, we can observe that sand and silt are intimately related, while clay is the principal contributor to PC2, grouping 100% of the sample in the graphical representation (Fig. 8b). In both groups of profiles, PC1 closely groups them over the vertical axis, sand and silt being the dominant variables. Therefore, we can deduce that Molle Yaco textures are of a sandier nature than those of Yasyamayo, which have more silt. By contrast, chemical APC shows that it is impossible to detect tendencies in any sense (Fig. 8c).

Taking each geomorphological unit separately, we found that Molle Yaco off-site profiles are more similar among them than the set of anthropic profiles; they are closer in the graphic that collects 63.94% of the variability (Fig. 9a). Loading variables for PC1 (representing 41.09% of variability) are silt, calcium, available phosphorous and iron, while for PC2 (representing 21.97% of variability) they are sand, pH, and available copper (Table 5). These profiles tend to have more Ca, Fe_a, and silt, while agricultural ones, though

Fig. 6. Agricultural terraces from Yasyamayo.

Fig. 7. Circular isolated unit from Yasyamayo.

Table 2
Profile descriptions and physicochemical data from Yasyamayo archaeological site. Y P1, P6 and P7: off-site profiles (control profiles); Y P2: isolated circular unit; Y P3 to P5: agricultural profiles. %OM: organic matter percent; ppm: parts per million; X_a: available element; P_o: organic phosphorous.

Sample/depth (cm)		% Sand	% Silt	% Clay	pH	%OM	Ca ppmx10^6	P_a ppm	P_o ppm	Fe_a ppm	Mn_a ppm	Cu_a ppm
Y P1 Control	C1-(0–10)	67.7	7.8	24.5	8.4	0.60	4.0	159	54	5.7	0.02	0.6
	C2-(10–20)	4.3	60.3	35.4	8.6	1.64	15.4	149	205	4.7	0.02	0.8
	C3-(20–30)	4.4	57.1	38.5	8.9	0.74	22.2	122	521	6.5	0.01	0.2
	C4-(30–40)	15.9	67.2	16.9	8.7	0.88	21.2	116	39	3.7	0.01	0.6
	C5-(40–50)	6.1	57.3	36.6	8.9	0.74	32.8	129	273	1.8	0.00	0.8
	C6-(50–60)	21.2	60.2	18.6	9.0	0.86	25.9	130	69	4.5	0.03	0.6
Y P2 Circular U	C1-(0–10)	5.8	58	36.2	8.7	0.92	9.2	143	375	0.9	0.00	0.6
	C2-(10–20)	8.2	62.1	29.7	8.7	1.32	14.2	170	531	0.0	0.05	0.8
	C3-(20–30)	33.9	32	34.1	8.9	0.65	12.3	167	520	0.0	0.01	0.8
	C4-(30–40)	23.9	64.1	12	8.6	1.04	19.8	211	628	7.3	0.01	1.1
Y P3 Terrace	C1-(0–5)	4.2	60.4	35.4	7.4	3.53	3.2	139	340	32.1	0.7	0.8
	C2-(5–14)	5.7	60	34.3	8.6	0.7	3.4	131	40	0.9	0.03	0.6
	C3-(14–24)	4.2	60.4	35.4	8.7	0.72	5.5	124	210	2.7	0.02	0.6
	C4-(24–32)	5.5	61	33.5	8.7	0.67	5.8	138	109	2.8	0.02	0.6
	C5-(32–40)	17.5	66.8	15.7	8.7	0.81	17.6	135	25	0.9	0.03	0.6
	C6-(40–50)	16	65.3	18.7	8.7	0.69	30.9	150	302	3.7	0.02	0.02
Y P4 Terrace	C1-(0–8)	9.2	58.1	32.7	6	3.70	4.4	150	543	19.6	0.26	0.6
	C2-(8–25)	17.9	66.1	16	7.5	0.49	0.9	180	509	1.9	0.06	4.0
	C3-(25–32)	10.2	58.8	31	8.6	0.09	2.7	164	802	4.8	0.01	0.0
	C4-(32–52)	17	65.7	17.3	9.1	0.00	2.6	166	343	1.9	0.07	0.6
	C5-(52–64)	12.5	85.6	1.9	9.1	0.26	1.8	157	366	4.8	0.08	0.6
Y P5 Terrace	C1-(0–10)	5.7	60	34.3	8	1.37	5.3	149	342	12.8	0.03	0.0
	C2-(10–20)	21.2	60.2	18.6	6.7	6.22	7.5	155	405	19.6	0.06	0.4
	C3-(20–30)	6.2	60	33.8	8.1	1.13	5.5	166	248	0.0	0.07	0.0
	C4-(30–40)	6.2	61	32.8	8.2	1.00	5.6	142	296	2.8	0.07	0.4
Y P6 Control	C1-(0–5)	64.8	9	26.2	0.4	0.4	4.5	140	60	5.5	0.01	0.3
	C2-(5–12)	7	60.3	32.7	1.1	1.1	16.4	135	198	4.6	0.02	0.6
	C3-(12–28)	7. .2	57.1	35.7	0.8	0.8	20.8	129	154	1.8	0.01	0.2
	C4-(28–38)	24.2	67.2	8.4	0.7	0.74	19.8	140	89	4.5	0	0.4
Y P7 Control	C1-(0–10)	63.8	9	27.2	8.4	0.7	3.7	170	70	6	0.01	0.5
	C2-(10–20)	15.9	67.2	16.9	8.7	1.5	14. .9	145	187	4.5	0.02	0.7
	C3-(20–30)	8.4	55.8	35.8	9	0.6	21.9	110	412	6	0.01	0.4
	C4-(30–40)	23.4	57.1	19.5	8.6	0.9	21.8	128	48	3.2	0.01	0.7

they are more variable, tend to be sandy-clay. Except for profiles MY P6 and MY P7, natural profiles show more nutrient concentration (Fig. 9b and c).

The results of Yasyamayo APC show that off-site profiles are sandier and have less nutrient concentration than agricultural ones, although these profiles present high variability, judging from the dispersion in the graphic (Fig. 10a). Loading variables for PC1 (representing 44.14% of variability) are sand, silt, organic matter, and available iron, while for PC2 (representing 25.09% of variability) they are clay, organic phosphorous, and available copper (Table 5). APC analysis of textures shows the same tendency representing 99.99% of the sample (Fig. 10b). Looking for tendencies on nutrient distribution, we saw that off-site profiles have higher %OM but less micro nutrient availability (Fig. 10c). As in Molle Yaco, the variability among agrarian profiles is higher than among natural ones (Fig. 10).

Table 3
Descriptive statistics of observed variables. %OM: organic matter percent; ppm: parts per million; X_a: available element; P_o: organic phosphorous.

Variable	Observations	Minimum	Maximum	Mean	Standard deviation
%Sand	15	8.850	61.630	38.781	21.241
%Silt	15	8.200	66.860	32.599	23.163
%Clay	15	19.780	34.350	28.575	3.548
pH	15	7.750	8.770	8.487	0.288
Ca (ppm)	15	0.760	43.100	13.932	14.255
%MO	15	0.510	15.570	3.015	5.085
P_a (ppm)	15	80.000	194.000	138.807	28.376
P_o (ppm)	15	125.250	531.800	372.860	143.948
Fe_a (ppm)	15	2.050	19.900	7.373	4.545
Mn_a (ppm)	15	0.003	0.140	0.047	0.043
Cu_a (ppm)	15	0.200	3.700	0.902	0.841

3. Discussion

The constructive characteristics of terrace walls are similar in Molle Yaco and Yasyamayo. Although in the first case terraces are full and the soil body reaches the top of the walls upslope, in Yasyamayo walls are almost 30 cm taller than the soil body. It was almost impossible to identify developed soils. As in every place where Entisols are the rule, horizons differentiation is almost null. In some cases, agricultural surfaces were inferred through the only layer with pedological structure that is normally buried and located upslope, close to the terrace wall base. As the type of soil at a regional level is Typic Torriorthents (Sayago et al., 1998b) they could include very variable characteristics. In this sense we found that the calculation of averages of each variable permitted a good characterization of each profile and the total sample. We made the PCA considering only profile averages as well as only the buried agricultural horizons with similar results.

Stronger sedimentation upslope terrace walls could be due to three major factors. First, according to antecedents Molle Yaco is an alluvial fan, landform of fluvial origin with high sediment selection. Considering the energy of the system and charge capacity of the rivers in the area, sands were the first sediments to be deposited and silt and clays were deposited downstream in the bottom valley. Yasyamayo is the product of a mass movement process, without textural selection, made of materials coming from the slopes and the top of the mountains. Fine materials were not eroded downstream. These results are also reflected by the PCA textural analysis.

Second, dominant slopes from Molle Yaco are higher than those of Yasyamayo, generating more intense erosive processes and faster aggradational processes upslope terrace walls.

Third, according to antecedents (Sampietro Vattuone et al., 2012) Molle Yaco settlements are earlier than Yasyamayo's and
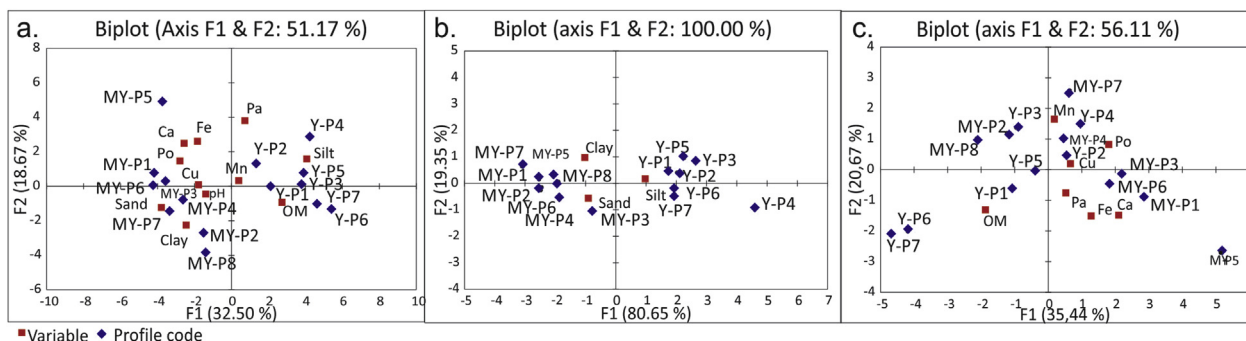
Fig. 8. Biplot graphics. All profiles together: (a) all variables; (b) texture; (c) nutrients.

Table 4
Factor loadings of variables in the bulk samples. OM: organic matter; X_a: available element; P_o: organic phosphorous.

	F1	F2	F3	F4	F5
Sand	**−0.469**	−0.193	−0.134	−0.064	−0.241
Silt	**0.477**	0.234	0.095	0.067	0.157
Clay	−0.310	**−0.369**	0.188	−0.058	0.398
pH	−0.188	−0.038	**−0.464**	0.200	0.600
Ca	−0.321	**0.389**	−0.123	−0.265	0.354
OM	**0.301**	−0.138	−0.487	−0.148	−0.033
P_a	0.056	**0.593**	−0.160	0.301	0.072
P_o	**−0.345**	0.245	0.235	0.244	−0.284
Fe_a	−0.228	0.431	0.021	**−0.526**	−0.084
Mn_a	0.035	0.034	**0.593**	0.184	0.391
Cu_a	−0.227	0.036	−0.195	**0.629**	−0.163

Table 5
Factor loadings of variables in the bulk samples. Molle Yaco archaeological site. OM: organic matter; X_a: available element; P_o: organic phosphorous.

	F1	F2	F3	F4	F5
Sand	−0.224	**0.373**	−0.330	**−0.378**	0.157
Silt	**0.399**	−0.329	0.019	−0.006	−0.054
Clay	−0.276	−0.012	0.393	**0.489**	−0.125
pH	0.237	**0.394**	0.335	−0.139	−0.441
Ca	**0.416**	−0.090	−0.027	0.316	−0.312
OM	0.314	0.281	−0.108	0.401	**0.544**
P_a	**0.372**	0.364	−0.036	−0.053	0.169
P_o	0.248	0.171	0.416	**−0.448**	−0.065
Fe_a	**0.426**	−0.216	−0.145	−0.067	0.153
Mn_a	−0.064	0.070	**0.617**	0.039	0.500
Cu_a	−0.025	**0.544**	−0.189	0.357	−0.252

they have been abandoned because of a climatic dry period that took place around 1000 BP. After that, the maintenance of the agricultural terraces of the sector probably stopped.

One structural feature found only at Molle Yaco is stone lines; we did not make excavations or samplings on them, and the lack of depth of the structures is evident. Regarding their functionality, some experiments were conducted at El Sahel concluding that stone alignments are efficient to reduce run-off, improve water infiltration, and reduce fine sediment transportation tramping clay and silt (Zougmoré et al., 2002).

According to Sullivan, who worked on highlands of American Southwest, stone alignments (which have characteristics similar to ours) placed perpendicular to drainage and slopes were designed to impede run-off and favor sediment tramping by creating terraces or planting surfaces. Chaotic chemical results made it difficult to explain small-scale run-off agriculture over soil fertility, although it was demonstrated that soils were not exhausted before abandonment (Sullivan, 2000). This variability, introduced by human intervention, is also present in our results (Figs. 8c, 9c and 10c). The

extension of the sampling will probably make it possible to establish some tendencies.

Caria et al. (2010) presented the physicochemical results of what they named agricultural *andenes* at Los Corrales gulch; however it is not possible to know if the soil body of the agricultural lands was manually filled. They are located only a few kilometers south of our study area. Unfortunately, given the lack of rigor in the presentation of results we can only appreciate that they present the same high variability as ours. Wall foundations have a gravel layer.

With regard to fertility, evaluations made in Northwest Argentina, Ogas et al. (2006) established that for three archaeological sites in Ambato valley in Catamarca Province (Las Juntas, Los Varela, and Los Talas) agricultural wall terraces, in that environment, favored the presence of deeper superficial horizons with higher percentage of clays and bioavailability of bases such as Ca, Mg, and K, probably linked to the enrichment of clays (Ogas et al., 2006).

One isolated physical characteristic of our profiles is the presence of some buried horizons (or layers?) in agrarian contexts from Molle Yaco and Yasyamayo. The construction of terrace walls
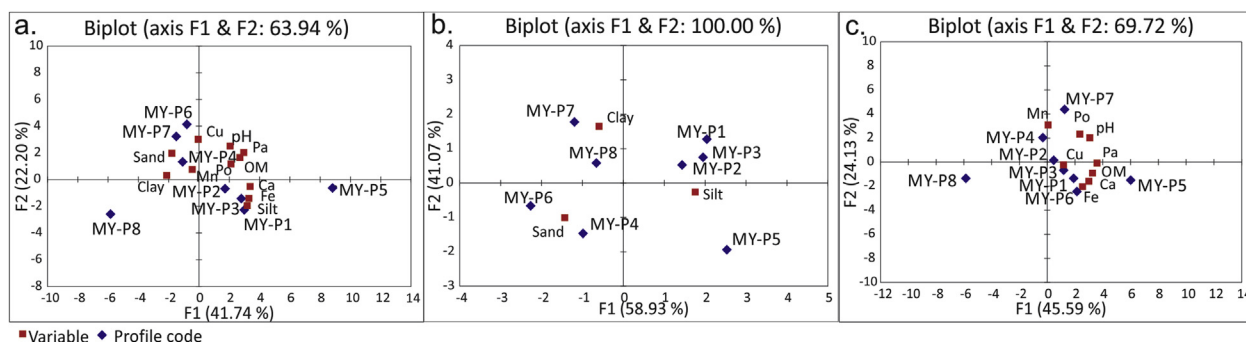

Fig. 9. Biplot graphics. Molle Yaco profiles: (a) all variables; (b) texture; (c) nutrients.
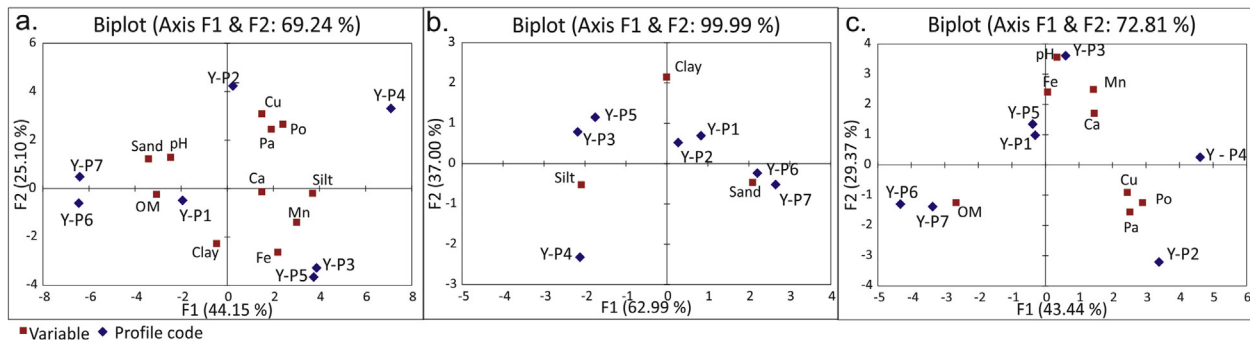
Fig. 10. Bibplot graphics. Yasyamayo profiles: (a) all variables; (b) texture; (c) nutrients.

probably favored in some cases the stability of the system and potential water retention making the development of structure in layers possible.

In all cases, human activities over agricultural lands, according to PCA, introduced variability in the manifestation of the considered variables. In the case of Molle Yaco, the bioavailability of nutrients is in general diminished in agrarian sectors while in Yasyamayo the situation is reversed (Figs. 9c and 10c). For a detailed analysis variable by variable and layer by layer see Roldán (2014).

About cultivated plants and their agronomical needs, the soils are undoubtedly very poor. Even physicochemical analyses obtained by Korstanje and Cuenya (2008) and Williams et al. (2010) are not comparable in a direct way. Together with Arreguez et al. (2010) and Cano (2011), these authors show which crops were selected in the region.

At Calchaquí Medium valley, Williams et al. (2010) demonstrates that given environmental conditions similar to ours, in agricultural lands without irrigation (inferred from the lack of diatoms and *Chrysophyceae*) and with a notorious decrease in organic matter contents, potato cultivation prevailed due to the abundance of its starch grains. This cultivation was done with manure aggregation. Agricultural structure construction started around 1240 ± 40 ^{14}C yr BP (Beta 232251) (Williams et al., 2010). The presence of non-identifiable starch grains is probable evidence of crop association and/or rotation. This practice compensates for some soil and environment deficiencies.

Reviewing evidence of crop debris in close archaeological sites indicates the preference of potato (*S. tuberosum*), maize (*Zea mais*), kidney beans (*Phaseolus vulgaris*), amaranth (*A. caudatus*), and quinoa (*C. quinoa*). From these cultivars, potato needs acid soils, while maize high organic contents, and kidney bean and amaranth precipitations higher than 400 mm. Therefore, only quinoa, with its high rusticity, was the crop most probably produced in the area because it reaches acceptable production levels under the harsh local environmental conditions previously described.

4. Conclusions

Two archaeological sites, Yasyamayo and Molle Yaco, located in the occidental piedmont of Calchaquíes Summits (Tucumán-Argentina) were analized. Both them present agricultural terraces, as they belong to different periods (Formative Period (2500–1000 BP) and Regional Developments Period (1000–600 BP)) the characteristics of the constructions are quite different. So far, we have not been able to find stone alignments in Yasyamayo; only Molle Yaco terraces are fully filled.

In Molle Yaco erosive conditions prevailed, as shown by the texture of agricultural profiles and the aggradation of terraces produced by the transportation of different kinds of sediments from upslope. Parental material and slopes of the alluvial fan made the landform more susceptible to erosion.

In both cases human intervention over lands introduced high variability in nutrient values. Nevertheless, Moye Yaco shows a decrease in nutrients in agricultural terraces. On the contrary, Yasyamayo control profiles showed more %OM while in agricultural profiles this component diminished with higher bioavailability of micronutrients, probably because of the environmental conditions created by the wall terraces. The presence of texturally finer materials made this bioavailability possible despite organic matter degradation.

Taking up the concept of fertility exposed before, we can see that even though absolute values of certain nutrients are low, soils are not exhausted. Major differences between one site and the other are caused by texture and linked to the genesis of the geomorphologic units. Thinner textures from Yasyamayo favor micronutrient retention and bioavailability even if agricultural use diminished organic matter.

Regarding local land effects of terrace construction and management, we have two opposite situations. The comparison among natural profiles in Molle Yaco showed that agricultural practices impoverished soils, while the reverse situation occurred in Yasyamayo.

Considering agronomical requirements of crops identified in the nearest and contemporaneous archaeological sites and the environmental characteristics of our study area, we can deduce that the only crop that could have a reasonable development without irrigation, and with our pedological characteristics, is quinoa (*C. quinoa*). However, crop association and irrigation could compensate for the deficiencies imposed by the environment improving the possibilities. Archaeobotanic studies are in progress to solve these questions.

Soil water availability is the most limiting factor in our study area and according to paleoenvironmental reconstructions, it was particularly scarce during the transition between the first and second millennia of our era, this piedmont being the most affected by the rain shadow of the mountain. It is probable that irrigation contributed to mitigate these deficits; research studies are in progress to elucidate this matter.

The present paper constitutes a solid contribution in several ways. Physicochemical and PCA analyses demonstrate the differences between archaeological sites where material evidence is scarce. Our conclusions pose new insights into soil and landscape in Pre-Hispanic management, which will improve dryland exploitation capabilities in the near future.

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