SOIL SCIENCE ANNUAL
2024, 75(1), 184338

https://doi.org/10.37501/soilsa/184338

Characterization of the "Waru Waru" soils on the Peruvian high plateau

Sandro Sardon Nina[1*], Juan Carlos Loaiza-Usuga[2], Diego Varga[3], Yoissy Pari Morales[4]

[1] Universidad Nacional del Altiplano – Puno, Facultad de Ciencias Agrarias, Escuela Profesional de Ingeniería Agronómica, Av. Floral N° 1153, 21001 Puno, Perú. ssardon@unap.edu.pe
[2] Universidad Nacional de Colombia – Sede Medellín, Facultad de Minas, Departamento de Geociencias y Medioambiente, Carrera 80 N° 65-223, Bloque M2, Office 312, Campus Robledo, 050036 Medellín, Colombia. jcloaiza@unal.edu.co
[3] Universitat de Girona, Departament de Geografía Física, Laboratori d'Anàlisi i Gestió del Paisatge, Edifici Sant Domènec i, Pl. Ferrater i Mora, 1, Despatx: Geografia, 17004 Girona, España. diego.varga@udg.edu
[4] Universidad Nacional Mayor de San Marcos, Laboratorio de Florística, Departamento de Dicotiledóneas, Museo de Historia Natural, Av. Arenales N° 1256, Lima 11, Perú. yoissy.pari@unmsm.edu.pe

* Corresponding author: Prof. M.Sc. Sandro Sardon Nina, ssardon@unap.edu.pe, ORCID iD: https://orcid.org/0000-0002-1999-1655

Received: 2023-07-28
Accepted: 2024-02-20
Published online: 2024-02-20
Associated editor: B. Repe

Keywords:

Soil sustainability
Wetland soils
Soil degradation
Andes highlands
Raised field

Abstract

The Puno-Peruvian high plateau have been shaped by humans over the last 8000 years. The Waru Waru system is a direct result of the agricultural activities of the pre-Inca in the last 2000 years. The present study was conducted in the circumlacustrine zone of Titicaca (445,532 ha) near the city of Puno, Peru. The parent material of the soils originates from the Quaternary alluvial and lacustrine deposits within the high plateau with flat landscapes, and the land is used for temporary and perennial cultivation as well as extensive natural pasture. The entire region was assessed through a preliminary soil survey, based on which three soil profiles were selected as representative Waru Waru soil structures. The soil samples were subjected to morphological and physicochemical analyses and the genesis in relation to historical use was investigated. The results showed that sandy loam and clay loam textures dominate and the average sand content is 52%, giving the parent material acidic characteristics. The soils are typically covered by natural grassland, with adequate drainage conditions and the presence of a hydrological discontinuity at a depth of 60 cm. The stagnic properties of the soils are related to the seasonally wet and paleohydromorphic conditions originating from paleolacustrine conditions and flooding. The soils exhibited high variability in base content, with pH ranging from acidic to neutral and evidence of ion leaching processes and incipient concentration of salts at depth. The predominant soils were Stagnosols, Cambisols and Phaeozems in the same order (IUSS Working Group WRB, 2022), corresponding to Inceptisols and Mollisols (Soil Survey Staff, 2022a). The Waru Waru agricultural system covers an area of approximately 123,000 ha, with 5% of this area consisting of natural grasslands. The degradation of the traditional agriculture system (Waru Waru) is influenced by the socio-cultural dynamics and modernization of the agricultural sector.

1. Introduction

The environment of the Titicaca basin has been transformed over centuries into a highly sculpted artificial landscape with the presence of constructions of stone-covered terraces (*andenes*), sunken gardens (*q'ochas*), wetlands extensive pastures, and raised fields (*Waru Waru*). Waru Waru (Quechua term) are pre-Inca agricultural systems found in the Peruvian highlands, which has been used widely since 2000 BP. This variety of agricultural infrastructure and the population land use has created an anthropogenic landscape (Erickson et al., 2000). Waru Waru carry ancestral agricultural practices of the pre-Inca, based on raised fields by means of furrows (Gondard, 2008), located in the Titicaca Lake cirumlacustrine zone (Fig. 2, Fig. 3 and Fig. 4), used by the inhabitants of the Peruvian and Bolivian high plateau to cultivate. These ancestral agricultural practices started to be replaced between the years 1,100 and 1,500 (Erickson, 2006).

Since the 1960s, archeologists, agronomists, and geographers in South and Central America have studied ridged fields, with a detailed description provided by Gondard (2008). There are evidences that ridges were used in Hertenrits (Surinam), Makuxi and Guato (Brazil), Barinas, Karinya and Caño Guanaparo (Venezuela), San Jorge Valley, Tumaco, La Depresión Momposina, Orinoco Valley and Bogotá Savanna (Colombia), Guayas in the Northern Andes in Ecuador, San Pablo Lake and La Tolita (Ecuador), the circumlacustrine ring of Lake Titicaca (Peru), Llanos de Moxos (Bolivia), Guyana Plain (French Guyana), Lerma Valley (Argentina), Nacajuca–Tabasco, and the Mexico City Valley in Mexico (Gondard, 2006, 2008; Pérez, J., 2007; Caillavet, 2008; GIAHS, 2017).

Row planting in wetland regions and their use as agricultural systems represent a key element in the culture and ecology of pre-Hispanic societies, although these have been studied sparingly in South America (Caillavet, 2008). These systems enabled the control of excess water during the rainy season (water regulation), created better microclimatic conditions, and reduced water erosion along wavy and steep surfaces (GIAHS, 2017).

Several studies have highlighted the benefits of using stagnant waters for combating cold weather conditions, with temperature increases of up to 2°C achieved in the regions with ridges fields close to Lake Titicaca. Waru Waru reduced the annual frost, improved soil water management, the capture, production, and recycling of soil nutrients, thereby enhancing the microclimate and aquaculture (Erickson, 2000; Gondard, 2008). The water held in the water table is absorbed by plant roots, and from there, it rises to a moisture zone that is within the reach of the roots, allowing for the infiltration of excess water in rainy periods. Plant growth is conditioned by the balance of water supply and demand in the soil-plant-atmosphere-continuum, which can be optimally regulated by sub-irrigation systems such as Waru Waru (Martínez-Ruiz, 2014; Robles et al., 2019).

The technological expertise of past cultures and systems is being used until nowadays to improve the productivity of the Andes highlands (Erickson et al., 1988). Pre-Hispanic agriculture systems used flood and water table rise as irrigation strategies for crop production, rendering it necessary to construct efficient drainage structures for improved salt contents, fertilization, and physical management of the soil (Erickson, 2000; Robles et al., 2019). Several studies have explored the spatial distribution of ridge fields in pre-Hispanic agricultural regions using various geoarchaeological techniques, such as imaging, landscape analysis, magnetic gradients, ground-penetrating radar, electrical resistivity, classical soil survey, and archaeobotanical and certain chemical characterizations (Herrera et al., 2001; Gondard, 2008; Perez-Perez et al., 2012; Rodrigues et al., 2018; Boixadera et al., 2019; Rojas-Mora and Montejo-Gaitán, 2021). The studies on the Amerindian agricultural systems have focused mostly on historical and anthropological characterization, while the associated soil characteristics remained poorly studied (Erickson, 2000; Caillavet, 2008; Boixadera et al., 2019). In this context, the aim of the present study is to quantify the area under Waru Waru structures abandoned and in-use in the Puno region, and reveal the soil characteristics of these agricultural system, causes of their destruction and current state of conservation. The findings of this characterization will enable an effective assessment of the current state of these high Andean ancestral systems and will facilitate the subsequent reconstruction and conservation measures.

2. Materials and Methods

2.1. Study site

This study was conducted in the circumlacustrine ring of Lake Titicaca, located between the western and eastern cordilleras of the Peruvian Andes, Department of Puno, Peru (Fig. 1). The studied area lies between 3800 m. a.s.l and 3900 m. a.s.l., and has a mean annual temperature of 8°C and receives an annual precipitation of 600 to 800 mm, with temperate climate to cold and a moderately rainy. The winters are dry, with strong frosts, while the summers are rainy (SENAMHI, 2021). The cropping period in the Peruvian highlands is during the summer season and coincides with the greatest quantity of rainfall, with temperatures reaching – 4°C (Díaz Aguilar, 2013). Geomorphologically, the region corresponds to a high plateau, with the landforms comprising a combination of flat surfaces with concavities and convexities.

The parent material are alluvial and lacustrine deposits composed by sandstones, red limestone, conglomerates, and volcanic materials sediments (Rodriguez et al., 2020) and includes gravels, sands, and cobbles. The predominant soils in the studied region are Stagnosols, Cambisols, and Phaeozems (IUSS Working Group WRB, 2022), which correspond to Inceptisols and Mollisols (Soil Survey Staff, 2022a). Soils are relatively thick, with dark colors and a variable high base content. Low soil pH is associated with materials of alluvial and lacustrine origin, both potentially affected by salts (unpublished data).

2.2. Soil mapping

The mapping of the Waru Waru systems was conducted in three stages. The first stage involved the review of the Andean agricultural infrastructure provided in the inventory maps at the Department of Puno - Peru, by the interinstitutional research project PIWA ("Proyecto Interinstitucional de los Waru Waru", in spanish) (1992, 1994). The original inventory maps from 1994 were digitized using the QGIS software and the regions with a high probability of Waru Waru presence were identified by means of an intensive soil campaign at a 1:25,000 scale. The second stage comprised field work, which involved georeferencing Waru Waru systems using a GARMIN 62S GPS navigator and capturing aerial optical images of the region using a Phantom 4RTK drone for better visualization of shape variability. The different systems were then classified, according to PIWA (1994), into fluvial, pluvial, and phreatic systems. The soils at the studied points (Fig. 1) were sampled using a manual soil auger and preliminary characterized

The final stage comprised field information processing using the satellite images updated until 2022, and a manual digitization of polygons by means of Google Earth version 7.3 and QGIS software.

2.3. Soil survey and characterization

Three soil profiles were selected as representative soils according to the auger sampled field information (paragraph 2.2) and subjected to complete soil survey and characterization according to the parameters established by Soil Science Division Staff (2017) and FAO (2006). The classification of the soil profiles was conducted according to IUSS Working Group WRB (2022) and Soil Survey Staff (2022a). Eleven soil samples and three representative soils profiles were evaluated for pH (water 1:1) and electric conductivity (saturated extract) U.S. Salinity Laboratory Staff. (1954) methodology, organic matter Walkley and Black method (Nelson and Sommers, 1982), available phosphorous Olsen method (FAO, 2021), available potassium, Ca^{2+}, Mg^{2+}, K^{+}, and

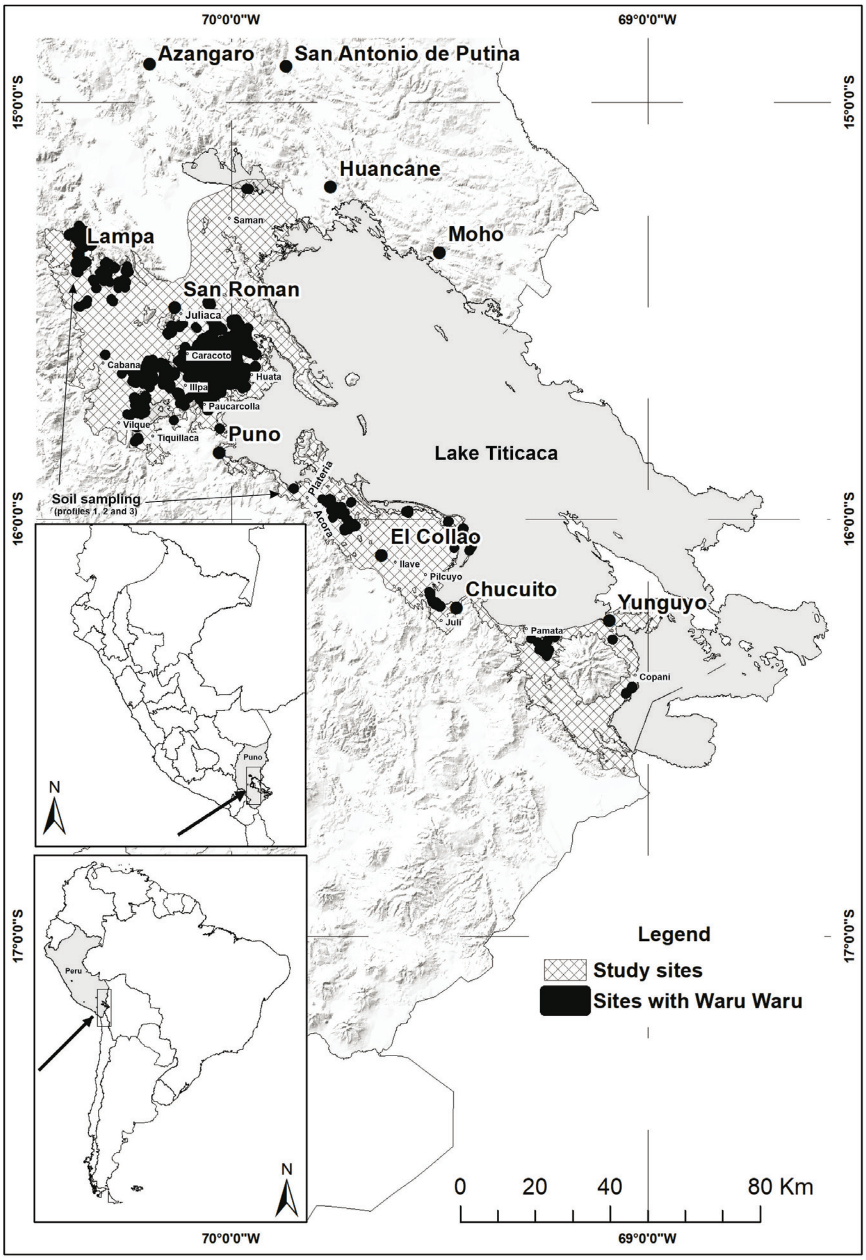

Fig. 1. Total area of the study site and spatial distribution of Waru Waru systems.

Na^+ (ammonium acetate pH 7), and Al^{3+} (1M KCl) according to Soil Survey Staff (2022b) methodologies, sand %, clay %, silt %, and texture (Bouyoucos, 1962), and bulk density (FAO, 2023) at the Soils Sciences Laboratory, Universidad Nacional de Colombia, Campus Medellin. The degradation state of the Waru Waru structures was determined according to PIWA (1992, 1994) system.

3. Results

3.1. Waru Waru spatial distribution

Waru Waru systems are located in the Yunguyo, Chucuito, El Collao, Puno, San Román, Lampa, Azángaro, and Huancané provinces in the department of Puno, Peru (Fig. 1) and covers an area of 3,899 ha (Table 1). Ridge systems distribution was determined according to PIWA (1994) methodology and is shown in Table 3. The maximum distance of Waru Waru sytems to the lake is 50 km, and the mean slope is < 2%, which favored an efficient water use and runoff, flood and phreatic water control. The fluvial system covers 14.5% of the study area, and its source are the rivers Coata, Lampa, Cabanillas, Illpa and Río Grande. The water is supplied to the Waru Waru system through the inlet and outlet channels that are regulated through dams constructed for the storage of water within the channels (Fig. 2a). The pluvial system covers 70.2% of the study area and uses rainwater accumulation at the foot of the slopes and is designed to collect water from the slopes or mountains, while in certain cases this system uses the drainage network (Fig. 2b). The phreatic systems, which covers 15.3% of the study area, are located on the shores of the lake and surrounding lagoons and are subjected to groundwater table seasonal variations and floods occurrence (Fig. 2c and 2d).

Fig. 2. The Waru Waru system examples. a. Fluvial system, b. Pluvial system, c. Phreatic system, d. Wave image of phreatic system acquired from a drone in the town of Chatuma, district of Pomata.

Table 1.
Estimate area of Waru Waru around Lake Titicaca

Year	Measured Surface (ha)	Metodology	**References**
Prehispanic time	82,000	Archaeological reconstruction	Erickson, 1988
1968	78,104	Aerial photos and field	Smith et al., 1968
1992	122,882	Aerial photos and field	Díaz and Velásquez, 1992
2023	3,899	Mapping on satellite image and field	Study results

Table 2.
State of conservation of the Waru Waru systems

State of conservation	Measured Surface (ha)	Measured Surface (%)
Preserved structures	21.87	0.56
Incipient state	3,877.00	99.44

Table 3.
Waru Waru systems according to water source

Waru Waru systems	Measured Surface (ha)	Measured Surface (%)
Fluvial systems	566.85	14.54
Pluvial systems	2,735.84	70.17
Phreatic systems	596.18	15.29

3.2. Current situation of the Waru Waru systems

A high percentage of Waru Waru structures used in the traditional agricultural regions (99.44%) have been transformed into grasslands or croplands using tractors. A transformation of the ridge areas into natural pastures began during Spanish colonization and was intensified during the 1960s with the introduction of agricultural cooperatives. This effect has been intensified in recent years due to land abandonment (migration of young people to the cities), drought, and the introduction of machinery (PIWA, 1992). These dynamics together favored the establishment of extensive cattle farms and land abandonment, thereby affecting the percentage of ridge lands. Currently, Waru Waru structures have varied dimensions for channel width, as well as different spacing between channels, ridge height, and fill height, with an east-west and north-south orientation. The distribution patterns, despite being varied and difficult to classify, follow the drainage network. Authors such as Smith et al. (1968), Earls et al. (1986) and Gondard, 2008 have reported approaches to pattern the classification of Waru Waru systems. Recent international projects have attempted to bring back the traditional Waru Waru systems for regenerative agriculture, for which solar disc shape structures have been introduced in the Acora and Illpa communities (Fig. 4).

Land use in the evaluated region comprises transitory and perennial crops, such as potatoes (*Solanum tuberosum*), alfalfa (*Medicago sativa*), barley (*Hodeum vulgare*), oat (*Avena sativa*), and quinoa (*Chenopodium quinoa*). The studied region has presence of grasslands with natural grasses, such as crespillo (*Deyeuxia vicunarum* Wedd.), chilligua (*Festuca dolichophylla* J. Presl), sillu sillu (*Alchemilla achilleifolia* J. Rémy), chiji (*Muhlenbergia peruviana* (P. Beauv.) Steud.), and ichu (*Jarava ichu* Ruiz and Pav.).

3.3. Characteristics of Waru Waru soils

In the studied Waru Waru, soils were classified according the following profiles: profile 1 and profile 2, which were defined as Fluvaquentic Eutrudepts Coarse-loamy, Spolic, Mixed, Active, Non-acid Isothermic, and profile 3 which was defined as Fluventic Hapludolls, Fine-loamy, Spolic, Mixed, Active, Non-Acid Isothermic (Soil Survey Staff, 2022a). According to IUSS Working Group WRB classification (2022), profile 1 is defined as Eutric Fluvic Stagnosol (Epiabruptic, Aric, Cambic, Capillaric, Drainic, Ochric, Transportic), profile 2 is defined as Eutric Fluvic Cambisol (Aric, Drainic, Ochric, Transportic), and profile 3 is defined as Cambic Fluvic, Stagnic Phaeozem (Pachic, Transportic). Fig. 3 shows the soil profiles and landscape studied in the present research. These soils had loam to sandy-loam textures and were a product of low-energy fluvial sedimentation. Similar results were reported by Boixadera et al. (2019) for hydromorphic soils in the Llanos de Moxos – Bolivia. Ap horizons < 20 cm in thickness have a higher organic matter content, granular structure, and abundant root channels. The subsurface Bw horizons have a thickness between 20 and 40 cm and a subangular blocky structure. The boundaries between the horizons are clear and smooth. All horizons of the soil profile up to 60 cm or 80 cm in depth, which have good structure and presence of root channels (Table 4). These structures had a maximum thickness of 80 cm and tended to be sandy toward the base with a gravel content of 5% to 10%, which facilitated drainage. Certain horizons present stagnic properties at depth, which were associated with seasonal oxidation-reduction and palaeohydrological processes. According to Boixadera et al. (2019), epi-saturation was responsible for the presence of redoximorphic features. Ridge (Waru Waru) structures assist in resolving both permanent and seasonal problems of water excess in the marshes and water management during drought and flood periods (Caivallet, 2008). The bulk density was low in Ap horizons due to its higher organic matter content and root activity. Bulk density increased slightly with depth, although with no evidence of deterioration due to soil compaction (USDA, 2001). The soil profile 1 comprised a slightly saline in-depth horizon (Bw3) due to the leaching of ions during rainy periods. The alkalinity values in Lake Titicaca are high (75–150 mg/l) and very high (> 150 mg/l), the content of carbonates and bicarbonates is high (Betran et al., 2015); favors the entry of salts in the soil profile from groundwater in phreatic Waru Waru systems, and in soils near the lake. The Ap horizons were strongly acidic to slightly alkaline. The presence of salts on the surface is associated with the use of irrigation water, and in flooding areas with drainage limitations (OEA, 1996). The pH conditions favor the availability of nutrients and the action of bacteria and actinomycetes (USDA, 2001), with good conditions for plant growth (Table 5). The presence of carbonates was not evident, the pH varied highly between the horizons in the same soil profile, with a tendency to be moderately acidic. Two horizons in profile 2 and profile 3 were strongly acidic, which was attributed to the nature of the parent material, which was siliceous. Merdy et al. (2022) reported that changes in the alkaline nature of wetlands could rapidly disappear upon altering the drainage conditions. The reworked materials from sandstones, red limestone, and conglomerates (Rodriguez et al., 2020) in lacustrine conditions favor the development of moderate to slightly acidic soils (Merly et al., 2022).

Profile 1. Phreatic system: Eutric Fluvic Stagnosol (Epiabruptic, Aric, Cambic, Capillaric, Drainic, Ochric, Transportic)

Profile 2. Fluvial system: Eutric Fluvic Cambisol (Aric, Drainic, Ochric, Transportic)

Profile 3. pluvial system: Cambic Fluvic, Stagnic Phaeozem (Pachic, Transportic)

Fig. 3. Anthropic soil profiles in the Waru Waru systems.

Fig. 4. Waru Waru system with a solar disk with irradiance shape.

Table 4.
Morphology of Anthropic soils in the Waru Waru

Hz	Depth (cm)	Munsell color (moist)	Structure	pedofeatures	Limit	HCl reaction
Profile 1						
Ap	0–11	7.5YR3/3	GR, M, ME	Medium and coarse roots	C, S	N
Bw_1	11–36	10YR4/2 (90%), 10YR2/1 (10%)	SB, M, ME	Few medium roots	A, S	N
Bw_2g	36–54	Gley 5/1 (80%), 5YR 5/8 (20%)	SB, M, ME	Stagnic properties, few medium roots	C, S	N
Bw_3	54–(65)	10YR 2/2	SB, M, ME	Cambic horizon, few medium roots	–	N
Profile 2						
Ap	0–12	7.5YR 4/2	GR, M, ME	Common fine and medium roots	C, S	SL
Bw_1	12–56	7.5YR 4/3	SB, M, ME	Common medium roots	G, S	N
Bw_2	56–(80)	10YR 3/2	SB, M, ME	Few fine roots, medium gravel (5%)	–	N
Profile 3						
Ap	0–20	10YR3/3	GR, M, ME	Abundant fine and medium roots	G, S	N
Bw	20–63	10YR 5/3 (60%), 7.5YR 4/6 (40%)	SB, M, ME	common fine and medium roots	G, S	SL
BC	63–84	10YR 5/4	SB, WE, FI	Few fine roots	C, S	N
2Cg	84–(130)	2.5Y 4/2	MA	Stagnic properties, few fine roots, medium gravel (10%)	–	NC

SB: subangular blocky, GR: Granular, MA: Massive, WE: Weak, ME: Medium, FI: fine, A: abrupt, C: clear, G: Gradual, S: smooth; N: Non-calcareous; SL: Slightly calcareous (FAO, 2006)

Table 5.
Physical and chemical characteristics of Waru Waru Anthropic soils

Hz	Depth	Sand	Silt	Clay	Textural	BD	pH	EC	$CaCO_3$	OM	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	BS	P	CEC
	cm	%			Class	g/cm³	1:1	dS m⁻¹	g. Kg⁻¹	%	Cmol(+)/kg					%	mg/kg	cmol(+)/kg
Profile 1																		
Ap	0–11	53	24	23	SCL	1.17	5.95	0.53	–	4.81	9.91	4.17	1.01	0.50	0.15	70	11.8	22.40
Bw_1	11–36	57	14	29	SCL	1.20	6.47	0.77	–	0.78	9.39	3.99	0.87	1.42	–	68	4	22.88
Bw_2g	36–54	49	28	23	L	1.17	5.83	1.31	–	1.95	7.27	3.68	0.78	1.77	0.10	70	19.3	19.20
Bw_3	54–(65)	47	18	35	SC	1.52	6.59	3.27	–	0.46	10.40	11.67	0.29	2.24	–	94	2.9	26.24
Profile 2																		
Ap	0–12	55	32	13	SL	1.28	7.27	0.26	–	1.95	12.70	2.30	0.71	0.22	–	100	10.9	16.00
Bw_1	12–56	47	38	15	L	1.28	5.39	0.03	–	1.43	6.08	2.23	0.34	0.34	0.10	66	8.5	13.60
Bw_2	56–(80)	67	20	13	SL	1.32	5.91	0.05	–	0.72	8.48	3.48	0.19	0.42	0.05	77	5.3	16.32
Profile 3																		
Ap	0–20	47	38	15	L	0.77	5.03	0.22	–	3.45	5.04	2.87	0.53	0.26	0.10	54	5.7	16.00
Bw	20–63	49	36	15	L	1.33	5.83	0.04	–	1.24	4.03	2.54	0.37	0.22	0.05	56	7.1	12.80
BC	63–84	69	20	11	SL	1.37	6.11	0.04	–	0.52	3.24	2.16	0.19	0.18	–	69	8.0	8.332
Cg	84–(130)	33	46	21	L	1.35	6.23	0.05	–	0.59	5.06	2.82	0.15	0.15	–	64	14.2	12.80

Hz: horizon, BD: bulk density, EC: electrical conductivity, OM: organic matter, BS: base saturation, CEC: cation exchange capacity, SCL: sandy clay loam; L: loam, SC: sandy clay, SL: sandy loam

The presence of horizons slightly saline and alkaline is related to soil management during drought and flooding periods, and the presence of Waru Waru maintain fertile layers *in situ* and prevent soil erosion (Caillavet, 2008). The base content comprised high differentiated horizons, increasing in depth and ion content, which evidenced leaching phenomena occurring within the soil profile and the movement of salts according to depth. The average proportion of ions (mean content) in the profile was as follows: $Ca^{+2} > Mg^{+2} > K^{+} > Na^{+}$, and P. In certain horizons of profile 1, Na > K, which evidenced a low rate of salinization under flooding conditions. The high content of different ions was associated with the agricultural management of these soils. Most of the wetlands have archaeological evidence of intensive farming and their use as raised fields, canals, and occupation mounds (Erickson, 2000).

4. Discussion

Remini and Achour (2014) report a degradation of 50% for old traditional phreatic and pluvial water management systems, which the authors attribute to the adoption of unconventional water table management techniques. The use of tractors increases the incidence of degradation due to erosion. In Waru Waru systems, it is possible to use traditional technologies such Andean foot plow (*chaquitaclla*) or soil manual scarification (*rawk'ana*) which are efficient soil tillage practices that ensures soil conservation (Smith et al., 1968). Waru Waru presence evolution at the surrounding Lake Titicaca along time from Prehispanic period until nowadays is shown in table 1. According to Smith et. al, (1968) data, Waru Waru existence was reduced in 5% of abundance in 1968 referring pre-Hispanic period. Posteriorly in 1992 the Peruvian government policies favored the agricultural traditional systems and Waru Waru presence increased a 49% (Díaz and Velásquez, 1992). This increase in the 1990s was because of the interest of the government, which led to PIWA initiating projects for the reconstruction of ancestral systems within the communities (1994). After this positive evolution, there was a demographic migration process, changes on land distribution as well as the abandonment of traditional agricultural practices, which implied that currently there are only a 5% of the amount of Waru Waru reported in the Prehispanic period.

The systems were mostly located on the northern side of Puno city, toward the Plain of Illpa, between the towns of Caracoto, Huata, Paucarcolla, Lampa, Juliaca, Vilque, and Tiquillaca, occupying 89.9% of the area (3,717 ha). The remaining 10.1% of the area (417 ha) was located in the south of Puno city, at the Plateria, Acora, Ilave, Pilcuyo, Juli, Pomata, Yunguyo, and Copani towns. The high density of Waru Waru in the north was attributed to the predominance of extensive agricultural models, used by large livestock companies, with natural grasslands. The area was used for extensive cattle raising, which could have helped to preserve the ancient Waru Waru systems. The demographic migration and destruction of the ancestral agricultural systems due to modern plow farming, urbanization, and road building are reported as reasons for the reduced use of ridge agricultural systems around Lake Titicaca, to an area of just 3899 ha. In other regions, high population density and land parceling (land pressure) deteriorated the Waru Waru systems due to the introduction of mechanization through intensive agricultural systems. Fig. 1 presents the distribution of the Waru Waru systems around Lake Titicaca.

In this research by means of drone images and field work, the current Waru Waru have ridges with an advanced state of deterioration (70% to 90% damaged) due to the abandonment of agricultural activities and grazing and the implementation of modern agricultural technologies, which accelerates water erosion over these structures. While the oldest structures have practically disappeared, a few old structures remain, with partial degradation due to livestock activity. Currently, the ridges have been abandoned, degraded by water erosion, and affected by salt concentrations, with a few currently devoid of vegetation or covered with native grasses with low levels of technological intervention (Fig. 2e). Authors such as Erickson (1988), Caillavet (2008), Martínez-Ruiz (2014), and GIAHS (2017) have highlighted the greater productivity, root development, soil aeration improvement, and efficiency in distribution, water storage, drainage, and soil conservation achieved through Waru Waru systems.

5. Conclusions

In the pre-Hispanic period and in the 1990s, the area covered by ridge structures, the latter being encouraged by government measures to restore traditional agricultural systems. In the last 50 years, the area under Waru Waru has decreased by 95%, due to the migration phenomenon, modernization of the agricultural sector and the high cost of labor, which has ultimately led to the expansion of grasslands and the degradation of Waru Waru. Currently, only 0.56% of the original area of Waru Waru remains. In the studied site, the main area was occupied by a pluvial system, with phreatic and fluvial systems occupying similar areas. The formation of the studied soils showed a pronounced variability, which was controlled by the seasonal oxidation-reduction processes under palaeohydrological conditions. Under fluvial-lacustrine conditions, the soils showed high organic matter contents related to grassland cover and the contribution of fluvial-lacustrine material. The process of organic matter accumulation favored the development of granular structures at the surface and improved soil fertility. Under conditions of low-energy sedimentation associated with fluvial systems, soils showed little pedogenetic development due to the continuous deposition of sediments. In the context of human influence, Waru Waru systems have been preserved through direct intervention by the state and communities, supporting research and development to adapt these systems to modern times.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This work was supported by anonymous research funds.

Acknowledgments

The authors gratefully acknowledge the wetland Titicaca Lake community for their contributions in recording soil samples. Thanks to the anonymous reviewers for the language and grammar edition.

References

Beltrán, D.F., Palomino, R.P., Moreno, E.G., Peralta, C.G, Montesinos, D.B., 2015. Calidad de agua de la bahía interior de Puno, lago Titicaca durante el verano del 2011. Revista Peruana de Biología 22(3), 335–340. https://dx.doi.org/10.15381/rpb.v22i3.11440

Boixadera, J., Esteban, I., Albert, R.M., Poch, R.M., 2019. Anthropogenic soils from Llanos de Moxos (Bolivia): Soils from pre-Columbian raised fields. Catena 172, 21–39. https://doi.org/10.1016/j.catena.2018.08.007

Bouyoucos, G.J., 1962. Hydrometer Method Improved for Making Particle Size Analyses of Soils. Agronomy Journal 54(5), 464–465. https://doi.org/10.2134/agronj1962.00021962005400050028x

Caillavet, C., 2008. A Native American System of Wetland Agriculture in Different Ecosystems in the Ecuadorian Andes (15th–18th Centuries). Environment and History 14, 331–353. https://doi.org/10.3197/096734008X333554

Díaz Aguilar, R.D., 2013. Estudio de caracterización climática de la precipitación pluvial y temperatura del aire para las cuencas de los ríos Coata e Ilave. Dirección regional SENAMHI-puno, Dirección General de Meteorología. Puno – Perú. 45p.

Earls, J., Erickson, C.L., Ochoa, J.F., Flores, P.P., 1986. Andenes y Camellones en el Perú Andino. CONCYTEC. Ed Bellido. Lima, Perú. 379 p.

Erickson, C.L., 1988. Raised Field Agriculture in the Lake Titicaca Basin: Putting Ancient Agriculture Back to Work. Expedition 30(1), 8–16. https://repository.upenn.edu/anthro_papers/18

Erickson, C.L., 2000. The Lake Titicaca Basin: A Pre-Columbian built landscape. In: D. Lentz (Ed.), Imperfect balance: Landscape transformations in the Precolumbian Americas (pp. 311–356). New York: Columbia University Press. https://repository.upenn.edu/anthro_papers/10/

Erickson, C., 2006. El valor actual de los Camellones de cultivo precolombinos: Experiencias del Perú y Bolivia. In F. Valdez (Ed.), Agricultura ancestral. Camellones y albarradas: Contexto social, usos y retos del pasado y del presente (pp. 315–339). Quito: Ediciones Abya-Yala.

FAO, 2006. Guidelines for Soil Description, a Framework for International Classification, Correlation and Communication. 4th Edition, FAO, Rome.

FAO, 2021. Standard operating procedure for soil available phosphorus – Olsen method. Rome.

FAO, 2023. Standard operating procedure for soil bulk density, cylinder method. Rome. https://doi.org/10.4060/cc7568en

GIAHS, 2017. Global important agricultural heritage systems. Food and Agriculture Organization of the United Nations – FAO. Rome, Italy. https://www.fao.org/giahs/en/

Gondard, P., 2006. Campos elevados en llanuras húmedas del modelado al paisaje camellones, Waru Warus o pijales. Agricultura Ancestral. Camellones y Albarradas. Contexto Social, Usos y Retos del Pasado y del Presente. Ediciones Abya-Yala, Quito, Ecuador, 25–53.

Gondard, P., 2008. Les camellones sud-américains. In: Agricultures singuličres. Mollard, É., Walter, A. Editors. IRD Éditions Institut de recherche pour le développement. Paris. 75–80.

Herrera, L.F., Sarmiento, G., Romero, F., Botero, P.J., Berrio, J.C., 2001. Evolución ambiental de la Depresión Momposina (Colombia) desde el Pleistoceno Tardío a los Paisajes actuales. Geología Colombiana 26, 95–121.

IUSS Working Group WRB, 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

Martínez-Ruiz, J.L., 2014. The Chinampa: a sustainable highly efficient agrohydrologic system for shallow lacustrine and wetland areas. Water Practice & Technology 9(3). https://doi.org/10.2166/wpt.034

Merdy, P., Gamrani, M., Montes, C.R., Rezende Filho, A.T., Barbiero, L., Ishida, D.A., Silva, A.R.C., Melfi, A.J., Lucas, Y., 2022. Processes and rates of formation defined by modelling in alkaline to acidic soil systems in Brazilian Pantanal wetland. Catena 210, 105876. https://doi.org/10.1016/j.catena.2021.105876

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. p. 539-579. In: A. L. Page et al. (ed.) Methods of soil analysis: Part 2. Chemical and microbiological properties. ASA Monograph Number 9.

OEA, 1996. Diagnostico Ambiental del Sistema Titicaca-Desaguadero-Poopo-Salar de Coipasa (Sistema TDPS) Bolivia-Perú. UNEP – División de Aguas Continentales Programa de al Naciones unidas para el medio ambiente. Gobierno de Bolivia, Gobierno del Peru. Washington, D.C

Pérez-Pérez, J., McClung de Tapia, E., Barba-Pingarrón, L., Gama-Castro, J., Peralta-Higuera, A., 2012. Remote sensing detection of potential sites in a prehispanic domestic agricultural terrace system in cerro San Lucas, Teotihuacan, Mexico. Boletín de la Sociedad Geológica Mexicana 64(1), 109–118.

Pérez Sánchez, J.M., 2007. El manejo de los recursos naturales bajo el modelo agrícola de camellones chontales en Tabasco. IBEROFORUM. Revista de Ciencias Sociales de la Universidad Iberoamericana, II (4), 1–9.

PIWA, 1992. Avances de Investigación sobre Microclimatología en el agroecosistema de Waru Waru. WARU–PIWA. Convenio: *PELT/INADE-IC/COTESU*, Puno–Perú.

PIWA, 1994. Priorización de las áreas potenciales para la (re) construcción de Waru Waru en el Altiplano de Puno. WARU–PIWA. Convenio: *PELT/INADE-IC/COTESU*, Puno–Perú.

Remini, B., Achour, B., 2014. The Foggara: A traditional system of irrigation in arid regions. GeoScience Engineering Journal 60(2), 32–39. https://doi.org/10.2478/gse-2014-0011

Robles, B., Flores, J., Martínez, J.L., Herrera, P., 2019. The Chinampa: An Ancient Mexican Sub-Irrigation System. Irrigation and Drainage 68. 115–122. https://doi.org/10.1002/ird.2310

Rodrigues, L., Lombardo, U., Veit, H., 2018. Design of pre-Columbian raised fields in the Llanos de Moxos, Bolivian Amazon: Differential adaptations to the local environment. Journal of Archaeological Science: Reports 17. https://doi.org/10.1016/j.jasrep.2017.11.023

Rodriguez, R., Sánchez, E., Choquehuanca, S., Fabián, C., Del Castillo, B., 2020. Geología de los cuadrángulos de Puno (hojas 32v1, 32v2, 32v3, 32v4) y Acora (hojas 32x1, 32x2, 32x3 y 32x4). INGEMMET, Boletín, Serie L: Actualización Carta Geológica Nacional (Escala 1: 50 000), 2, 109 p., 8 mapas.

Rojas-Mora, S., Montejo-Gaitán, F., 2021. The pre-Hispanic Raised Fields System of the Mompós Depression in the Colombian Caribbean Region. A Preliminary Archaeological Report. In: Bonomo, M., Archila, S. (eds) South American Contributions to World Archaeology. One World Archaeology. Springer, Cham. https://doi.org/10.1007/978-3-030-73998-0_8

SENAMHI, 2021. Climas del Perú – Mapa de Clasificación Climática Nacional. Servicio Nacional de Meteorología e Hidrología del Perú. Ministerio de Medioambiente. 70p.

Smith, C.T., Denevan, W.M., Hamilton, P., 1968. Ancient ridged fields in the region of Lake Titicaca. The Geographical Journal 134, 353–367. https://repository.upenn.edu/anthro_papers/18

Soil Science Division Staff, 2017. Soil survey manual. C. Ditzler, K. Scheffe, and H.C. Monger (eds.). USDA Handbook 18. Government Printing Office, Washington, D.C. Soil Science Division Staff (SSS).

Soil Survey Staff, 2022a. Keys to Soil Taxonomy, 13th edition. USDA Natural Resources Conservation Service.

Soil Survey Staff, 2022b. Kellogg Soil Survey Laboratory methods manual. Soil Survey Investigations Report No. 42, Version 6.0. U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA, 2001. Soil Quality Test Kit Guide. United States Department of Agriculture, Agricultural Research Service, Natural Resources Conservation Service, Soil Quality Institute. 88p.

U.S. Salinity Laboratory Staff, 1954. Diagnosis and improvement of saline and alkali soils. USDA Agricultural Handbook No. 60. U.S. Government Printing Office.