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Mapping and Geospatial Analysis of Ancient Terrace Agricultural Systems in Lucanas Province, Peruvian Andes, Based on Satellite Imagery, High-Resolution DSMs, and Field Surveys

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Keywords: GIS applications | human–environment interactions | prehispanic period | South America | terrace agriculture

ABSTRACT

This paper presents a unique set of maps and geospatial data covering 16 ancient terrace agricultural systems in the upper part of the Río Grande de Nasca drainage. These systems are located on the western Andean flank (1200 and 3800 m asl), in the districts of Llauta, Laramate, and Ocaña in Lucanas province, Ayacucho region, southern Peru (14.5° S). Spanning various periods of the prehispanic era (1000 BCE–1532 CE), only limited sections of these terraces are still in use today. Our field methods include archaeological, geomorphological, and drone surveys. The terrace systems were mapped using (1) satellite imagery and (2) high-resolution Digital Surface Models (DSMs) within a Geographic Information System (GIS). The geospatial analysis and mapping results encompass parameters such as elevation range, terrace area, number and condition of terrace walls, length and height of terrace walls, area of individual terraced fields, associated architecture (e.g., irrigation canals), slope, current vegetation and use, and chronology. By documenting the widespread distribution, extent, and diversity of agricultural terraces in the region, this data set is extremely valuable for understanding prehispanic human-environment interactions and land use dynamics, as well as indigenous agricultural practices and resilience strategies in response to environmental and climate change.

1 | Introduction

Prehispanic terrace agriculture significantly transformed Andean landscapes and serves as a key indicator of ancient land use and human–environment interactions throughout the region (Aguirre-Morales 2009; Canziani 2021; de la Torre and Burga 1986; Denevan 2001; Kendall and Rodríguez 2009; Londoño et al. 2017). Ancient terrace farming systems also offer valuable insights into the indigenous socioeconomic strategies and resilience in response to environmental and climate change. In addition to creating flat surfaces for farming in mountainous environments, terracing provides many essential agricultural functions, such as soil formation and conservation, water conservation and distribution, provision of pasture for livestock, erosion and landslide control, and nighttime frost mitigation by absorbing the strong highland sun during the day through the terrace walls (Erickson 2019; Treacy and Denevan 1994).

Ancient terrace agricultural complexes were often part of much larger systems and associated infrastructure. Many terrace systems were directly connected to settlements encompassing both public and domestic spheres, invoking the term "agricultural terrace-settlement system" (Mader et al. 2024). These terrace-settlement systems often included trails, way stations (*tambos*), water reservoirs, boundary markers, and stone-walled corrals for llama (*Lama glama*) and alpaca (*Vicugna pacos*) herding—architectural features that facilitated the movement of people, animals, water, raw materials, crops, and tools (Beresford-Jones et al. 2023; Mader et al. 2022; Mader, Reindel, and Isla 2023). The terrace agricultural systems themselves often included not only fields but also irrigation canals, storage facilities, paths with steps and ramps, wall niches for shelter, buildings, and sometimes even towers for supervision (Denevan 2001; Erickson 2019).

Terrace agriculture was a cornerstone of the pre-Hispanic Andean economy, as demonstrated by the widespread presence of terraces across the region. However, these agricultural systems remain underexplored. The absence of systematic mapping approaches that integrate spatial and chronological data has limited our understanding of ancient socioeconomic-ecological dynamics, land use changes, and resilience. This knowledge is vital for tackling contemporary challenges in the region, including climate change and water scarcity. The lack of research on terrace agricultural systems may be due to their rather ordinary character compared to more prominent archaeological sites such as large settlements and sacred buildings. Additionally, methods to detect and map complex terrace systems in detail have only recently been developed. While aerial imagery has long been used in archaeology and geography, recent advancements in geospatial data collection and analysis now allow for large-scale documentation of terrace agricultural systems. These advancements include satellite imagery, airborne laser scanning (ALS, LiDAR), high-resolution drone imagery, Digital Surface Models (DSMs), and Machine Learning (ML) approaches for data collection, organization, and analysis, as applied to terraced landscapes in other parts of the world (e.g., Ding et al. 2021; Spanò et al. 2018; Winzeler et al. 2023; Zhao et al. 2021).

By compiling the data set presented in this article, we address this gap and introduce extensive data on terrace agriculture and chronology. Our study area in the province of Lucanas, southern Peruvian highlands, is particularly suitable for investigating terrace agricultural systems, as it exemplifies a densely terraced landscape. The study area is part of the Río Grande de Nasca drainage, one of the archaeologically and geoscientifically best-studied areas in the Andes, investigated for over 25 years by the interdisciplinary Nasca-Palpa Archaeological Project of the German Archaeological Institute (DAI). The regional prehispanic settlement and environmental history is, therefore, uniquely well-documented (e.g., Isla and Reindel 2017; Mächtle and Eitel 2013; Mader, Reindel, Isla, Behl, et al. 2023; Reindel 2009; Reindel and Wagner 2009; Schittek et al. 2015; Soßna 2015; Unkel et al. 2012). Based on high-resolution archaeological surveys and excavations, more than 1500 prehispanic sites have been registered in the area, spanning from the Archaic (8000–3500 BCE) to the arrival of Europeans in the sixteenth century (Figure 1). According to the survey results, at least 90 of the recorded archaeological sites in our study area are associated with ancient agricultural terraces (Figure 2).

Our main goal is to survey and map the ancient terrace agricultural systems and associated settlements in our study area to understand the broader human-environment interactions and socioeconomic dynamics in the prehispanic southern Peruvian Andes. In this article, we introduce a unique geospatial data set that includes maps and data from 16 ancient terrace agricultural systems in Lucanas province on the western flank of the Andes, ranging from 1200 to 3800 m above sea level (m asl; Figure 2). These agricultural complexes span different periods of the prehispanic era (1000 BCE–1532 CE), with only limited sections still in use today (Figure 3). It is important to emphasize that most of the complexes were built and used before the Late Horizon (1450–1532 CE), predating the well-known Inka terraces (e.g., Canziani 2021; Castro et al. 2019; Kendall and Rodríguez 2009; Ortloff 2019).

We conducted archaeological, geomorphological, and drone surveys to explore and select the terrace systems presented here. The digital mapping approach is based on (1) satellite imagery and (2) high-resolution DSMs using a Geographic Information System (GIS). Our geospatial analysis and mapping results include parameters such as terraced area, number and condition of terrace walls, length and height of terrace walls, area of individual terraced fields, associated architecture (e.g., irrigation canals), slope, aspect, current vegetation and use, and chronology. Other terrace systems in this study area, particularly Cutamalla (Te-07), Sihuilca, and Ayllapampa, were described in detail elsewhere (Leceta et al. 2024; Mader et al. 2024). Overall, our methodological mapping approach and compiled data have great potential to serve as a blueprint for future studies in the Andes and beyond.

2 | Regional and Chronological Background

2.1 | Holocene Environmental and Prehispanic Settlement History of the Río Grande de Nasca Drainage, Western Andes

The Río Grande de Nasca drainage extends from the Pacific coastal desert to elevations above 4000 m asl, encompassing all

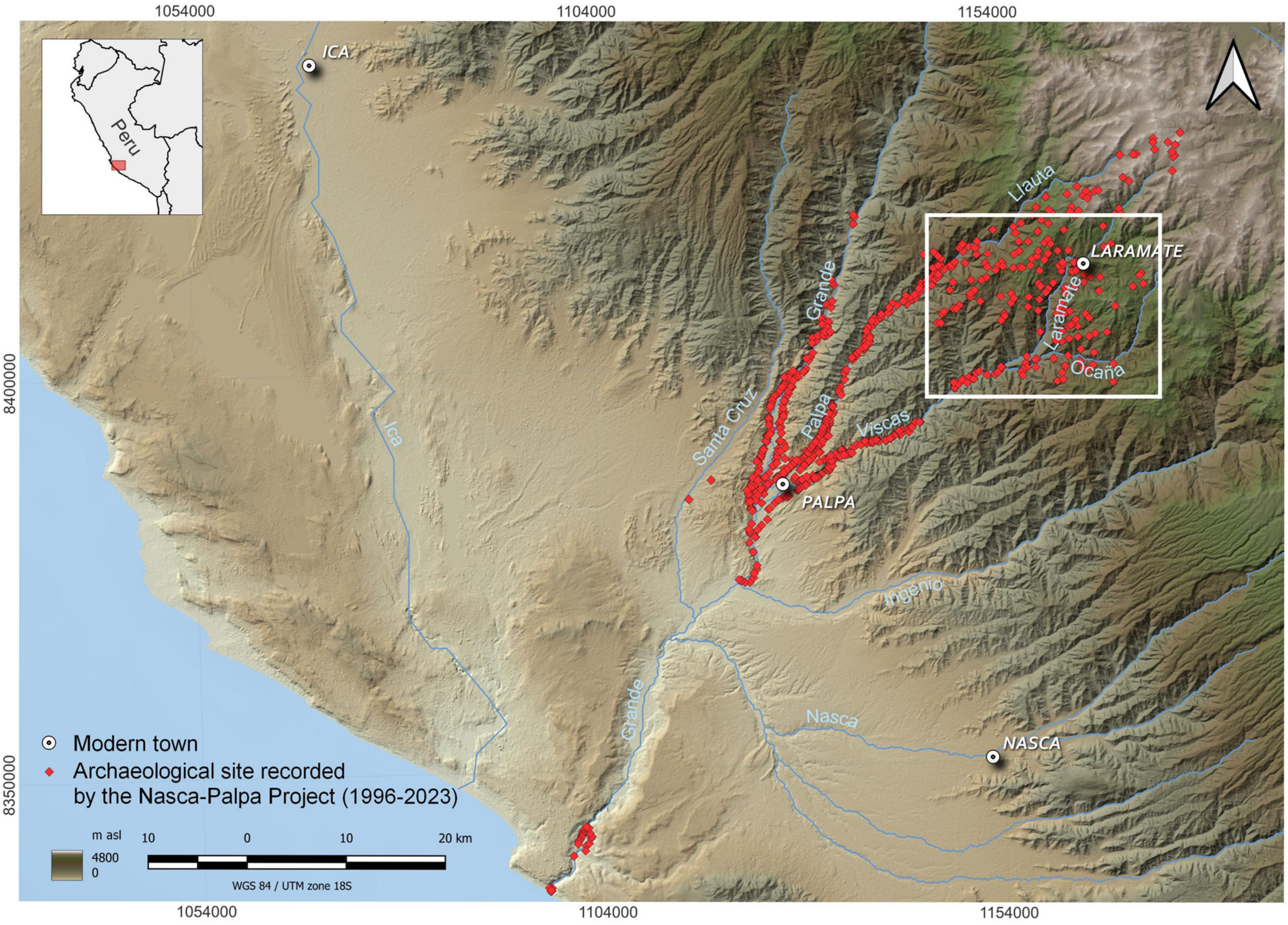

FIGURE 1 | Map of the Río Grande de Nasca drainage showing the study area (white rectangle) and the archaeological sites recorded by the Nasca-Palpa Archaeological Project. Base map: SRTM 90 v4.1 DEM (Jarvis et al. 2008).

ecological levels of the western Andean flank and the valleys of the Viscas (Laramate and Ocaña in the highlands), Palpa (Llauta in the highlands), Grande, and Santa Cruz rivers in southern Peru (Figure 1). In this region, which has an enormous diversity of ecological zones and a corresponding diversity of climate, vegetation, fauna, and economic opportunities, it has been possible to document an almost uninterrupted sequence of prehispanic history. This spans from the first manifestations of sedentary life during the Archaic period (8000–3500 BCE) to Inka sites from the early 16th century (Mader, Reindel, Isla, Behl, et al. 2023; Reindel 2009; Reindel and Isla 2013a; Soßna 2015). Analysis of various geoarchives indicates that climatic conditions were not stable but experienced significant variations over the centuries. These fluctuations resulted in shifts in the desert margin and zonation of ecological tiers, leading to changes in the economic bases of the human societies living in those zones (Eitel et al. 2005; Eitel and Mächtle 2009; Mächtle and Eitel 2013; Schittek et al. 2018, 2015). Consequently, adaptation strategies, including settlement patterns, land use, and mobility across the western Andes, were also affected (Beresford-Jones et al. 2023; Mader et al. 2022; Reindel and Isla 2013a; Soßna 2015).

Regarding the settlement history, the Cerro Llamocca sacred mountain complex (4487 m asl) includes the oldest archaeological site hitherto recorded in the larger region: a rock shelter with evidence of human occupation from the Early Archaic period, around ~8000 BCE (Mader, Reindel, Isla, Behl, et al. 2023). The mid-Holocene period (6600–3600 BCE) was characterized by episodic dry spells alternating with more humid periods. Following a pronounced dry period from 2600 to 2200 BCE, the climate generally became more humid (Eitel and Mächtle 2009; Mächtle and Eitel 2013; Reindel and Isla 2013a; Schittek et al. 2015). This shift coincided with increased settlement and land use activities during the Formative period (1700–200 BCE), particularly toward the end of the Paracas period (800–200 BCE). Extensive archaeological excavations at Paracas settlements such as Collanco (1630 m asl) and Cutamalla (3300 m asl) have provided rich data on the chronology, layout, and use of these settlements (Mader 2019a; Mader, Reindel, and Isla 2023; Reindel and Isla 2017, 2018; Reindel et al. 2015). These settlements were associated with cultivation on extensive terrace agricultural systems surrounding the sites. In particular, Cutamalla was an agricultural and economic center of the Paracas culture. The high population density on the coast during this time facilitated significant exchanges of goods such as maize, camelid wool, and obsidian, often transported by llama caravans (Mader 2019a, 2019b; Mader et al. 2018, 2022, 2023a, 2024; Reindel and Isla 2013b).

Between 200 BCE and 600 CE, a humid and relatively stable period coincided with the flourishing of the Nasca archaeological culture in the western Andes. An abrupt switch to a sustained dry period occurred between 600 and 800 CE, broadly contemporaneous with

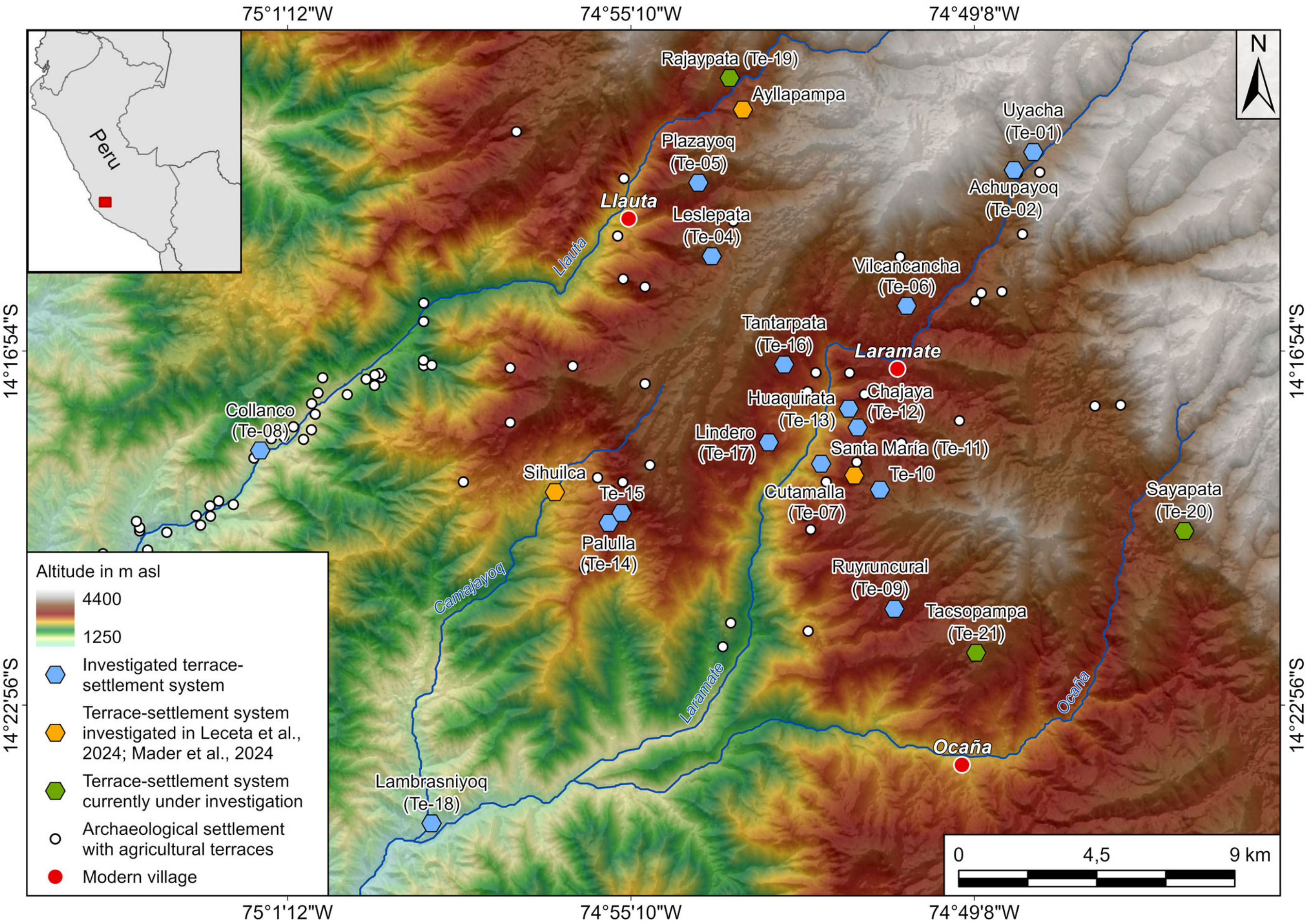

FIGURE 2 | Overview map of the study area in the southern Peruvian Andes, highlighting the locations of ancient terrace agricultural systems discussed in this article, as well as those examined in Leceta et al. (2024), Mader et al. (2024), and sites currently under investigation. Base map: SRTM 90 v4.1 DEM (Jarvis et al. 2008).

the demise of the Nasca culture at the end of the Early Intermediate Period (200 BCE–600 CE) and the rise of the Wari culture during the Middle Horizon (600–1000 CE) in the Río Grande de Nasca drainage (Eitel and Mächtle 2009; Mächtle and Eitel 2013; Reindel and Isla 2013a; Schittek et al. 2015, 2018). Huayuncalla (3100 m asl) is a representative Nasca and Wari site in the highlands, which has been extensively excavated to obtain reliable settlement data (Isla and Reindel 2014, 2021). Toward the end of the Nasca Early Intermediate Period, the coast experienced aridization, while the highlands maintained more favorable climatic conditions for agriculture, leading to an increase in population density. During the Middle Horizon, the expansive Wari state, originating in the highlands, occupied ancient Nasca settlements and extended its influence into coastal regions (Isla and Reindel 2014, 2021; Reindel and Isla 2013a). Markedly drier conditions prevailed until 1250 CE. After 1250 CE, more humid but hydrologically variable conditions likely benefited settlement and agricultural activities during the Late Intermediate period (1000–1450 CE). In the seventeenth century, aridization led to a profound environmental shift characterized by dry conditions (Eitel and Mächtle 2009; Mächtle and Eitel 2013; Reindel and Isla 2013a; Schittek et al. 2015, 2018).

Overall, significant cultural changes in the Río Grande de Nasca drainage appear to have coincided with major paleoclimatic shifts (Mächtle and Eitel 2013; Reindel and Isla 2013a; Schittek et al. 2015). Andean communities adapted to the specific conditions of various ecological regions and developed economic activities suited to each natural environment. Additionally, the mobility of people, llamas, and commodities was a crucial component of cultural and economic development in the prehispanic Andes (Beresford-Jones et al. 2023; Mader 2019a; Mader et al. 2022; Mader, Reindel, Isla, Behl, et al. 2023). Terrace agriculture was an adaptation strategy to environmental change (Leceta et al. 2024). Associated highland settlements often served agricultural purposes, focusing on crops such as grains, tubers, and vegetables (Mader et al. 2024).

2.2 | Study Area

Our study area is located in the upper part of the Río Grande de Nasca drainage and ranges from 1200 to 3800 m asl on the western flank of the Andes, within the districts of Llauta, Laramate, and Ocaña in the province of Lucanas, Ayacucho, southern Peru (14.5° S, Figure 1). This study area encompasses the maritime *yunga* (500–2300 m asl), *quechua* (2300–3500 m asl), and *suni/jalca* (3500–4000 m asl) ecological zones, featuring a variety of microenvironments with corresponding diversity in climate, topography, soils, vegetation, and fauna (Pulgar Vidal 1981; Sandweiss and Richardson 2008).

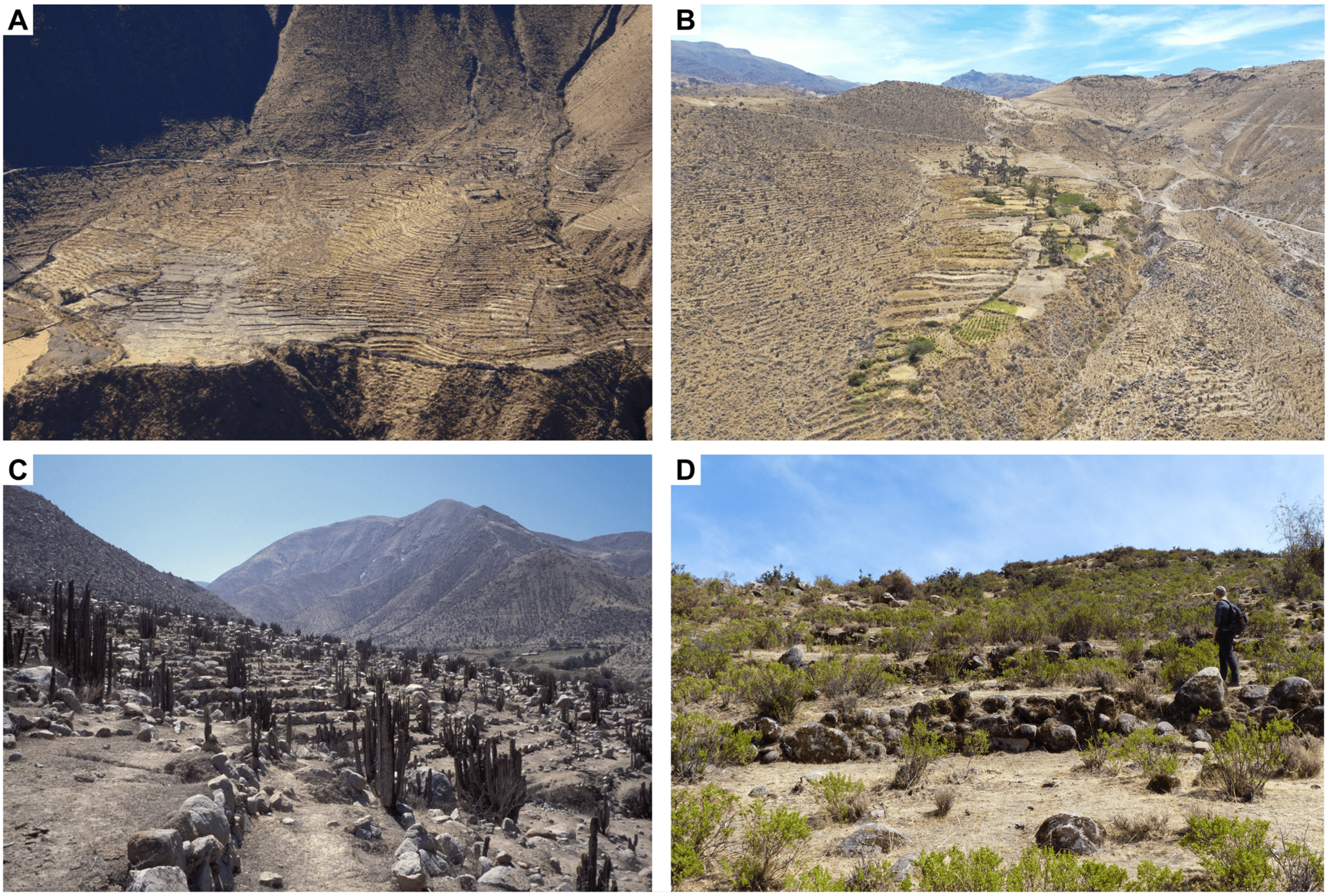

FIGURE 3 | Photographs of selected agricultural terrace-settlement systems in the study area: Santa María (A), Huaquirata (B), Collanco (C), and Leslepata (D).

The maritime *yunga* is characterized by steep river valleys, ravines or *quebradas*, and slopes. Irrigation is of fundamental importance to agriculture in this zone due to the dry and hot climate and low amounts of precipitation. The environmental conditions of the maritime *yunga* encourage especially the cultivation of fruits and coca (*Erythroxylum coca*). Native fruits grown here encompass, for instance, the avocado (*Persea americana*), the common guava (*Psidium guajava*), the chirimoya (*Annona cherimola*), and the lúcuma (*Pouteria lucuma*). Different cactus and agave species and the Peruvian pepper tree (*Schinus molle*) dominate the natural vegetation (Pulgar Vidal 1981; Sandweiss and Richardson 2008).

The *quechua* is the most favorable ecological zone for farming in the western central Andes. Today, the climate of the *quechua* in our study area is characterized by a mean annual temperature of 10°C, a mean annual rainfall of 250–300 mm, and a distinct rainy season in summer (November–April) accounting for about 90% of the rainfall (Leceta et al. 2024). Factors benefitting agricultural production here include the moderate climate (yet with strong diurnal fluctuation in temperature), fertile soils, and seasonal precipitation, allowing rainfed and irrigated forms of agriculture. Thus, there is a wide spectrum of crops cultivated in the *quechua*, also representing the upper boundary for the cultivation of maize (*Zea mays*), one of the most significant agricultural products in this ecological tier. Other important crops comprise many species of beans, squashes, and root vegetables, such as the potato (*Solanum tuberosum*) and arracacha (*Arracacia xanthorrhiza*; Pulgar Vidal 1981; Sandweiss and Richardson 2008).

The *suni* or *jalca* is defined by a colder climate, frequently with nocturnal frosts, and often a steeper topography with less arable land in comparison with *quechua* environments. Despite these major limitations for arable farming, a lot of Andean crops are cultivated in the *suni*, including chenopods or goosefoots such as quinoa (*Chenopodium quinoa*) and kaniwa (*Chenopodium pallidicaule*); tubers such as oca (*Oxalis tuberosa*), olluco (*Ullucus tuberosus*), and mashua or añu (*Tropaeolum tuberosum*); and the lupin tarwi (*Lupinus mutabilis*). In addition, the cool climate of the *suni* and other high-altitude zones provide ideal conditions for the production of storable foodstuff such as *ch'uñu* (freeze-dried bitter potatoes) and *ch'arki* or jerky (dried camelid meat; Pulgar Vidal 1981; Sandweiss and Richardson 2008).

3 | Materials and Methods

The terrace agricultural systems described in this article were systematically surveyed and studied using a variety of archaeological and geoscientific methods to collect a range of data (see also Leceta et al. 2024; Mader et al. 2024). To demonstrate the diversity of ancient Andean agricultural terraces, we selected 16 systems of different sizes from different ecological zones and dating to different prehispanic periods (Figure 2).

3.1 | Archaeological and Geomorphological Survey

Ancient farming terraces and associated archaeological sites have been identified by extensive regional pedestrian surveys and aerial archaeology (satellite and drone images) in two field seasons (in November 2021 and October 2022). During our surveys, we collected and analyzed surface artifacts, recorded the preservation and architecture of the terraces, and documented the current vegetation and terrace use. Another important aspect of our archaeological and geomorphological surveys was to locate appropriate spots for soil testing (for location, see individual maps of the terrace agricultural systems). Soil samples taken are currently being analyzed and will be discussed in future studies (see also Leceta et al. 2024; Mader et al. 2024).

3.2 | Drone Survey and DSM Generation

Drone surveys of selected terrace systems ($n = 9$) were conducted in October 2022 using a DJI Mavic 2 Pro for aerial photography and photogrammetric documentation. Photography was conducted in two stages. Initially, the entire area of interest was systematically covered in a grid pattern at an altitude of 250 to 400 m above ground level, with each photograph having a minimum of 60% forward and lateral overlap. Subsequently, specific features, such as structures or segments of the terrace systems, were photographed at a lower altitude of approximately 25–50 m above ground level to capture higher detail. Depending on the area, between 200 and 4000 photographs were taken for each terrace system. The aerial photographs were processed using Agisoft Metashape, OpenDroneMap, and RealityCapture to align the images and create depth maps. High-resolution DSMs of the terrace agricultural systems were then generated from these depth maps using Structure from Motion (SfM). The DSM resolution ranges from 3 to 17 cm per pixel, depending on the agricultural system. The primary benefits of creating DSMs using drone flights are the low cost and minimal effort required, which significantly reduces fieldwork time (Uysal et al. 2015). The Collanco terrace agricultural system was initially surveyed and mapped in 2013 using laser scanning and photogrammetric techniques in collaboration with ArcTron 3D (Reindel and Isla 2018; Reindel et al. 2015).

3.3 | Mapping Based on Satellite Imagery

To accurately map the terrace agricultural systems, we utilized satellite imagery within a GIS environment (QGIS). Initially, high-resolution QuickBird satellite images with a spatial resolution of 60 cm covering the agricultural areas were manually georeferenced using Google Earth Pro data. These satellite images were meticulously analyzed for parallel patterns and lines indicative of terraces, allowing for the manual identification and digitization of individual terraces and boundary walls. When the lighting conditions of the QuickBird satellite imagery were insufficient, Google Earth Pro satellite imagery was used to supplement the mapping, following the same procedure (Mader et al. 2024).

3.4 | Mapping Based on High-Resolution DSMs and GIS Analysis

High-resolution DSMs are excellent tools for analyzing the micro-topography of a site and identifying agricultural terraces. The GIS-based identification and analysis of terraces and terrace boundaries from high-resolution DSMs rely primarily on slope differences and profile curvatures (Cucchiaro et al. 2021; Spanò et al. 2018; Tarolli et al. 2014; Zhao et al. 2021). To map the agricultural terraces, the DSMs were first pre-processed using the DTM slope-based filter (Vosselman 2000) in SAGA GIS to remove small irregularities, such as stones, before both slope gradients and profile curvatures were calculated. Due to the varied terrain and terraces of varying sizes and states of conservation, initially, homogeneous subareas based on slope gradients had to be defined within each agricultural system. Given the terrain's heterogeneity, the raster data of terraces and terrace walls were analyzed, automatically classified, vectorized, and converted into shapefiles based on site-specific threshold values for slope and curvature (see also Mader et al. 2024). In cases of extremely difficult terrain with highly deformed terraces, manual corrections were necessary. To evaluate the reliability and accuracy of the calculated terrace areas, the statistical measure Cohen's κ was calculated for selected reference areas with abandoned and currently used terraces by comparing the calculated terrace data with reference terrace data, mapped by hand using orthophotos, satellite images, and slope gradients. The obtained kappa values ranged from 0.35 to 0.81 (mean: 0.65; SD: 0.15; $n = 7$), suggesting moderate to substantial agreement (Landis and Koch 1977) and demonstrating that the methodological approach is well-suited to mapping the terraces in the study area. The best mapping results were obtained where the vegetation was sparse and the terraces well-preserved.

In addition, we derived further data from the GIS-based analysis of the DSMs, which included general characteristics of the agricultural systems (such as slope and aspect) and specific details of the terraces (such as shape and terrace lengths). The average height of the terrace walls and the width of the terraces were determined from several longitudinal terrain profiles ($n = 4$–10 per system, containing 31–94 terraces) at selected sections of six agricultural terrace systems (for locations, see individual maps; see also Mader et al. 2024).

Vegetation on the terrace systems was categorized as “sparse vegetation,” “moderate vegetation,” or “dense vegetation” using the Normalized Difference Vegetation Index (Atun et al. 2020; Silverio and Jaquet 2009) based on Sentinel-2 satellite imagery. The elevation range of each terrace system was determined at the lowest and highest terrace using the SRTM 90 m v4.1 Digital Elevation Model (DEM; Jarvis et al. 2008).

3.5 | Cross-Validation of Mapping Approaches

Importantly, we used the DSMs to validate the mapping derived from satellite imagery and to correct misinterpretations caused by vegetation and animal tracks. Whenever possible, we validated the mapping of the terrace systems through field observations during our pedestrian surveys, refining and adjusting the accuracy of the mapping where necessary. However, due to time constraints, a comprehensive on-site verification of the digital mapping results for all agricultural terrace systems has not yet been possible.

4 | Results

4.1 | Uyacha Terrace Agricultural System (Te-01)

Uyacha is located in the valley of the Laramate River, northeast of the modern village of Atocata (Figure 2). Facing southeast, Uyacha is the highest terrace system (3621–3774 m asl) included in this data set and was exclusively used for livestock grazing. This is evident in the layout of the complex, the circular shape of the stone terraces (ideal for water retention), and its current use for animal husbandry. The total terraced area is 0.7 ha. The 25 recorded terrace walls have an average length of 26.5 m, totaling about 663.4 m (Figure 4; Table 1). The walls are quite weathered. Based on the terrace architecture and surface finds collected during our archaeological and geomorphological surveys (including the associated ancient settlement), Uyacha dates to the Paracas and Nasca periods (800 BCE–600 CE).

4.2 | Achupayoq Terrace Agricultural System (Te-02)

Achupayoq is situated in a protected tributary valley of the Laramate River, northeast of the modern village of Atocata (Figure 2). The total terraced area is 4.0 ha, ranging from 3568 to 3686 m asl and includes 32 terrace walls with a total length of 1.4 km, boundary walls in peripheral areas, and several irrigation canals, all constructed of stone (Figure 5; Table 1). There is a small water reservoir to the north of this agricultural system. Achupayoq features both abandoned and currently used terraces. The abandoned terraces cover relatively large fields with a total area of 2.4 ha. Except for one long and massive terrace, the average terrace area is 633.5 m^2. The average length of the terrace walls is 32.1 m (SD: 18.2 m), with a total length of 961.7 m. Some terrace walls are up to 2.5 m high. The slope in this sector ranges from 9.5 to 27.8° (mean: 17.9°).

The terraces still in use are mostly connected and situated to the southwest; they cover an area of 1.6 ha. The 10 terrace walls recorded in this sector have an average length of 43.6 m (SD: 21.0 m), with a total length of 480.1 m. The average slope is 15.6°. The fields are used for crop production—including maize (*Z. mays*), barley (*Hordeum vulgare*), and alfalfa (*Medicago sativa*)—as well as for animal grazing. Overall, the walls and canals are in fairly good condition. Based on the terrace architecture and surface finds collected during our archaeological and geomorphological surveys (including the associated ancient settlement), Achupayoq dates back to the Late Intermediate period (1000–1450 CE) and may have been in continuous use until today.

4.3 | Leslepata Terrace Agricultural System (Te-04)

Leslepata is located just west of the modern hamlet of Cusoro and southeast of the modern town of Llauta (Figure 2). The total terraced area is 65.5 ha, ranging from 2603 to 3492 m asl, and

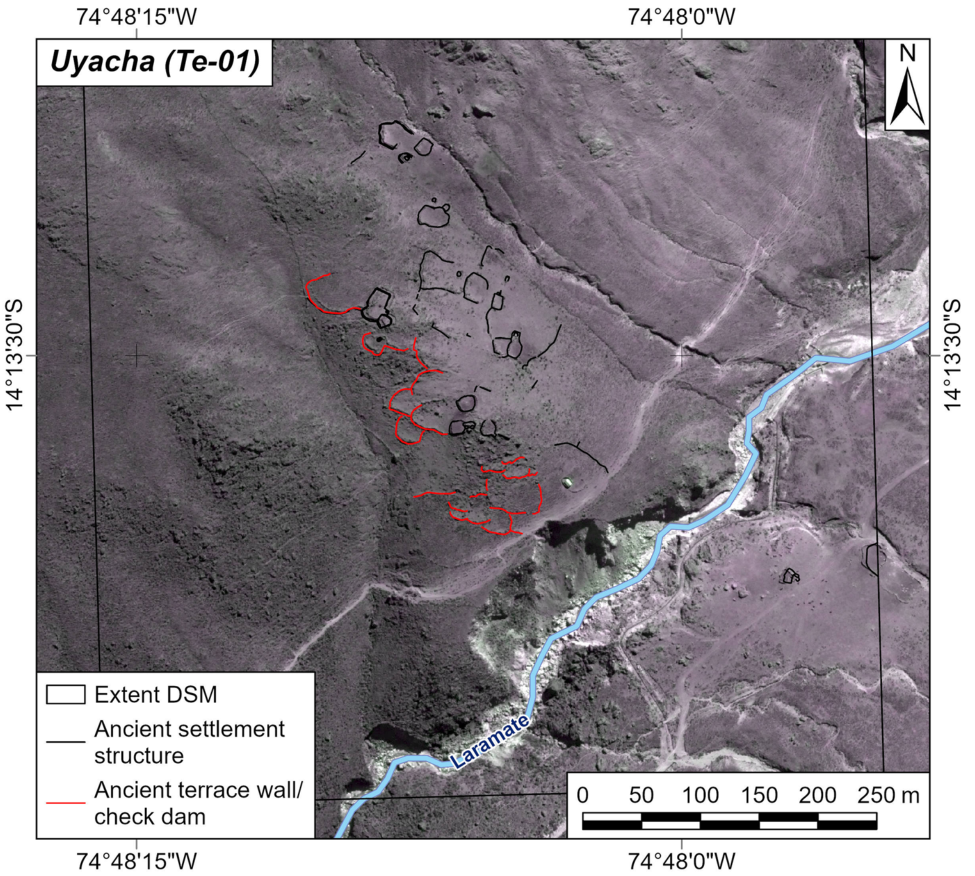

FIGURE 4 | Map of the Uyacha terrace agricultural system based on a high-resolution DSM and satellite imagery.

TABLE 1 | Collected geospatial and chronological data of the studied terrace agricultural systems.

Terrace agricultural system	Ecological zone after Pulgar Vidal (1981)	Altitude range in m asl	Total terraced area in ha	Number of terrace walls	Total length of terrace walls in km	Period
Uyacha (Te-01)	*Suni/jalca*	3621–3774	0.7	25	0.7	Paracas and Nasca periods (800 BCE–600 CE)
Achupayoq (Te-02)	*Suni/jalca*	3568–3686	4.0	32	1.4	Late Intermediate period (1000–1450 CE) until today
Leslepata (Te-04)	*Quechua*	2603–3492	65.5	749	48.5	Formative and Nasca periods (1000 BCE–600 CE)
Plazayoq (Te-05)	*Quechua*	2754–3572	534.0	1217	15.7	Late Intermediate period (1000–1450 CE) until today
Vilcancancha (Te-06)	*Quechua*	3263–3323	5.3	26	2.2	Late Intermediate period (1000–1450 CE)
Collanco (Te-08)	Maritime *yunga*	1550–1700	200.0	650	50.6	Late Paracas to Late Intermediate period (370 BCE–1450 CE)
Ruyruncural (Te-09)	*Quechua*	3098–3292	135.1	852	68.3	Late Paracas and Early Nasca periods (370 BCE–200 CE)
Te-10	*Quechua*	3214–3504	54.8	1221	62.3	Late Paracas and Early Nasca periods (370 BCE–200 CE)
Santa María (Te-11)	*Quechua*	2592–2786	39.0	692	33.8	Middle to Late Horizon (600–1532 CE)
Chajaya (Te-12)	*Quechua*	2860–2942	16.8	689	27.5	Late Paracas to Late Intermediate period (370 BCE–1450 CE)
Huaquirata (Te-13)	*Quechua*	2623–3163	27.0	1752	80.5	Middle Horizon and Late Intermediate Period (600–1450 CE)
Palulla (Te-14)	*Quechua*	2839–3085	11.5	89	4.2	Nasca period and Middle Horizon (200 BCE–1000 CE)
Te-15	*Quechua*	2921–3175	7.1	—	—	Late Intermediate period (1000–1450 CE)
Tantarpata (Te-16)	*Quechua*	2841–3375	42.2	1854	29.7	Formative to Late Intermediate period (1000 BCE–1450 CE)
Lindero (Te-17)	*Quechua*	2959–3244	18.5	261	10.4	Nasca period and Middle Horizon (200 BCE–1000 CE)
Lambrasniyoq (Te-18)	Maritime *yunga*	1258–1326	5.2	63	5.2	Middle Horizon and Late Intermediate periods (600–1450 CE)
		Total	1166.7	10,172	441.0	Formative period (1000 BCE) to today (2024 CE)

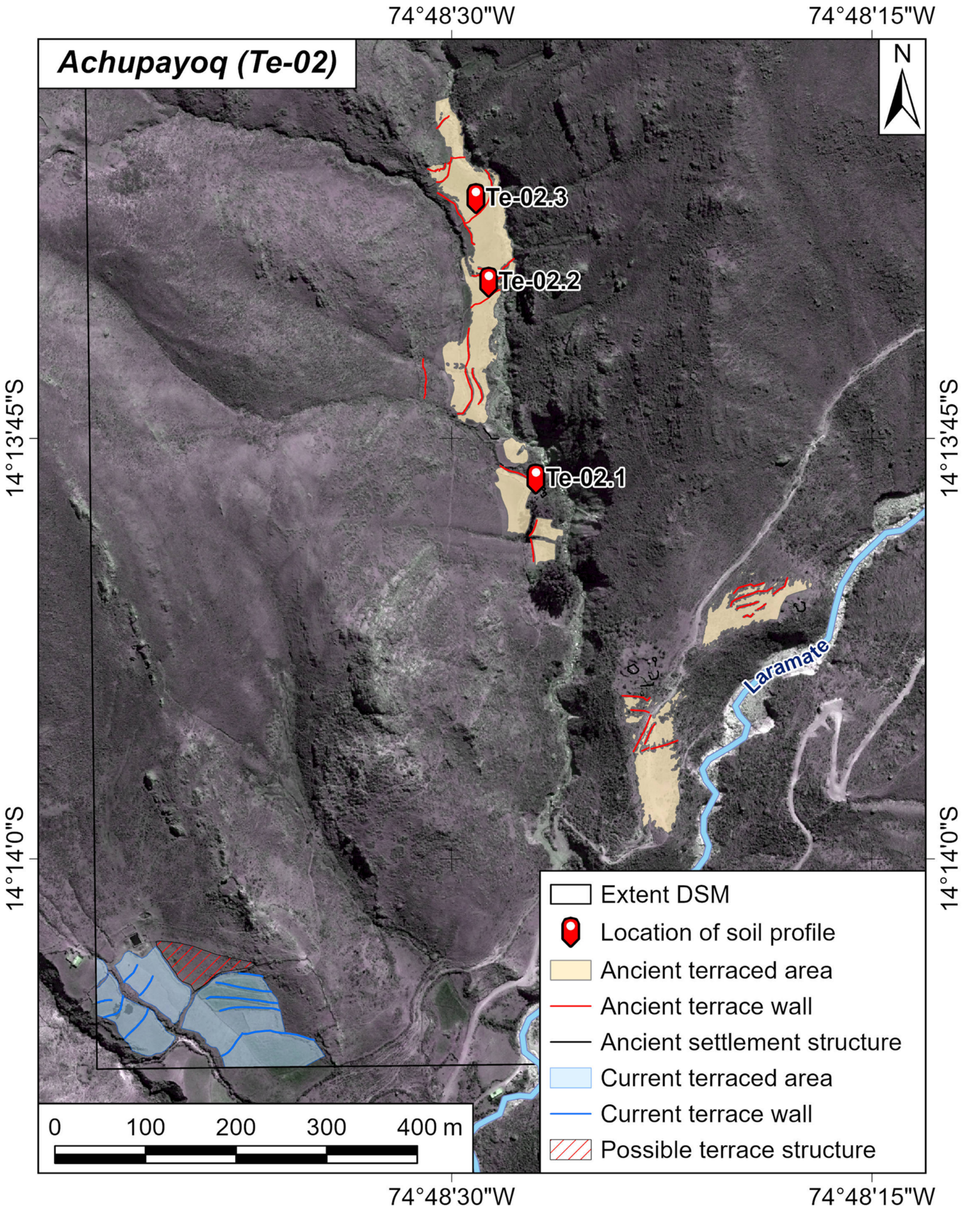

FIGURE 5 | Map of the Achupayoq terrace agricultural system based on a high-resolution DSM and satellite imagery.

includes both ancient terraces and those currently used for crop cultivation and animal grazing (Figure 6; Table 1). The ancient agricultural system consists of 527 stone terrace walls with a total length of 37.9 km. The area of terraced fields and the number of walls are likely higher but could not be precisely determined due to the dense vegetation on the main slope. The ancient terraces primarily extend along this slope but also include scattered sections further west and south, covering a total of 49.0 ha. The area of individual terraces ranges from 5.2 to 75,660.0 m^2, with an average area of 930.5 m^2 (SD: 4809.3 m^2). The slope ranges from 7.5° to 29.6° (mean: 14.0°, SD: 2.9°). We evaluated six slope profiles (total length: 462.0 m) to obtain more detailed terrace data for these sections. The 31 terraces analyzed have an average length of 12.7 m, ranging from 2.5 to 29.6 m (SD: 7.1 m), and an average width of 2.9 m (SD: 1.4 m). The average slope is 12.3° (SD: 3.6°). The terrace walls have an average height of 1.5 m (SD: 1.5 m). The ancient terraces are heavily weathered. Apart from the dense vegetation on the main slope, the rest of the agricultural system has sparse to moderate vegetation.

Another 222 terraces still in use are situated mostly in the east but also in the west of the Leslepata complex, covering a total of 16.5 ha and including a total wall length of 10.6 km. Based on the terrace architecture and surface finds collected during our archaeological and geomorphological surveys (including the associated ancient settlement with numerous circular architectural structures), Leslepata dates to the Formative and Nasca periods (1000 BCE–600 CE).

4.4 | Plazayoq Terrace Agricultural System (Te-05)

Plazayoq is located south of the modern town of Pucará and northeast of the modern town of Llauta (Figure 2). The total terraced area is 534.0 ha, ranging from 2754 to 3572 m asl, and includes both ancient and currently used terraces (Figure 7; Table 1). The terraced fields range in size from 180.0 to 1600.0 m^2. There are 600 ancient terrace walls and 598 ancient

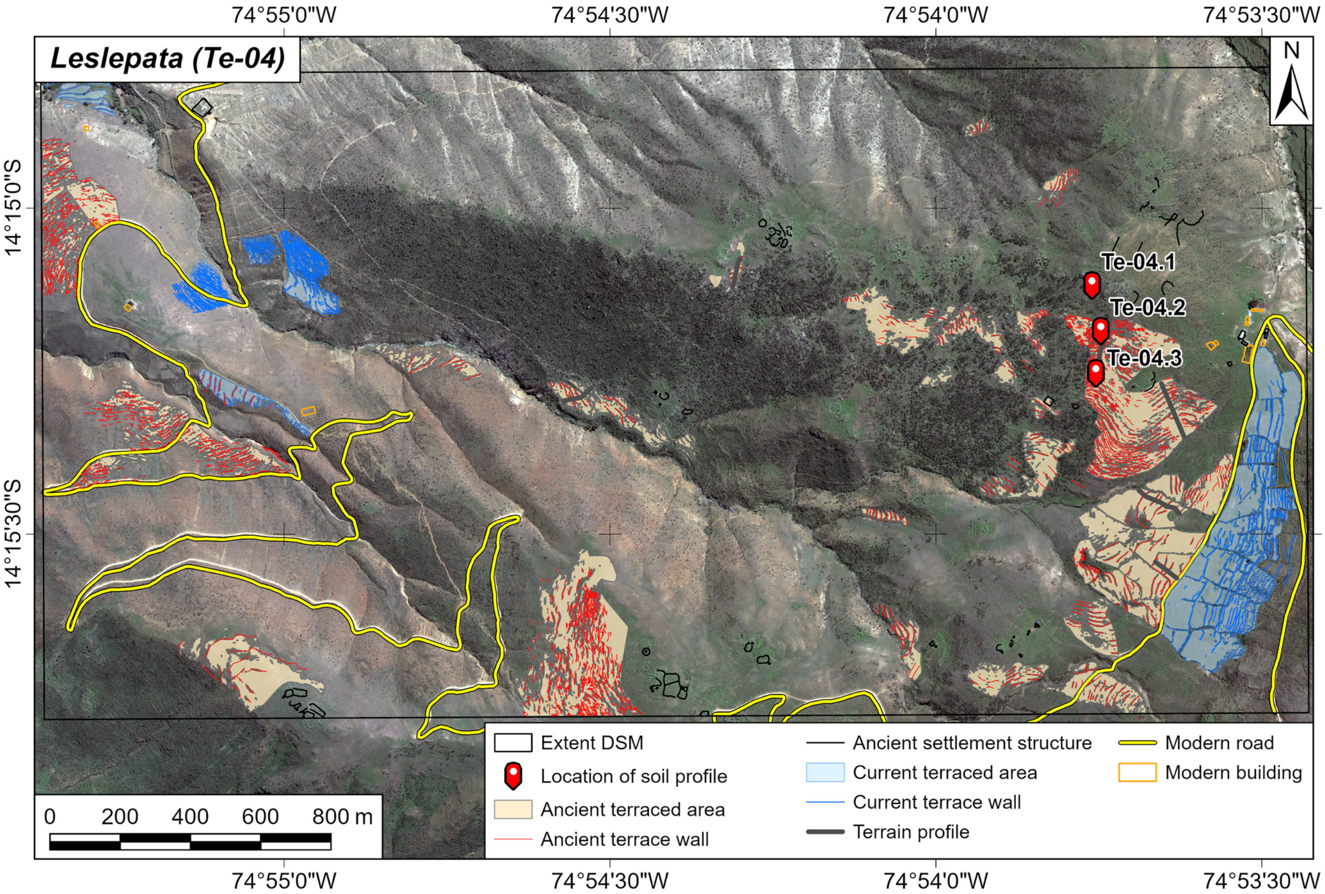

FIGURE 6 | Map of the Leslepata terrace agricultural system based on a high-resolution DSM and satellite imagery.

boundary walls, with an average length of 25.8 m (SD: 17.8 m, total length: 15.4 km), all solidly built of stone. Despite the moderate to dense vegetation, most of the walls are in fairly good condition. The DSM of Plazayoq is distorted (about 10%) in marginal areas, where detailed analysis was not possible. We analyzed 10 terrain profiles (average length: 77.4 m) to obtain more detailed terrace data for the ancient sections. The 82 terraces analyzed have an average width of 8.0 m (SD: 5.6 m), with an average slope of 10.9° (SD: 5.2°). The boundary walls have an average height of 1.6 m (SD: 0.9 m).

In the northern part, there is a terrace section (1.7 ha) that is currently in use and includes 19 boundary walls with a total length of 461.5 m. Based on the terrace architecture and surface finds collected during our archaeological and geomorphological surveys (including the associated ancient settlement with numerous architectural structures), Plazayoq dates to the Late Intermediate period (1000–1450 CE) and may have been in continuous use until today.

4.5 | Vilcancancha Terrace Agricultural System (Te-06)

Vilcancancha is situated in a fertile valley plain of the Laramate River, north of the modern town of Laramate amidst numerous agricultural complexes (Figure 2). The terraced area spans 5.3 ha, ranging from 3263 to 3323 m asl, and includes 26 stone terrace walls with a total length of 2.2 km and a canal system for irrigation (Figure 8; Table 1). The walls and canals are well-preserved due to the ongoing use of the terrace system for crop cultivation and grazing. Crops rotated here include maize (*Z. mays*), potatoes (*S. tuberosum*), beans (*Phaseolus lunatus*), onions (*Allium cepa*), and alfalfa (*Medicago sativa*). Given its current agricultural use, it is challenging to pinpoint when Vilcancancha was first converted to agricultural land. However, based on the terrace architecture and surface finds gathered during our archaeological and geomorphological surveys, Vilcancancha likely dates back to at least the Late Intermediate period (1000–1450 CE).

4.6 | Collanco Terrace Agricultural System (Te-08)

Collanco is located in the valley of the Palpa River, known as Llauta, further upstream, southwest of the modern village of Collanco (Figure 2). The total terraced area covers 200.0 ha, ranging from 1550 to 1700 m asl, and includes 650 terrace walls with a total length of 50.6 km, several boundary walls, and irrigation canals, all constructed of stone (Figure 9; Table 1). The terraced fields of Collanco are relatively small, with some covering only a few square meters. Many of the terrace walls show signs of erosion. Today, only the lowest terraces near the river are still in use, primarily for cultivating avocados (*P. americana*), which has altered and, in some cases, destroyed the ancient terrace structures. The irrigation system combined rainfed and irrigated agriculture. Rainwater was collected in

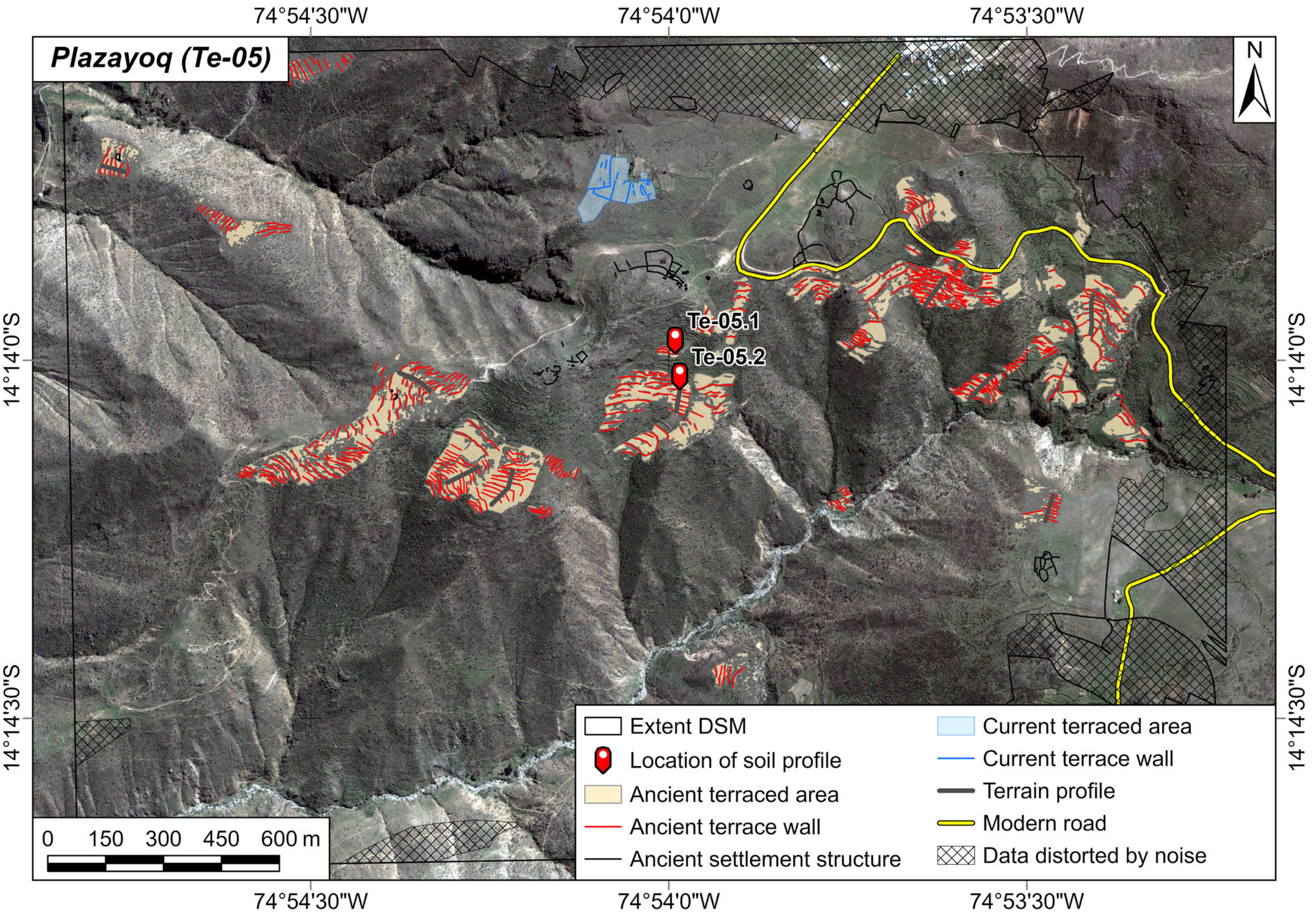

FIGURE 7 | Map of the Plazayoq terrace agricultural system based on a high-resolution DSM and satellite imagery.

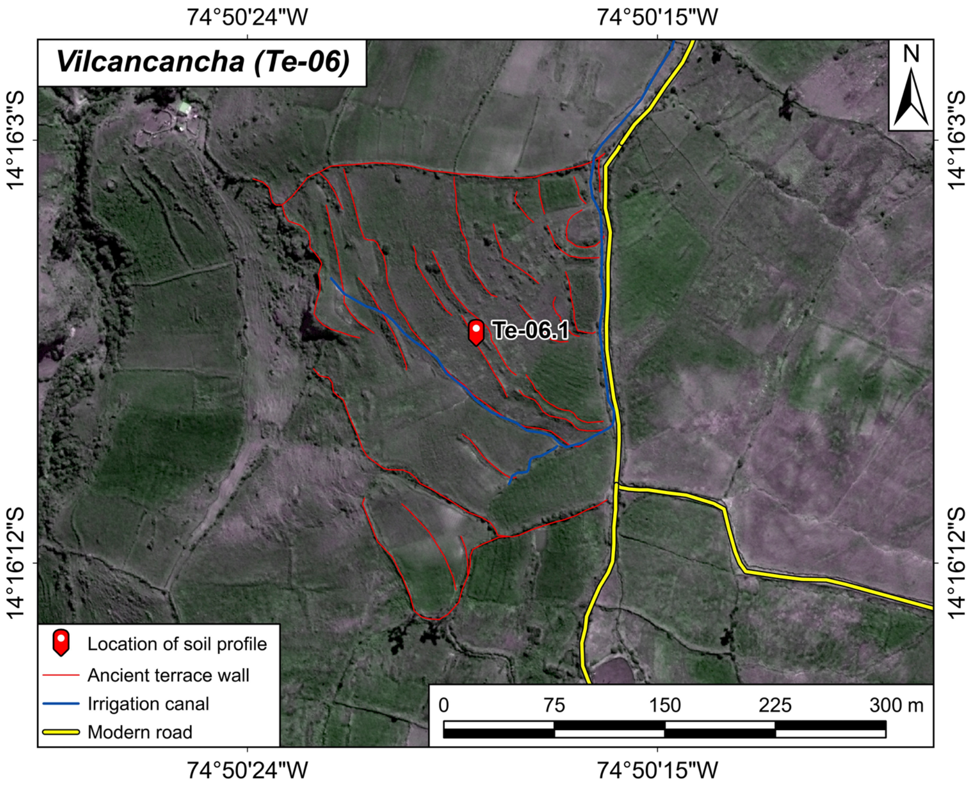

FIGURE 8 | Map of the Vilcancancha terrace agricultural system based on satellite imagery.

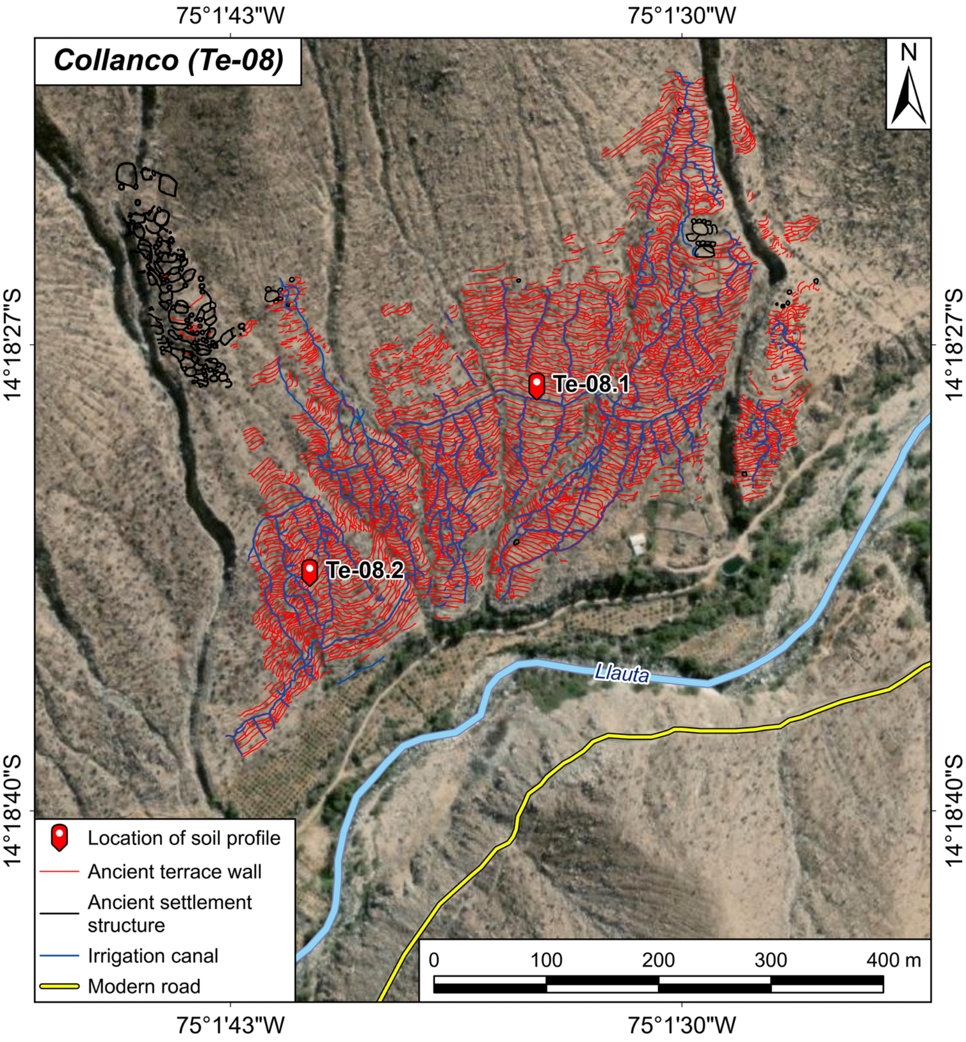

FIGURE 9 | Map of the Collanco terrace agricultural system based on a high-resolution DSM and satellite imagery.

upper areas and in horizontal intermediate canals, then distributed through vertical canals across the agricultural system. Based on the terrace architecture and surface finds gathered during our archaeological and geomorphological surveys (including excavations conducted at the associated ancient settlement with numerous architectural structures), Collanco dates from the Late Paracas to the Late Intermediate period (370 BCE–1450 CE).

4.7 | Ruyruncural Terrace Agricultural System (Te-09)

Ruyruncural is situated just north of a modern hamlet called Pocpoca (Figure 2). This agricultural complex spans a terraced area of 135.1 ha, ranging from 3098 to 3292 m asl, and includes 852 stone terrace walls with a total length of 68.3 km (Figure 10; Table 1; Mader et al. 2024). The walls exhibit significant weathering. Based on the terrace architecture and surface finds gathered during our archaeological and geomorphological surveys (including excavations at associated ancient settlements with numerous architectural structures), Ruyruncural dates back to the Late Paracas and Early Nasca periods (370 BCE–200 CE).

4.8 | Te-10 Terrace Agricultural System

Te-10 is situated south of the modern town of Laramate (Figure 2). The total area of agricultural terraces spans 54.8 ha, ranging from 3214 to 3504 m asl, and comprises 1221 stone terrace walls, totaling 62.3 km in length (Figure 11; Table 1). Detailed DSM data is available for the northern part of Te-10 (Figure 11). For this area, we evaluated six terrain profiles (total length: 476.0 m) to obtain detailed terrace data. The 80 terraces analyzed have an average width of 4.5 m (SD: 2.7 m), ranging from 0.6 to 15.5 m. The slope of the terraced area ranges from 5.6° to 20.6° (mean: 11.7°, SD: 2.4°). The average height of the terrace walls is 0.7 m (SD: 0.4 m). The terrace walls exhibit significant weathering, with areas of moderate to dense vegetation that pose challenges for mapping. Moreover, there are some flat areas without terraces, covering 10.1 ha, which may have also been utilized for agricultural production and related purposes.

Te-10, together with Cutamalla directly to the northwest and Ruyruncural to the south, constituted a larger agricultural system, indicated by similar terrace architecture and layout, although Te-10 and Ruyruncural appear as subsystems with more scattered terraced fields (Mader et al. 2024). Based on the

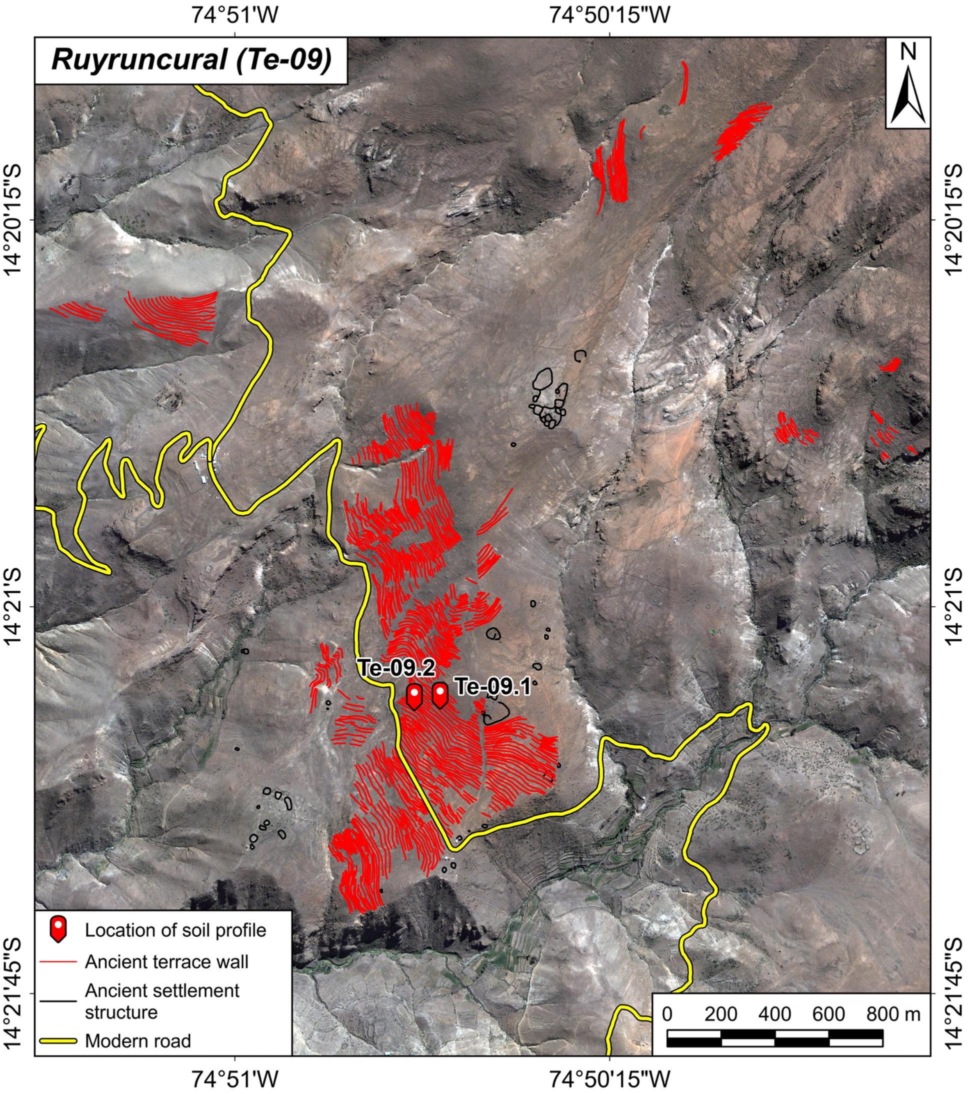

FIGURE 10 | Map of the Ruyruncural terrace agricultural system based on satellite imagery.

terrace architecture and surface finds gathered during our archaeological and geomorphological surveys (including at the associated ancient settlement), Te-10 dates to the Late Paracas and Early Nasca periods (370 BCE–200 CE).

4.9 | Santa María Terrace Agricultural System (Te-11)

Santa María is situated in the Laramate River valley, southwest of the modern town of Laramate (Figure 2). The terraced area covers 39.0 ha (2592–2786 m asl) and includes 692 stone terrace walls with a total length of 33.8 km (Figure 12; Table 1; Leceta et al. 2024). The terraces predominantly face west and exhibit a heterogeneous pattern that corresponds to the topographic relief. The width of the terraces varies from 2.0 to 10.0 m. Most of the walls are in good condition, showing only slight weathering. However, the current cultivation of avocados (*P. americana*) in the lowest sector of Santa María, near the river, has altered and destroyed ancient terrace walls. Based on the terrace architecture and surface finds gathered during our archaeological and geomorphological surveys (including the associated ancient settlement with numerous architectural structures), Santa María dates from the Middle to the Late Horizon (600–1532 CE).

4.10 | Chajaya Terrace Agricultural System (Te-12)

Chajaya is situated on the southern slope of a narrow valley leading to the Laramate River, southwest of the modern town of Laramate (Figure 2). The total terraced area spans 16.8 ha, encompassing both abandoned and currently used terraces, all built of stone (Figure 13; Table 1). The abandoned terraces cover 9.4 ha (2860–2942 m asl) and include 345 ancient stone terrace walls with a total length of 20.2 km, which exhibit significant erosion. The average slope is 22.0°. We analyzed four terrain profiles (average length: 50.0 m) to gather detailed terrace data for these sections. The 45 terraces analyzed have an average width of 4.1 m (SD: 3.1 m), with an average slope of 13.7° (SD: 5.2°). The average height of the terrace walls is 1.2 m (SD: 0.6 m).

The terraces currently in use are located near the rivers, covering 7.4 ha with 344 terrace walls (total length: 7.3 km).

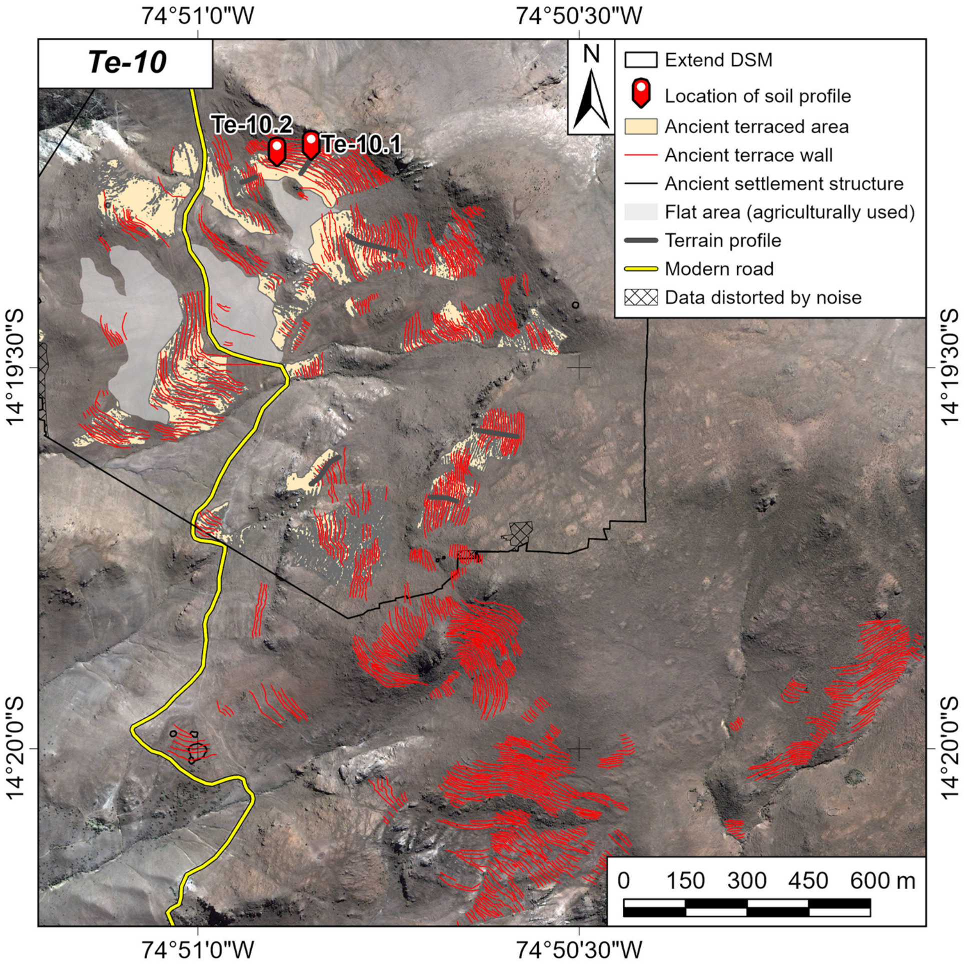

FIGURE 11 | Map of the Te-10 terrace agricultural system based on a high-resolution DSM and satellite imagery.

According to the terrace architecture and surface finds collected during our archaeological and geomorphological surveys, Chajaya dates from the Late Paracas to the Late Intermediate period (370 BCE–1450 CE).

4.11 | Huaquirata Terrace Agricultural System (Te-13)

Huaquirata is situated on the western side of the Laramate River valley, southwest of the modern town of Laramate (Figure 2). The total terraced area spans 27.0 ha (2623–3163 m asl), encompassing both ancient and currently used terraces, all built of stone (Figure 14; Table 1). The ancient terraces cover 15.8 ha and consist of 728 terrace walls totaling 68.9 km in length. Many of these walls show signs of erosion, and dense vegetation is prevalent throughout the agricultural system, particularly on its southern slope. We carried out evaluations along six terrain profiles to collect detailed terrace data for these sections. The 94 terraces analyzed have an average length of 2.3 m (SD: 1.2 m), with an average slope of 28.1° (SD: 6.8°). The average height of the terrace walls is 1.3 m (SD: 0.7 m).

The terraces currently in use are located near the rivers, covering 11.2 ha with 1024 terrace walls (connected terraces on the same level were counted as one terrace wall) and several boundary walls (total length: 11.6 km). According to the terrace architecture and surface finds collected during our archaeological and geomorphological surveys (including the associated ancient settlement with numerous architectural structures), Huaquirata dates to the Middle Horizon and Late Intermediate Period (600–1450 CE).

4.12 | Palulla Terrace Agricultural System (Te-14)

Palulla is situated south of the modern town of Locchas (Figure 2) and is part of the extensive terrace agricultural system known as Sihuilca (Leceta et al. 2024). It covers a terraced area of 11.5 ha (2839–3085 m asl) and comprises 89 stone terrace walls with a total length of 4.2 km (Figure 15; Table 1). The walls exhibit significant weathering. According to the visible terrace architecture and surface finds collected during our archaeological and geomorphological surveys (including at the associated ancient settlement with numerous architectural structures), this agricultural system dates to the Nasca period and the Middle Horizon (200 BCE–1000 CE).

4.13 | Te-15 Terrace Agricultural System

Te-15 is located southeast of the modern town of Locchas. This agricultural system spans a terraced area of 7.1 ha (2921–3175 m asl). The walls show extensive erosion, and the entire complex

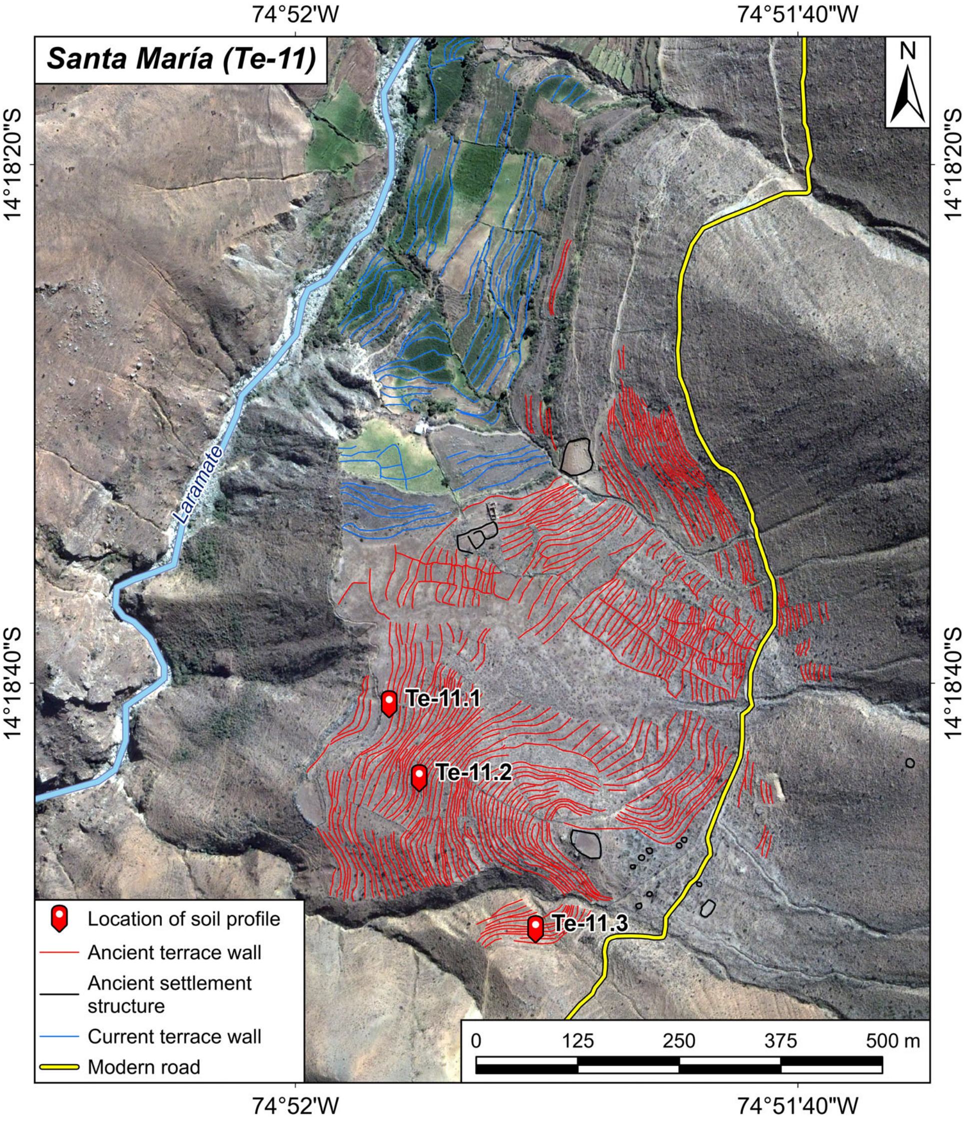

FIGURE 12 | Map of the Santa María terrace agricultural system based on satellite imagery.

is overgrown with dense vegetation. Based on the terrace architecture and surface finds gathered during our archaeological and geomorphological surveys (including at the associated ancient settlement), Te-15 dates to the Late Intermediate period (1000–1450 CE).

4.14 | Tantarpata Terrace Agricultural System (Te-16)

Tantarpata is situated on the western side of the Laramate River valley, west of the modern town of Laramate (Figure 2). The total terraced area spans 42.2 ha (2841–3375 m asl), encompassing both ancient and actively maintained terraces (Figure 16; Table 1). The site features 1854 stone terrace walls in total. The ancient agricultural terraces ($n = 1790$) are mainly located in the central to western area, covering 27.7 ha with an average wall length of 13.8 m (SD: 15.4 m, total length: 25.6 km). The slope varies from 8.5° to 29.4° (mean: 14.7°, SD: 2.3°). The terrace walls exhibit significant weathering, and vegetation is typically moderate at Tantarpata. Seven terrain profiles were examined to provide detailed terrace data for these sections. The average width of the 58 abandoned terraces analyzed is 4.8 m (SD: 2.0 m), ranging from 0.8 to 11.7 m. The slope varies from 2.2 to 17.4° (mean: 9.7°, SD: 3.4°). The terrace walls have an average height of 2.0 m (SD: 1.0 m).

The currently utilized terraces ($n = 64$) are located in the southeastern and western parts of the agricultural complex, covering 14.5 ha. The average length of the terrace walls in these sectors is 55.3 m (SD: 40.3 m, total length: 4.1 km), and the slope ranges from 11.5 to 46.0° (mean: 18.2°, SD: 4.8°). Based on the terrace architecture and surface artifacts recovered during our archaeological and geomorphological surveys, including findings from the associated ancient settlement with numerous architectural structures, Tantarpata dates back from the Formative to the Late Intermediate period (1000 BCE–1450 CE).

4.15 | Lindero Terrace Agricultural System (Te-17)

Lindero is situated on a plateau to the west of the Laramate River valley, southwest of the modern town of Laramate

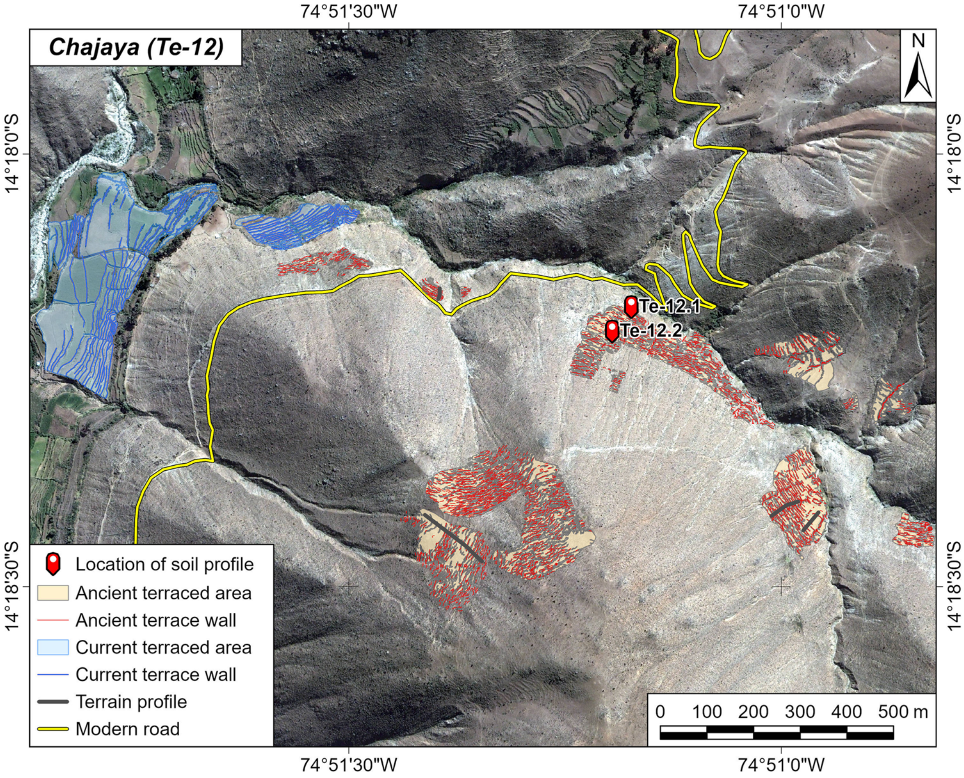

FIGURE 13 | Map of the Chajaya terrace agricultural system based on a high-resolution DSM and satellite imagery.

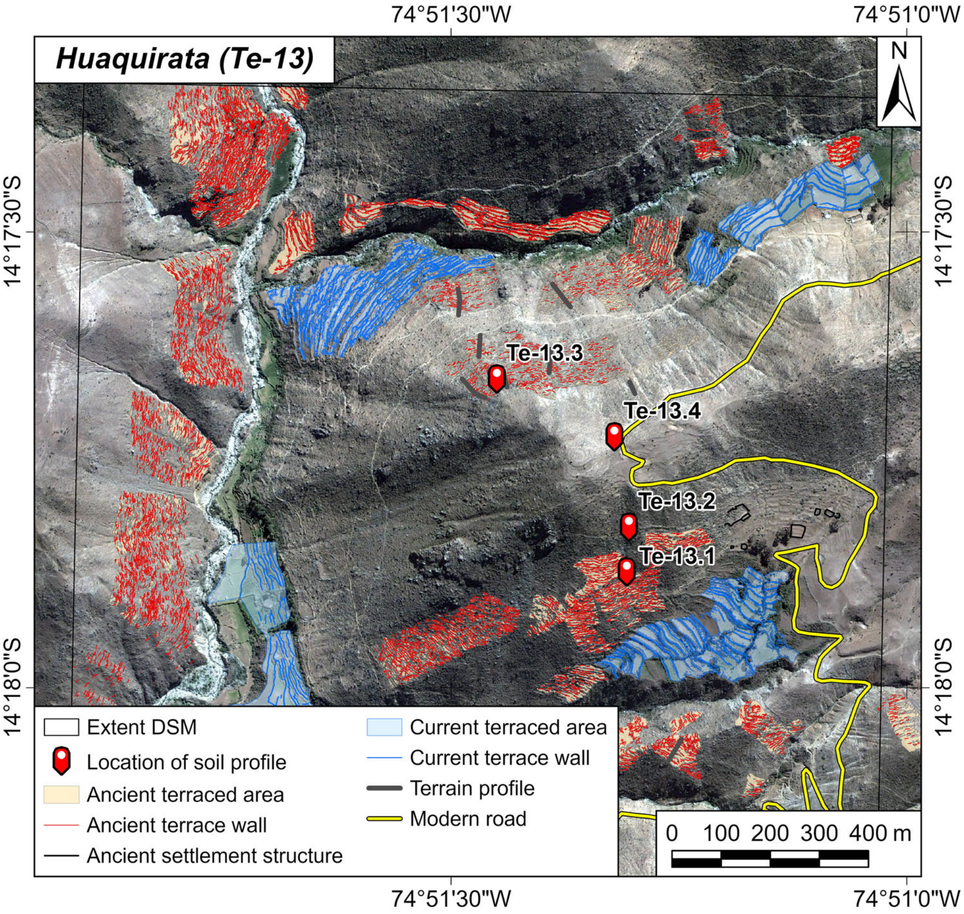

FIGURE 14 | Map of the Huaquirata terrace agricultural system based on a high-resolution DSM and satellite imagery.

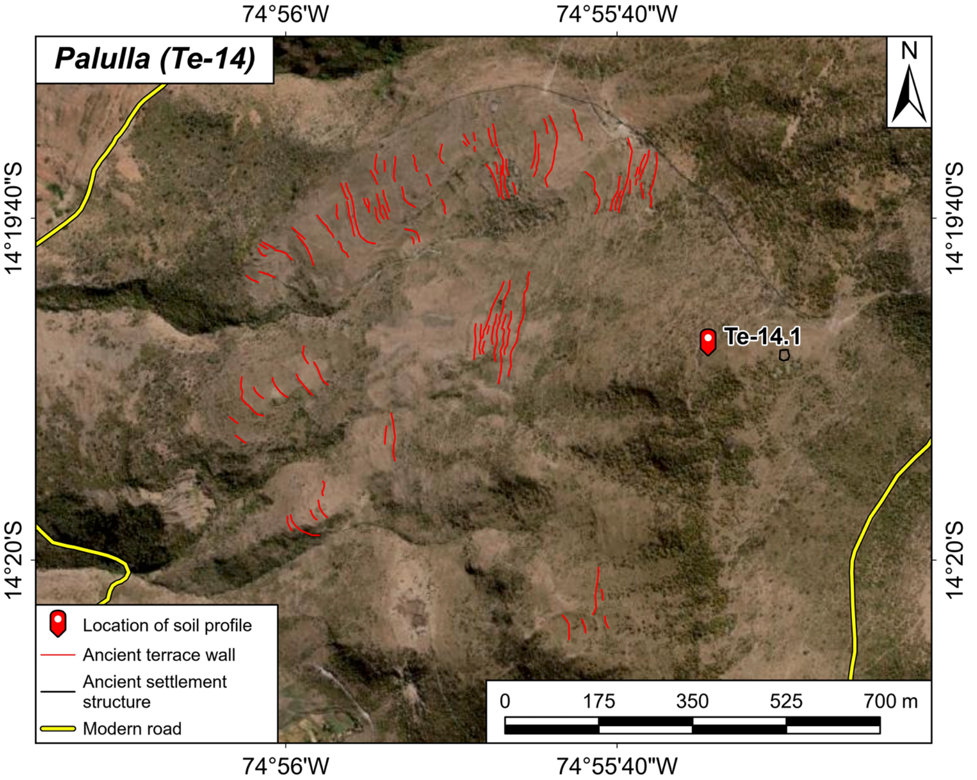

FIGURE 15 | Map of the Palulla terrace agricultural system based on satellite imagery.

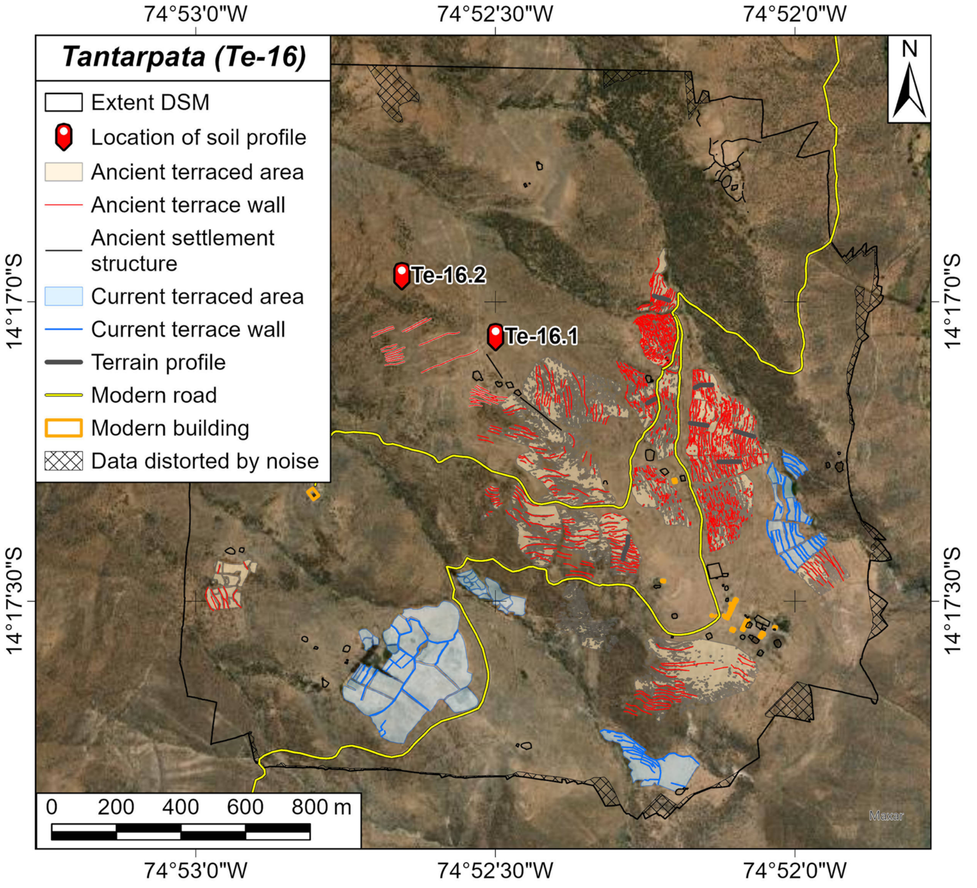

FIGURE 16 | Map of the Tantarpata terrace agricultural system based on a high-resolution DSM and satellite imagery.

(Figure 2). The terraced area covers 18.5 ha (2959–3244 m asl) and includes 261 stone terrace walls (Figure 17; Table 1). These walls have an average length of 39.8 m (SD: 23 m), totaling 10.4 km. The slope ranges from 5.2° to 21.9° (mean: 12.6°, SD: 2.4°). The walls show significant erosion, and the entire complex is sparsely vegetated. At the ancient settlement of Lindero, located in the southeastern part of the terrace system, there are several sculptured rocks depicting agricultural landscapes with terraces and irrigation canals (Figure 18). Based on the terrace architecture and surface artifacts gathered during our archaeological and geomorphological surveys, including excavations at the associated ancient settlement with numerous architectural structures, Lindero dates back to the Nasca period and the Middle Horizon (200 BCE–1000 CE).

4.16 | Lambrasniyoq Terrace Agricultural System (Te-18)

Lambrasniyoq is located in the valley of the Viscas River, known further upstream as Laramate, where the Camajayoq River joins from the north (Figure 2). It represents the lowest terrace agricultural system in this data set, ranging from 1258 to 1326 m asl. The total terraced area is 5.2 ha and includes both ancient and actively used terraces (Figure 19; Table 1). There are 63 stone terrace walls with an average length of 44.3 m (total length: 5.2 km). The ancient abandoned terraces primarily occupy the central and southern parts of the Lambrasniyoq complex, covering 1.1 ha. Terrace walls in this area average 49.0 m in length (total length: 2.9 km), with additional boundary walls present. The average slope measures 7.4°, and the terrace walls generally remain in good condition. The DSM of Lambrasniyoq exhibits distortion in marginal areas, where detailed analysis was challenging. Dense vegetation near the river further complicated mapping efforts in these regions.

The terraces still actively used are located in the southwest of the complex, covering 4.1 ha dedicated to cultivating maize (*Z. mays*), beans (*P. lunatus*), and cotton (*Gossypium barbadense*). In this area, the slope varies from 6.3° to 26.6° (mean: 11.0°, SD: 4.1°). Lambrasniyoq also has check dams and non-terraced farmland covering 8.0 ha. Based on terrace architecture and surface artifacts collected during our archaeological and geomorphological surveys, including excavations at the associated ancient settlement with numerous architectural structures, Lambrasniyoq dates back to the Middle Horizon and Late Intermediate periods (600–1450 CE).

5 | Discussion

Our mapping approach was successful in digitally mapping 16 terrace farming systems in challenging highland environments, which present both significant opportunities and constraints for agriculture. These systems showcase the diversity of pre-hispanic Andean terrace agriculture in terms of location,

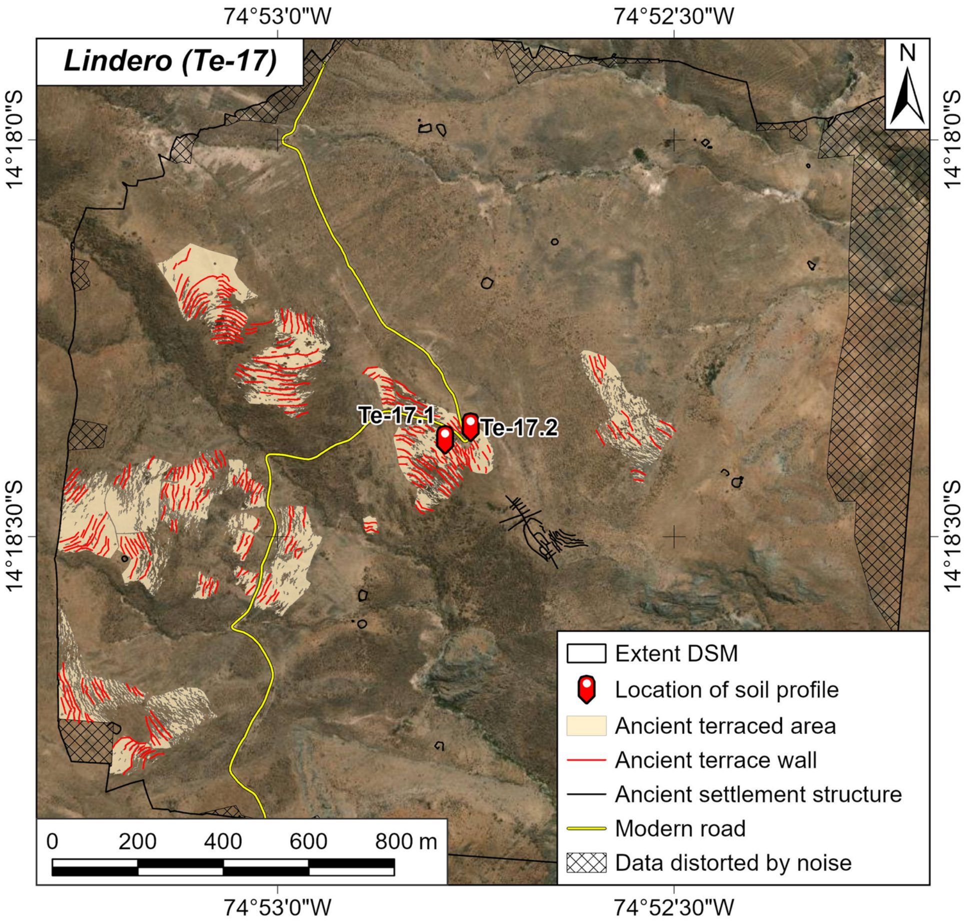

FIGURE 17 | Map of the Lindero terrace agricultural system based on a high-resolution DSM and satellite imagery.

FIGURE 18 | Sculptured rock depicting an agricultural landscape with terraces and irrigation canals at the ancient settlement of Lindero. Note the terraces of the Santa María agricultural system in the background on the left.

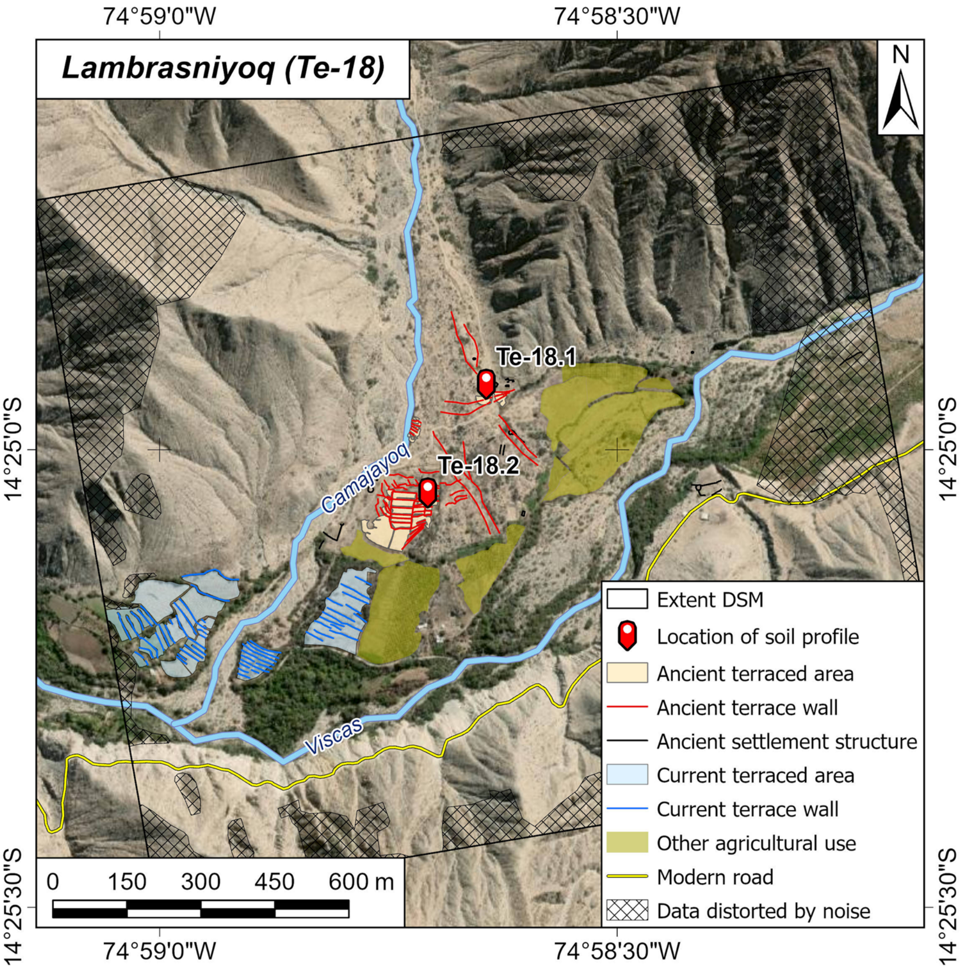

FIGURE 19 | Map of the Lambrasniyoq terrace agricultural system based on a high-resolution DSM and satellite imagery.

ecology, size, chronology, architecture, technology, and function, reflecting a wide range of land use practices. By building on previous archaeological and geographic research, we have collected and outlined comprehensive land use data that provide a clearer picture of socioeconomic-ecological developments in the prehispanic period. On a broader scale, the integration of methods and expertise from both the humanities and natural sciences in a core area of Andean cultural development enabled us to gain new insights into ancient South American societies and economies.

The terrace agricultural systems described in this article originated and were primarily used during the prehispanic period (1000 BCE–1532 CE), with some sections continuing to be cultivated during the colonial period (1532–1824 CE) and into the present day. Notably, many terrace systems were not continuously in use throughout the entire prehispanic era but were instead active during specific periods and in various regions. These temporal and spatial variations reflect adaptations to changes in climate, environment, demography, cultural-economic practices, and terrace technology over time (Leceta et al. 2024). Our data set is particularly significant for understanding the origins and long-term evolution of Andean terrace agriculture, as most of the systems we studied predate the better-known and more extensively investigated Inka terraces of the Late Horizon. As recently discussed by our research team (Leceta et al. 2024), the prehispanic history of terrace agriculture in the region spans multiple phases, which this study has helped to confirm and refine.

The establishment of agricultural terraces began around 1000 BCE during the Formative period (1700–200 BCE). An initial peak in terrace agriculture occurred during the Late Paracas and Nasca periods (370 BCE–600 CE), exemplified by terrace-settlement systems such as Collanco (Te-08), Cutamalla (Te-07), and Sihuilca (Leceta et al. 2024; Mader et al. 2024). This period of intensive agricultural use, supported by a humid climate, is characterized by relatively simple terrace architecture. During the Middle Horizon (600–1000 CE), under the influence of the expansive Wari state, terrace farming remained stable. However, drier environmental conditions led to adaptations, such as the use of volcanic soils for terrace agriculture, as observed in the Ayllapampa terrace system (Leceta et al. 2024). The Late Intermediate period (1000–1450 CE) witnessed a systematic expansion of terrace agricultural systems, driven by humid but hydrologically variable conditions and advancements in agrarian techniques. This expansion extended to less favorable locations, as seen in the Chajaya (Te-12) and Huaquirata (Te-13) systems, which were developed on steep slopes and northern exposures.

Interestingly, the presence of the expansive Inka state during the subsequent Late Horizon (1450–1532 CE) was minimal in our study area. Santa María (Te-11) is one of the few sites where Inka architecture is preserved (Soßna 2015). Beyond Santa María, there is no evidence of terraces being reused or refurbished during this period. Instead, the gradual abandonment of terrace agriculture began after the Late Intermediate period, accelerating with the onset of the colonial period in 1532 CE. Significant demographic shifts and the reorganization of production systems during the colonial period led to the decline of terrace farming in the region. Agricultural activities dramatically decreased, and terrace agriculture never regained its prehispanic prominence. This historical trajectory underscores the adaptability and resilience of prehispanic communities, who innovatively employed terrace agriculture to navigate changing environmental conditions and sustain agricultural practices across diverse landscapes.

The dating of the agricultural complexes is based on documented terrace architecture, surface artifacts collected during our archaeological and geomorphological surveys, and, where available, associated settlement data from excavations, surveys, and remaining architecture. The average size of stones used in building terrace walls varies considerably and appears to have evolved from using larger to smaller stones over the prehispanic period. Additionally, the height and quality of terrace walls, as well as the area of arable land, show significant variation. These variables seem to be influenced by factors such as slope inclination, farming practices, and the terracing knowledge, experience, and standards of different time periods—intriguing relations that warrant further investigation in future studies. Moreover, for most of the agricultural systems, we have radiocarbon data from soil testing of the terraces, which we will discuss in detail in forthcoming studies (see also Leceta et al. 2024; Mader et al. 2024).

The agricultural complexes vary greatly in size, ranging from 0.7 (Uyacha/Te-01) to 534.0 ha (Plazayoq/Te-05), likely influenced by their proximity to settlements, demographic factors, location, period, and function. Larger terrace systems are often associated with larger settlements, as seen at Leslepata (Te-04), Plazayoq (Te-05), Collanco (Te-08), and Santa María (Te-11). They are also found in areas where the terrain is more gently sloping, such as on debris cones, alluvial fans, colluvial deposits, or fluvial terraces (Leceta et al. 2024). Using settlement data from the study area as a proxy for demography, it is evident that the Late Intermediate period had the highest population density (Soßna 2015), which coincides with the dating of a significant number of the terrace agricultural systems studied. During this period, terracing expanded significantly, even in areas that were less suitable for agriculture, due to very steep slopes, lower soil fertility and soil moisture availability, and higher solar radiation (Leceta et al. 2024). In addition, the function of agricultural terraces, whether used for crop cultivation or grazing, apparently influenced the size of the systems.

The majority of the studied terrace systems are located within the *quechua* ecological zone, situated between 2300 and 3500 m asl ($n = 12$). However, terraces are most prevalent starting at 2600 m asl, with the highest density ($n = 9$) of terrace-settlement systems found between 2800 and 3200 m asl. This elevation range encompasses a total terraced area of 858.3 ha, representing approximately 75% of all mapped systems (Table 1). The *quechua* zone is the most suitable region for farming in both the study area and the western central Andes, owing to its temperate climate, fertile soils, and seasonal rainfall, which supports rainfed agriculture. With the exception of Vilcancancha (Te-06), which has modern irrigation canals, our archaeological and geomorphological surveys of the *quechua* terrace systems did not reveal any irrigation infrastructure. Among the variety of crops cultivated in the *quechua*, maize stands out as one of the most important, both historically and currently (Leceta et al. 2024; Mader et al. 2024). The extensive terrace agricultural systems of the *quechua* can serve as reliable indicators of prehispanic demography and labor, and they provide evidence of past climate changes and environmental dynamics. For example, many of the terrace systems investigated date to the first millennium BCE ($n = 4$) and the Late Intermediate period ($n = 7$), both characterized by humid climate conditions (Fehren-Schmitz et al. 2014; Mächtle and Eitel 2013; Mächtle et al. 2017; Schittek et al. 2015), suggesting favorable agricultural conditions. Today, the average annual precipitation is about the absolute minimum required for rainfed cultivation on the prehispanic *quechua* terraces (Rosegrant et al. 2002). In this context, it is also important to note that the current population density in the study area is relatively low and that the local population does not depend on the large prehispanic terrace systems. In the recent surge of market-oriented cash crops, avocados have become the primary crop cultivated, particularly in the Palpa/Llauta valley. Avocado tree cultivation requires significant amounts of water. As a result, the ancient agricultural terraces still in use today are limited to small sections, typically located along rivers and streams. These sections rely on modern irrigation systems and mechanized farming techniques, which often modify or damage the original ancient terraces.

The remaining terrace agricultural systems are located in the maritime *yunga* zone (500–2300 m asl, $n = 2$) and the *suni* zone (3500–4000 m asl, $n = 2$, Table 1). The two terrace systems in the drier *yunga*—Collanco (Te-08) and Lambrasniyoq (Te-18)—are distinguished by their sophisticated water management systems. At Collanco, irrigation canals supported the entire complex of terraced fields. Lambrasniyoq is strategically located at the confluence of the Camajayoq and Viscas rivers, enabling the direct use of their combined waters for agriculture. The two terrace systems in the *suni*—Uyacha (Te-01) and Achupayoq (Te-02)—are relatively small and have distinct features compared to other terrace complexes. Uyacha exemplifies agricultural terraces, or rather check dams, similar to those described by Denevan (2001). These were likely used for rearing and feeding llamas and alpacas in prehispanic times, animals that were highly valued by Andean peoples for their economic and social importance (Bonavia 2008; Capriles and Tripcevich 2016; Mader et al. 2022). The technology applied here is simple yet efficient, conserving water to promote better grass growth on these terraced fields (see also Flores Ochoa and Paz Flores 1986; Lane 2014; Lane et al. 2022). Achupayoq, on the other hand, is located in an extremely protected valley, creating a favorable microenvironment for agriculture in the harsher climatic conditions of the *suni*. With the exception of Uyacha, which was used for animal husbandry, all other terrace systems were primarily used for crop production.

In terms of methodology, mapping agricultural terraces using satellite imagery and drone-generated DSMs is cost-effective and time-efficient compared to other approaches, such as LiDAR or tachymetric surveying (Diaz-Varela et al. 2014; Nikolakopoulos et al. 2017). While satellite imagery generally provides less accuracy than high-resolution DSMs, it offers a practical alternative for large-scale mapping projects. However, several limitations can hinder the identification and digitization of terraces. These include dense vegetation, animal tracks, geological formations that mimic terrace walls, varied terrain, terrace deformations, and satellite images with poor lighting conditions or insufficient detail. Regarding the sample size of the studied terrace systems, they represent only a small subset of the numerous ancient agricultural complexes in our study area and beyond. However, the selection of these 16 systems was intentionally based on their varied ecological zones, locations, sizes, and prehispanic periods. This approach ensures that we capture and study the diversity of ancient Andean terrace systems and agricultural practices. Overall, there is a need for more comprehensive and interdisciplinary research on agricultural terraces to uncover clearer regional, supraregional, and temporal land use patterns in the Andes.

6 | Conclusions and Outlook

The terrace agricultural systems described in this paper highlight the diversity, extensive distribution, and historical chronology of terraces in the southern Peruvian Andean region. These 16 systems span various prehispanic periods (1000 BCE–1532 CE), with only fragments still under cultivation today. Our detailed maps of these systems employ a methodological approach integrating archaeological and geomorphological surveys, high-resolution DSMs derived from drone surveys, and GIS-based mapping of satellite imagery and DSM data. These maps and associated geospatial data sets are invaluable for understanding the variety and resilience of prehispanic agricultural strategies, as well as the indigenous technologies and adaptations to the Andean landscape, climate, and environmental shifts. Our mapping approach provides a crucial foundation for our broader geoarchaeological research program and future studies, which include archaeological excavations at settlements associated with terrace farming systems. Current investigations focus on soil profiles and samples for radiocarbon dating, as well as analyses of phytoliths, starch, organic matter, and carbon-to-nitrogen ratios. These efforts aim to reconstruct agricultural practices and refine the timeline of terrace construction and use (Leceta et al. 2024; Mader et al. 2024). Looking ahead, we plan to strengthen this integrated approach by incorporating additional methods and collecting new datasets to further enhance our understanding of socioeconomic-ecological dynamics in prehispanic South America.

Our maps and geospatial data set are designed to support reuse and analysis across a wide range of archaeological, geoscientific, and community-based collaborative methods. They are particularly valuable for long-term studies on topics such as ecology, human-environment interactions, landscape change, land use dynamics, agricultural production, and crop use. Understanding ancient terrace agricultural systems can inform the development of sustainable land use strategies to address contemporary environmental and social challenges, including climate change, water scarcity, and economic-driven depopulation in our study area and beyond (see Kendall 2005, 2013). Finally, our systematic mapping approach and the collected geospatial data can serve as a valuable reference for research projects documenting and analyzing agricultural systems in other parts of the Andes and around the world.

Author Contributions

Christian Mader: conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft,

writing – review and editing, visualization, supervision, project administration, funding acquisition. **Philipp Godde:** methodology, software, validation, formal analysis, investigation, data curation, writing – original draft, visualization. **Elena Hägele:** methodology, software, validation, formal analysis, investigation, data curation, visualization. **Mike Lyons:** methodology, software, validation, formal analysis, investigation, data curation. **Ann-Kristin Weber:** methodology, software, validation, formal analysis, investigation, data curation. **Rachel Odenthal:** methodology, software, validation, formal analysis, investigation, data curation. **Paul Stryjski:** methodology, software, validation, formal analysis, investigation. **Christoph Binder:** methodology, formal analysis, investigation. **Fernando Leceta:** methodology, formal analysis, investigation. **Johny Isla:** resources, writing – review and editing, supervision, project administration. **Markus Reindel:** conceptualization, validation, formal analysis, investigation, resources, data curation, writing – review and editing, supervision, project administration, funding acquisition. **Julia Meister:** conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft, writing – review and editing, visualization, supervision, project administration, funding acquisition.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data that support the findings of this study are available from the corresponding authors upon reasonable request.

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