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Andean Landscape Legacies: Comprehensive Remote Sensing Mapping and GIS Analysis of Long-Term Settlement and Land Use for Sustainable Futures (NW Argentina)

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Abstract: The Andes region has an exceptional record of high-altitude settlements integrated within widespread regional chains of mobility and exchange. The Sierra de Aconquija (NW Argentina, south-central Andes) is an effective climatic barrier that has afforded an enduring indigenous approach to land use, mobility, and exchange over millennia. Despite this rich history, the Sierra has been largely considered marginal in pre-Columbian regional cultural developments. Today, the expansion of extractive industries threatens the region's heritage and the sustainable futures of local communities. Innovative, integrative methodologies are needed for landscape characterisation, heritage assessment, and sustainable policy development. Building on earlier work, we undertook the first comprehensive mapping of archaeological features over 3800 sq. km of the Sierra using interpreter-led assessment of commercial and open-access satellite imagery and DSM data, to verify earlier assumptions and to identify previously unnoticed trends in the aggregation, distribution, and connectivity of archaeological features. The mapping identified 6794 features distributed unevenly but with clear tendencies towards maximising topographic, ecologic, and connectivity advantages expressed consistently across the study area. The outcomes confirm the important role the Sierra had in pre-Hispanic times, highlighting the significance of ancient indigenous practices for the sustainability of vulnerable upland landscapes both in the Andes and worldwide.

Keywords: Andes; archaeology; landscape; remote sensing; satellite imagery; DEM; spatial analysis; multispectral; heritage; sustainability

1. Introduction

The south-central Andes region provides an exceptional record of combined high-altitude settlement with the circulation of humans, goods, animals, and plants. Studies of land use and connectivity have identified important temporal continuities and variations in the region's long history of human presence in the region (e.g., [1–4]). However, the rich variety of ancient indigenous strategies remains poorly understood. The subsequent knowledge gap about the past not only affects the historical understanding of local indigenous societies, but also prevents the assessment of ancient technologies and land strategies as potential solutions to present-day socio-cultural and environmental challenges affecting the region.

This article presents extensive new spatial and remote sensing data on ancient land use and connectivity on the western slope of the Aconquija Sierra of NW Argentina (66°15′ Long W; 27°15′ Lat S), a sub-Andean mountain range located within the broader southern Calchaquí valleys area of NW Argentina, itself part of the south-central Andean region (Figure 1). The project aimed at understanding the role of the Sierra in the connectivity networks since its earliest sedentary occupation, as well as assessing how knowledge of the the region's past productivity and connectivity strategies might be of use to present-day communities. Our spatial analysis approach was designed to start building a baseline of data that can enable the investigation of these questions.

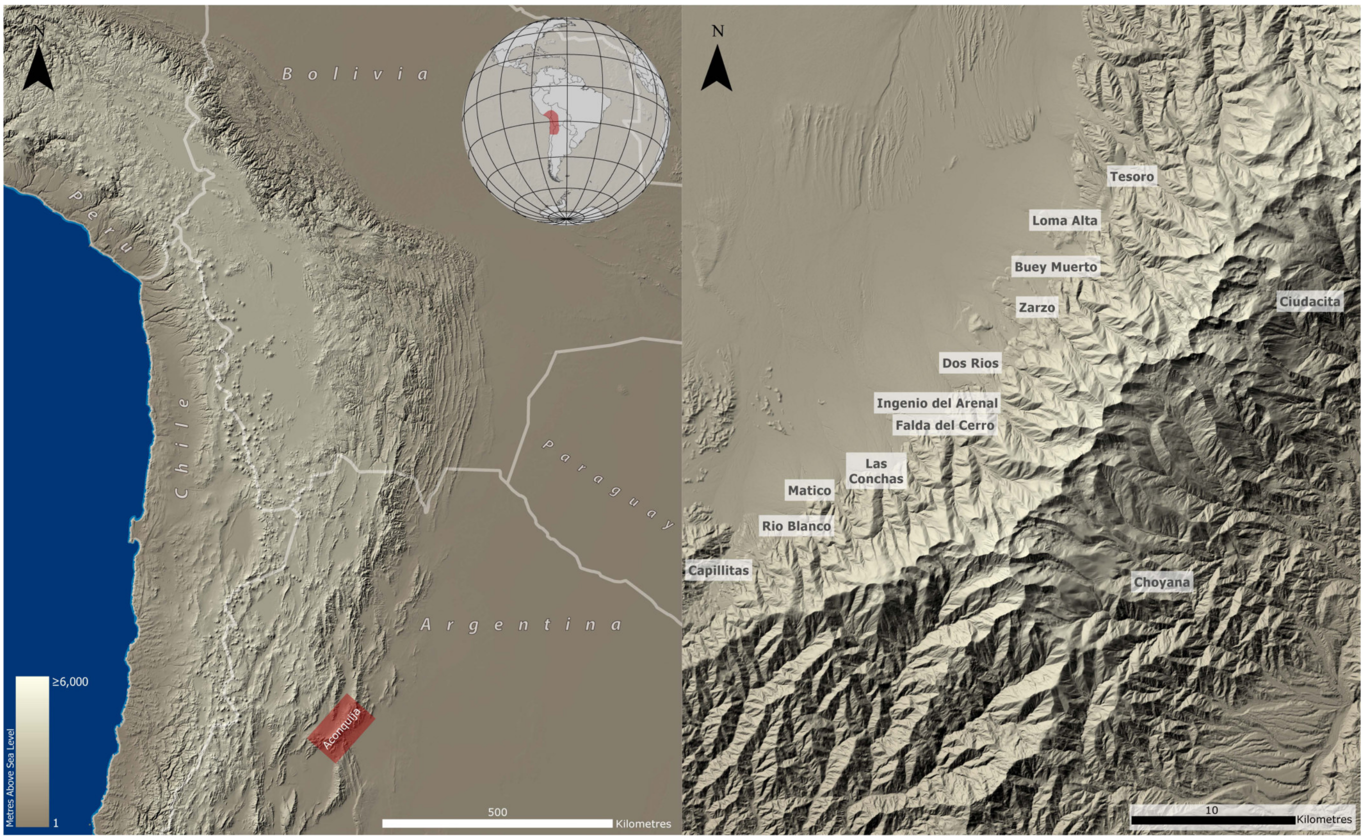

Figure 1. Location of study area. Hillshade and elevations derived from the JAXA ALOS Global Digital Surface Model AW3D30.

The Sierra runs north to south between the provinces of Tucumán and Catamarca, creating "the most effective climatic barrier known in Argentina" [5] (p. 9, our translation), stopping the humid easterly wind, which results in a marked difference in each flank's annual rainfall (700–1000 on the eastern side, 100–250 mm per year on the western side) [5] (p. 5). The Sierra has a long history of human occupation on both its flanks, spanning part of the regional Formative Period (~BC 1000–AD 1000, FP), the Late Period or Regional Developments Period (AD 1000–1436, LP), and the Inka Period (AD 1436-1536, IP) [6–10]. Despite this long pre-Columbian history, the Sierra has often been portrayed as 'marginal' in relation to major cultural developments within the wider NW Argentina region, [11] which are more apparent in other sectors of the region [9,11–14]. Yet the strong presence of the Inkas (AD 1436–1536), albeit with a distinct character compared to this empire's presence elsewhere in NW Argentina, testifies to the broad relevance and significance of the Sierra in the region's socio-cultural processes. Notable examples of this relevance are the iconic high-altitude settlement of Pucará de los Nevados del Aconquija (also known as *La Ciudacita*) perched at 4500 m asl on the Sierra's eastern slope (a protected section of the World Heritage List Site *Qhapac Ñan* or Inka road system), and various road posts (*tambos*) on the way across the Sierra and on the road towards the Capillitas mining district (a traditional copper mining area since pre-Columbian times, Figure 1) [14–18].

The western flanks of the Sierra de Aconquija are currently covered by vegetation consisting principally of low shrubs that tend to occur in small clusters which are occasionally circular or ring-shaped and up to 5 m in diameter. The area today is sparsely populated, and while local dwellers remember pockets with extensive agricultural activities in the recent past, currently, agriculture is minimally practised by a handful of families alongside some animal husbandry (cattle and goats mainly). Modern agriculture involves a variety of native and European plants depending on the sector of the Sierra and the altitudinal level [19] (p. 46). The southern sector of the Sierra has increasingly attracted the interest of large-scale mining exploration and exploitation in recent years. This situation signals a depletion of biocultural resources, particularly when comparing the present reality with the diverse regional practices archaeologically and historically documented, such as agriculture, Andean camelid herding, foraging, hunting, and craft production [16,20–24].

Previous archaeological research has successfully identified and mapped a wide variety of structures, sites, and features across the area via ground surveying assisted by aerial photographs [11,19,25–28]. This earlier mapping effort identified and characterised settlements within a 3 km wide zone that runs N-S for 25 km between 2500 m asl and 3100 m asl [19] (p. 36)—part of which can be considered an 'optimal strip' for settlements [19] (p. 46)—identifying a trend towards lower ground settlements for historic and modern occupations.

Drawing on this earlier work, our study employs remote sensing in combination with GIS mapping and spatial analysis consistently over 3800 sq. km of the Aconquija, to verify earlier assumptions and to identify previously unnoticed trends in the aggregation, distribution, and connectivity pertaining to archaeological structures and features. This way, we provide a fuller and more systematic understanding of ancient landscape use and configuration, particularly in relation to how connectivity, afforded by the topography and geomorphology of the area, shaped productive activities at a wider variety of altitudinal levels. In terms of hydrology, while previous research demonstrated its crucial importance for settlement growth and concentration of productive structures, a more detailed analysis based on high-resolution data was needed to discern settlement aggregation trends.

Beyond the essential identification of key trends in archaeological data, our research raises the question of how the landforms and features of the Sierra, as imposing as they are, were also structured and shaped by the long-term actions of humans and their associated nonhuman beings. Our methodology stems from the theoretical principles defined by Ingold's concept of *taskscape* [29] as the backbone of landscapes (understood beyond nature/culture divides), but also, crucially, from our earlier use [24,30] of Gosden's [31] notion of *social landscape*—land structured by networks and connections of mutual obligation. This theoretical toolkit enables us to integrate the investigation of landscapes, productivity, and exchange networks, which have traditionally been studied separately. In addition to benefitting archaeological investigation, our holistic, integrative understanding of landscape formation that considers all facets of human practice may be beneficial to assist local communities in their search for recognition and protection of their heritage [32].

2. Archaeological Evidence

From north to south, a system of ravines placed at regular distances [3–4 km] channels seasonal rivers, giving the western foothills their unique character. The modern localities in these ravines are Tesoro, Cerrillos, Buey Muerto, Loma Redonda, Dos Ríos, Ingenio del Arenal, Las Conchas, Mático, and Río Blanco [19] (Figure 1), with archaeological research undertaken at the sites Antigal de Tesoro and Tesoro 1 (Tesoro ravine), Loma Alta (Cerrillos ravine), Buey Muerto (Buey Muerto ravine), Loma Redonda (Dos Ríos ravine), Falda del Cerro, Centro, and Médanos (Ingenio del Arenal ravine), Las Conchas, and Río Blanco [16,20,21,23,27,28,33–36]. Previous studies ascertained that most archaeological sites are located on the alluvial fans of these ravines within the altitude 'optimal strip' mentioned above, on slopes with an average inclination of 11.47% [19] (p. 54) (6.5 degrees). Dispersed and low-intensity settlement outside the strip, both on higher and lower ground, has also been noticed, with a trend for later and modern settlement to occur on lower altitudinal levels. Earlier studies also yielded evidence of ancient irrigation channels (*acequias*) in some locations, particularly at the sites of Loma Alta and Loma Redonda. Although the strip is a good area for tuber agriculture, archaeobotanical evidence, unfortunately, has yet to provide direct evidence of this activity [19] (p. 52) and [37].

The archaeological sites consist mostly of stone-walled structures, standing 50–80 cm above ground level at present, including dwelling compounds scattered across agricultural enclosures and corrals. The dwelling compounds consist of small (2–6 m diameter) or medium-sized (5–10 m) circular or subcircular structures. Some dwelling compounds range between 500 and 1000 sq. m, but most of them do not exceed 100–200 sq. m [27] (p. 88). The pattern of small circular structures surrounding a central larger structure or patio is known as 'cellular pattern' or 'Tafí pattern' [27,38], and is characteristic of Formative Period architecture across the region, contrasting with Late Period architecture, which shows a shift towards rectangular architecture, further pronounced during the Inka period.

Despite morphological variations across time, the pre-Hispanic occupation of the Sierra shows a persistent pattern of domestic dwellings scattered among larger (>15 m) stone-walled enclosures that vary in size, shape, form, and layout. Excavations have confirmed the presence of a wide range of activities within clusters of smaller adjoined structures forming compounds (e.g., stone tool knapping, metalwork, ceramic production, food consumption/preparation), which confirms their classification as dwellings. However, given that some of the larger enclosures have also yielded evidence of food preparation and craft activities, the classification of structures as either 'residential/domestic' or 'productive' should be considered hypothetical until further examination [33].

Despite the overall similarity observable across the sites, there are some marked variations in terms of the density of dwelling compounds compared to the number of considerably larger stone-fenced structures destined for agriculture and herding activities [19]. In addition to this variability, some of these sites, such as Loma Alta and Antigal de Tesoro, show different phases of settlement without pronounced changes in material culture, possibly signalling the generational growth of the settlements [33]. While more dates are needed to refine this chronology, the earlier studies successfully demonstrated the existence of a characteristic settlement pattern in the area, with consistent features that endured through the first millennium AD, with some changes towards increased aggregation by the transition to the Late Period [11]. Fully assessing this existing hypothesis exceeds the scope of this paper. Yet our study of land use, connectivity, and hydrology provides a detailed and comprehensive analysis that offers a baseline for future assessments.

3. Materials and Methods

Our study involved a multi-scalar research strategy implemented in two phases. The first, conducted in 2019, included interpreter-led mapping of archaeological sites conducted using freely available Very-High-Resolution (VHR) satellite imagery in Google Earth Pro (GE) and Bing Maps Imagery (BMI). Although sub-metre-resolution imagery was not available at the time for the entire study area, this pilot exercise successfully located 6794 structures consisting of enclosures clustered together or separated and spread unevenly across a stretch of 22 km between Ingenio del Arenal in the south and Tesoro in the north, far exceeding earlier estimates [25]. It also enabled us to understand the parameters for interpreting structures as part of the pre-Hispanic settlement in the Sierra, with some ambiguities around the continuity of circular-shaped corrals and some large rectangular structures into later historical periods. For our long-term approach, this issue becomes less relevant, however, as we prioritise whether structures are currently in use or not and whether there is evidence of their overlap with modern use.

The second phase of work considerably expanded both the geographical coverage and methodological complexity of the preliminary assessment, thanks to the acquisition of VHR multispectral and panchromatic satellite imagery covering 40 km along the entire western slope of the Aconquija Sierra between Tesoro and Río Blanco. We used a range of archival satellite imagery and terrain data as a combination of Maxar 8-band 46 cm resolution orthorectified bundles over 688 square kilometres acquired between 1 June 2012 and 17 May 2018 by the WorldView 2 and GeoEye 1 satellites. The data had not been mosaicked to allow for occasional comparative assessment of feature visibility at different points across that time span. Additionally, a 2.5 m spatial resolution JAXA—ALOS AW3D Digital Surface Model (DSM) was acquired for the entire area to enable additional spatial analysis, relief visualisation, and contextualisation.

A controlled and systematic interpreter-led mass mapping of archaeological features was conducted over the entire study area, at a time when similar mapping exercises were being carried out elsewhere in the Andes (e.g., [39–41]), allowing us to corroborate our previous findings and to expand them using a combination of satellite imagery sources and datasets. BMI, sourced by an API key, served as the primary interpretation layer by being integrated into ArcMap 10.4.1 and ArcGIS Pro 2.8.2. We opted for BMI as this service provides rapid access to contiguous-resolution imagery for the entirety of the study area, allowing the maintenance of an easy-to-consult base layer with minimised discrepancies [42]. Thus, archaeological features were first identified and checked in BMI and later validated and expanded upon with the processed pan-sharpened commercial satellite imagery mentioned above in the form of true colour images and composites (see below).

In archaeological remote sensing, it is common practice to employ vegetation indices such as the Normalised Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI), Modified Soil-Adjusted Vegetation Index (MSAVI), Thiam's Transformed Vegetation Index (TTVI), and Tasselled Cap (TC) to enhance the visualisation of archaeological features, particularly in crop marks (e.g., [43–46]). However, the arid environment of the Sierra de Aconquija, and the characteristic archaeological pattern of extant stone-walled structures scattered within patchy, low-lying shrub vegetation, requires adjustments to the standard approaches. We tested out the enhanced visibility of archaeological features subject to the spectral range of our datasets using the Corrected Transformed Vegetation Index (CTVI), Adjusted Transformed Soil-Adjusted VI (ATSAVI), MSAVI, NDVI, Tasselled Cap, and Transformed Vegetation Index (TVI) indices on pan-sharpened images by entering these as mathematical operations in the Band Math tool on ENVI 5.6 [47–51]. The calculations and resulting raster were verified on the published Loma Alta site plan [27], resulting in the CTVI and TC being the most consistent and better indices for visualising and highlighting standing structures (see Figure 2). Furthermore, Band 2 of CTVI and Band 2 of TC were particularly successful in highlighting architectural features ranging from 0.5 to 40 m in diameter, and in discerning them from neighbouring bare soil and shrubby vegetation on relatively flat terrain, within the parameters of the available resolution. For the CTVI, the detection range for such features is between 224 and 255 nm, whereas, for TC, it is between 1 and 112 nm, which was confirmed using ENVI's Raster Colour Slice (Figure 2g,h). Given the enhanced visualisation of architectural features provided by the CTVI (g) and TC (h), these were used as base layers in ArcGIS Pro to detect new features and to allow cross-verification of findings in conjunction with true colour, BMI, and GE imagery.

Individual architectural structures identified on satellite imagery were vectorised in ArcGIS Pro to be further analysed (e.g., area calculations, elevation, slope, geometric shape) (Figure 3). They consisted of morphologically diverse structures that are organically shaped and have dimensions broadly corresponding to the larger examples noted by field surveys (Figure 4). A basic distinction was operated based on the estimated extent of the corrals calculated in ArcGIS Pro. The area calculations for a total of 6794 individual architectural structures identified on satellite imagery were divided into 5 separate categories for corrals: up to 100 square metres (Category 1), 100–500 square metres (Category 2), 500–1000 square metres (Category 3), 1000–5000 square metres (Category 4), >5000 square metres (Category 5). This allowed us to identify patterns of spatial distribution according to feature size. However, based on their frequency identified in the earlier studies mentioned above, we believe that our results retain a relative underrepresentation of structures smaller than two metres in diameter (Figure 3). We also assigned an altitude value to the centroid of each feature, derived from the 2.5 DSM.

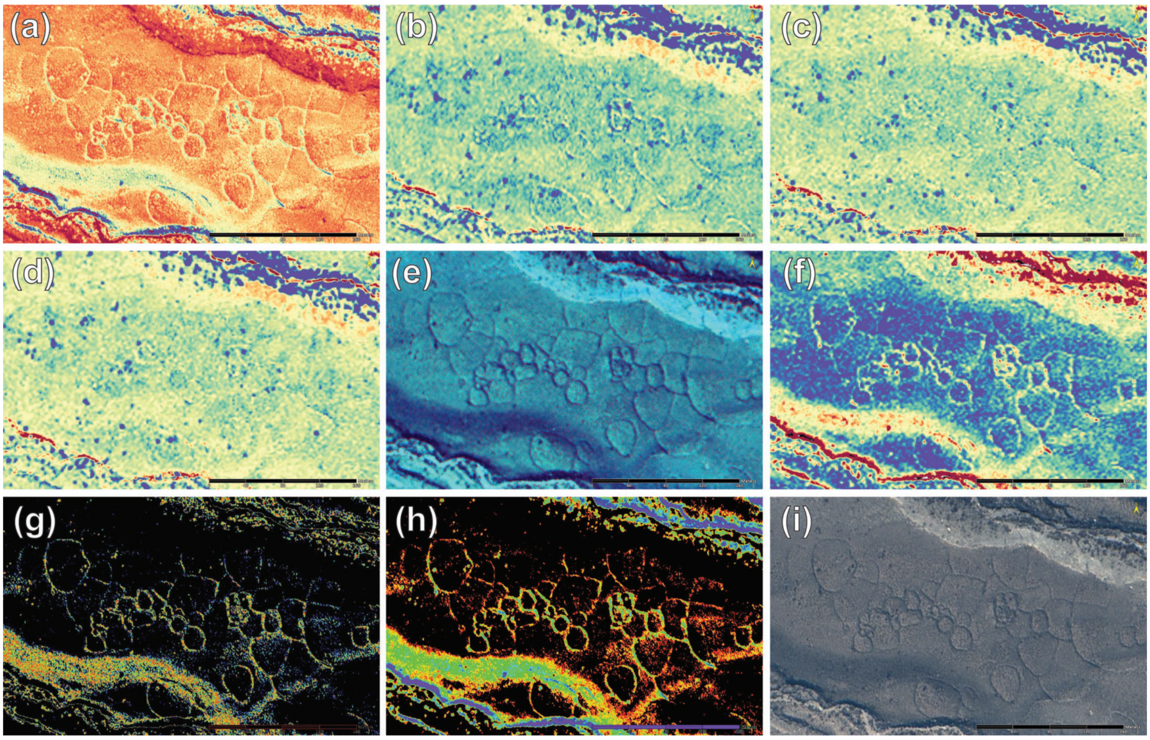

Figure 2. Indexes obtained from a pan-sharpened WV2 dataset obtained in June 2018 showing the Loma Alta site. The scale bar represents 160 m. (**a**) CTVI; (**b**) ATSAVI; (**c**) NDVI; (**d**) MSAVI; (**e**) Tasselled Cap; (**f**) TVI; (**g**) CTVI Band 2; (**h**) Tasselled Cap Band 2; (**i**) true colour composite. Outputs derived from (**g**,**h**) indexes were used as base for the analysis.

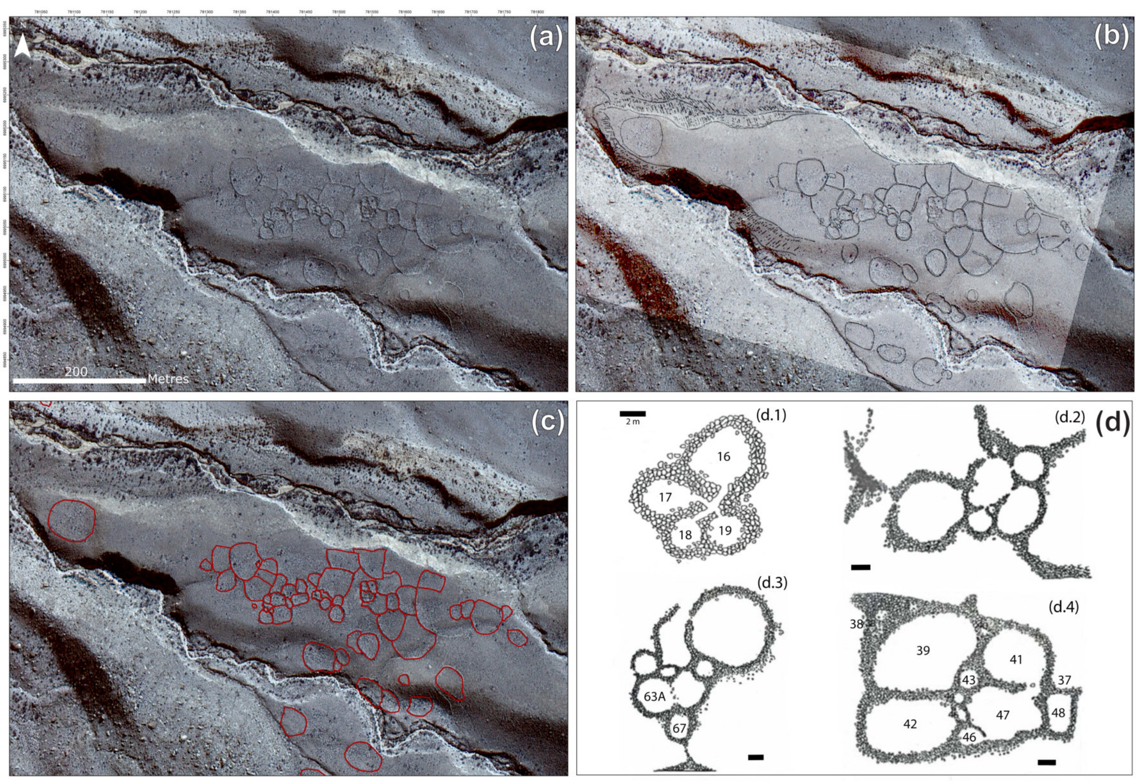

Figure 3. Archaeological structures in the Loma Alta sector of Cerrillos ravine as seen on (**a**) satellite imagery, (**b**) a georeferenced field map, (**c**) mapped polygons in GIS based on satellite imagery, (**d**) examples of domestic compounds mapped by field survey, including (**d.1**) compound A, (**d.2**) compound G, (**d.3**) compound F, (**d.4**) compound E [26] (pp. 90, 95).

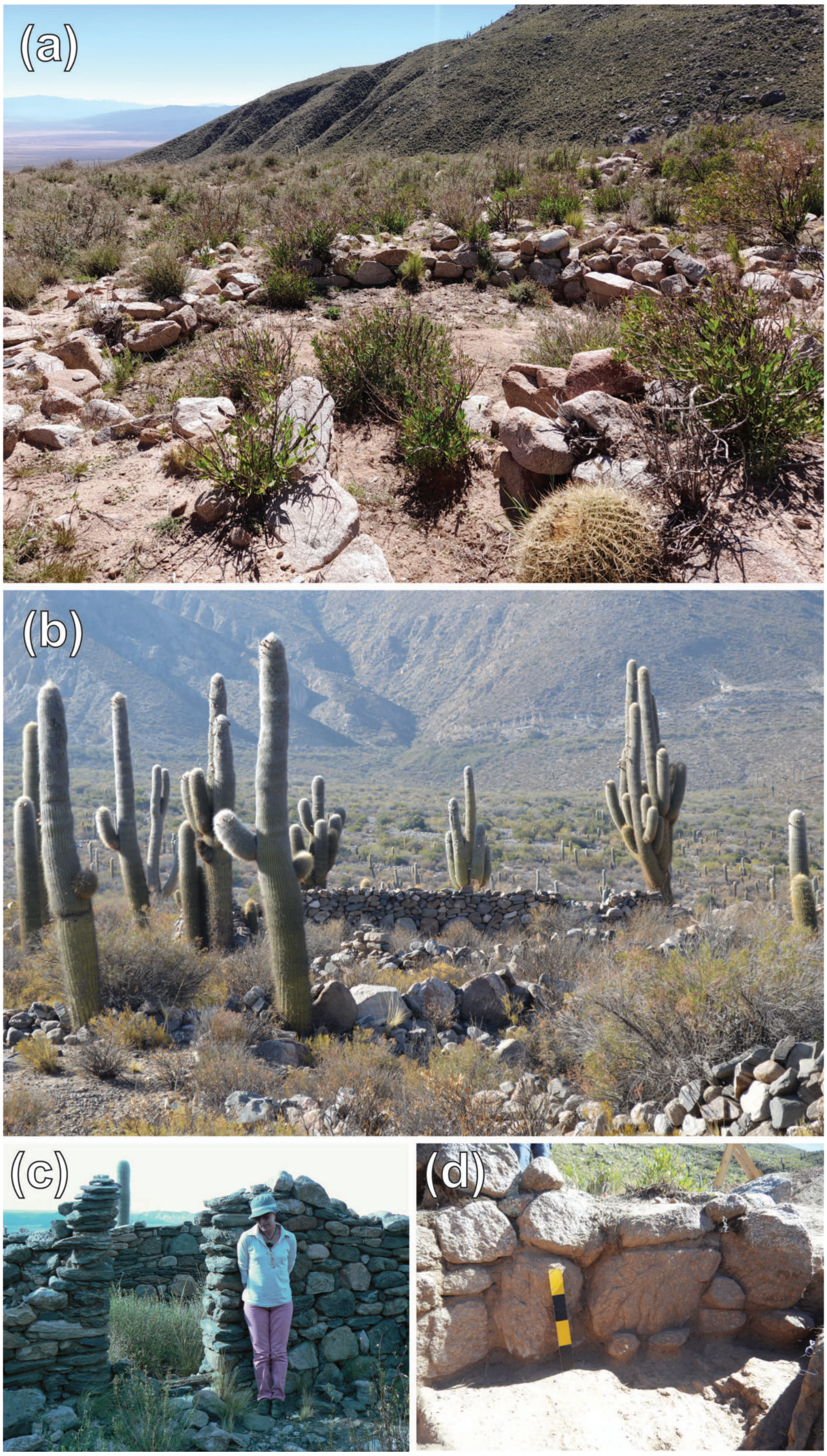

Figure 4. Examples of stone-walled compounds seen from the ground: (**a**,**d**) Falda del Cerro de Ingenio del Arenal and (**b**,**c**) Río Blanco. Details show survival and building techniques that were (**c**) possibly Inka/historical, or (**d**) from the Formative Period. Image (**c**) includes author Scattolin for reference.

The outcomes of the interpreter-led mapping process described above were verified via integration with a slope analysis of the DEM dataset using previous ground-based observations, which indicated that compounds located in the area were aligned with local topography [19,25]. Centroid calculations for average slope values were performed in ArcGIS Pro, enabling the visualisation of trends across the study area. This process also helped us with the identification of potential early Formative Period settlements at the origin of the conoids (see below).

The spatial analysis in ArcGIS Pro employed in the present study included density analysis alongside hydrology and mobility analysis. These helped us better understand settlement aggregation and identify potential aggregation trends within high-altitude settlement, the hydrological potential of water streams and flows that influenced the relative spread of settlement along natural conoids, and, finally, connectivity patterns across the area to evaluate optimal routes between high-density archaeological sites based on modelled routes and slope-dependent anisotropic movement. The joint consideration of these proxies typically not considered at a landscape scale enabled us to reach a holistic and more integrated perspective on human settlement in the region.

Density analysis was conducted on the centroids of each structure to highlight trends in their distribution and settlement aggregation. Kernel density analysis [52] was performed in ArcGIS Pro, configured with a cell size of 5 m, which helped us quantify the extent of aggregated settlement in the past. The resulting raster was processed using a stretch rendering based on percent clip (see interpretation section below).

To explore the probability of movement using a combination of approaches, we performed a series of calculations for a selection of locations in Aconquija using the centroid of the sites as the place of origin or destination. The calculation of potential pathways and connectivity was made using the R package movecost [53] and standard tools from the ArcGIS Pro hydrology toolbox applied to accumulated cost surfaces. Movecost allows line vectorial features to be obtained from a highly customisable code as Least-Cost Paths (LCPs), networks of LCPs, and isochrones, and raster in the form of corridors, cost surface, and accumulated cost surface. For our path calculations, we employed both Tobler's off-path [54] and Llobera and Sluckin's [55] cost functions in movecost to obtain LCPs, LCP networks, corridors, and single-origin accumulated cost surfaces. Even though movecost offers a wide range of functions for calculating accumulated slope-dependent anisotropic cost surfaces, we have chosen to use the traditionally most successful function to represent mobility in pre-industrial contexts [55], alongside the function whose results aligned best with fossilised stretches of paths identifiable on satellite imagery (Tobler, see Figure 12), a tried-and-tested combination in other mountainous regions [56,57]. We used both to obtain alternative representations of how topography may have influenced movement choices according to the differences in perceived cost as considered by these functions, thereby avoiding biasing our understanding of movement in Aconquija.

The paths and renderings of connectivity between origin and destination points available in the traditional methods offered in movecost were complemented with a less prescriptive approach offered by the Focal Mobility Network method, widely known in Spanish as MADO (Modelo de Acumulación del Desplazamiento Óptimo) [58,59]. With MADO, by feeding an accumulated cost surface to the ArcGIS Pro hydrology toolbox, it is possible to achieve movement and accessibility affordances defined from single origin points, as opposed to by the Least-Cost Path approach of designating a point of origin, offering the possibility to generate a probabilistic network of LCPs without the conventional inference of defining a destination. It is worth noting that the MADO approach has already been employed successfully in archaeology (e.g., [56,57]).

4. Interpretation of Results

Within the 3800 sq. km study area, we vectorised 6794 features, together covering 3.27 sq. km in total (i.e., 0.086% of the study area). The spatial resolution of the datasets that allowed the recognition of features mapped as polygons ranged considerably (see above), yet it was sufficient to allow several issues to become apparent.

Among the recognised features, those that were morphologically consistent with field-verified archaeological structures (see above) did not exceed individually 5000 sq. m, with 69% of them being within the lower ranges (Categories 1 and 2, n = 1381 and n = 3308 enclosures, respectively). Only 21% (n = 1472) of the mapped features covered areas up to 1000 square metres (Category 3), and 9.3% were larger than that (n = 600 in Category 4 and n = 33 in Category 5) (Figure 5b). These results provide quantitative support to on-the-ground observations and previous archaeological investigation indicating that clusters of smaller individual structures (up to 100 sqm), considered as possible locations for dwelling compounds, are usually interspersed among the larger stone-walled enclosures [11,19,25,27].

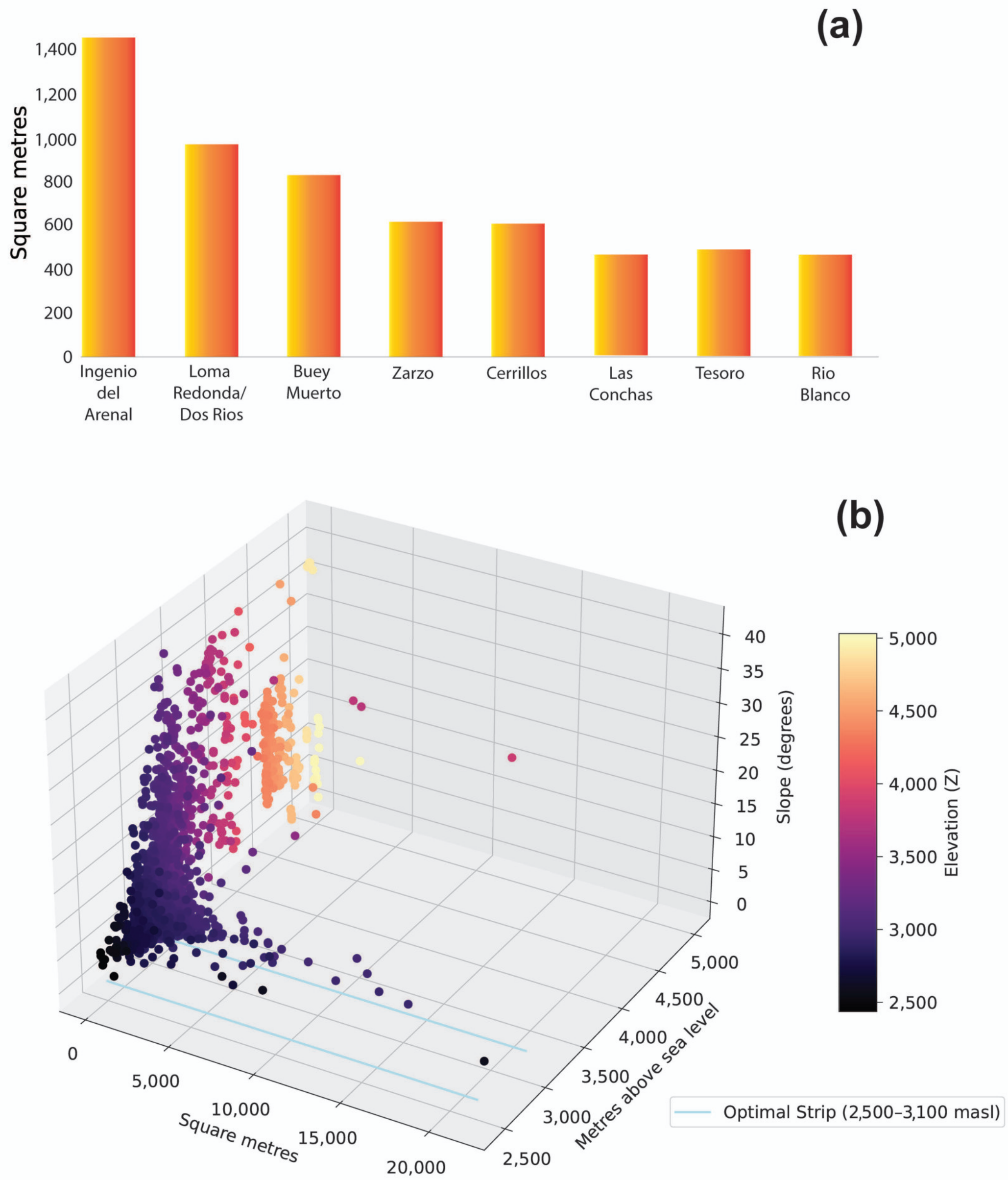

Figure 5. (**a**) Aggregated settlement size according to structure count on the western slope of the Sierra de Aconquija; (**b**) structure size, elevation, and inclination as slope.

The results also confirm the 'optimal strip' defined in previous studies as the focal point of settlement across the study area, with 5550 (81.7%) features located between 2500 and 3100 m asl. However, they also enabled us to visualise human presence both above and below the limits of this strip more consistently and accurately, establishing a baseline for further analysis of productivity and land use across all altitudinal levels (Figure 6).

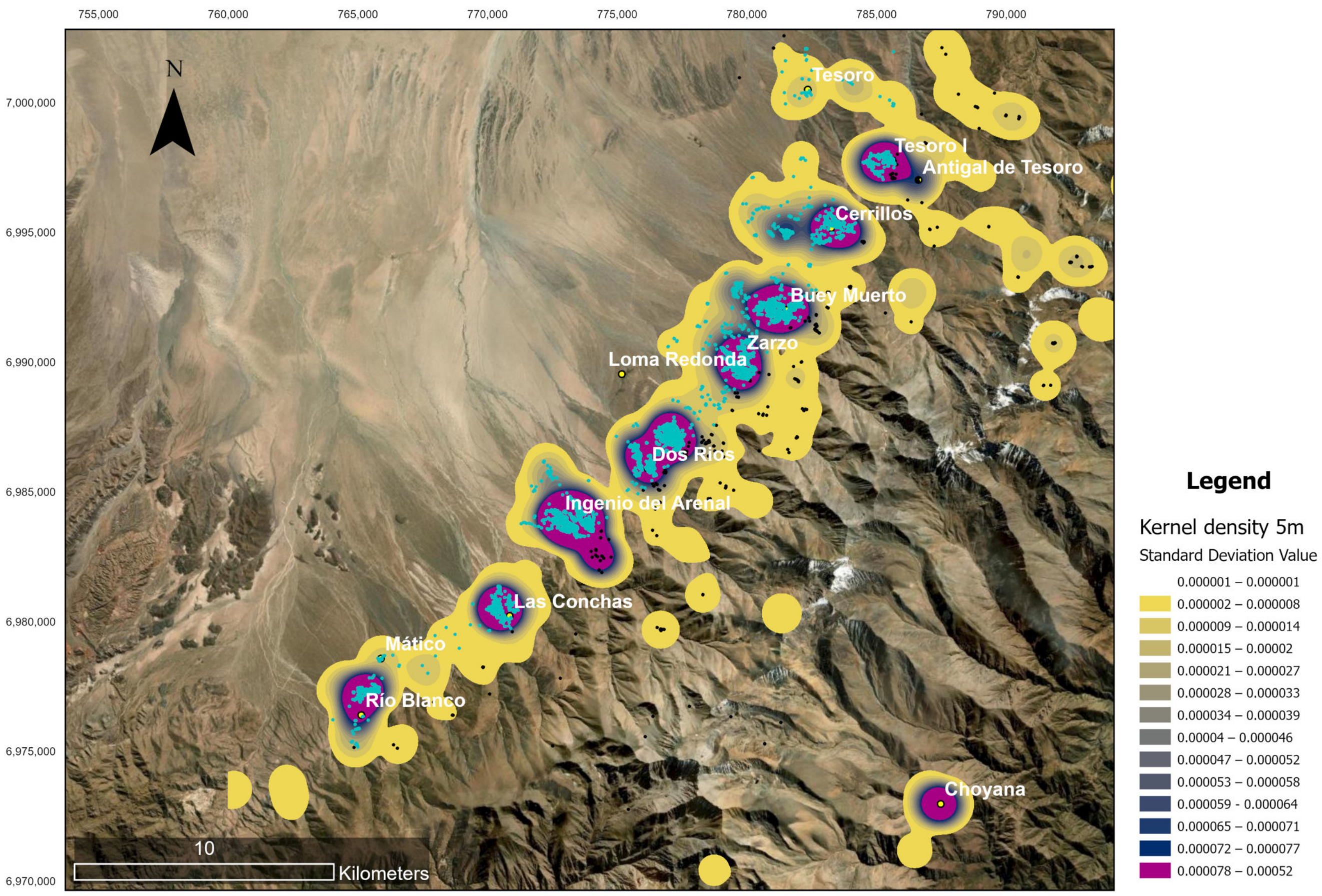

Figure 6. Spatial distribution of archaeological structures and their aggregation patterns revealed by kernel density analysis. Centroids of enclosures (black dots) within the optimal altitude zone are highlighted in blue. The white line represents a vehicle road connecting some of the conoids.

In addition to these main trends of general homogeneity in the settlement structure across the western slope of the Sierra, our data enabled us to investigate the following main aspects: (a) diverse aggregation patterns across ravines; (b) altitude-related distribution of aggregated areas; (c) multi-directional connectivity.

(a) Diverse aggregation patterns

While there is no clear pattern distinguishing northern and southern sectors of the Sierra, Ingenio del Arenal emerges as the ravine with the highest number of structures, and Loma Redonda–Dos Ríos appears as second in number of structures (Figure 7).

The higher number of structures at Ingenio del Arenal may be partly explained by the fact that its river has the highest volume of flow among all the rivers on the western flank (432 L/s) [19] (p. 53), and it also has one of the longest records of human occupation in the region [16,34]. Dos Ríos has a lower volume of flow (199.08 L/s) [19] (p. 53), and possibly a shorter temporal span of occupation than Ingenio del Arenal [11], which may indicate a particular population process behind the apparent high number of structures.

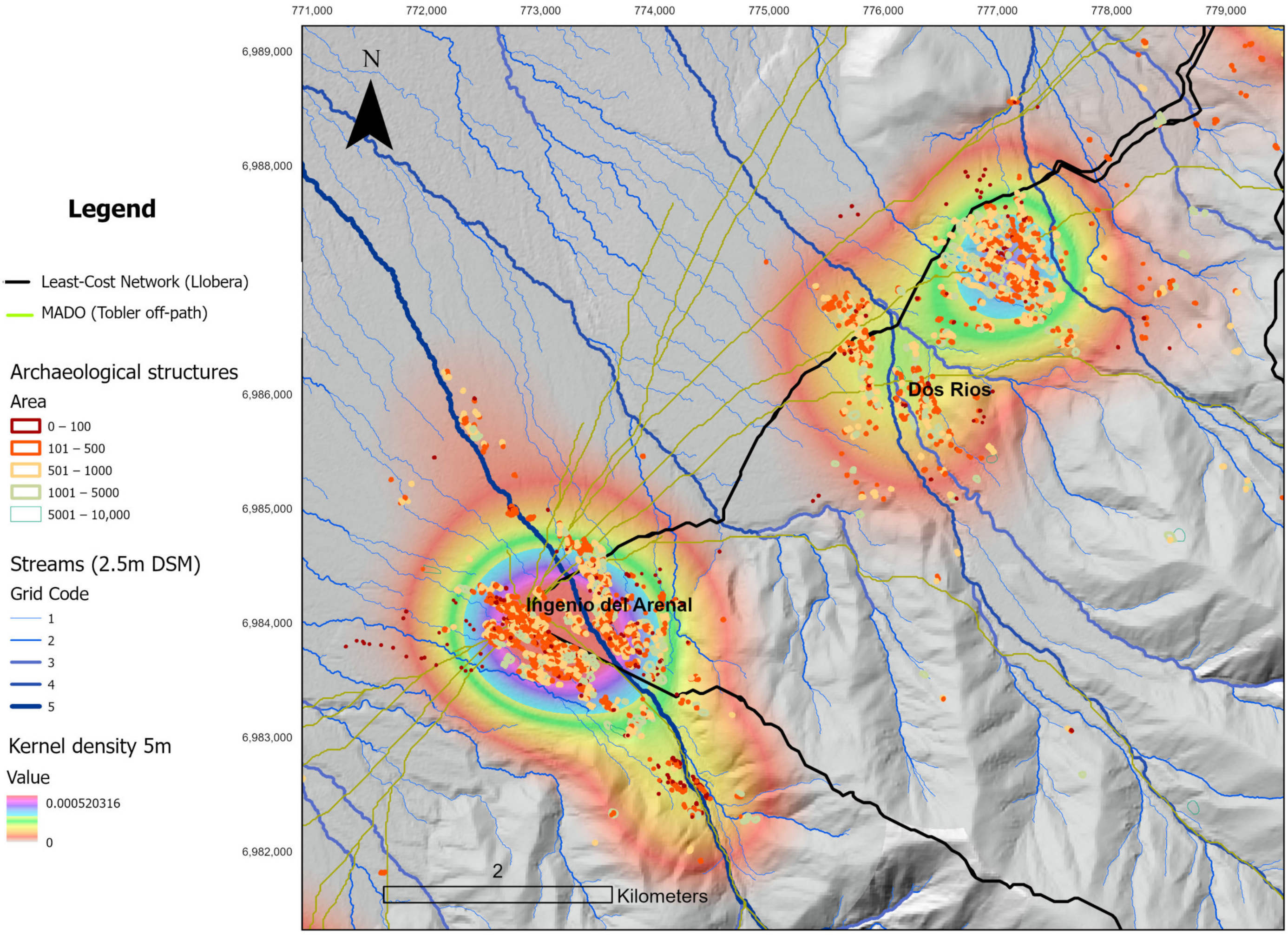

Figure 7. Ingenio del Arenal–Dos Ríos–Loma Redonda, showing the distribution of compounds within specific aggregation zones and in relation to streams and mobility lines.

If we look at the density ratios (i.e., the number of structures in the densest areas in every conoid), the densest area of Ingenio del Arenal has double the density of structures compared to Loma Redonda, and Buey Muerto is denser than Loma Redonda (Figure 6). These results provide support to earlier hypotheses that proposed a denser occupation during the Formative Period, with a small peak towards increased density and aggregation in the transition to the Late Period (represented by Loma Redonda), a trend that did not continue in the subsequent centuries [11].

The observed pattern is consistent with the idea that these settlements resulted from a long sequence of occupation, with many enclosures that accreted gradually one onto another, rather than being the result of a single episode [11,27,33]. The data also suggest the possibility of a 'spillover' effect, with 'founder' settlements expanding onto adjacent alluvial fans; a hypothesis that will require a systematic chronological assessment. An indication of how such processes might have occurred in the past is provided by the kernel density analysis, which frequently extended clusters of higher aggregation onto adjacent conoids or further down-stream from the densest one, as in the case of Loma Redonda–Dos Ríos, or the upper-conoid sector of Ingenio del Arenal (Figures 7 and 8).

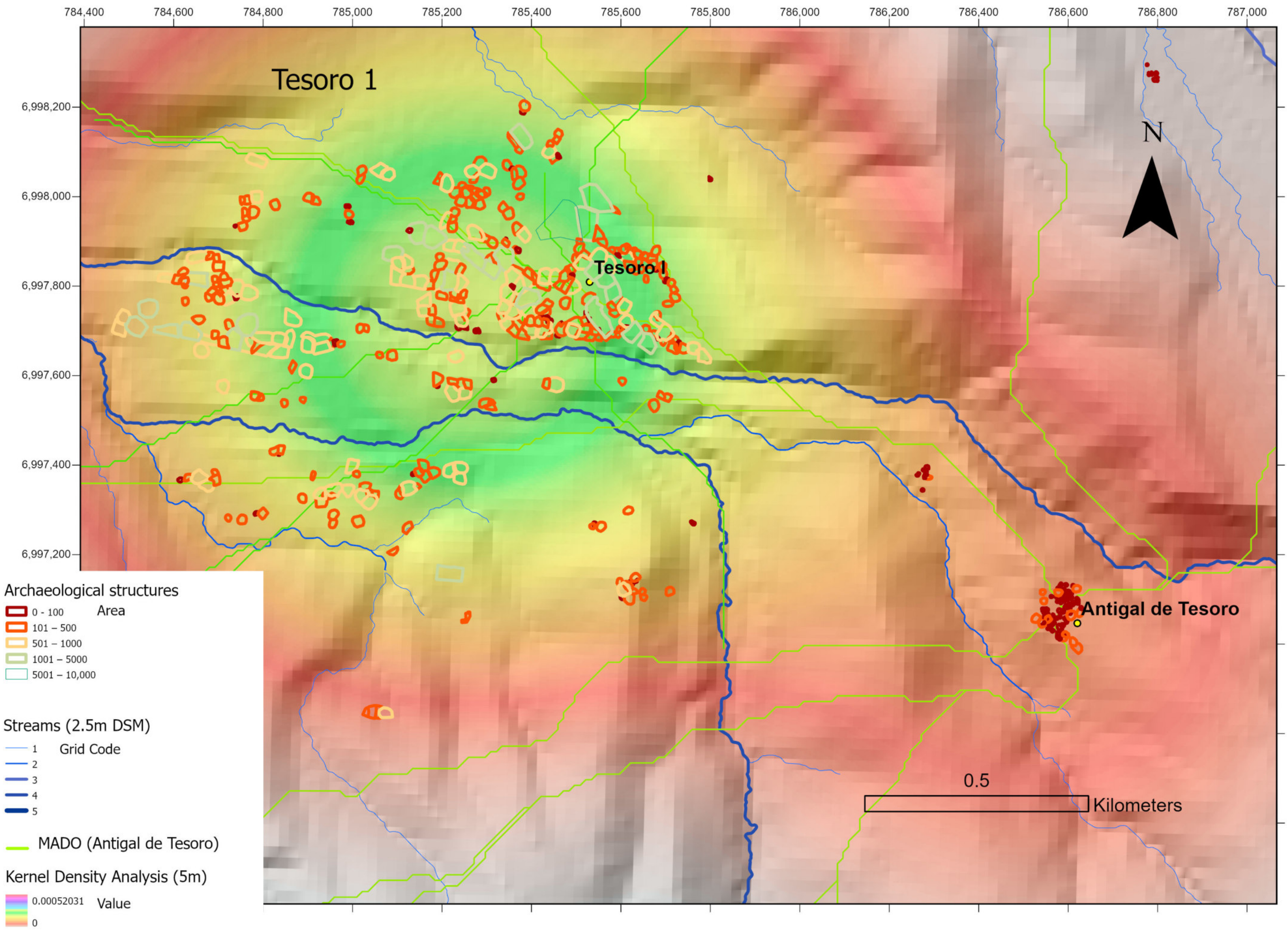

Figure 8. Archaeological structures at Tesoro ravine, with results of Tobler off-path MADO and kernel density analysis.

(b) Altitude-related distribution of aggregated built areas

Apart from the concentration of structures in the 'optimal zone' discussed above, there are also small pockets of aggregation outside of it, which may, in many cases, correspond to different chronologies. Inka presence seems limited to some locations, either at very high altitudes (e.g., the several logistical stations, *tampus*, on the road to *La Ciudacita*) or at lower elevations, such as the site of Ingenio del Arenal–Médanos (2436 m asl) [15,16]. On the other end of the chronological spectrum, two of the largest settlements dated to the first centuries AD (early Formative Period), Falda del Cerro de Ingenio del Arenal and Antigal de Tesoro, are situated at an elevation range above the 'optimal strip' (3100–3400 m asl), on relatively flatter areas overlooking the confluence of two streams; a pattern that contrasts with the wider, more spread settlement that characterises the middle and lower sectors of the alluvial conoids [11,33]. The presence of earlier Formative Period settlements at both the Ingenio del Arenal and Tesoro ravines adds to the results of the kernel density analysis discussed above and gives an indication of possible processes of settlement evolution, from smaller aggregations at higher altitude towards gradual settlement of the alluvial fans (Figures 7 and 8). Kernel density analysis highlights that possibility in at least three other ravines: Cerrillos, Buey Muerto, and Río Blanco (Figure 9).

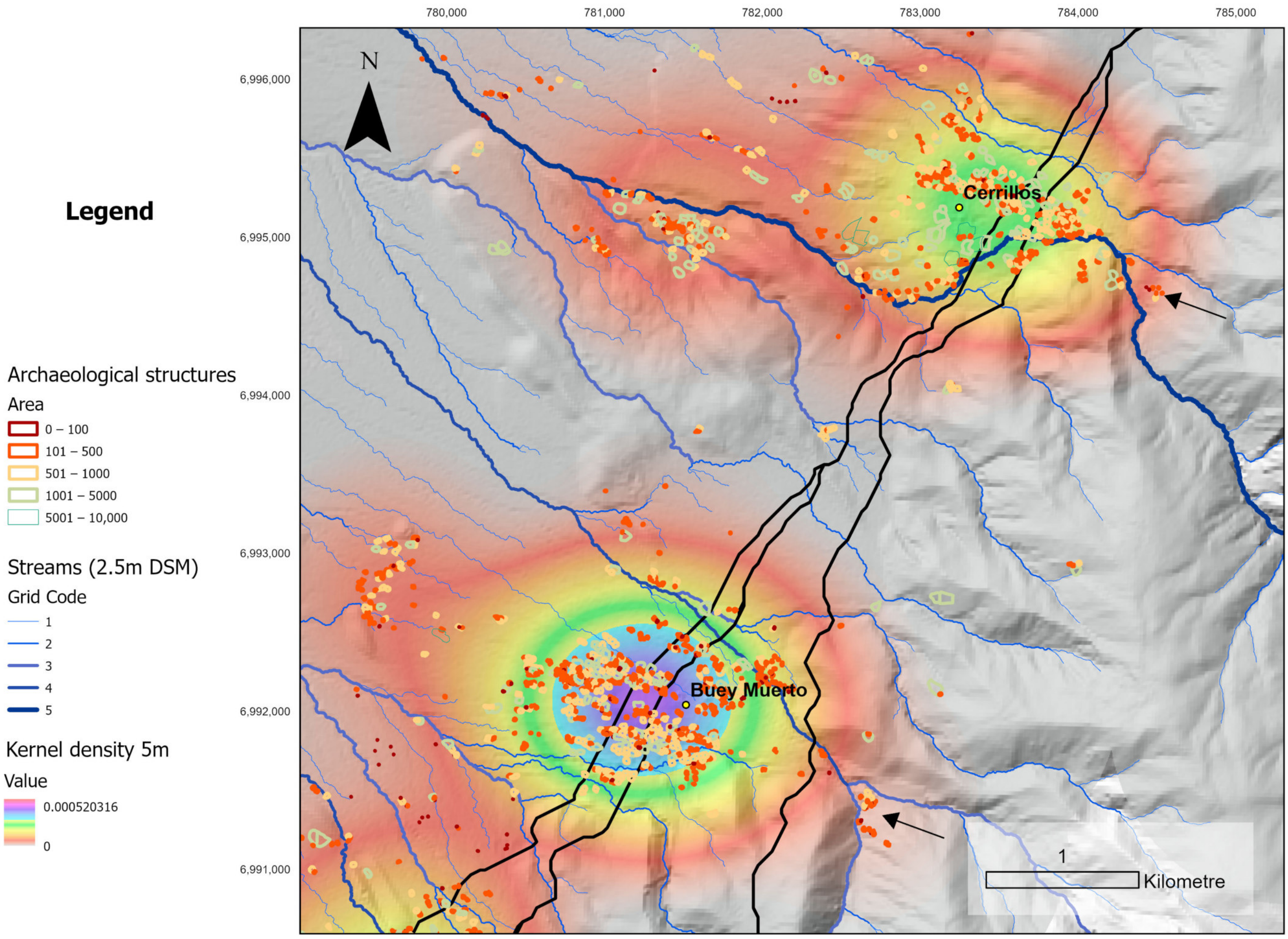

Figure 9. Kernel density analysis at Cerrillos and Buey Muerto, showing archaeological features at river confluences on the higher ground on the edge of their aggregation.

(c) Multi-directional connectivity

Our mobility analysis indicates that connectivity was instrumental to settlement growth in two distinct yet complementary ways: (1) N-S axis connectivity along the western flank across alluvial fans and (2) E-W axis connectivity, with the latter indicating significant potential for movement between the uplands and the lowlands, and across the peaks of the Sierra.

(1) *N-S axis connectivity* linking the alluvial fans at the base of the Aconquija Mountains is by far the dominant trend. This is consistently demonstrated by both Least-Cost network analysis and MADO, which have generated the largest number of paths within this sector (Figure 10). Most notably, the paths are skirting the altitudinal line at the highest point of the alluvial fans, where rivers are easier to cross. This outcome is unsurprising given the dominant presence of settlement within that sector, and that the trend has been retained by modern vehicle-based connectivity in western Aconquija. In recent historical times, there was a vehicle-accessible road skirting this altitude line, which, today, is only usable on foot or horseback. The annual festivity of San Roque sees pilgrims walking from Río Blanco to San José in the Santa María valley along one of the N-S axis roads skirting the western flank of the Sierra [60].

(2) *E-W axis connectivity* optimal routes have been flagged up consistently by MADO analysis for main aggregated sites (Figure 10). Given that Least-Cost calculations will identify routes or corridors in any scenario where both the start and the end point of the journeys are specified, MADO is a better method to explore routes’

potential, considering any optimal scenario around a central point. Accordingly, a range of optimal routes linking uplands with lower altitudes has been highlighted by this method, including in the Tesoro ravine, where a main optimal route could connect the early Formative Period site Antigal de Tesoro with both the main cores of aggregation within the larger settlement Tesoro I, and with peripheral aggregations borderline to the upper limit of the optimal zone (Figure 8). Further on, this site could also connect naturally with other main site agglomerations on the western flank of the Sierra, with roads skirting the upper sections of the alluvial fans (see above) and descending through the middle section of the terrace where Tesoro 1 is located, which offers flatter and higher ground relative to the riverbed (Figure 10b). Some MADO lines also connect Antigal de Tesoro with the higher edges of the alluvial fan above the 'optimal strip' where the larger site is located, suggesting potential complementary productive uses that must be further investigated. MADO analysis in this ravine also shows several opportunities for optimal movement eastwards across the mountains, including—but not limited to—the well-known crossing point of Abra del Toro [17,61] (4400 m asl, the lowest crossing point in the Sierra) and the path that leads to *La Ciudacita* (Figure 10b). The latter was further visualised via LCP and corridor analysis to provide a sensible image of an alternative movement strategy. The mobility lines and statistical accumulation as corridors coincide with well-known roads and crossing points of the Sierra still in use [17], giving further confidence in the outcomes of this analysis.

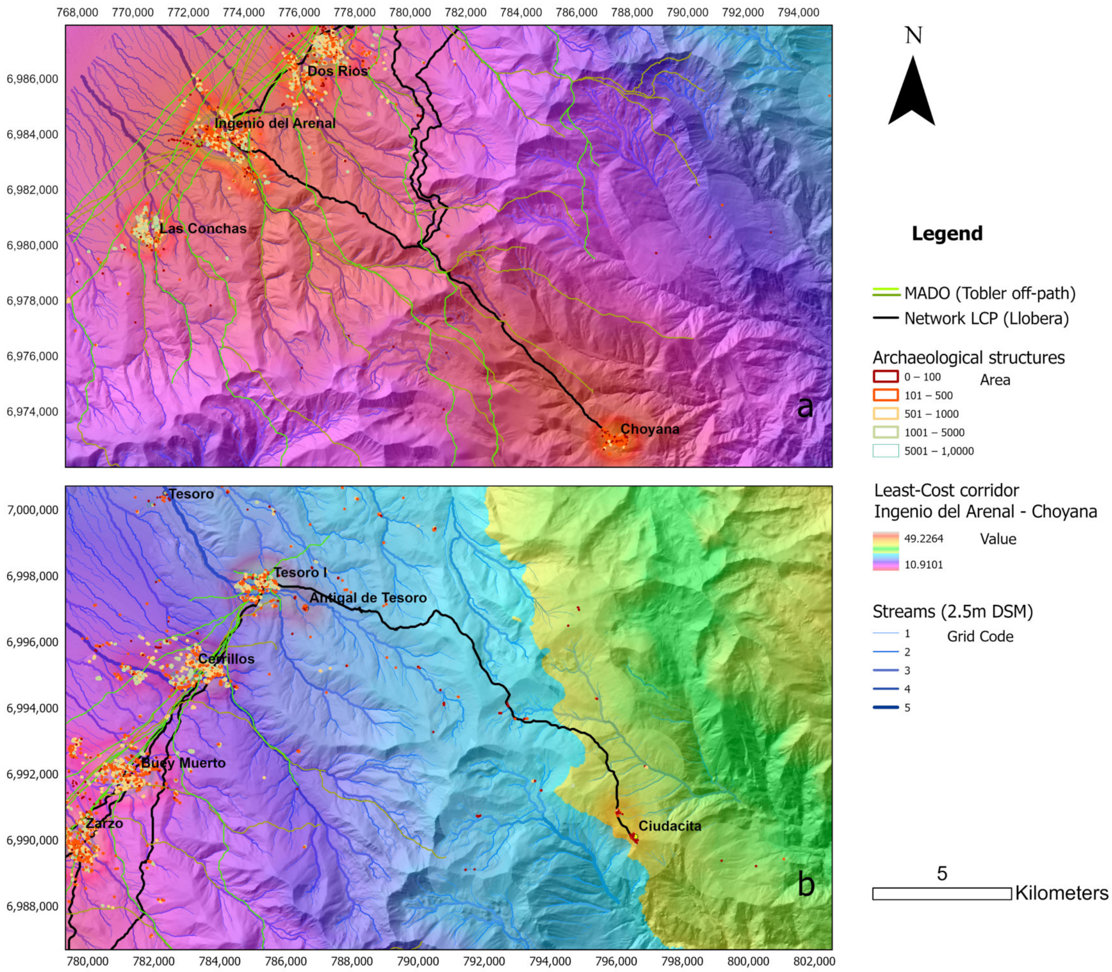

Figure 10. Mobility patterns represented as LCP, Least-Cost corridor, and MADO analyses for (**a**) Choyana–Ingenio del Arenal ravine and (**b**) for the Tesoro ravine.

At Ingenio de Arenal, MADO analysis shows optimal routes connecting the earlier site of Ingenio del Arenal–Falda del Cerro (located slightly above the optimal zone) with its busier sector further below, towards the NW, which draws potential parallels with Antigal de Tesoro in settlement evolution. The MADO lines in this ravine align closely with the clusters of structures of the main settlement, suggesting a possible pattern of settlement growth over the alluvial fan in which ancient inhabitants may have followed streams and rivers as they settled in the conoids building their dwellings, fields, and corrals, yet further assessment is required to explore the chronological unfolding of this spatial pattern.

In terms of E-W mobility, the Ingenio del Arenal ravine would have also benefitted from a previously unknown range of optimal travel paths across the Sierra, such as the paths linking the newly discovered high-altitude settlement site at Choyana ravine, perched at 3200 m asl on the eastern flank (Figures 10a and 11). The potential connection between Ingenio del Arenal sites and the Choyana mining area was already noted by Scattolin and Williams [16] (p. 82), but they did not identify an archaeological site in the Choyana area in their publication. The identification of the site is a remarkable find, since the earlier literature indicates that, while crossing the Sierra in its southern sector is possible through this ravine, descent towards the western side is extremely difficult [5] (p. 10). Despite the reported difficulty, there are several instances of fossilised paths coinciding with MADO lines (Figure 12), both in the northern and southern sectors, confirming earlier observations that even the highest crossing points could have been used by earlier inhabitants of the region [62] (p. 336).

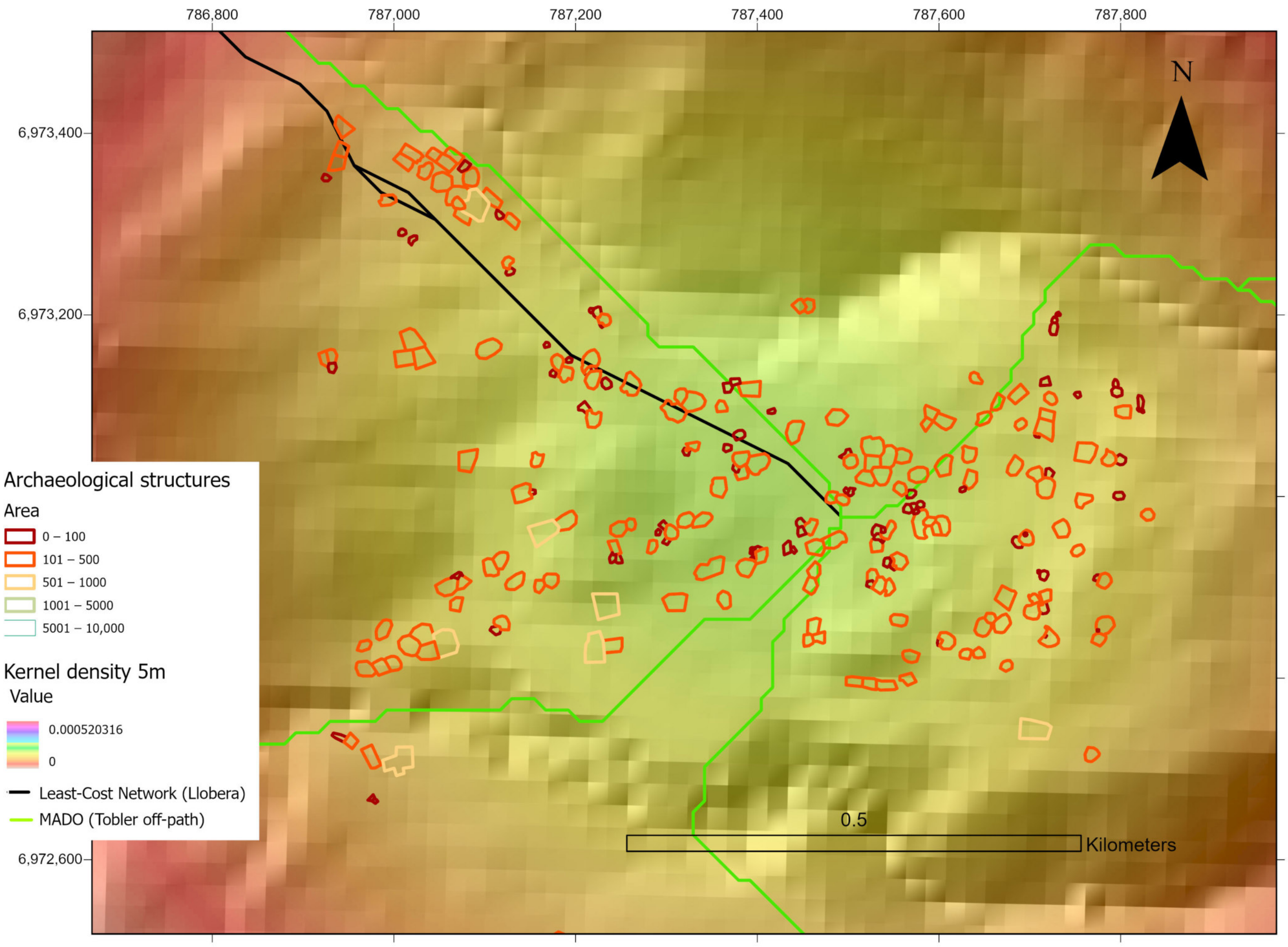

Figure 11. Distribution of archaeological structures within specific aggregation zones and in relation to mobility lines at the Choyana site.

Upstream mobility may have been linked to high-altitude springs, *vegas* or *bofedales* (high-altitude wetlands with cushion plants) [63], and to the river sources. These upper areas offer excellent pastures and hunting grounds for guanacos (*Lama guanicoe*) and tarucas (*Hippocamelus antisensis*), but, also, accessing them connected ancient inhabitants with water springs and mountain peaks, notoriously powerful entities in the Andes [14,18] (for Andean references of such a role, see [64,65]). While these aspects may be rendered most visible by the Inka structures in the northern sector, such as *La Ciudacita* and related road outposts, further analysis may uncover more structures related to upland practices in other sectors of the Sierra. Importantly, and as is often apparent in present-day local dwellers' uphill walking practices, E-W mobility may not always have followed waterways closely. In this regard, optimal mobility lines calculated via LCP or MADO offer great potential for further exploration.

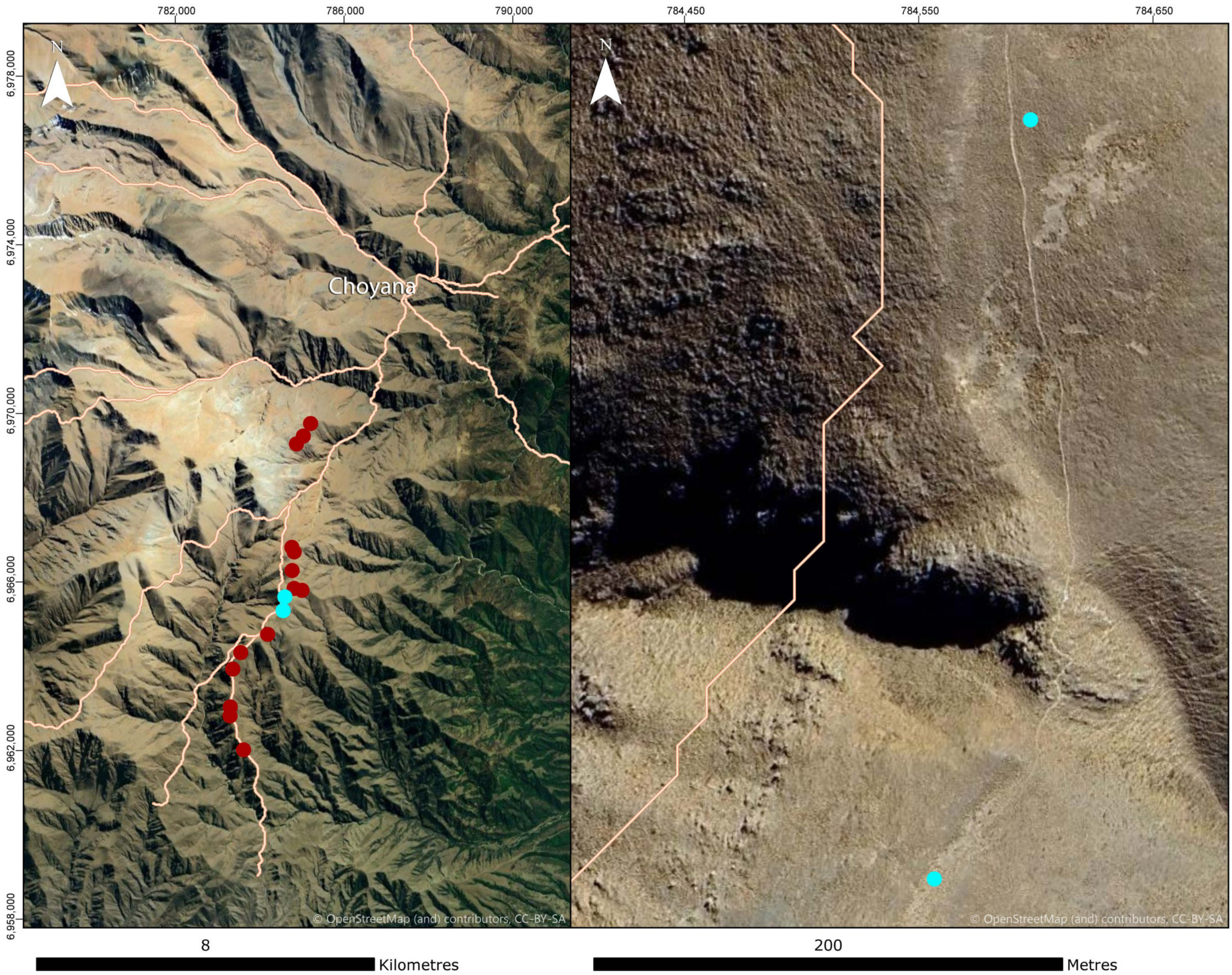

Figure 12. Example of fossilised paths confirming the directionality of a line generated by Tobler off-path MADO coming from the Choyana site (**left**). The red dots represent places where ancient roads have been identified, and the light blue dots represent the location of the close-up image. (**right**) A close-up shows the overlap between well-preserved footpaths and the mobility lines given by the MADO modelling.

5. Conclusions

This article contributes towards understanding the complexity of ancient economic and social practices that created a unique signature on the Aconquija Sierra landscape. Building on earlier studies, our research undertook for the first time the systematic and integrative large-scale identification of main data trends, to generate new hypotheses about the reasons for these similarities as well as for the observed variations. Our results highlight not only the close relationship between topography and human settlement and mobility, but also how ancient communities modified the landscape extensively, creating a wealth of infrastructure and material knowledge to be passed on to future generations.

Overall, the data agree with the general observations advanced by some of the earlier studies in the Sierra discussed above, which described the settlement pattern as largely homogenous, repeating a distribution of dispersed dwellings among fields and corrals, concentrated in the main areas of the alluvial fans. Our study also shows trends in settlement observed elsewhere in the Andes, with dwellings concentrated at altitude ranges with the highest potential yields of staple crops, and additional stations at different altitude levels to ensure an extra harvest or to cultivate a variety of produce (e.g., potatoes, quinoa, corn, peppers) [66,67] (p. 34), although further studies are needed to confirm the uses of such stations in the Sierra.

The pattern of sequential growth indicated by chronological data [11,22,23] and reinforced by our spatial and mobility analysis also aligns well with Andean studies, which have shown how settlements grow through the gradual fission of households over generations. Such studies have shown how larger dwellings usually belong to older family members, while younger generations splinter into smaller units as they form new families [65,68] (p. 408).

While better chronological resolution is needed, it is possible to propose as a working hypothesis that, in each site, a small number of residential units oversaw building, using, and maintaining a relatively large number of productive units. Cooperative ties across the sites contemporarily occupied [22,33]—a pattern well described for similar small-scale settled societies in other sectors of NW Argentina (e.g., [68,69])—would have resulted in the overall spread of structures and general uniform morphology, which, given its efficacy, would have been passed down as intergenerational knowledge. Further chronological and mapping verification work is needed to explore the development of colonisation and settlement from the early Formative Period onwards. An important question that requires additional analysis is how to assess subtle transformations in the generalised distributed settlement pattern that seems to endure across millennia. This issue is not only relevant for understanding the processes affecting communities as the Late Period unfolded [11,28], but also for assessing the actual impact of the Inka occupation. To what extent the Sierra's particularly enduring pattern of land use and overall lifestyle may have been affected by the imposition of the Inka administrative and ritual settlement system at key locations and crossings—seemingly without massively changing the composition of material culture assemblages found at sites located on the alluvial fans [16]—remains to be further assessed. In a similar vein, the Spanish colonial and subsequent Republican period occupations, primarily oriented towards mining resource extraction [70,71], may have imprinted the landscape in ways that have yet to be systematically assessed.

Additionally, the extensive mapping effort in this research has produced a substantial body of information, sufficient to commence the training of object identification models via machine learning. While this type of approach is increasingly standard in remote sensing and archaeology, in the Andes, given the ecological diversity and distinctive features, bespoke models for every region are required, depending on vegetational, land use, and geological elements. Moreover, this training process can be augmented with image segmentation, leveraging the promising results obtained with the vegetational indexes tested in this study. Consequently, we anticipate that a combination of these techniques, together with a programme of systematic ground-truthing and verification, will enable a large-scale approach for the continual identification of compounds, structures, cultivation installations, and many other features visible from above in the Andes.

In synthesis, our results contribute towards (1) evaluating factors affecting settlement and connectivity in the past, (2) generating comprehensive records of architectural features that enable assessment of the imprint of ancient practices on regional landscape, (3) proposing hypotheses for further work towards a better understanding of spatial, temporal, and functional variations in the past settlement of the area, and (4) providing an archaeological baseline for developing recommendations for the protection and management of this landscape of productivity and connectivity. This last is a particularly important point, as extensive excavations in the Sierra are neither feasible, due to the difficulties in access to sites, nor desirable, for conservation reasons. As we adopt transcultural research methodologies that enable local communities' increased autonomy in heritage management [72], an integrated remote sensing approach combined with ground-truthing via field methods can contribute to the understanding of changes and continuities in patterns of aggregation and dispersion. This, in turn, can help to build a model of settlement and connectivity based on a contextual understanding of what standard archaeological categories, such as 'residential/domestic' and 'productive', really mean in this area. Developing archaeological and geospatial data classification systems that are better aligned with the enduring lifestyle and land knowledge that characterises the region can contribute towards building a solid foundation for equitable collaborations between academic and indigenous communities.

The results highlight the important role the Sierra had in the past, not only as a climatic barrier, but as a landscape shaped by the cumulative actions of communities over millennia, who turned to the Sierra for shelter, sustenance, and connections, as well as seeking its tutelar role as a controller of climate and waters [64]. Far from being marginal or deserted, the Sierra was a vibrant, key agent in the long-term history of humanity in the region. It can continue to act in a similar way in the future, provided appropriate collaborative and inclusive protective, productive, and development strategies are implemented, that are better aligned with local knowledge, histories, and understandings [64].

Our approach brings a new perspective to current Andean and worldwide scholarship on landscape and interaction and highlights the significance of ancient indigenous practices for the future of landscapes severely threatened by ever-increasing destructive landslides and expanding industrial-scale resource extraction endeavours [73]. In such contexts, ancient landscapes' legacies not only testify to the long history of human ingenuity and adaptability, but also provide a uniquely rich source of knowledge that can inform 'best practice' for sustainable and collaborative heritage and socioeconomic management.

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Data Availability Statement: The datasets presented in this article are not readily available because the data are part of an ongoing collaborative research endeavour with the relevant communities. Requests to access the datasets should be directed to the corresponding author. Commercial satellite imagery utilised for this study is not available due to licencing restrictions.

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