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Spatio-temporal analysis of land use and land cover change (2011–2024) in the Huaytapallana Regional Conservation Area, Peruvian Andes

Sheyli Diana Gomez Rodriguez[1], Pabel Mariano Meza Mitma[2], Jairo Edson Gutiérrez-Collao[2], Julio Miguel Angeles-Suazo[2], Evelyn Ruth Palomino-Santos[3], Leticia Leiva Arauco[4], Wilfredo Tello-Zevallos[5], Roberto Angeles Vasquez[6], Nataly Angeles-Suazo[7*]

[1] Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Master's Program in Management and Conservation of Tropical Forests and Biodiversity, Turrialba, Costa Rica
[2] Universidad Nacional Autónoma de Tayacaja "Daniel Hernández Morillo", Escuela Profesional de Ingeniería Forestal y Ambiental, Tayacaja, Perú
[3] Facultad de Ciencias Forestales y del Ambiente, Universidad Nacional del Centro del Perú, Huancayo, Perú
[4] Universidad Nacional Intercultural de la Selva Central "Juan Santos Atahualpa", Chanchamayo, Junín, Perú
[5] Universidad Nacional Agraria de la Selva, Tingo María, Perú
[6] Facultad de Ingeniería Civil, Universidad Nacional del Centro del Perú, Huancayo, Perú
[7] Universidad Tecnológica del Perú, Campus Huancayo, Huancayo, Perú
* Corresponding author's e-mail: nati2643@hotmail.com

ABSTRACT

Land use and land cover (LULC) changes within protected areas can threaten ecosystem integrity despite formal conservation status. This study analyzes spatiotemporal LULC dynamics in the Huaytapallana Regional Conservation Area (HRCA) in the Peruvian Andes between 2011 and 2024. Using data from MapBiomas and multitemporal geospatial analysis, we quantified changes in major land cover classes within the conservation area. The results reveal substantial losses of forest (−508.68 ha), grassland (−4,975.02 ha), and glaciers (−6,682.5 ha), accompanied by significant increases in rocky outcrops (+11,719.89 ha) and shrubland (+6,329.34 ha). These trends indicate accelerated glacier retreat, landscape aridification, and increasing anthropogenic pressure within the HRCA. The observed transformations suggest ongoing ecological degradation that may compromise ecosystem functionality and conservation objectives. Our findings indicate that current governance and monitoring strategies are insufficient to maintain the long-term sustainability of this high-Andean protected area.

Keywords: Huaytapallana Regional Conservation Area, land cover and land use, remote sensing.

INTRODUCTION

The growth of environmental degradation poses complex challenges for global society, as it has effects on economic development, sustainability, and human health (Galaz et al., 2018; Rehman et al., 2022), in addition to the loss of natural resources, increased water and air pollution, depletion of biodiversity, and increased climate change (Gao et al., 2024). For example, globally, species on the International Union for Conservation of Nature (IUCN) Red List are affected by habitat destruction and overexploitation, representing major high-impact threats (Hogue and Breon, 2022).

High-altitude grasslands play a crucial role in global carbon storage and nutrient cycling (Goldstein et al., 2020), yet they are increasingly threatened by temperature and precipitation shifts, overgrazing, land use change, mining, and urban expansion (Qi et al., 2025; Zhang et al., 2025; Fayiah et al., 2020). These pressures reduce ecosystem resilience, increase vulnerability of livestock systems, and contribute to desertification (Bengtsson et al., 2019; Song et al., 2020). Similarly, forest ecosystems, particularly in the Amazon, face degradation from agricultural expansion, illegal extraction, and climate change, resulting in biodiversity loss, soil erosion, and impaired climate regulation (Feurer et al., 2025; Leal Filho et al., 2025; Lapola et al., 2023). Despite these known impacts, quantitative assessments of land use and land cover (LULC) change in high-Andean protected areas remain limited, leaving critical knowledge gaps regarding ecosystem transformation at regional scales.

In Peru, approximately 13.78% (177,592.82 km²) of the territory was degraded in 2017 (Rojas et al., 2020) and between 2000 and 2009, 7% of high Andean grasslands were reduced due to urban and agricultural expansion. These grasslands are also used as fodder for cattle, sheep, camelids, and vicuñas (Cerna et al., 2024). Thus, in its fight against deforestation and altered landscapes, the Peruvian government created Protected Areas (PAs) with the intention of maintaining floral diversity and ecosystem services and mitigating the regional impacts caused by climate change (Cotrina et al., 2021). Despite these and other conservation initiatives, PAs still experience losses at a slower rate than unprotected areas, but with a trend remarkably similar to global forest and grassland loss (Cotrina et al., 2021; Wade et al., 2020). This highlights the need for quantitative monitoring of LULC changes to evaluate PA effectiveness.

The Junín region, located in central Peru, encompasses a wide variety of altitudinal zones stretching from the Andes to the high jungle, giving it remarkable biological and landscape diversity (Chanamé-Zapata et al., 2019; Maldonado-Fonkén et al., 2024; Yaranga et al., 2025), For this reason, there are important conservation areas such as the Nor Yauyos – Cochas (NYLRC), the Huayllay National Sanctuary (HNS), the Pui Pui Protection Forest (PPPF), and the Huaytapallana Regional Conservation Area (HRCA) (Servicio Nacional de Áreas Naturales Protegidas por el Estado [SERNANP], 2025). These areas protect unique ecosystems such as montane forests, high Andean grasslands, wetlands, and cloud forests, all of which are considered essential for biodiversity conservation and the provision of ecosystem services (Tejedor et al., 2012). However, HRCA remains understudied in terms of spatial and temporal LULC changes, limiting the understanding of ongoing ecological transformations.

The HRCA faces multiple conservation challenges, including visitor impacts (Maldonado and Custodio, 2020), glacier retreat (Torres et al., 2018), and vulnerability of flora to anthropogenic pressures (Bravo et al., 2022). These factors drive progressive ecological degradation, affecting biodiversity, ecosystem services, and the socio-cultural potential of the region (Reyes et al., 2025). Quantifying such changes remains challenging, limiting understanding of land use dynamics and their economic and ecological implications. Previous studies have emphasized the strategic importance of assessing environmental degradation in Peruvian PAs to support effective conservation planning (Garagatti et al., 2020; Cotrina et al., 2021; Arizapana et al., 2024), including identification of ecosystem components, threats, and restoration opportunities (Zandebasiri et al., 2023; Das, 2024; Singh, 2024).

Therefore, the valuation of natural capital is an essential pillar for moving towards a sustainable development model. Measuring the consumption of natural capital and transitioning to a circular economy make it possible to effectively address the challenges associated with ecological degradation (Nulkar, 2024), making it necessary to strengthen forest governance, improve institutional frameworks, and promote innovative financial mechanisms, such as payments for ecosystem services, that support conservation and restoration initiatives (Shukla and Dhyani, 2025). However, in HRCA, a lack of detailed spatial-temporal data on LULC changes limits the design of targeted conservation and restoration strategies.

Therefore, this study aims to quantitatively analyze land use and land cover changes in the HRCA between 2011 and 2024 using remote sensing data, in order to identify the extent and patterns of ecosystem transformation, including glacier retreat, forest loss, and grassland degradation. By providing a detailed spatial-temporal assessment, this research seeks to fill the knowledge gap regarding the effectiveness of conservation measures in high-Andean PAs.

MATERIALS AND METHODS

Study area

The study was conducted in the HRCA, located in the provinces of Concepción and

Huancayo, in the department of Junín, Peru (https://geo.sernanp.gob.pe/visorsernanp/). The study area is located approximately at 11°35′S and 75°05′W within the WGS84/UTM Zone 18S reference system, with elevations ranging from 4,946 to 5,565 m a.s.l. (Figure 1), estimated from a Digital Elevation Model (DEM) derived from ALOS PALSAR (Advanced Land Observing Satellite – Phased Array type L-band Synthetic Aperture Radar), from the hi-res terrain corrected archive, corresponding to January 1, 2011, with a spatial resolution of 12.5 × 12.5 m, available at https://search.asf.alaska.edu. The region has a temperate climate with moderate precipitation and a pronounced dry season. Daytime temperatures range between 12 and 14 °C, with nighttime lows reaching -2 °C. The landscape is characterized by the presence of high-Andean ecosystems of great ecological importance, including the humid puna grasslands, bofedales, periglacial zones, glaciers, lakes, and lagoons, according to the National Map of Ecosystems of Peru (Ministerio del Ambiente [MINAM], 2019). These environmental conditions provide a unique setting for assessing changes in land use and land cover in high-altitude ecosystems.

Classification of land use and land cover

Data source and characteristics

Information on land use and land cover was obtained from the MapBiomas Peru Project Collection 3.0, covering the period 2011–2024, which is publicly available at https://peru.mapbiomas.org/ (accessed September 7, 2025). This product was developed by the Instituto del Bien Común (IBC), in collaboration with the Amazonian Network for Georeferenced Socio-Environmental Information (RAISG), as part of the MapBiomas Network initiative. The dataset provides annual LULC maps derived from Landsat images (4, 5, 7, 8, and 9) with a spatial resolution of 30 m, classified into 27 thematic classes using machine learning algorithms. The products are distributed in the WGS84/UTM zones 18S, 19S, and 20S reference system (Bravo et al., 2025). The ACRH is located entirely within UTM zone 18S; all spatial analyses were performed in this projection. Within the ACRH, 14 land cover and land use classes derived from the MapBiomas product were identified (Table 1). The methodology for generating, classifying, and validating the maps is described in the Algorithm Theoretical Basis

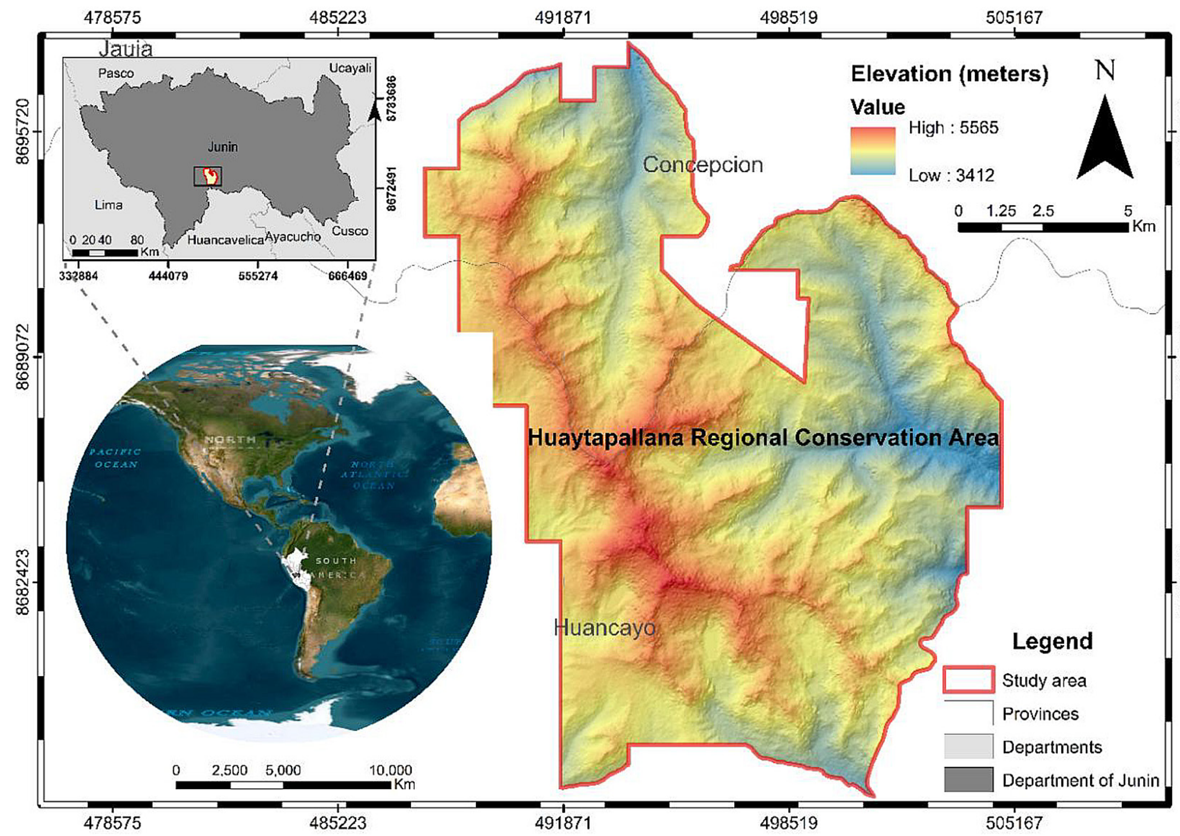

Figure 1. Geographic location of the study area

Document (ATBD) – MapBiomas Peru Collection 3.0, available at https://peru.mapbiomas.org/acceda-a-los-atdbs/. For this study, the annual mosaics were cropped to the HRCA area using its official polygon in shapefile format, obtained from the SERNANP Geoportal (https://geo.sernanp.gob.pe/visorsernanp/).

Classification methodology

The generation of LULC maps in MapBiomas Peru follows a methodological workflow consisting of four main stages: (i) generation of annual mosaics, (ii) supervised classification, (iii) post-classification, and (iv) validation (Figure 2) (Bravo et al., 2025). In the first stage, annual Landsat mosaics are constructed from multiple images available for each year, which have been pre-processed to remove clouds and shadows using algorithms such as CloudScore and CFmask. Valid pixels are integrated using statistical operators to generate representative annual composites. In the second stage, annual classification is performed using the Random Forest machine learning algorithm, employing spectral variables, derived indices, texture metrics, spectral fractions, and topographic variables. In the third stage, the classified maps undergo post-classification processes, including spatial and temporal filters designed to correct inconsistencies, fill in gaps, and stabilize classes throughout the time series. Finally, the fourth stage involves validation, based on stratified random sampling and confusion matrices to estimate thematic accuracy metrics.

Geospatial data processing

Raster data processing was performed in R version 4.5.0 using the raster, sf, dplyr, OpenLand, and ggplot2 packages. The annual LULC maps from MapBiomas Peru for the period 2011–2024 were imported using the raster() function. The ACRH polygon was loaded in shapefile format using the st_read() function from the sf package and was used as a spatial mask for the analysis. Subsequently, each annual raster was cropped and masked to the boundary of the ACRH using the crop() and mask() functions from the raster package, ensuring that the analyses were performed exclusively within the

Table 1. Description of the 14 LULC classes identified in the ACRH based on MapBiomas Peru Collection 3.0

ID	Classes	Description
3	Forest	Relict Andean forests characterized by scattered, low-growing trees (≤10 m), located on mountain slopes between 2.800 and 3.800 meters above sea level.
11	Wetland	High-Andean wetlands of the bofedal type, characterized by dense, perennial vegetation growing on waterlogged or poorly drained soils in the bottoms of fluvial-glacial valleys, volcanic cones, and plains, located at elevations of 3.800 meters above sea level and higher.
12	Grassland	Puna grasslands (Andean grasslands) dominated by grasses and short-statured turf, found at elevations of approximately 3.000–4.800 meters above sea level.
13	Other non-forest formation	Vegetation dominated by shrubs, herbs, or low-growing grasses, including cardonales and sclerophyllous scrublands in Andean environments.
15	Pasture	Areas dominated by natural or planted grasslands associated with livestock farming in high-Andean landscapes.
21	Agricultural mosaic	Diverse agricultural landscapes, characterized by livestock farming and the cultivation of grains, tubers, and vegetables, typical of Andean valleys and hillsides.
25	Other non-vegetated area	Human-modified areas with little or no vegetation, including bare ground, areas undergoing agricultural conversion, roads, and urban sprawl.
27	Undefined	Areas with no information or an undetermined classification in the MapBiomas product.
29	Rocky outcrop	Naturally exposed rock surfaces with little soil cover and rock-dwelling vegetation, commonly found in periglacial environments or stone forests.
30	Mining	Areas affected by mining activities, including the extraction and accumulation of materials in open-pit mines or alluvial mining.
33	Water bodies	Natural or artificial surface water bodies, such as rivers, lakes, lagoons, or reservoirs found in Andean landscapes.
34	Glacier	Permanent masses of ice and snow formed by the accumulation, compaction, and recrystallization of snow that falls in the Andes Mountains at elevations ranging from 4,800 to 6,768 meters above sea level.
66	Shrubland	Vegetation dominated by shrubs with some herbaceous plants, found at elevations ranging from 2,000 to 3,500 meters above sea level up to the transition zones leading to grasslands.
68	Other natural non-vegetated area	Natural areas with little or no vegetation that are not classified in other categories, such as exposed soils, volcanic deposits, or riverbanks.

Source: Adapted from MapBiomas (2025) and MINAM (2015)

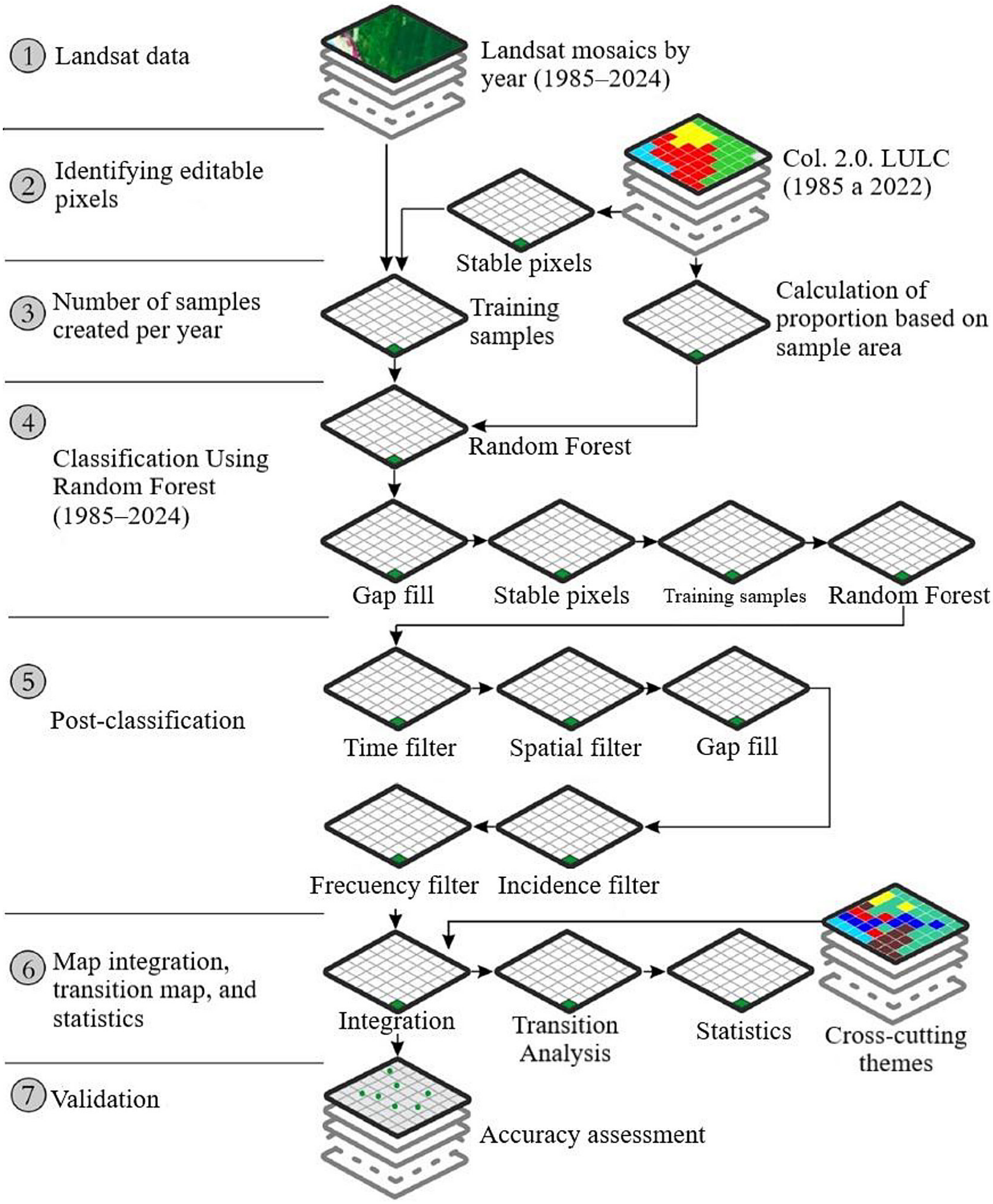

Figure 2. Methodological workflow for MapBiomas Peru Collection 3.0

study area. The resulting rasters were integrated into a multitemporal series using the stack() function. The analysis of land-use dynamics was performed using the OpenLand package, employing the contingencyTable() function to generate transition matrices between classes and quantify land-cover changes in terms of area. The barplotLand(), sankeyLand(), and chordDiagramLand() functions were used to visualize transitions between classes and graphically represent the dynamics of change. Class frequencies and calculations of net gains and losses were performed through data aggregation and manipulation using functions from the dplyr package, while results were visualized using ggplot2. All spatial analyses were performed in the WGS84/UTM Zone 18S reference system, corresponding to the location of the ACRH. No additional resampling or reprojection processes were necessary, as MapBiomas products are distributed in this same coordinate system. Finally, the cartographic processing and final visualization of the multitemporal maps were performed in QGIS version 3.40.6, ensuring consistency in the cartographic projection, symbology, and spatial representation of the results.

Data validation and reliability

The thematic reliability of the maps used in this study was based on the official validation framework of MapBiomas Peru, which employs stratified random sampling, visual interpretation of reference points, and confusion matrices to estimate classification accuracy. This procedure includes approximately 71,500 reference points, interpreted with the aid of Landsat imagery, SWIR-NIR-RED spectral bands, and high-resolution data available on Google Earth. The metrics reported by the platform include global accuracy, user accuracy, and producer accuracy (Bravo et al., 2025). The complete validation results are available on the official MapBiomas Peru platform (https://peru.mapbiomas.org/exactitud/). Consequently, this study used MapBiomas products as a pre-validated cartographic source for the multitemporal analysis of the ACRH. According to Matos et al. (2025), the project maintains robust temporal consistency in its estimates, based on a sample of 85,152 validation points used in the quality assessment of the annual series. Complementarily, Zenke and Madureira (2021) recorded an overall accuracy of close to 85% when comparing MapBiomas data with reference maps in the state of Rio de Janeiro, which supports the reliability of the product for multitemporal land use and land cover analysis.

Additionally, an independent local validation was conducted for 2024 to assess the map's accuracy in the study area. For this purpose, Landsat 8 and Landsat 9 satellite images with a spatial resolution of 30 m were used, selected for their cloud cover of less than 20%. Stratified random sampling was applied, considering the map classes as strata, following the recommendations of Olofsson et al. (2014). The sample size was allocated using a mixed scheme, establishing a minimum of 30 points for classes with low spatial representation, including forest, wetland, agricultural mosaic, undefined, mining, shrubland, and other natural non-vegetated areas. The remaining points were distributed proportionally to the area of the larger classes. In total, 500 validation points were generated and randomly distributed within the ACRH. Point assignment and verification were performed in QGIS using visual interpretation supported by Landsat imagery and high-resolution data. A confusion matrix was then constructed to compare map classes with reference classes. From this matrix, the following accuracy metrics were calculated: overall accuracy, user accuracy, producer accuracy, and Kappa index. These metrics allowed for the evaluation of the map's thematic consistency and its reliability for LULC analysis in the ACRH.

Local validation

A local validation was conducted for the year 2024 to assess the map's accuracy within the ACRH. Stratified random sampling was applied, using the map classes as strata, in accordance with the recommendations of Olofsson et al. (2014). The sample size was assigned using a mixed scheme, adding 30 points to all classes, since there are very small areas (less than 4 hectares), which result in low spatial representation when performing proportional distribution of the classes according to their areas. In total, 526 validation points were generated from an initial sample size of 138 points, estimated according to methodological criteria for accuracy assessments in the study area (MINAM, 2014). This number was adjusted by assigning a minimum of 30 points per class, with the aim of improving the representativeness of minority classes. The points were randomly distributed within the ACRH. The assignment and verification of the points were performed through visual interpretation, using high-resolution images available on Google Earth Pro, selecting scenes corresponding to the year 2024 (Table 2).

Next, a confusion matrix was constructed by comparing the classes predicted by the MapBiomas 2024 map with the reference classes obtained through visual interpretation of high-resolution images in Google Earth Pro for 2024 or very close to that date. This matrix allowed us to evaluate the agreement between the two information sources at the pixel level. Based on this, the main accuracy metrics were calculated: overall accuracy, user's accuracy, producer's accuracy, and the Kappa index. Overall accuracy quantifies the total proportion of correct classifications, while user's accuracy and producer's accuracy allow for the evaluation of commission and omission errors for each class, respectively. The Kappa index was used as an additional measure of agreement adjusted for chance. Together, these metrics allowed for the evaluation of the map's thematic consistency and its level of reliability for the multitemporal analysis of changes in LULC in the ACRH.

Table 2. Point records used for local validation, areas corresponding to 2024

Clases	Area (ha)	%	Original points	Validation points
Forest	399.08	1.78	2.46	32
Wetland	838.98	3.75	5.17	35
Grassland	12348.27	55.13	76.08	106
Other non-forest formation	71.22	0.32	0.44	30
Pasture	1334.83	5.96	8.22	38
Agricultural mosaic	27.82	0.12	0.17	30
Other non-vegetated area	3.52	0.02	0.02	30
Undefined	2.06	0.01	0.01	30
Rocky outcrop	5387.85	24.06	33.20	33
Mining	0.65	0.00	0.00	30
Water bodies	133.25	0.59	0.82	31
Glacier	1183.58	5.28	7.29	37
Shrubland	664.75	2.97	4.10	34
Other natural non-vegetated area	1.38	0.01	0.01	30
Total	22397.24	100.00	138.00	526

RESULTS

Quantification of ecological degradation in HRCA

Figure 3 shows that in 2011, twelve main classes of land cover and land use were identified, including forest, wetland, grassland, other non-forested formations, pastures, agricultural mosaic, other areas without vegetation, undefined, rocky outcrop, lake, glacier, and other natural areas without vegetation. However, starting in 2012, the category of scrubland was added, reflecting the expansion of shrub vegetation in areas previously dominated by grasslands. Subsequently, in 2016, the mining category was recorded for the first time and remained in use until 2024, highlighting new forms of land use within the study area. Thus, by 2024, a total of fourteen land cover and land use categories had been established.

Figure 3a summarizes the main changes in land cover and land use in the land conservation area (LCA) between 2011 and 2024. The chain diagram reveals a clear trend toward the replacement of glaciers and grasslands by rocky outcrops, scrub, and other non-forested formations, reflecting processes of deglaciation and landscape aridification. Minor shifts toward anthropogenic land uses, such as agricultural mosaics and mining, are also identified, indicating localized human pressure in the area.

Figure 3 shows the temporal dynamics of land cover and land use in the LCA between 2011 and 2024. Notable variations are observed in the extent of the main land cover classes, reflecting the ecological and territorial transformation processes of the Andean landscape. Of particular note is the downward trend in grasslands, which, although they remain the dominant land cover, show a progressive reduction during the analyzed period. At the same time, glaciers show a marked decline, reflecting the accelerated retreat of ice due to climate change. In contrast, a sustained increase in rocky outcrops and scrub is observed, suggesting a process of replacement of areas previously covered by herbaceous vegetation or ice with more arid surfaces and secondary vegetation. Likewise, wetland areas show a slight expansion, possibly related to ice melt and increased surface runoff. Other types of land cover, such as forests, grasslands, and agricultural mosaics, remain relatively stable with minor fluctuations, indicating a degree of stability in altered or managed areas. Overall, the Figure 4 shows an ecological transition toward drier and more heterogeneous landscapes, with a loss of snow-herbaceous cover and a consolidation of rocky and shrubby formations.

Table 3 shows the cumulative gains (green bars), losses (red bars), and net changes (black dots) for the different land cover and land use classes in the HRCA between 2011 and 2024. The results reflect contrasting landscape dynamics, with significant reductions in high-mountain natural cover, while arid formations and secondary vegetation tend to expand. The largest net loss corresponds to grasslands, with reductions of

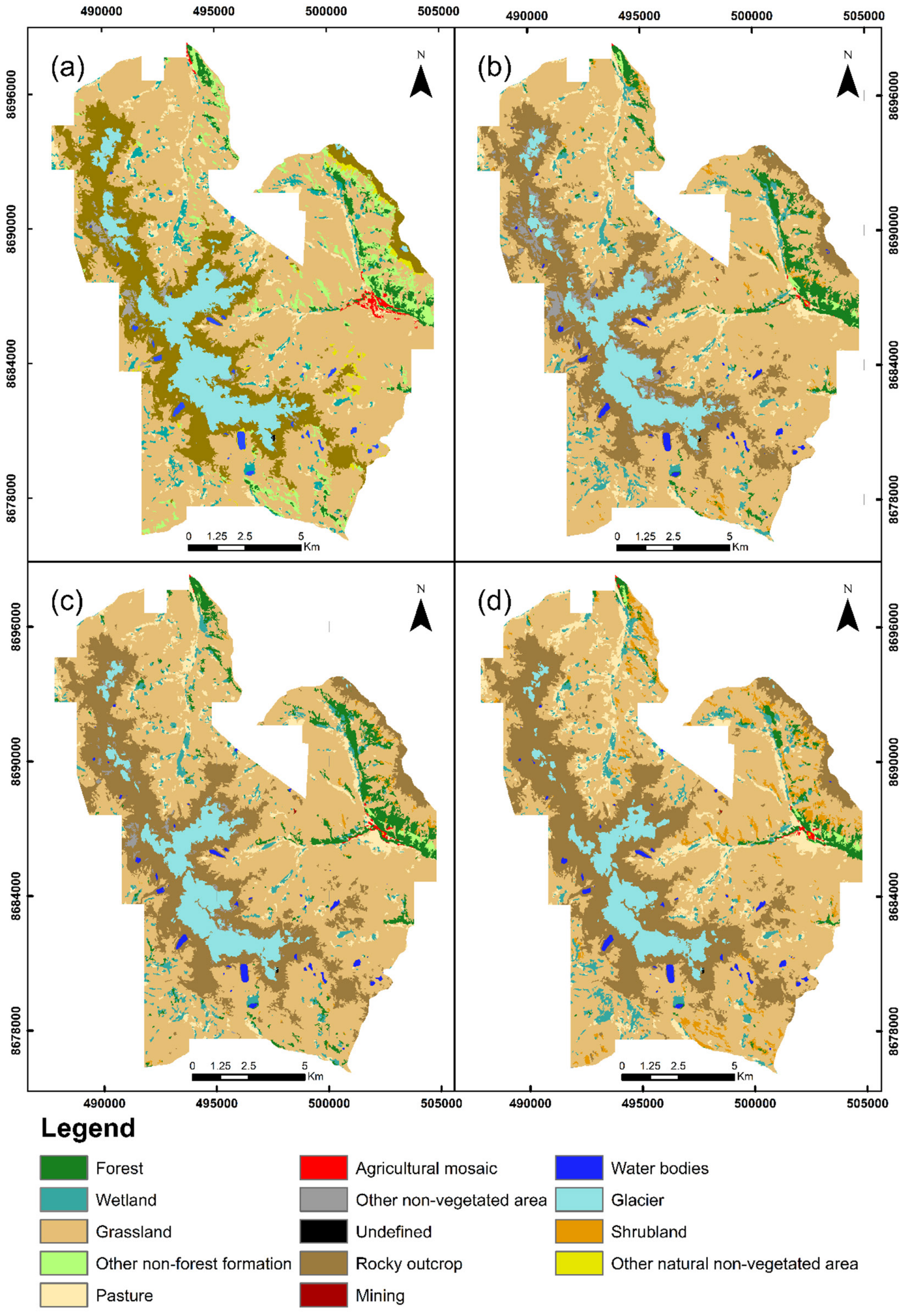

Figure 3. Land cover and land use classification in the ACRH for (a) 2011, (b) 2016, (c) 2020, and (d) 2024

nearly 9×10^4 ha, indicating a process of degradation and replacement of herbaceous vegetation by rocky outcrops and scrublands, which show the greatest increases. Likewise, glaciers show a notable decline, confirming the accelerated glacial retreat characteristic of the tropical Andes.

In contrast, areas of rocky outcrops and scrubland show the greatest net gains, indicating a process of aridification and a transition toward more stable vegetation cover under conditions of lower humidity and greater exposure. Other categories, such as wetlands and grasslands, show

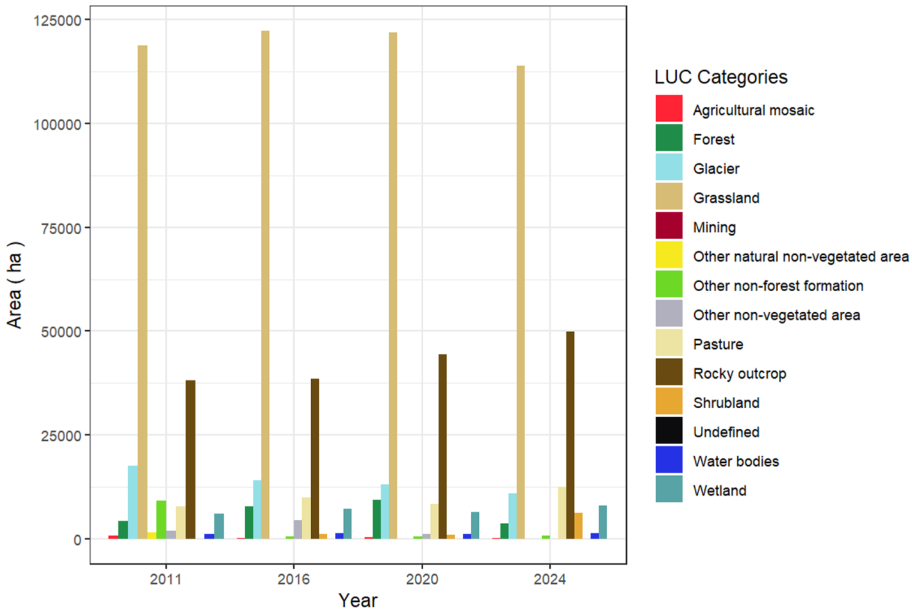

Figure 4. Annual change in LULC area for 2011, 2016, 2020, and 2024

moderate increases, possibly linked to hydrological processes or the local recovery of degraded soils. Overall, there is a progressive loss of high-Andean water and vegetation cover, accompanied by the expansion of rocky surfaces and secondary vegetation, reflecting a profound ecological transformation associated with climate change and the natural dynamics of mountain ecosystems.

In addition, the study presents the losses, gains, and net changes in the main types of land cover and land use within the LCA during the 2011–2024 period. The results reveal significant spatial changes, dominated by the reduction of natural and glacial cover and the expansion of arid areas and secondary vegetation. The largest decreases were recorded in other non-forested formations (−8,513.1 ha), glaciers (−6,682.5 ha), and grasslands (−4,975.02 ha), reflecting a substantial loss of herbaceous vegetation and snow associated with glacial retreat and environmental degradation processes. Minor reductions were also observed in other areas without vegetation (−1,937.52 ha), other natural areas without vegetation (−1,605.42 ha), agricultural mosaics (−515.16 ha), and forest (−508.68 ha), suggesting a contraction of productive and forested

Table 3. Cumulative changes in LUC from 2011 to 2024

Color	Category names	Value	Gains (ha)	Losses (ha)	Net changes (ha)
#1f8d49	Forest	3	16,021.8	16,530.48	-508.68
#57a3a5	Wetland	11	14,552.46	12,602.79	1,949.67
#d6bc74	Grassland	12	86,542.83	91,517.85	-4,975.02
#6dd826	Other non-forest formation	13	9,663.3	18,176.4	-8,513.1
#ede3a3	Pasture	15	34,567.56	29,867.94	4,699.62
#ff2336	Agricultural mosaic	21	629.37	1,144.53	-515.16
#b0b0be	Other non-vegetated area	25	5,477.22	7,414.74	-1,937.52
#0c0c0e	Undefined	27	17.01	27.54	-10.53
#694A10	Rocky outcrop	29	44,895.87	33,175.98	11,719.89
#a6002e	Mining	30	14.58	8.1	6.48
#2532e4	Lake	33	590.49	547.56	42.93
#93dfe6	Glacier	34	2,380.59	9,063.09	-6,682.5
#E6A832	Shrubland	66	28,390.5	22,061.16	6,329.34
#f6e91f	Other natural non-vegetated area	68	2,144.88	3750.3	-1,605.42

areas, possibly related to land-use restrictions within the protected area or the abandonment of agricultural activities.

The largest increases were observed in rocky outcrops (+11,719.89 ha) and scrublands (+6,329.34 ha), indicating the expansion of arid areas and secondary vegetation into areas previously covered by ice or grasslands. An increase was also observed in grasslands (+4,699.62 ha), associated with the expansion of livestock areas or the recovery of degraded soils, and a moderate increase in wetland areas (+1,949.67 ha), possibly related to hydrological processes resulting from melting ice. Changes in mining (+6.48 ha), lakes (+42.93 ha), and the undefined category (−10.53 ha) were minor, with no significant influence on the overall landscape structure.

Local validation results

The local LULC validation for 2024 showed an overall accuracy of 65% and a Kappa coefficient of 0.61, indicating a moderate level of agreement between the classification and the MapBiomas data. At the class level, significant variability was observed in the accuracy metrics. Coverage associated with water bodies (WAT), glaciers (GLA), mining (MIN), natural non-vegetated areas (ONN), and wetlands (WET) had the highest producer accuracy values (100%), indicating correct identification of these classes in the reference data. Likewise, classes such as pastures (PAS; 97.4%), grasslands (GRA; 98.1%), and water (WAT; 96.8%) recorded high user precision values, indicating a low false positive rate.

In contrast, some classes showed limited performance. The forest (FOR) class exhibited low accuracy values for both the producer (7.7%) and the user (3.1%), suggesting high confusion with other land cover types, particularly grasslands and non-forest formations. Similarly, the agricultural mosaic (AGR) and rocky outcrop (ROC) classes exhibited moderate to low producer accuracies (40.0% and 49.3%, respectively), indicating difficulties in correctly distinguishing them. The "Undefined" (UND) class did not record any correct assignments, reflecting limitations in its representation or in the classification process. Omission errors were particularly high in classes such as forest (92.3%) and agricultural mosaic (60.0%), while commission errors were high in classes such as non-vegetated areas (ONV; 90.0%), shrubland (SHR; 82.4%), and forest (96.9%), indicating spectral confusion between land cover types with similar characteristics (Table 4).

The classes evaluated include the following classes and their respective abbreviations: forest (FOR), wetland (WET), grassland (GRA), other

Table 4. Accuracy evaluation metrics derived from the confusion matrix

Classes	FOR	WET	GRA	ONF	PAS	AGR	ONV	UND	ROC	MIN	WAT	GLA	SHR	ONN	Classsified totals	Producer accuracy	Omission error
FOR	1	3	0	8	0	1	0	0	0	0	0	0	0	0	13	7.7	92.3
WET	0	22	0	0	0	0	0	0	0	0	0	0	0	0	22	100	0
GRA	24	8	104	3	1	0	0	1	0	19	0	0	23	0	183	56.8	43.2
ONF	0	0	0	19	0	1	1	0	0	0	0	0	0	0	21	90.5	9.5
PAS	0	2	2	0	37	2	3	0	0	0	0	0	5	0	51	72.5	27.5
AGR	0	0	0	0	0	26	23	0	0	0	0	0	0	16	65	40	60
ONV	0	0	0	0	0	0	3	0	0	0	0	0	0	0	3	100	0
UND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
ROC	4	0	0	0	0	0	0	29	33	0	1	0	0	0	67	49.3	50.7
MIN	0	0	0	0	0	0	0	0	0	11	0	0	0	0	11	100	0
WAT	0	0	0	0	0	0	0	0	0	0	30	0	0	0	30	100	0
GLA	0	0	0	0	0	0	0	0	0	0	0	37	0	0	37	100	0
SHR	3	0	0	0	0	0	0	0	0	0	0	0	6	0	9	66.7	33.3
ONN	0	0	0	0	0	0	0	0	0	0	0	0	0	14	14	100	0
True totals	32	35	106	30	38	30	30	30	33	30	31	37	34	30	526	Total points	
User accuracy	3.1	62.9	98.1	63.3	97.4	86.7	10	0	100	36.7	96.8	100	17.6	46.7	343	Classified correctly	
Commission error	96.9	37.1	1.9	36.7	2.6	13.3	90	100	0	63.3	3.2	0	82.4	53.3	0.65	Global accuracy	

non-forest formation (ONF), pasture (PAS), agricultural mosaic (AGR), other non-vegetated area (ONV), undefined (UND), rocky outcrop (ROC), mining (MIN), water bodies (WAT), glacier (GLA), shrubland (SHR), and other natural non-vegetated area (ONN).

The results indicate that, although the map has limitations in distinguishing certain classes – especially those with similar spectral signatures, it provides an acceptable representation of general land use and land cover patterns, making it useful for exploratory analyses and assessments of change in the Huaytapallana Regional Conservation Area (ACRH).

DISCUSSION

Glacier retreat and transformation in the HRCA

The results obtained show a notable decrease in glacier coverage (−6,682.5 ha) in the HRCA between 2011 and 2024, representing a rapid transformation of cryospheric systems in the tropical Andes. The study by López-Moreno et al. (2014) showed that, over a 28-year period, the glaciers in the Huaytapallana mountain range decreased by 55%. In addition, the average annual temperature was between 3.435 °C and 5.227 °C in the period from 1986 to 2016, with an estimated glacier retreat trend of 11.86 km^2 by 2016 (Bulege-Gutiérrez and Custodio, 2020). This trend is in line with regional assessments that have documented accelerated retreat of Andean glaciers in recent decades, driven by rising atmospheric temperatures and changes in precipitation patterns. Rabatel et al. (2013) reported that glaciers in the tropical Andes have lost between 30% and 50% of their surface area since the end of the 20th century, while Vuille et al. (2018) noted that the central Andes are one of the mountain regions most vulnerable to climate change globally.

The vast majority of Andean glaciers are retreating rapidly and uniformly in response to anthropogenic warming (Stansell et al., 2023). This retreat is exposing surfaces, causing geomorphological and ecological changes in high mountain ecosystems. Similar processes have been observed in several regions of the Andes, where the loss of glacier mass has allowed rocky areas, moraines, and bare substrates to expand, giving way to primary ecological succession processes, with a 37% decrease, with Junín and Ancash showing the greatest change (Mark et al., 2017) and -29 % (-548.5 ± 65.7 km^2) due to changing climatic conditions in Peru between 2000 and 2016, with a retreat of -7 % (-139.6 km^2) (Seehaus et al., 2019). The notable increase in rocky outcrops in the HRCA (+11,719.89 ha) is a clear reflection of this dynamic and suggests that we are seeing a transition towards high mountain landscapes with less vegetation. Transformations of this type have also been documented in glacial basins in Peru and Bolivia, where glacier retreat is linked to greater geomorphological instability and the creation of proglacial ecosystems (Schoolmeester et al., 2018).

In addition, glaciers in the tropical Andes are crucial for regulating water supply during the dry season, helping to maintain water flows in mountain basins and downstream areas (Buytaert et al., 2006; Vuille et al., 2018). In this regard, the decline in glacier area observed in the HRCA could cause changes in the region's hydrological patterns and increase environmental vulnerability in the Mantaro River basin.

Decline of grasslands and vegetation dynamics in high Andean ecosystems

One of the most significant changes detected in this study is the notable reduction in high Andean grasslands (-4,975.02 ha). These ecosystems are essential to the tropical Andean landscape, as they provide water regulation, carbon storage, and biodiversity maintenance (Liu et al., 2013; Young, 2009). The decline observed in the HRCA indicates that there are increasing ecological pressures within the conservation area. For example, Cuesta et al. (2019) showed that the páramo and puna ecosystems in the tropical Andes are experiencing changes in species distribution and vegetation structure due to rising temperatures. Meanwhile, Samanamud et al. (2025) indicate that high Andean ecosystems are very sensitive to climate variations, which can lead to changes in grassland dominance and an increase in scrubland. In other areas of Peru, in the Jalca region in the department of Cajamarca, there is an overall loss of -1.5%/year of vegetation cover and -2.8%/year of Andean forest and scrub, including an area protected by the state called the Sunchubamba hunting reserve (Tovar et al., 2013).

Anthropogenic pressures in protected areas

Despite being a protected area, the HRCA shows clear signs of human influence. The simultaneous reduction of forests and grasslands indicates that human activities continue to affect landscape dynamics, even in conservation areas. This phenomenon has been documented in various parts of Latin America, where land use changes continue in protected areas due to the expansion of agriculture, grazing, infrastructure development, and natural resource extraction (Aide et al., 2013).

CONCLUSIONS

The analysis showed a significant reduction in glacier coverage (−6,682.5 ha), a decrease in high Andean grasslands (−4,975.02 ha) and forest cover (−508.68 ha), accompanied by an increase in rocky outcrops (+11,719.89 ha) and scrubland (+6,329.34 ha). This suggests a gradual transformation of the landscape, driven both by glacier retreat and various environmental and human pressures.

It is evident how these changes are occurring within a high mountain protected area, where greater ecological stability would normally be expected. The results indicate that, even in landscapes under formal conservation regimes, significant transformations are taking place. This suggests that the combined effects of climate change and the socio-ecological dynamics of the region may be exceeding the protective capacity of these ecosystems.

In addition, information is provided on recent land cover dynamics in glacial ecosystems in the central Andes of Peru. This study combines the analysis of various land cover categories using remote sensing tools and multi-temporal data, offering a more comprehensive view of landscape transformation in a protected high Andean ecosystem.

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