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Projections of Land-Cover Change in a Tropical High-Andean Lake

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Abstract

Land use and land cover change is one of the main drivers transforming high Andean ecosystems in Colombia. This study examines the spatial dynamics of land use in the La Cocha Ramsar Wetland between 1989 and 2020 and projects land cover scenarios to the year 2050 using spatial modeling techniques. Land cover maps for 1989 and 2020 were developed using satellite imagery and photo-interpretation, following the CORINE Land Cover methodology adapted for Colombia. A transition matrix and change indicators defined by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) were used for multitemporal analysis, allowing the identification of processes such as forest fragmentation and recovery, agricultural expansion, and the spread of pastures. Future projections were modeled with the Land Change Modeler (LCM) module in the IDRISI Selva software, incorporating biophysical and socioeconomic variables with significant association (Cramér's $V > 0.4$). Eight dominant transitions were identified, and change potential maps were generated. The model was validated through random field sampling and a confusion matrix analysis, yielding a Kappa index of 0.76, indicating strong agreement between simulated and observed data. Results show that 91.06% of the area remained unchanged, while 8.94% underwent transformations attributed to human activities. A net increase of 66.75 ha in dense forest is projected by 2050, along with growth in fragmented forest areas and agro-pastoral mosaics.

Keywords: Land Use Change; Spatial Modeling; Ramsar Wetland La Cocha; Land Change Modeler; Projection.

1. Introduction

High-mountain ecosystems provide economic, ecological, and social functions by meeting the needs of lowland populations [1] and supplying ecosystem services such as water regulation, soil protection, carbon storage and sequestration [2], and habitat for diverse flora and fauna [3, 4]. Páramo ecosystems have high biodiversity, with more than 4,000 plant species occurring at elevations between 2,800 and 5,000 m.a.s.l., combining characteristics of high-mountain ecosystems and wetlands [5]. However, in the last decades, changes in land use and land cover have generated significant transformations [6] in high-Andean ecosystems, affecting the provision of essential ecosystem goods and services for local communities. Forest fragmentation is one of the most critical processes, reducing ecological connectivity and compromising biodiversity [7]. This phenomenon has been intensified by agricultural expansion, unplanned urbanization, and natural resource exploitation, processes that directly impact ecosystem structure and functionality [8]. The loss of rural landscapes and natural cover has led to droughts, floods, and a reduction of water resources essential for both human communities and ecosystems [9].

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In response to these pressing problems, the Ramsar Convention was established in 1971 to promote the conservation and sustainable use of wetlands of international importance. Currently, there are approximately 2,391 recognized Ramsar sites worldwide, yet most countries lack adequate management planning and reporting on the ecological character of their wetlands [10]. In this context, Colombia has approximately 20 million hectares of wetlands, including swamps, marshes, peatlands, lagoons, savannas, and flooded forests [11], distributed across four of the five geographic regions (Caribbean, Andean, Orinoco, and Amazon) [12]. The country implements technical, regulatory, and planning measures for the conservation and sustainable use of these wetlands, as outlined in management plans that define management criteria; however, no significant progress has been achieved to ensure their conservation and sustainable use for local populations.

La Cocha Lagoon, located on the border between the Andean and Amazon regions, is also affected by these pressures. Its location confers particular biological and sociocultural richness, making it a key area for the conservation of the cultural and artistic traditions of its communities [13]. The territory is inhabited by indigenous communities of the Kamsa, Inga, Quillasingas, and Kofan [14], as well as peasant communities, who share the ecosystem services provided by the wetland. Unsustainable activities such as agriculture, cattle ranching, fish farming, and tourism have generated land-use conflicts between conservation and economic exploitation interests [15]. In addition, timber extraction for charcoal production has significantly contributed to the fragmentation of primary and secondary forests, páramo ecosystems, and geological reserve areas [16]. Therefore, studies on this topic are essential to monitor and propose sustainable management of natural resources in response to growing demands for basic human needs and welfare [17].

Within this framework, spatial simulation models are valuable tools for land-use planning, functioning not only as technical instruments but also as communication and learning platforms for stakeholders involved in decision-making. These models enable the projection of future scenarios and provide information that can serve as an early warning system for potential land-use transformations [18]. This approach allows for the identification of critical points and the definition of priority areas for detailed studies to support management strategies aligned with the ecological, social, and economic conditions of the territory [19].

In this context, the transformation of the territory, whether driven by anthropogenic actions or natural processes, requires effective governance mechanisms to ensure the continuity of natural components, both in terms of goods and ecosystem services. Under this premise, planning instruments such as the Plan de Gestión del Humedal Ramsar de La Cocha guide interventions in this ecosystem by establishing zones for protection, recovery, and sustainable production. These zoning schemes aim to mitigate the negative effects of inappropriate land use while promoting the conservation of the wetland’s strategic resources [20].

In a complementary manner, environmental governance plays a critical role in enabling the active participation of civil society and the private sector [21] in land management processes. This collaborative approach has progressively consolidated, as evidenced by the establishment of about 52 civil society nature reserves managed by families who have voluntarily chosen to conserve their lands in the absence of government support. This situation reflects, on one hand, a strong sense of belonging and local commitment to conservation and, on the other, the limited presence of the State in supporting and strengthening these community initiatives [13].

Given the above, modeling future scenarios is an important tool to support land-management decision-making. This type of analysis makes it possible to anticipate potential transformations in land use and land cover by integrating biophysical and socioeconomic variables that influence territorial dynamics. These models not only describe observed patterns but also enable the projection of scenarios under different assumptions, which is fundamental for designing informed and adaptive intervention strategies. In this context, the Land Change Modeler (LCM) is one of the most robust and widely used tools for this purpose. This model combines methods such as artificial neural networks (ANN), Markov chains, and cellular automata, allowing it to simulate complex spatio-temporal dynamics and predict future patterns with high accuracy [22]. Its strength lies in its capacity to identify transitions between cover classes, generate suitability maps, and estimate probabilities of change based on historical satellite imagery and explanatory variables such as altitude, slope, distance to roads, and population density. Studies such as Leta et al. (2021) [22] have shown that, through the integration of machine learning techniques, this model can not only validate scenarios with high accuracy using statistics such as the Kappa index but also project trajectories under assumptions of continuity or change in current dynamics. Likewise, Ceballos Freire et al. (2024) [23] emphasize that the application of LCM in local contexts, with the participation of community stakeholders, enables the formulation of prospective conservation and land-use proposals that are better aligned with territorial and cultural realities.

In this sense, the objective of this research was to analyze the spatial dynamics of land use in the La Cocha Ramsar Wetland between 1989 and 2020, and to project change scenarios to 2050 using spatial modeling techniques. The methodology combined land-cover mapping from satellite imagery following the CORINE Land Cover method adapted for Colombia with the Land Change Modeler (LCM) module of the IDRISI Selva software. Biophysical and socioeconomic variables with significant associations (Cramer's $V > 0.4$) were incorporated, and eight dominant landscape transitions were identified. Model validation through field sampling and a confusion matrix yielded a Kappa index of 0.76. Among the most relevant findings, 91.06% of the territory remained unchanged, while 8.94% underwent transformations mainly associated with anthropogenic activities. The 2050 projections indicate a net increase of 66.75 hectares in dense forest, accompanied by expansion in fragmented forest and agricultural mosaic areas.

2. Material and Methods

The Ramsar Wetland Laguna de La Cocha is located in the Andean-Amazonian zone, within the Bordoncillo Patascoy – La Cocha ecoregion, in the department of Nariño, southern Colombia. It lies between the geographical coordinates 0°53′28.55″ and 1°20′36.40″ N latitude, and 76°50′50.41″ and 77°14′17.37″ W longitude. It forms part of the upper basin of the Guamues River, which feeds into the Putumayo and San Miguel rivers—major tributaries of the Amazon River [16]. This ecosystem covers approximately 41,000 hectares, spanning the departments of Nariño and Putumayo [24, 25].

2.1. Methodology

To determine land-cover change indicators, two land-use/land-cover maps corresponding to the study periods were used. The 1989 map was produced from a Landsat 8 satellite image, while for 2020, Sentinel-2 L2A Highlight Optimized Natural Color imagery captured on April 22, 2020, and downloaded from the Sentinel Hub portal (https://apps.sentinel-hub.com), was employed. Photointerpretation was conducted using the visual interpretation technique in ArcGIS 10.2. This process also incorporated auxiliary sources, including high-resolution satellite imagery available from Google Earth. Finally, prospective modeling for 2050 was performed using the Land Change Modeler (LCM) module in the IDRISI Selva software (Figure 1).

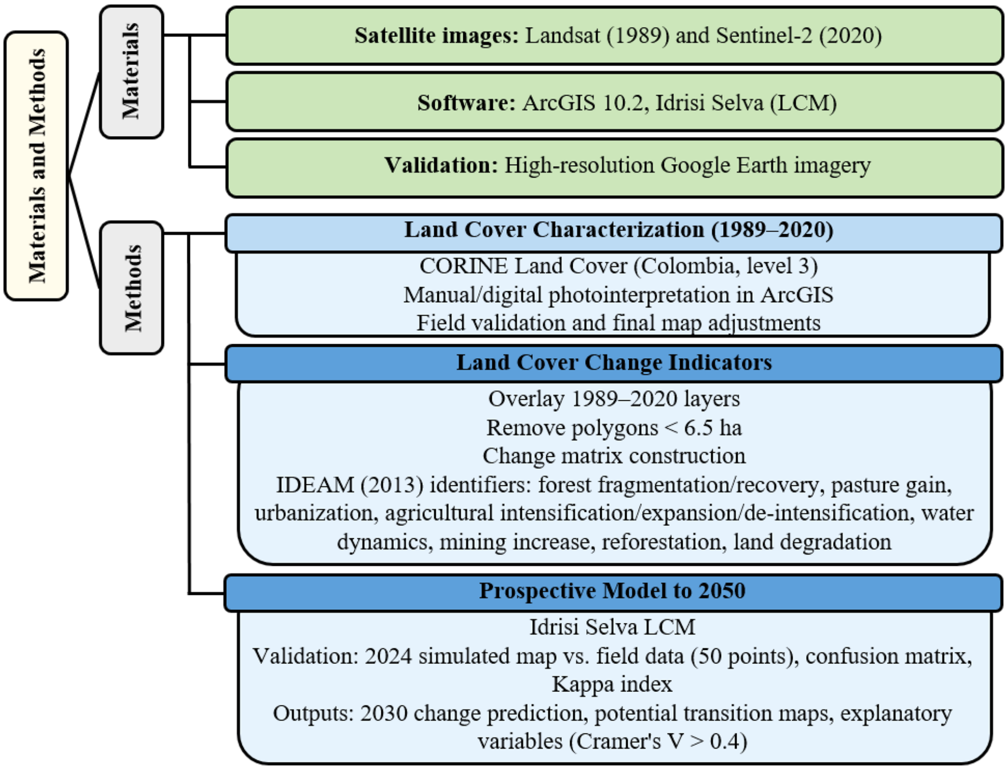

Figure 1. Schematic representation of materials and methods

2.2. Land Cover Characterization

Land-cover characterization for 1989 and 2020 followed the CORINE Land Cover methodology adapted for Colombia to level 3 [26]. The analysis was conducted at a scale of 1:25,000, with a minimum mapping unit of 6.25 ha. Consequently, coverages with an area smaller than this threshold were merged into the adjacent category that met the minimum mapping unit. For map preparation, the 1989 and 2020 satellite images were analyzed using a mixed approach of visual and digital interpretation, following the methodology proposed by Posada et al. [27].

During the photointerpretation stage, the direct on-screen visual interpretation technique was applied, involving the manual delineation of polygons on the satellite images used as the primary input. Subsequently, a general evaluation of the quality of the cartographic product was performed to verify the correct classification of the coverages through field validation. This process ensured the accuracy and consistency of the final map, ensuring that the data used in the subsequent modeling accurately reflected the real conditions of the territory (Figure 2).

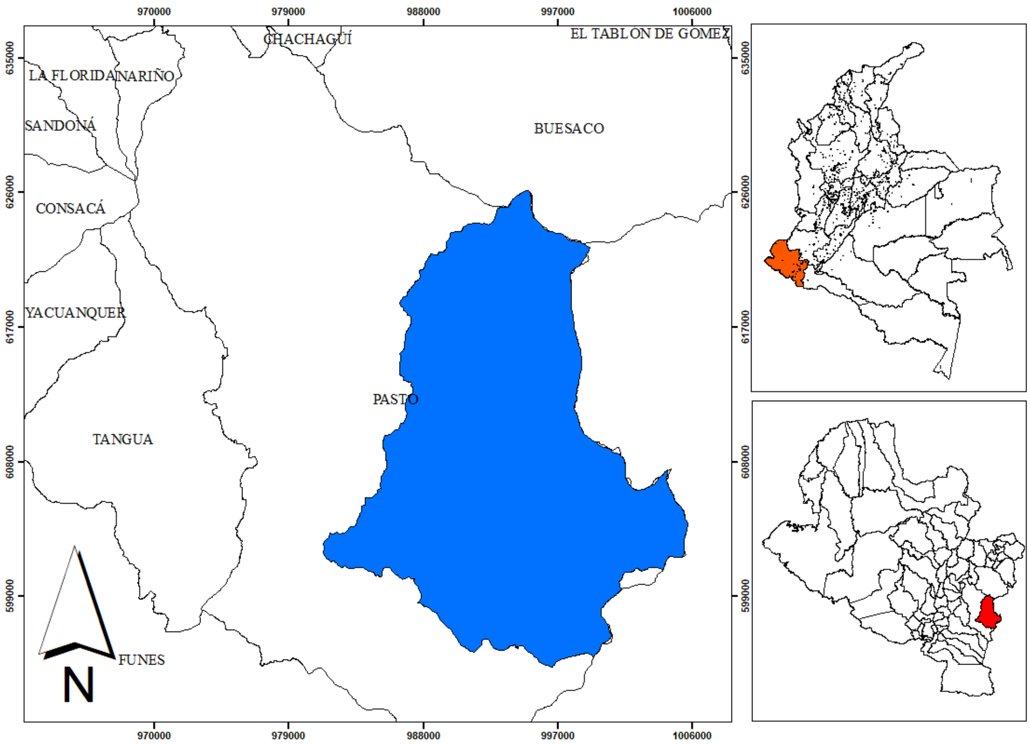

Figure 2. Geographic location of the study area

2.3. Land Cover Change Indicators

A land cover change matrix was developed to analyze the transformations that occurred between 1989 and 2020. The classification of changes was based on the main land use processes (2005), using the indicators defined by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) [28, 29]. These indicators group the most relevant processes in land cover transformation, such as forest fragmentation and recovery, pasture expansion, urbanization, agricultural intensification and expansion, water body dynamics, mining increase, reforestation, and land degradation (see Table 1).

Table 1. Land Cover Change Indicators between the Periods 1989 and 2020 (Source: Institute of Hydrology, Meteorology and Environmental Studies IDEAM [29])

Identifier	Indicator	Description
NA	No information available	Areas with cloud cover present in either of the two periods, where it is therefore not applicable to perform land cover change analysis.
0	No change	Areas where the same level 3 land cover code appears in both the 1989 and 2020 maps; therefore, no land cover change occurred in those periods.
1	Similar change	This indicator includes areas where the level 3 land cover codes differ, but the types of cover are considered similar for the purposes of multitemporal analysis. For example, dense forests (311) that changed to gallery forests (314) or vice versa.
2	Forest fragmentation	All forest areas in the 1989 map that appear as fragmented forests in the 2020 map are quantified and spatially identified by this indicator.
3	Forest recovery	This indicator includes areas that were not forest in 1989 but appear as any type of forest in 2020. It also includes fragmented forests from 1989 that recovered and are now classified as dense or gallery forests in the 2020 map.
4	Pasture gain	Areas with any type of pasture that did not exist in 1989 but are present in 2020.
5	Urbanization	This includes artificialized land areas present in the 2020 map that did not exist in the previous period, excluding mining areas, which are covered under a separate indicator.
6	Agricultural intensification	This indicator quantifies all mosaic areas that had natural spaces in 1989 but shifted to other mosaics without natural elements or to pure pasture or crop areas.
7	Agricultural expansion	This indicator identifies areas converted to crops that, in 1989, were covered by natural vegetation or pastures.
8	Water body dynamics	This indicator reflects changes in water bodies between the two analyzed periods.
9	Agricultural de-intensification	This includes areas that had some form of crop or pasture, either pure or in mosaic, in 1989 but were converted to some type of natural cover or mosaic with natural elements by 2020.
10	Mining increase	Given the national importance of mining, this indicator identifies which types of cover were replaced by mining areas present in the 2020 map.
11	Reforestation	Areas with forest plantations present in the 2020 map that did not exist in the previous land cover map.
12	Land degradation	This indicator identifies areas that appear as rocky outcrops or degraded lands in 2020 but had some form of natural or anthropogenic vegetation cover in the previous map.
13	Other changes	This indicator includes changes not considered in the multitemporal analysis, including both illogical changes and logical ones deemed irrelevant for analysis.

To construct the matrix, land cover codes up to level three of the national legend were used, according to the classification established by IDEAM [29]. The overlay of the 1989 and 2020 land cover maps was performed using the spatial analysis tool “intersection”. This process generated a new layer in which polygons smaller than 6.25 hectares were removed in order to retain only significant combinations between the codes from both periods. Each resulting combination was assigned a specific identifier according to the change definition matrix. For example, polygons with code 311 in 1989 and 231 in 2020 were classified with identifier 4, corresponding to the pasture gain indicator. Finally, the areas of all spatial units in the resulting layer were calculated, allowing for precise quantification of the change processes [29].

A land cover change matrix was developed to analyze the modifications that occurred between two specific periods. The classification of changes was based on the main land use processes (2005). To this end, the indicators defined by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) [29], were used, which group the most relevant processes in land cover transformation, such as forest fragmentation, forest recovery, pasture gain, urbanization, agricultural intensification, agricultural expansion, agricultural de-intensification, water body dynamics, mining increase, reforestation, and land degradation (Table 1). In constructing the change matrix, land cover codes up to the third level of the national legend were used, in accordance with the classification established by IDEAM [29].

2.4. Prospective Model to the Year 2050

Land use change modeling was carried out using the Land Change Modeler (LCM) module in the IDRISI Selva software. Land cover transformations were evaluated between 1989 (Time 1) and 2020 (Time 2), with the aim of projecting a future scenario for 2050 (Time 3), based on maps of relative transition potential. The model considered transitions between different cover categories, from which potential change maps were generated to identify areas susceptible to transformation.

The multitemporal analysis enabled the identification of eight priority transitions, which correspond to areas with the greatest changes in coverage and were selected based on their magnitude in terms of area (Table 2). For each transition submodel, explanatory variables were chosen by considering Cramer's V, a statistical measure of correlation that ranges from 0 to 1 [30].

Table 2. Potential Transitions in the La Cocha RAMSAR Wetland

Transition No.	Categories		Area
1	Mosaic of pastures with natural spaces	Dense forest	558.99
2	Dense forest	Fragmented forest	221.01
3	Mosaic of pastures with natural spaces	Mosaic of crops, pastures, and natural spaces	400.68
5	Dense forest	Mosaic of pastures with natural spaces	550.09
6	Mosaic of crops, pastures, and natural spaces	Mosaic of pastures with natural spaces	268.59
8	Mosaic of crops, pastures, and natural spaces	Mosaic of pastures and crops	175.15
9	Mosaic of pastures with natural spaces	Clean pastures	159.80

In this case, variables with values greater than 0.4 were considered, indicating a strong relationship with the observed changes [30]. The selected biophysical and socioeconomic variables influencing each transition were Civil Society Natural Reserves, Port, Lagoon, Isotherms Map, Single Drainage, and Double Drainage, all with Cramer's V values greater than 0.4. According to Abuelaish & Olmedo [31], Cramer's V values above this threshold indicate variables with strong potential to explain the phenomenon. For the selected variables, a Euclidean distance analysis and raster reclassification were performed using the "Distance" command of the IDRISI Selva software. Finally, socioeconomic variables included in the model must be mappable.

For the calibration of the land use and land cover change model, the Run Transition Sub-model function of the IDRISI software was applied. Potential transition maps were generated from the six selected explanatory variables. For each type of transition, 1,000 iterations were established, following technical recommendations to ensure adequate model convergence [32]. Calibration was performed by comparing two actual maps corresponding to 1989 and 2020, without using intermediate simulations. To validate the model, a simulation for 2024 was generated and compared with field observations obtained through simple random sampling at 50 georeferenced points [22].

This comparison assessed the predictive capacity of the model under real historical conditions, yielding an accuracy rate of 78.82%. This value indicates an adequate level of spatial agreement between observed and estimated patterns of change and falls within the accepted range for land cover simulation studies [33, 34].

3. Results

3.1. Land Cover Characterization

In the study area for the year 2020, covering 39,935 hectares, 73.6% of the territory was identified as forest and semi-natural areas. Agricultural areas represented 15.3%, water bodies 10.9%, and artificial surfaces only 0.1%. A total of 13 land cover types were recognized, with a marked dominance of dense forest, occupying 23,291 hectares, equivalent to 58.3% of the total area (Figure 3). This conservation trend can be attributed, in part, to community strategies aimed at acquiring land to expand protected areas, a practice that has been reinforced in recent years. Likewise, the environmental governance processes initiated with the formulation of the Ramsar Wetland Management Plan in 2011 have contributed to reducing human intervention and the degradation of strategic ecosystems, while promoting sustainable productive alternatives designed to decrease pressure on forests from timber extraction for charcoal production, and providing new economic opportunities that support the welfare and livelihoods of local communities.

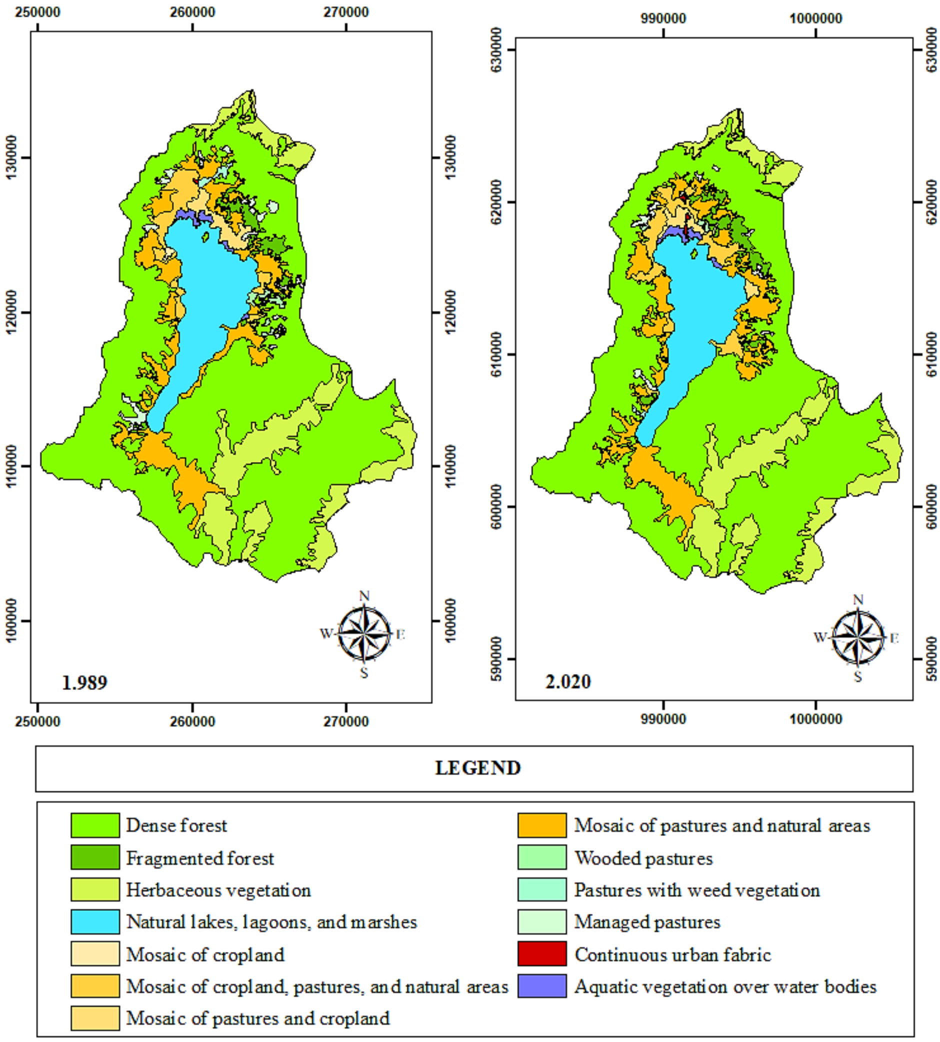

Figure 3. Land cover map of the La Cocha RAMSAR Wetland, year 1989 and 2020

The second largest cover corresponds to dense dry land grassland, with an area of 5,318 hectares, representing 13% of the total area. This cover is of great ecological importance, as it includes moorland, sub-moorland, and azonal moorland areas, the latter being endemic ecosystems characterized by their location below 3,000 meters above sea level. The representative vegetation includes frailejonal-arbustal with species such as *Espeletia cochensis* and *Espeletia schultesiana*, as well as shrubs such as *Pentacalia andicola, Pentacalia vaccinioides, Ageratina tinifolia, Hesperomeles glabrata, Baccharis latifolia,* and *Hypericum jussieui* [35].

On the other hand, the mosaic of pastures with natural spaces covers 4,206 hectares (10.5%) and has originated mainly from agricultural activities. Areas that were previously covered by forests have been progressively transformed for the introduction of cattle and sheep, as well as for the cultivation of potatoes, onions, and various vegetables [36], destined both for self-consumption and commercialization. In many cases, these lands are inherited, which contributes to maintaining the traditional use of the soil, but also represents a factor in the deterioration of its physical and chemical properties.

Studies conducted by Cuaspa & Escobar (2022) [37] in the study area show that soil characteristics vary according to land use. The conservation areas have soils with a high clay content (81.8%), which favors infiltration and good drainage, as well as adequate aeration, due to the size of the particles and the large pores that separate them. This type of soil generally drains well and retains limited amounts of water [38]. In contrast, agricultural areas have sandy loam soils with higher moisture than conservation areas, attributed to plowing, a practice that reduces the protective capacity of the soil against wind and water erosion.

In terms of bodies of water, lagoons, lakes, and natural marshes cover 4,176 hectares (10.46%), with the Laguna de La Cocha as its main exponent. This lake, the second largest in the country, is an essential source of resources for local communities and an important tourist attraction. It is also the site of aquaculture activities that represent a significant source of income. Finally, the fragmented forest occupies approximately 2% of the territory, which is evidence of continuous degradation and loss of ecological integrity. This fragmentation is mainly associated with agricultural and livestock expansion, as well as timber extraction for charcoal production, practices that compromise biodiversity and jeopardize the resilience of the region's strategic ecosystems.

3.2. Land Cover Change Indicators

The analysis of land cover change indicators for the period 1989 to 2020 (Table 3) (Figure 4) shows variations in some of the existing categories. However, the transformations are not highly significant, so that in certain areas there are increases in dense forest, mosaic of pasture and crops, and mosaic of pasture and crops with natural spaces, to mention some categories.

Table 3. Land Cover in 1989 and 2020

		1989		2020	
	Land Cover Type	**Area (ha)**	**Area (%)**	**Area (ha)**	**Area (%)**
	Dense forest	23169.5	58	23291.1	58.3
	Grassland	5319	13.3	5318.55	13.3
	Natural lakes, lagoons, and swamps	4191.01	10.4	4176.15	10.4
	Mosaic of pastures with natural spaces	4182.44	10.4	344.33	0.9
	Mosaic of crops, pastures, and natural spaces	968.29	2.4	1247.13	3.1
	Fragmented forest	668.25	1.7	799.71	2
	Clean pastures	508.05	1.3	254.41	0.6
	Mosaic of pastures and crops	466.42	1.3	4206.68	10.5
	Wooded pastures	172.02	0.43	46.47	0.1
	Aquatic vegetation over water bodies	166.29	0.42	175.28	0.4
	Overgrown pastures	97.74	0.24	24.44	0.1
	Crop mosaic	33.54	0.08	10.36	0.03
	Continuous urban fabric	7.56	0.02	40.57	0.1

Between 1989 and 2020, La Cocha Lagoon experienced significant changes in its land cover and land use, evidencing both productive expansion processes and conservation efforts. The continuous urban fabric (TUC) increased from 7.56 to 40.57 hectares, mainly at the expense of areas previously classified as MCPEN and MPC, reflecting the pressure of urban growth on semi-natural cover and the tension between development needs and sustainable practices. Dense grassland (HD), composed of páramo vegetation, maintained a stable extent of 5,319 hectares, thanks to the natural conditions of the páramo that limit intensive human activities and to the resilience it has shown to anthropogenic pressures. This ecosystem plays a key role in water regulation and in protecting against soil erosion by intercepting rainfall and reducing runoff. However, there are contrasts in the perception and management of HD by the population: some landowners value its expansion for the benefits in conservation and ecosystem services, while practices such as selective tree cutting, insecticide use, and controlled burning persist, which degrade organic matter and alter biogeochemical cycles.

Dense forest (BD) showed a slight increase from 23,169 to 23,250 hectares, reflecting forest recovery processes, although it continues to face pressures from agriculture and urban expansion. Between 1989 and 2020, 22.11% of the changes corresponded to the transformation of BF, LLCN, and MCPEN to BD, showing an interest in recovering tree cover in intervened landscapes. In contrast, fragmented forest (BF) increased from 668.25 to 798.39 hectares as a result of agricultural and livestock expansion, with loss of ecological connectivity and functionality. Conversion to BF came mainly from MCPEN, PA, and PE (10.28% of total changes), reflecting attempts to conserve fragments in productive matrices. The survey of local stakeholders showed that 66.7% engage in agriculture and 62.5% in forestry activities, confirming the coexistence of mixed uses, although with pressure on biodiversity.

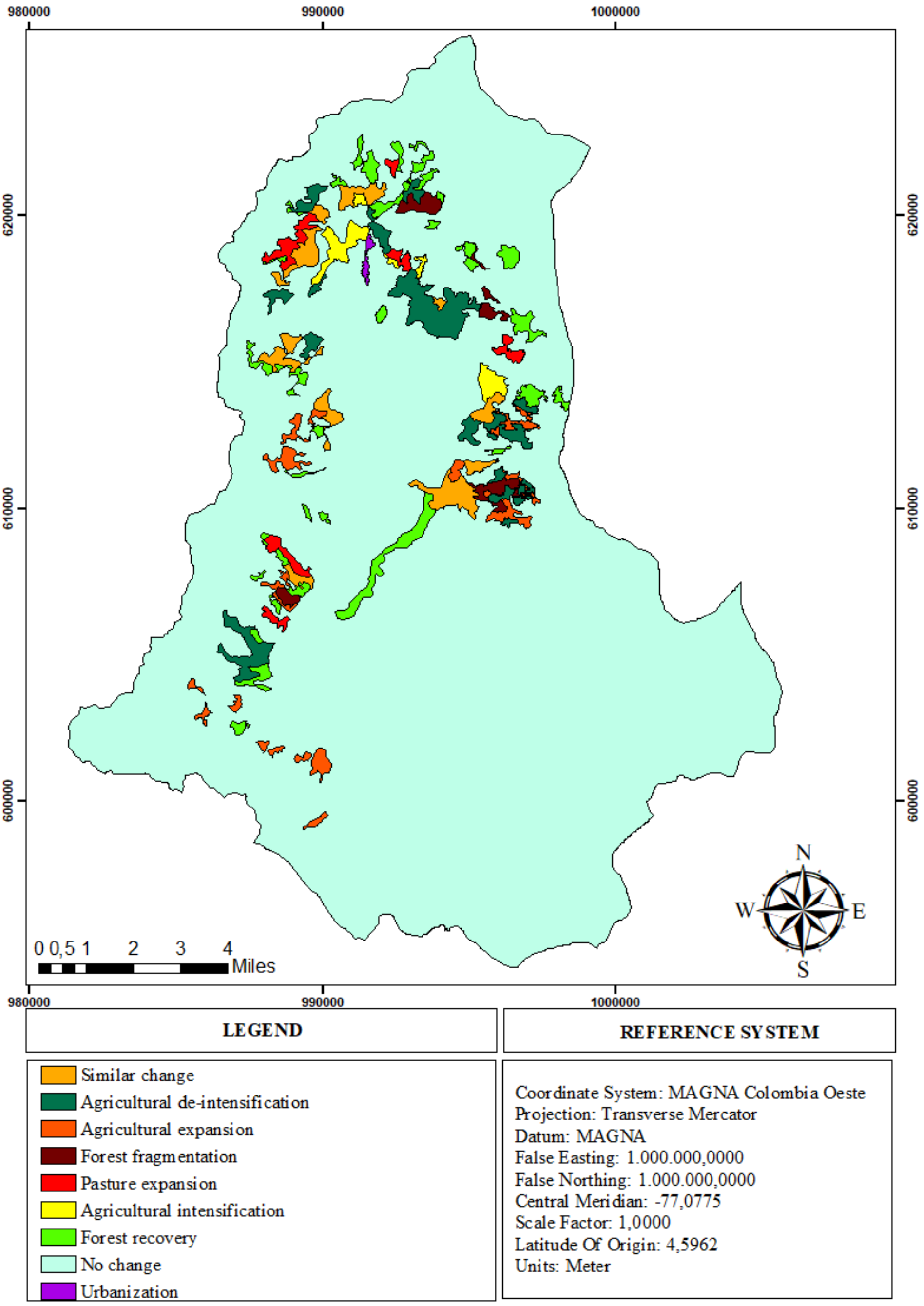

Figure 4. Land cover change indicator map in the La Cocha RAMSAR Wetland between 1989 and 2020

In terms of agro-productive cover, crop mosaic (CM) decreased from 33.54 to 10.36 hectares, being replaced by intensive cattle ranching and monocultures, which reduces the diversity of agricultural systems. The mosaic of pastures with natural areas (MPEN) remained almost stable, from 4,182.44 to 4,192.92 hectares, integrating cattle ranching with conservation through practices such as living barriers and crop rotation. This category received contributions from BD, BF, MCPEN, PL, and VASCA, representing 19.24% of total changes, and evidencing diversified territorial management. The mosaic of pastures and crops (MPC) declined from 466.42 to 346.44 hectares, indicating a transition toward more specialized and profitable activities. On the other hand, the mosaic of crops, pastures, and natural spaces (MCPEN) increased from 968.29 to 1,260.22 hectares, accounting for 33.54% of total changes. This increase is largely due to the incorporation of 400.68 hectares from MPEN, reflecting mixed management that integrates conservation and production. However, in the southern zone of the wetland, slopes of up to 60% make it difficult to implement sustainable livestock-raising practices. In grazing categories, wooded pastures (PA) decreased from 172.02 to 45.47 hectares, and pastures with weeds (PE) from 97.74 to 24.54 hectares, as a result of the conversion from BD, BF, and MPEN to less intensive systems, which conserve some vegetation cover but reduce connectivity. Clean pastures (PL) declined from 508.05 to 251.46 hectares, representing 5.15% of total changes, in a process linked to the transition to profitable crops or urban use, which increases vulnerability to degradation and biodiversity loss.

Regarding aquatic ecosystems, lagoons, lakes, and natural swamps (LLCN) maintained their extent at 4,191.01 hectares, confirming their role as regulators of the hydrological cycle and as essential habitat for biodiversity. Aquatic vegetation (VASCA) increased from 166.29 to 211.63 hectares, equivalent to 1.39% of total changes, favored by the natural expansion of cattail and sedimentation processes that influence the increase in aquatic vegetation.

3.3. Model Validation

To assess the accuracy of the simulation model, a validation was conducted using a projection for the year 2024, which was compared with field data. A simple random sampling approach was applied, including 50 georeferenced points where the existing land cover was recorded using GPS coordinates. The collected data were analyzed using ArcGIS 10.2 software with the "Extract Values to Points" tool to extract the simulated land cover values corresponding to each point. Subsequently, a confusion matrix was constructed to compare the simulated classes with those observed in the field, allowing for the identification of omission and commission errors for each land cover category.

The validation results show an overall accuracy of 78% and a Kappa index of 0.76, indicating a substantial level of agreement between the simulated and observed land cover, according to the criteria established by Landis & Koch [39]. The detailed class-by-class evaluation matrix is presented in Table 4, where it can be seen that dense forest, clean pastures, aquatic vegetation, and natural water bodies exhibit the highest levels of accuracy.

Table 4. Confusion matrix for the La Cocha Ramsar Wetland land cover simulated for the year 2024 and georeferenced points

Land Cover	HB	BD	CP	MCPNS	FF	MPNS	CUF	NLW	AV	MPC	CM	Total	Prod. Accuracy (%)	Omission Error (%)
Grassland – HB	2	1	0	0	0	0	0	0	0	0	0	3	66.67	33.33
Dense forest – DF	0	9	0	0	0	0	0	0	0	0	0	9	100	0.00
Clean pastures – CP	0	0	1	0	0	0	0	0	0	0	0	1	100	0.00
Mosaic of crops, pastures, and natural spaces – MCPNS	0	0	0	3	2	3	0	0	0	1	0	9	33.33	66.67
Fragmented forest – FF	0	0	0	0	6	0	0	0	0	0	0	6	100	0.00
Mosaic of pastures with natural spaces – MPNS	0	1	0	0	0	7	0	0	0	0	0	8	87.5	12.50
Continuous urban fabric – CUF	0	0	0	0	0	0	2	0	0	0	0	2	100	0.00
Natural lakes, lagoons, and wetlands – NLW	0	0	0	0	0	0	0	3	0	0	0	3	100	0.00
Aquatic vegetation – AV	0	0	0	0	0	0	0	0	4	0	0	4	100	0.00
Mosaic of pastures and crops – MPC	0	0	0	1	0	0	0	0	0	2	1	4	50	50.00
Crop mosaic – CM	0	0	0	0	0	1	0	0	0	0	0	1	0	100.00
Total	2	11	1	4	8	11	2	3	4	3	1	50		
User Accuracy (%):	100	81.82	100	75	75	63.64	100	100	100	66.67	0			
Commission Error (%):	0	18.18	0	25	25	36.36	0	0	0	33.33	100			
Overall Accuracy:%	78%													
Kappa Index:%	76%													

These results support the reliability of the developed model and reinforce its usefulness as a tool for projecting future scenarios in the wetland. Likewise, they allow for more accurate identification of areas susceptible to change and help guide restoration and conservation actions based on the anticipated spatial dynamics.

3.4. Prospective Model for the Year 2050

3.4.1. Hedges with a Tendency to Stability

The dense forest shows remarkable stability, increasing from 58% in 1989 to a projected 58.5% in 2050 (Table 5, Figure 5), with an absolute gain of 188.35 ha over the entire period. This trend indicates that current conditions have favored its permanence. Community actions such as land acquisition, the creation and expansion of conservation areas mainly in páramos and high Andean forests by civil society, along with regulations such as the Ramsar Wetland Management Plan, which serves as public policy providing management guidelines within the wetland, and protection under national and international conservation frameworks such as Ramsar, have been key strategies for ensuring the conservation of the wetland's strategic ecosystems. Likewise, dense dry land grassland (páramo) maintains a constant value of 13.3% from 2020 to the 2050 projection, indicating no significant change in its extent. Wetlands and natural water bodies (10.4% in both 2020 and 2050) also remain stable.

Table 5. Projected Land Cover for the Year 2050

	1989		2020		2050	
Land Cover Type	**Area (ha)**	**Area (%)**	**Area (ha)**	**Area (%)**	**Area (ha)**	**Area (%)**
Dense forest	23169.5	58	23291.1	58.3	23357.85	58.5
Grassland	5319	13.31	5318.55	13.3	5318.15	13.3
Natural lakes, lagoons, and swamps	4191.01	10.49	4176.15	10.4	4176.3	10.4
Mosaic of pastures with natural spaces	4182.44	10.47	344.33	0.9	4400.47	11
Mosaic of crops, pastures, and natural spaces	968,29	2.42	1247.13	3.1	1239.44	3.1
Fragmented forest	668.25	1.67	799.71	2	894.97	2.2
Clean pastures	508.05	1.27	254.41	0.6	102.8	0.3
Mosaic of pastures and crops	466.42	1.17	4206.68	10.5	149.73	0.4
Wooded pastures	172.02	0.43	46.47	0.1	46.53	0.1
Aquatic vegetation over water bodies	166.29	0.42	175.28	0.4	175.19	0.4
Overgrown pastures	97.74	0.24	24.44	0.1	24.51	0.1
Crop mosaic	33.54	0.08	10.36	0.03	149.73	0.4
Continuous urban fabric	7.56	0.02	40.57	0.1	40.56	0.1

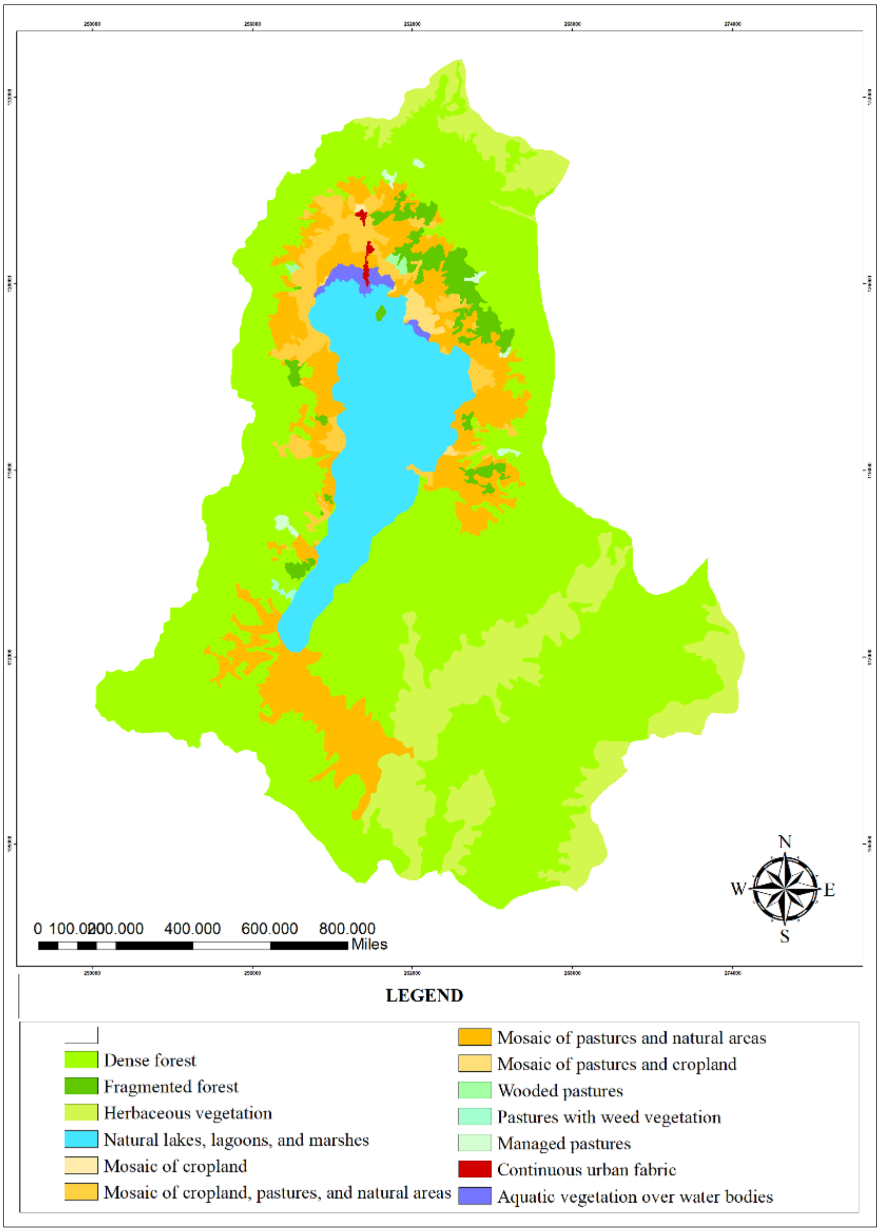

Figure 5. Simulated land cover map of the La Cocha RAMSAR Wetland for the year 2050

3.4.2. Coverage Losses

The mosaic of pastures and crops shows a significant reduction (Table 6 and Figure 5) of 10.5% in 2020 (4206.68 ha) only 0.4% projected in 2050, which implies an estimated loss of 4056.95 ha. This change, coinciding in magnitude with the gain of the mosaic of pastures with natural spaces, suggests a process of direct substitution between both coverages. Clean pastures decrease progressively from 1.27 % in 1989 to 0.3 % in 2050 (reduction of 405.25 ha), possibly reflecting abandonment or conversion to more heterogeneous systems. Grasslands also show a reduction from 0.24 % to 0.1 %, maintaining a marginal area in the landscape matrix. Finally, wooded pastures drop from 0.43% to 0.1%, a loss that could impact the provision of dispersed habitat and connectivity between forest patches.

3.4.3. Ecological and Management Implications

The stability of significant areas of forest and wetlands indicates that, under projected conditions, massive losses of primary habitat are not expected. However, the notable transformation between agricultural use categories suggests changes in productive strategies, probably oriented towards more mixed systems with a greater presence of natural elements. The increase in fragmented forest, although positive in area, alerts us to the need for restoration strategies that prioritize connectivity and reduce patch isolation.

The correlation between the loss of pasture and crop mosaic and the increase of pasture mosaic with natural spaces becomes an opportunity to strengthen productive restoration schemes, integrating biodiversity conservation with local economic activity.

4. Discussion

4.1. Land Cover Characterization

The Ramsar Wetland, like the department of Nariño, is characterized by an economy primarily based on agriculture. According to the 2019 National Agricultural Census [40], and used for agricultural purposes covered 262,218 ha, while livestock activities occupied 716,448 ha. In this region, a significant portion of the population earns its income from agricultural and livestock activities carried out on smallholdings, with an area smaller than a Family Agricultural Unit (UAF). Agricultural production is mainly focused on crops such as potatoes, peas, beans, vegetables, coffee, sugarcane for panela, fique, and milk in the highland municipalities, whereas coastal municipalities are dominated by the cultivation of oil palm, cocoa, coconut, plantain, timber, and fishing. This productive diversity is influenced by the department's climatic and topographic variability [41]. In the livestock sector, the dairy chain involved 39,862 producers in 2010, generating approximately 159,448 direct jobs in milk production [42].

In the Ramsar Wetland in particular, land cover types associated with agricultural and livestock activities include the mosaic of pastures with natural spaces (4,206.68 ha), the mosaic of crops, pastures, and natural spaces (1,247.13 ha), and the mosaic of pastures and crops (344.33 ha). According to the Ministry of the Environment [43], land use in La Cocha is predominantly agricultural and livestock-based, albeit on a small scale, characterized by smallholder production systems aimed at subsistence and local supply. Agricultural production focuses on crops such as vegetables, potatoes, onions, and blackberries, while livestock activity is based on the raising of cattle and guinea pigs.

Agricultural and livestock activities have been concentrated in easily accessible rural areas, leading to a reduction in the diversity of traditional home gardens in favor of monoculture systems, mainly of potatoes and onions. This process has resulted in the loss of local crop varieties such as potato, onion, ulluco, oca, and broad bean, which have ceased to be part of the population’s daily diet [13, 28].

In this regard, Ramírez-Padilla et al. [44] point out that cultivated areas are primarily distributed around the vicinity of La Cocha Wetland, following a crop rotation pattern involving temporary crops such as onion, potato, broad bean, pea, flowers, and vegetables. In some areas, small plots were also identified for permanent crops, mainly fruit trees such as greengage (*Prunus amygdalus Stokes*), peach (*Prunus persica Stokes*), tamarillo (*Solanum betaceum Cav*.), Andean blackberry (*Rubus glaucus Benth*.), apple (*Malus domestica (Suckow) Borkh*.), and pear (*Pyrus communis L*.).

Pastures are distributed around the lake and along the road toward the San Antonio páramo, where naturalized or native forage species predominate, especially kikuyu grass (*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone), velvet grass (*Holcus lanatus* L.), perennial ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.), and orejuela (*Alchemilla orbiculata* Ruiz & Pav.). These grasslands support a dual-purpose livestock system [24].

On the other hand, the expansion of the agricultural frontier has generated a land use conflict over 5,461.6 ha, resulting from processes such as spontaneous settlement, agricultural frontier expansion, forest intervention, and the establishment of agricultural and livestock activities in areas unsuitable for such uses [43].

In the area of influence of the RAMSAR wetland, the intensive exploitation of natural resources is evident, driven by high population pressure and the need for access to land and housing. This phenomenon has led to the conversion of areas strictly suited for forestry into agricultural and livestock uses. Currently, the region has 1,399 plots smaller than 5 ha, 371 plots between 5.1 and 20 ha, and 142 plots larger than 20.1 ha, the latter accounting for 36% of the wetland’s total area [45].

The analysis highlights the need to implement land-use planning and conservation strategies aimed at mitigating the expansion of the agricultural frontier, preserving biodiversity, and promoting sustainable production models that minimize environmental impact on the region's strategic ecosystems.

4.2. Land Cover Change Indicators

In 2005, forest cover in Colombia represented 53.6% of the national territory. By 2015, this percentage had decreased to 52.2%, equivalent to an approximate loss of 1.5 million hectares. The largest areas of natural forest are located in the Amazon (67%) and Andes (18%) natural regions. Between 2005 and 2015, the greatest loss of forests nationwide occurred in the Caribbean and Andean regions. In 2005, the Andes region retained 36% of its natural forests, which dropped by nearly 1.5% in 2015, with a deforestation rate of 29,263 hectares per year [46]. Regarding the municipality of Pasto, from 2002 to 2023, 639 ha of primary humid forest were lost, accounting for 26% of its total tree cover loss during the same period [47].

In the department of Nariño, rural areas are essential for the cultivation of staple foods; however, forest destruction has had a significant negative impact on local communities that depend on the land for their livelihoods. Deforestation alters soil fertility, which is crucial for the growth of agricultural crops [48]. The removal of tree vegetation reduces the soil's capacity to retain nutrients and moisture, negatively affecting agricultural productivity [49]. Additionally, forest loss can lead to increased soil erosion and a decrease in water resources, further impacting farmers' ability to grow food sustainably [50]. The disruption of ecological cycles and the loss of natural habitats also affect the biodiversity of pollinators and other organisms vital to food production [51].

Added to this is the alteration of the local microclimate, where the absence of vegetation cover increases soil temperatures, reduces relative humidity, and alters precipitation patterns, creating less favorable conditions for crops [52]. Likewise, the decline in forest cover weakens associated ecosystem services such as hydrological cycle regulation, carbon sequestration, and protection against extreme events like floods and droughts [48]. These conditions not only reduce agricultural productivity but also increase the socio-environmental vulnerability of rural communities, compromising food security, resilience to climate change, and the sustainability of local agroecological systems [33, 53].

In the case of the La Cocha RAMSAR wetland, forest fragmentation has occurred over 229.83 ha, which can be attributed to the expansion of the agricultural frontier and the extraction of forest resources for fuelwood purposes. According to IAvH et al. [45] in El Encano, primary forest, secondary forest, páramo ecosystems, and geological reserve zones have been deforested for charcoal extraction, producing 480 tons of charcoal per month, equivalent to 5,760 tons per year, resulting in the destruction of approximately 520 hectares of forest. Although this charcoal production activity has declined due to reduced forest areas, it still holds economic importance for local residents. Likewise, the agricultural frontier expanded by 625 ha per year due to the low availability of land suitable for farming [43].

According to IAvH et al. [45] forest cover located in higher-altitude areas (e.g., in the Bordoncillo páramo) has been deforested or logged using the same cultural practices passed down since the 1900s through family generations. As a general rule, this silvicultural activity begins by "removing" those timber species with significant commercial value (mate, pine, cedar, mahogany), and then continues by converting any other wood considered less valuable into charcoal.

Despite anthropogenic intervention in natural cover, forest recovery totaling 819.05 ha is noteworthy. This may be related to the creation of the José Gabriel de La Cocha Network of Natural Reserves, which emerged in 1991 as a conservation initiative led by rural landowners who voluntarily chose to preserve remnants of natural ecosystems on their properties. Initially motivated by the need to ensure their own subsistence and protection, this effort evolved into a synergistic strategy for biodiversity conservation, generating environmental, social, and economic benefits. At the same time, the consolidation of these reserves was strengthened by the integration of the Asociación para el Desarrollo Campesino (ADC) into the National Network of Civil Society Natural Reserves, which facilitated the acquisition of new knowledge, the formation of strategic alliances, and the sustainable planning of landholdings [54, 55].

Likewise, some mosaics of agricultural cover are associated with natural areas that play an important role in ecological continuity, serving as connection zones between natural ecosystems and areas under anthropogenic use. These conservation initiatives have been recognized with the Blue Globe Award. This honor pays tribute to the Asociación de Desarrollo Campesino, the organization that promoted the creation of the La Cocha Natural Reserves Network. In this context, farming families have implemented sustainable production systems, promoting responsible agricultural practices and proper livestock management in harmony with ecosystem conservation [56].

In this way, the various ecosystems present play an important and decisive role in species diversity. The RAMSAR zone is characterized by high bird biodiversity, due to factors such as its location within the Andean Amazonian zone, the presence of different ecosystems including wetlands, páramos, and cloud forests, variations in forest conservation status, ranging from pastures and regenerating areas to secondary and mature forests, the presence of microhabitats, and the area's high floristic diversity [25]. Additionally, according to IAvH, 23,075.83 ha are part of the La Cocha Patascoy Páramo Complex [28].

According to Ramírez-Padilla et al. [44] the main biomes in the area include high Andean forests and both zonal and azonal páramos. This zone is characterized by a wide diversity of vascular flora typical of Andean forests and páramos, as well as riparian vegetation. Among the floristic resources, species can be identified that have been conserved primarily for forest preservation and for their economic uses; the latter are found in both natural environments and anthropogenic areas. The vascular plants present in the upper Guamués River basin are represented by 122 families and 362 genera of native or naturalized plants, which are grouped into four main categories: Lycophytes, represented by 3 families and 5 genera; Monilophytes, with 19 families and 39 genera; Gymnosperms, with 1 family and 1 genus; and basal Angiosperms and Magnoliids, with 6 families and 10 genera; and Angiosperms with 93 families and 307 genera. Within the latter group are Monocots with 16 families and 71 genera, and Eudicots with 77 families and 236 genera [57].

4.3. Prospective Model for the Year 2050

For the development of the prospective model it was possible to establish that the Cramer's V transition variables that had the greatest influence in the study area were single drainage, double drainage, the presence of the port, the presence of the lagoon, the temperature variable established in the isotherms and the presence of reserves, since they presented values from 0, 4 in this factor (Table 6), studies developed by Ceballos et al. [23] identify proximity to rivers as the most influential variables, which coincides with the present research in which single and double drainage as well as the lagoon become important variables for modeling. In relation to the variables with low values such as precipitation and vias Muñoz [21] and Ceballos et al. [23] do not discard them completely, they consider that there is a possibility that they generate significant patterns in the data, since there may be complex relationships that require further analysis.

Table 6. Cramer's V factor values for the variables studied

Variable	Cramer's V values
Roads	0.3548
Single drainage	0.7214
Double drainage	0.4056
Port	0.4808
Lagoon	0.7270
Isohyets	0.2287
Isotherm	0.4268
Reserves	0.4931

On the other hand, the variations identified in the projections allow us to understand possible future scenarios in the RAMSAR La Cocha Wetland and offer key elements for territorial planning. Thus, an increase of 95.27 ha of fragmented forest is projected, which can be attributed to the advance of intensive production systems or the transition to urban uses. IAvH et al. [45] emphasizes that in the RAMSAR area, the resident families sustain the regional economy by exploiting available natural resources (e.g., water, soil, forest, fauna), with the objective of guaranteeing their food security; making use of or benefiting directly from agricultural, livestock and charcoal activities.

On the other hand, the most notable gain in land cover corresponds to the mosaic of pastures with natural spaces, with a projected increase of 193.79 ha. This growth may be associated with the intensification of livestock farming. According to Ramírez-Padilla et al. [44] dual-purpose cattle ranching is a highly relevant economic activity located around the lake, involving species such as *Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone, *Holcus lanatus* L., *Lolium perenne* L., *Trifolium repens* L., and *Alchemilla orbiculata* Ruiz & Pav. Likewise, IAvH et al. [45] indicate that livestock farming is a basic livelihood activity in the region, represented by around 1,500 head of cattle for both rearing and milking, producing an average of 8,400 liters of raw milk per day. Overgrazing by cattle may pose a critical issue as it affects the soil's porous horizon, reducing infiltration and leading to erosion processes [45].

There is also a trend towards the recovery of forest ecosystems with an increase of 66.75 ha in areas of dense forest that may be associated with natural regeneration processes, the implementation of conservation measures or the abandonment of agricultural land. This recovery can have positive effects on biodiversity and its ecosystem services. Considering that this is an area of great relevance for the region, it has three conservation categories: National Protected Forest Reserve, Ramsar Wetland of International Importance, and National Natural Park Zone. Studies developed by Muñoz-Guerrero et al. [21] in the Paja Blanca paramo, with the Land Chance model, showed similar recovery patterns as in the study area, where the areas of dense forest and paramo cover increased, thanks to the management processes by the environmental authority and the communities. Hence, the success in maintaining conservation areas and reducing fragmentation is related to the active participation of the communities present in the area.

From the hydrological point of view, Lake Guamués or Laguna de La Cocha has a water potential with a supply of 503.6 m3 , which allows defining the richness of the area with respect to this resource [45]. Twelve water flows are found in the area, of which, five are configured in micro-watersheds, the streams of: Santa Lucía, Ramos, Motilón, El Laurel, El Laurel river; the remaining area is considered as areas of direct runoff to the Lake, among which are, Quillinsayaco, San José, Afiladores, Romerillo, Carrizo, Río Negro and El Naranjal [58] Which explains why the drainage and lagoon variables have some of the highest values in Cramer's V factor.

The RAMSAR zone is characterized by a high avifaunal biodiversity thanks to key factors such as its location within the Andean-Amazonian zone, great floristic variety and the presence of different ecosystems (e.g., wetlands, moorlands and cloud forests), which serve as refuge for different species that are threatened by causes such as hunting and the continuous reduction of their habitat [45]. The variety of birds in La Cocha lagoon is abundant, with the presence of resident and migratory birds that visit the area. There are a large number of multicolored butterflies, 7 species of amphibians of the genus Pristimantis. Mammals are scarce, mainly rodents and bats. Birds include: *Fulica ardesiaca, Podylimbus podiceps, Nycticorax nycticorax, Zonotrichia capensis*, *Ampelion rubrocristatus, Turdus fuscater, Turdus serranus, Myioborus melanocephalus, Myioborus ornatus, Synallaxis brachyura, Diglossa cyannea, Diglossa caerulescens, Atlapetes schistaceus, Colibri coruscans, Coeligena torquata* and *Troglodytes aedon* [57].

The natural aquatic and terrestrial vegetation is a mosaic composed of communities at various stages of succession, including some sectors of mature forest, which feature a more open understory and a variety of epiphytes, particularly bromeliads. Records show up to 117 orchid species. The area also contains the world's lowest páramos, at 2,750 m, which act as a buffer cushion for the lake [5]. A total of 341 plant species have been described, belonging to 87 families and 190 genera. The composition of the dense mature secondary forest is dominated by *Maytenus clarendonensis* Britton, *Machilus sericeus* (Nees) Blume, *Hieronyma macrocarpa* Müll.Arg., *Brunellia tomentosa* Bonpl., *Bejaria aestuans* Mutis, *Aegiphila bogotensis* (Spreng.) Moldenke, *Weinmannia auriculata* var. *auriculata*, *Myrcianthes rhopaloides* (Kunth) McVaugh, *Clusia* sp., and *Hesperomeles obtusifolia* var. *obtusifolia* [36].

This biological richness represents a strategic component within the guidelines of the Wetland Management Plan and its declaration as a Ramsar site [58] by supporting the effective conservation of protected areas. Beyond its intrinsic ecological value, biodiversity is configured as a fundamental instrument to guarantee the stability and permanence of natural cover in the projections to the year 2050. The presence of a high diversity of species, habitats and ecological functions strengthens the resilience of the system, allowing areas such as the dense forest and the páramo to remain stable over time, even in the face of environmental or socioeconomic change scenarios.

Against this backdrop, there are concrete opportunities for strengthening the prospective model. The integration of variables such as demographic factors and territorial development plans would allow the construction of more comprehensive scenarios. Likewise, the incorporation of traditional knowledge through participatory mapping and the active participation of the communities would enrich the analysis and reinforce the relevance and local acceptance of the model.

The findings of the study provide important elements for the design of conservation measures and sustainable land use. It is recommended to prioritize ecological restoration strategies in areas of fragmented ecological connectivity, as well as to consolidate sustainable productive systems developed by rural communities. These actions can be aligned with Colombia's commitments under the Ramsar Convention, strengthening the protection of the wetland as a site of international importance.

5. Conclusions

The stability of natural land cover in the La Cocha wetland reflects a relative resilience of the ecosystem, albeit with signs of localized anthropogenic pressure. A total of 91.06% of the territory did not exhibit significant changes between 1989 and 2020, indicating a certain degree of natural landscape conservation. However, forest fragmentation, the expansion of pastureland, and agricultural growth reveal transformation processes that, although limited in scope, could compromise ecological connectivity and the provision of ecosystem services if not properly managed.

Changes in land cover have not resulted in major transformations. Forest recovery and agricultural de-intensification may be attributed to regeneration processes, while forest fragmentation and agricultural expansion could pose risks to ecological connectivity. Therefore, it is important to monitor the dynamics of agricultural and natural land cover conversion to ensure sustainable land use.

The prospective modeling for the year 2050 suggests a dual trend: recovery of forest cover and an increase in forest fragmentation. A net gain of 66.75 ha in dense forest is projected, possibly associated with conservation strategies and natural regeneration. However, the increase of 95.27 ha in fragmented forest highlights the persistence of degradation dynamics. This situation underscores the need to prioritize restoration and management actions in vulnerable areas of the wetland.

The land cover prediction model for the year 2050 indicates a trend toward the recovery of forest ecosystems and the expansion of mosaics with natural spaces, which would be favorable for the conservation of biodiversity and its ecosystem services, ensuring ecological connectivity and facilitating species movement between habitat fragments.

The developed model constitutes a valid tool for territorial planning and decision-making in scenarios involving land use change. With an overall accuracy of 78% and a Kappa index of 0.76, the model demonstrated a good level of agreement with field data. This allows for more precise identification of areas most susceptible to transformation and helps define priority zones for the conservation and ecological restoration of the La Cocha Ramsar Wetland.

6. Declarations

6.1. Author Contributions

Conceptualization, S.M.; data curation, S.M. and D.M.; formal analysis, S.M. and D.M.; methodology, S.M. and D.M.; validation, S.M. and D.M.; writing—original draft preparation, S.M. and D.M.; writing—review and editing, S.M. and D.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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