Dynamics of Urban Expansion in the Inter-Andean Valleys: Projecting Scenarios for Sustainable Territorial Planning

Mónica Enríquez[1], Jaqueline Morocho[1], Divar Castro-Rodas[2,3], Paulo Escandón-Panchana[4,5], Lucas Lima Raiol[6], Andrés Velastegui-Montoya[1,3]

[1] Faculty of Engineering in Earth Sciences, ESPOL Polytechnic University, Guayaquil, Ecuador – (monienri, jaqmoroc)@espol.edu.ec
[2] Faculty of Mechanical Engineering and Production Sciences, ESPOL Polytechnic University, Guayaquil, Ecuador – divecast@espol.edu.ec
[3] Laboratory of Geoinformation and Remote Sensing, Faculty of Engineering in Earth Sciences, ESPOL Polytechnic University, Guayaquil, Ecuador – dvelaste@espol.edu.ec
[4] Departamento de Ingeniería Cartográfica y Topografía, Universidad Politécnica de Madrid (UPM), Madrid, Spain – pc.escandon@alumnos.upm.es
[5] Escuela de Ciencias Ambientales, Universidad Espíritu Santo, Samborondón, 0901952, Ecuador
[6] Programa de Pós-Graduação em Ciências Ambientais (PPGCA), Institute of Geosciences (IG), Federal University of Pará (UFPA), Belém, Brasil – lucas.raiol@ig.ufpa.br

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Abstract

Urban growth in inter-Andean valleys has accelerated the transformation of the territory, driven by the expansion of road infrastructure and the occupation of environmentally fragile areas. In this context, the Ruta Viva highway has reconfigured urbanization patterns in the parishes of Cumbaya and Tumbaco, advancing the urban frontier into agricultural areas and moderate slopes. The objective of this study is to evaluate the dynamics of urban expansion in the parishes of Cumbaya and Tumbaco during the period 2002-2032, using a multitemporal and predictive approach to project future urbanization scenarios and generate inputs for sustainable territorial planning and land management. The methodology integrated multitemporal analysis of land use and land cover data from MapBiomas (2002-2022), predictive modelling using CA-Markov-MOLUSCE, and urban expansion analysis. The results show a 3% increase in urban coverage during the 2002-2022 period and a projected 12% growth by 2032, concentrated south of the Ruta Viva corridor and within the agricultural mosaic. Simulations show that slopes below 25° are more susceptible to urbanization, while vegetation cover loss reaches 30% on the slopes of Ilalo Hill. This study provides a robust, replicable tool for anticipating urbanization scenarios in Andean environments, guiding land management and environmental conservation strategies in regions of high urban pressure.

1. Introduction and previous work

After the Industrial Revolution, urban growth became one of the most transformative processes in history (Guo & Liu, 2022), acting simultaneously as an engine of economic development and a source of socio-environmental challenges (Kyule & Wang, 2024). Advances in medicine and increased life expectancy in recent decades have driven exponential population growth worldwide, intensifying demand for urban land (Garmany et al., 2021). It is projected that by 2050, nearly 68% of the world's population will live in urban areas, putting increasing pressure on ecosystems and infrastructure (United Nations Department of Economic and Social Affairs, 2019). This uneven urbanization process responds to geographic, political, socioeconomic and cultural factors (Sun et al., 2020), and often the capacity for institutional planning, generating informal expansion, landscape fragmentation and loss of ecosystem services (Angel, 2023; Seto et al., 2012; Xhafa & Kosovrasti, 2015).

Among the multiple factors that explain urban expansion, road infrastructure occupies a central place (Adugbila et al., 2023). Studies have shown that the construction of roads and strategic corridors accelerates land-use transformation by facilitating access to new areas and promoting real estate speculation in peri-urban areas (Ahar et al., 2023; Wei et al., 2022). In metropolitan regions of Latin America, this relationship has been evident, as in the cases of Bogotá, Quito, and Lima, which have shown intensified growth patterns around road solutions, acting as catalysts for urban expansion into rural and mountainous areas (Benítez-Ramírez et al., 2026; Jilani et al., 2025; Pinto & Myriam, 2024).

The city of Quito, the capital of Ecuador, is not immune to the aforementioned urban growth, which is expanding towards the adjacent inter-Andean valleys (Ortiz-Báez et al., 2022). This process responds to the physical geographic restrictions of the relief, since the city is delimited by mountain ranges and deep ravines that limit its horizontal expansion (Chao et al., 2023). In this context, the valleys of Cumbaya and Tumbaco have emerged as growth points due to their location and the availability of land for urbanization (Villavicencio-Ordóñez et al., 2024). S However, the accelerated transformation was triggered by the inauguration of the Ruta Viva in 2014 (Macanchi et al., 2025), a road corridor connecting the Mariscal Sucre International Airport with the north of Quito, reducing travel times and reconfiguring metropolitan mobility patterns.

Additionally, Ruta Viva acted as a catalyst for the real estate market in Cumbaya and Tumbaco. In just a few years, the residential, commercial, and service offerings expanded, leading to a transition from rural to urban land (Santiago, 2017). One of the most sensitive areas to this expansion has been the Ilalo hill, a mountainous ecosystem of environmental and cultural value that, despite its fragility, has been subject to urbanization, deforestation and irregular occupation (Salazar et al., 2020). This pattern shows that road infrastructure accelerates peri-urban urbanization, especially in the absence of control mechanisms (Castro-Rodas et al., 2026; Costa et al., 2025).

Despite the importance of urban growth, studies examining the interaction between road infrastructure and geographic constraints in mountainous areas remain limited (Ahasan & Güneralp, 2022). Some of these studies have focused on metropolises with flat topographies, leaving gaps in mountainous contexts (Mou et al., 2023). In the inter-Andean valleys, steep slopes and the presence of natural hazards increase urbanization, thereby increasing socio-environmental vulnerability (Puente-Sotomayor et al., 2021). This scenario makes risk management a component of territorial planning (Watson et al., 2022).

In this sense, understanding the urbanization patterns in Cumbaya and Tumbaco enables the development of planning tools that reconcile urban development with environmental conservation and risk reduction to improve habitability (Macanchi et al., 2025). From a methodological perspective, remote sensing and geographic information systems (GIS) have proven to be powerful tools for analyzing the spatial and temporal dynamics of land use and land cover change (LULC) (Escandón-Panchana et al., 2022; Raiol et al., 2025). The availability of open-access databases, such as Landsat and MapBiomas, together with predictive models based on machine learning (ML) and cellular automata (CA) (Amini et al., 2022), offers opportunities to study these types of processes with greater precision and replicability.

The objective of the study is to evaluate the dynamics of urban expansion in the parishes of Cumbaya and Tumbaco during the period 2002-2032, using a multitemporal and predictive approach that integrates the CA-Markov model implemented in the QGIS plugin "Modules for Land Use Change Evaluation" (MOLUSCE) (QGIS Development Team, 2024). The purpose is to project future urbanization scenarios and generate inputs for sustainable territorial planning and land management in contexts of high anthropogenic pressure associated with road infrastructure, particularly the Ruta Viva. The combination of multi-temporal approaches and predictive models provides a technical and scientific basis for decision-making at the local and regional levels.

2. Study area

The study area includes the parishes of Cumbaya and Tumbaco, located in the province of Pichincha, Ecuador, with an approximate area of 8,633.37 hectares (Figure 1).

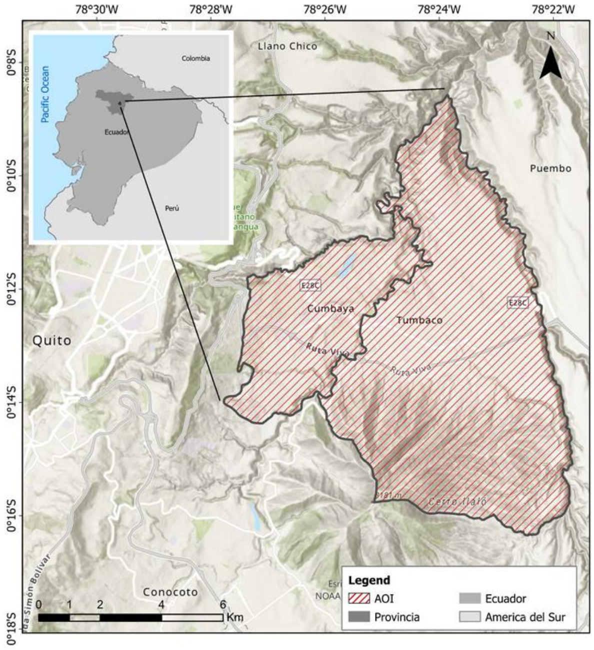

Figure 1. Geographic location of the study area in the parishes of Cumbaya and Tumbaco, province of Pichincha, Ecuador.

Both parishes are located in the inter-Andean valley of Quito, an area that in recent decades has experienced a notable process of urbanization and economic development, driven mainly by the construction of the Ruta Viva, an integration route inaugurated in 2014 to connect the Mariscal Sucre International Airport with the metropolitan area of Quito (Serrano et al., 2020). Since the opening of the infrastructure, urban growth has been concentrated mainly in the south of the road corridor, on the slopes of Cerro Ilalo, where residential and commercial expansion have progressively replaced natural and agricultural areas (Chiguano et al., 2023; Valdospinos et al., 2020).

The climate in the area is warm and dry, with average annual temperatures between 12°C and 18°C. The altitude ranges from 2,200 to 2,335 m above sea level, with a maximum of 3,188 m at the top of Ilalo Hill. The average annual rainfall is between 1,000 and 1,166.5 mm (Calvas et al., 2019). The predominant vegetation consists of shrubby and herbaceous formations, with reduced and fragmented forest cover, typical characteristics of the dry ecosystems of the inter-Andean valley.

3. Methodology

The methodological approach of the study is shown (Figure 2), segmented into three main phases: I) data preprocessing, II) Processing and predictive modelling, and III) Urban expansion analysis. This methodology integrated ArcGIS Pro tools and the MOLUSCE plugin in QGIS, allowing for the analysis of the spatiotemporal dynamics of urban growth in Cumbaya and Tumbaco between 2002 and 2032.

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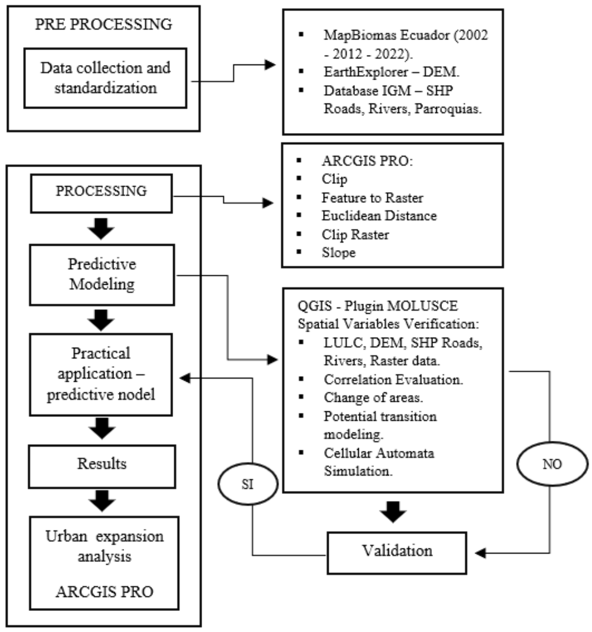

Figure 2. Methodological scheme of the study.

3.1 Data preprocessing

Geospatial information used as input to the model was collected and standardized. The LULC maps from the MapBiomas Ecuador collection for 2002, 2012, and 2022 were used in GeoTIFF format, providing consistent imagery for detecting temporal changes in LULC (MapBiomas, 2024).

The land cover and use classes are previously defined by MapBiomas (MapBiomas Ecuador, 2024), in this study the following were considered: (1) forest, which includes native tree ecosystems; (2) forestry as forest plantation or management of existing forests; (3) non-forest floodable natural formation such as shrub and herbaceous vegetation; (4) herbaceous, which includes areas such as grasslands; (5) agricultural mosaic that includes areas of agricultural production; (6) urban infrastructure; (7) water and (8) other non-forest natural formation.

The 30 m resolution Digital Elevation Model (DEM) was downloaded from the Google Earth Engine platform (Gorelick et al., 2017). At the same time, the vector layers of roads and the hydrographic network were obtained from the Military Geographic Institute (IGM) of Ecuador (IGM, 2025). All inputs were projected to the UTM Zone 17S system and normalized in resolution, extent and raster format, ensuring spatial compatibility between layers.

3.2 Predictive processing and modelling

The processing was carried out using the spatial analysis tool in ArcGIS Pro (ESRI, 2024). The Clip tool was used to delimit the roads and rivers in the study area, which were converted to raster format using Feature to Raster. Subsequently, Euclidean distance maps of roads and rivers, and a slope map derived from the DEM, were generated (Shi et al., 2023; Wang et al., 2021).

For the predictive model, the MOLUSCE plugin in QGIS was used, which combines machine learning algorithms with cellular automata to simulate land-use change patterns (Al Mazroa et al., 2024). MOLUSCE was selected for its open access, replicability, and compatibility with multitemporal raster data from platforms such as MapBiomas, making it an ideal tool for territorial planning studies in Latin American contexts (Ulloa-Espíndola & Martín-Fernández, 2021).

The model used a Multilayer Artificial Neural Network (ANN) to estimate the transition probabilities between coverage categories (Al Mazroa et al., 2024). The configured parameters were: 1-pixel neighborhood, 0.085 learning rate, 300 iterations, and 12 hidden layers, values defined after an empirical adjustment process aimed at minimizing the Root Mean Square Error (RMSE) and avoiding overfitting. Integrating an ANN with CA-Markov enables the capture of complex nonlinear relationships in urban growth dynamics (Xu et al., 2022).

Model validation was carried out in three stages: (1) calibration (2002-2012), training the model with the 2002 and 2012 maps to generate the 2022 simulation; (2) intermediate verification (2012-2022), comparison between the simulated map of 2022 and the one observed in MapBiomas, calculating the confusion matrix and Cohen's Kappa index (k=0.76), which reflects a substantial level of agreement. (3) projection (2022-2032), use of the calibrated model to generate the future urban expansion scenario (Zhou et al., 2019).

3.3 Urban expansion analysis

This phase focused on identifying and quantifying the areas transformed into urban infrastructure during the periods 2002-2022 and 2022-2032. To do this, the Change Detection Wizard tool in ArcGIS Pro was applied, under the Change by Category method, which allows comparing multitemporal raster maps and determining the most significant transitions (Chinwendu et al., 2025).

This analysis enabled estimating the areas of agricultural, grassland, and forest cover converted to urban areas, as well as detecting spatial patterns of expansion concentrated along the Ruta Viva road axis and on the slopes of Ilalo Hill. The results were integrated with projections from the CA-Markov model to characterize the dynamics of urbanization and identify areas with the greatest projected anthropogenic pressure for 2032.

4. Results

The temporal analysis of LULC maps (2002-2022) revealed landscape transformation in the parishes of Cumbaya and Tumbaco (Figure 3). During this period, the agricultural mosaic increased by 9%, mainly at the expense of grassland cover, which decreased by 13%.

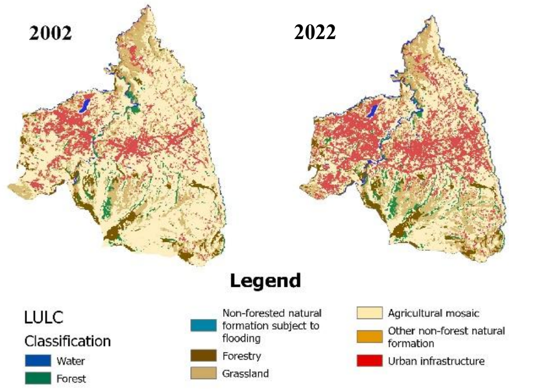

Figure 3. LULC maps for 2002 and 2022 were generated from MapBiomas.

Urban expansion increased by 3%, concentrated in the southern and central sectors of both valleys, especially along the Ruta Viva axis, where connectivity has driven residential and commercial growth (Table 1).

Table 1. Surface area and percentage of LULC categories for the years 2002 and 2022.

Change of category	Area [ha] 2002	%	Area [ha] 2022	%
Agricultural mosaic	4347.88	50.36	5151.34	59.67
Grassland	2480.37	28.73	1337.63	15.49
Urban Infrastructure	792.13	9.18	1075.08	12.45
Forest	295.72	3.43	278.91	3.23
Silviculture	332.47	3.85	434.58	5.03
Other non-forest natural formation	208.11	2.41	261.22	3.03
Water	132.26	1.53	92.4	1.07
Non-forest floodable natural formation	44.43	0.51	2.21	0.03

The most notable conversion corresponds to the transition from agricultural mosaic to urban infrastructure with 308.7 ha, followed by the transformation from grassland to urban with 233.9 ha (Table 2). There is a change in the remaining coverage area, as 9 hectares have been converted into urban infrastructure. These results confirm the trend of replacing natural and agricultural land cover with urban uses, highlighting urbanization concentrated in easily accessible areas.

Table 2. Quantification of areas of change for the period 2002-2022.

Coverage transition	Area [ha] 2002 - 2022
Agricultural mosaic → Urban Infrastructure	308.7
Grassland → Urban Infrastructure	233.91
Forest → Urban Infrastructure	8.28
Other non-forest natural formation → Urban Infrastructure	5.04
Water → Urban Infrastructure	4.68
Non-forest floodable natural formation → Urban Infrastructure	1.53
Silviculture → Urban Infrastructure	0.99

The predictive model projects a significant increase in urban coverage by 2032, reaching 24.07% of the total area. This increase represents 12% compared to 2022 (Figure 4). This expansion is mainly due to agricultural mosaics, whose area would decrease by more than 1,427 ha, and, to a lesser extent, to the grassland, with a net loss of 213.7 ha (Table 3).

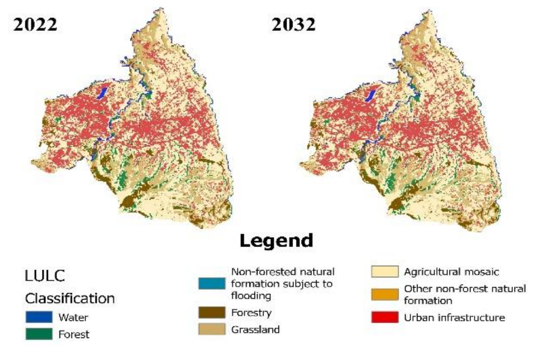

Figure 4. Projection of land use changes to the year 2032 using CA-Markov-MOLUSCE.

Table 3. Surface area and percentage of LULC categories for the years 2022 and 2032.

Change of category	Area [ha] 2022	%	Area [ha] 2032	%
Agricultural mosaic	5151.34	59.67	3723.83	43.13
Grassland	1337.63	15.49	1668.19	19.32
Urban Infrastructure	1075.08	12.45	2077.79	24.07
Forest	278.91	3.23	353.23	4.09
Silviculture	434.58	5.03	445.41	5.16
Other non-forest natural formation	261.22	3.03	212.88	2.47
Water	92.4	1.07	149.63	1.73
Non-forest floodable natural formation	2.21	0.03	2.41	0.03

Figure 5 shows the spatial analysis, which reveals that urban expansion is oriented towards the northeast of Cumbaya and the south of Tumbaco, coinciding with the sectors adjacent to the Ruta Viva and the slopes of Ilalo Hill. These areas, characterized by gentle slopes and road accessibility, concentrate on the highest rates of growth and environmental vulnerability (Table 4).

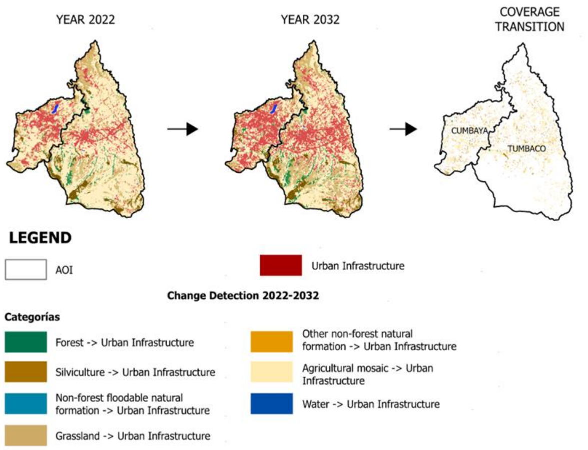

Figure 5. Projected urban expansion areas.

Table 4. Quantification of areas of change for the period 2022-2032.

Coverage transition	Area [ha] 2022 - 2032
Agricultural mosaic → Urban Infrastructure	855.63
Grassland → Urban Infrastructure	231.66
Forest → Urban Infrastructure	5.94
Other non-forest natural formation → Urban Infrastructure	8.37
Water → Urban Infrastructure	1.53
Non-forest floodable natural formation → Urban Infrastructure	0.18
Silviculture → Urban Infrastructure	5.31

Projected results for 2032 indicate that urban expansion will primarily affect agricultural and grassland cover, while forest loss will be more localized. In Cumbaya, the expansion is heading northeast, while in Tumbaco it is advancing south of the Ruta Viva, directly impacting the slopes of Ilalo Hill, an ecosystem of high ecological fragility. The lack of a formal protection declaration for this area has led to illegal construction, increasing the risk of fragmentation and the loss of ecosystem services.

5. Discussion

This study contributes a methodological approach that simulates and projects urban expansion in Andean contexts of topographic complexity, enabling sustainable territorial planning in regions of rapid urban dynamics. The application of the predictive model allowed a reliable spatial representation of urban growth in the inter-Andean valleys of Quito. Statistical validation (k=0.769) confirms significant accuracy, supporting the model's ability to project urban scenarios in topographically complex contexts.

The results reflect a direct correlation between road infrastructure and urban expansion, a trend documented in other Andean cities (Briceño-Garmendia et al., 2015; Dominguez et al., 2021; Guzman et al., 2021). Similarly, studies in Temuco, Chile (Maturana et al., 2021) and Esmeraldas, Ecuador (Mena et al., 2022) highlight the importance of incorporating environmental variables, slope, and water bodies to improve the accuracy of CA-Markov models.

The planned expansion into agricultural and grassland areas confirms the conflict between urbanization and ecological sustainability, particularly on Ilalo Hill, were vegetation loss and habitat fragmentation compromise landscape stability. These results demonstrate the need to integrate geospatial predictive models into land-use planning tools to anticipate urban pressure scenarios and prioritize conservation areas.

The implementation of a hybrid approach based on ANNs and cellular automata demonstrated greater capacity to reproduce urbanization patterns than traditional linear models, by capturing the interactions between anthropogenic and natural factors. This finding aligns with the literature (Chen & Wang, 2024; Xu et al., 2022), which demonstrates that this approach improves the spatial sustainability of urban modelling. Finally, the results of this study reaffirm the value of MOLUSCE as an open-source tool, handy for local governments in developing countries, where urban planning resources are often limited.

6. Conclusion

The predictive model demonstrated high accuracy in simulating and projecting urban expansion in Cumbaya and Tumbaco, confirming its application in Andean territories where topography strongly influences urbanization patterns. This study contributes to geospatial science by demonstrating that hybrid models can overcome the limitations of traditional linear approaches by incorporating spatial dynamics and the combined influence of natural and anthropogenic variables in mountainous areas.

Road infrastructure, especially Ruta Viva, is one of the factors driving urban expansion into agricultural and grassland areas, putting pressure on fragile ecosystems such as Ilalo Hill and highlighting the potential to incorporate predictive tools into sustainable territorial planning. These tools provide technical input to public and urban planning entities, enabling them to anticipate land-use scenarios, identify areas of urban pressure, and define preventive land-use measures.

The accuracy of the model depends on the resolution and the frequency of updates of the cartographic inputs used. Future research should: (1) integrate socioeconomic and regulatory scenarios into modelling, (2) assess environmental and risk impacts associated with projected expansion, and (3) compare the performance of hybrid CA-Markov models with deep learning algorithms to improve spatial prediction of urban growth.

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