

Article

Urban–Rural Interface Dynamics in an Intermediate Andean City: An Integrated Territorial Taxonomy from Loja, Ecuador

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Abstract

This study examines the urban–rural interface of Loja, Ecuador, as a differentiated socio-ecological system shaped by environmental structure, the persistence of productive land, reliance on infrastructure, and terrain-adaptive settlement patterns. An integrated territorial taxonomy was developed using a four-phase methodological framework that combined morphological analysis, socio-territorial characterization, adaptive tectonic interpretation, and multivariate synthesis. Ten representative polygons located within Loja’s Andean periphery were evaluated using indicators of Biotic Porosity (BP), Degree of Hybridity (DH), Infrastructure Dependency (ID), and Alimentary Autonomy Extent (AAE), complemented by spatial analysis, field verification, and exploratory correlation assessment. The results revealed strong positive associations between socio-territorial hybridity and alimentary autonomy ($\rho = 0.92$), and strong negative associations between hybridity and infrastructure dependency ($\rho = -0.88$). A moderate positive relationship was identified between biotic porosity and hybridity ($\rho = 0.67$). The analysis also identified three adaptive tectonic typologies—Terracing, Cantilever, and Platform Urbanization—and a territorial taxonomy composed of Resilient, Adaptive, and Consolidating Edges. These findings demonstrate that the Andean urban periphery operates as a heterogeneous continuum rather than a homogeneous expansion zone. Although the statistical relationships should be interpreted as exploratory due to the limited sample size, the framework provides a useful basis for comparative research and resilience-oriented planning in intermediate mountain cities undergoing rapid territorial transformation.

Keywords: urban–rural interface; socio-ecological taxonomy; adaptive territorial edges; adaptive tectonics; intermediate Andean cities; territorial resilience



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1. Introduction

Urban–rural interface dynamics have become one of the defining characteristics of contemporary expansion in intermediate Andean cities. Rather than following traditional concentric growth models, these cities increasingly develop through heterogeneous transition zones where urban and rural activities coexist spatially and functionally [1,2]. These interfaces are characterized by fragmented settlement patterns, mixed land uses, and heterogeneous environmental conditions that challenge conventional planning approaches based on rigid urban–rural distinctions [1–3]. Consequently, they function as dynamic socio-ecological systems in which ecological processes, productive activities, and urban expansion interact across heterogeneous spatial and environmental conditions [4,5].

Rather than constituting fixed territorial boundaries, urban–rural interfaces should be understood as relational landscapes continuously shaped by interactions between human

practices and environmental processes [6]. In many cases, areas traditionally regarded as residual are increasingly recognized as territories with latent ecological, social, and spatial potential, consistent with the notion of *terrain vague* [7]. Studies of urban–rural gradients in Andean cities further demonstrate that landscape transformation follows spatially heterogeneous and non-linear patterns, producing increasingly fragmented territorial mosaics [8,9]. Although planning systems often rely on standardized zoning schemes, territorial dynamics are shaped by multiple actors and adaptive processes that frequently exceed formal regulatory frameworks [10,11]. Consequently, dispersed growth in mountain cities should not be interpreted solely as spatial disorder but as part of adaptive territorial processes that generate distinctive spatial configurations and perceptual structures under topographic, environmental, and socio-economic constraints [12–14].

Urban–rural interfaces also perform essential ecological and productive functions that are frequently underestimated by conventional planning. In intermediate cities, these peripheral territories are commonly associated with dispersed urban expansion and peri-urban sprawl, although such interpretations often overlook their environmental and productive roles [15]. In Andean cities, these peripheral interstices frequently operate as informal green infrastructure, contributing to thermal regulation, hydrological balance, ecological connectivity, and the provision of ecosystem services [16,17]. At the same time, conventional compact-city planning approaches often conflict with the physical and functional conditions of settlements located on steep mountain slopes and peri-urban environments [18,19]. Moreover, continuing urban expansion constitutes one of the principal drivers of habitat transformation and biodiversity loss, reinforcing the need to reconcile urban development with ecological conservation [20]. Progressive urban consolidation reduces ecological permeability, increasing ecosystem vulnerability and limiting the provision of ecosystem services [21,22]. Understanding how urban occupation patterns affect ecological continuity and ecosystem-service provision, therefore, remains a critical challenge for planning rapidly expanding mountain cities and highlights the need for analytical frameworks capable of integrating ecological and territorial processes.

In addition to their ecological functions, urban–rural interfaces exhibit marked socio-territorial hybridity. The incremental production of urban space offers a useful analytical lens for understanding the coexistence of residential and productive activities within peripheral territories [23]. In many Andean cities, adaptive territorial practices combine housing, family agriculture, and other small-scale productive activities, generating multifunctional landscapes that strengthen household resilience and livelihood diversification under recurrent socio-economic pressures [23–27]. Similar forms of functional integration have also been documented in informal settlements, where residential use, productive activities, and heterogeneous spatial configurations coexist under conditions of limited infrastructure and increasing urban density [24]. Rather than representing transitional or temporary conditions, these adaptive practices continuously reshape the functional boundaries between urban and rural systems, producing dynamic socio-territorial configurations. Nevertheless, urban consolidation and landscape fragmentation progressively reduce productive intra-plot spaces, weakening local support systems associated with everyday subsistence practices and diminishing territorial resilience [28]. Productive land continuity, therefore, constitutes a fundamental dimension for understanding socio-territorial transformation and the adaptive dynamics that characterize urban–rural interfaces [28].

Mountainous topography further conditions settlement morphology and patterns of urban occupation. In areas where slopes frequently exceed 30%, urbanization has generated adaptive construction practices—including terracing, slope-adapted structural solutions, and incremental building techniques—that minimize terrain modification while enabling habitation under demanding environmental conditions [25–27]. These locally developed

responses illustrate how territorial adaptation emerges from continuous interaction between environmental constraints and everyday spatial practices. However, such adaptive solutions are frequently overlooked or penalized by planning regulations conceived for predominantly flat urban environments [19]. This mismatch highlights the persistent tension between standardized planning frameworks and the adaptive territorial practices that sustain urbanization in mountainous landscapes.

Despite increasing recognition of urban–rural interface dynamics in mountain cities, an important scientific gap remains in the development of analytical frameworks capable of integrating their multiple territorial dimensions. Existing studies have advanced the understanding of peri-urban dynamics [1], landscape fragmentation [8,9], territorial transformation [10], ecological resilience and landscape sustainability [21,22], and adaptive settlement processes [25–27]. However, these dimensions have generally been examined independently, limiting the capacity to explain how ecological permeability, productive continuity, infrastructural dependence, and terrain-adaptive occupation interact in shaping urban–rural interface dynamics. Consequently, relationships among spatial configuration, ecological performance, productive resilience, and terrain-adaptive construction remain insufficiently explained within a unified socio-ecological framework applicable to intermediate mountain cities.

To address this research gap, this study develops a socio-ecological taxonomy to analyze adaptive territorial boundaries within the urban–rural interface of Loja, Ecuador. The principal contribution of the proposed framework is the integration of ecological permeability, productive continuity, and terrain-adaptive urbanization within a unified analytical structure specifically designed for intermediate mountainous cities. The framework is organized around three complementary analytical dimensions. Biotic porosity evaluates ecological permeability and the continuity of ecological processes across fragmented landscapes. Functional hybridity examines the coexistence of residential, productive, and ecological functions within peripheral territories, while adaptive tectonics analyzes terrain-responsive construction strategies that enable habitation under steep topographic conditions while maintaining varying degrees of environmental integration. These dimensions are operationalized through a four-phase methodological framework combining morphological, socio-territorial, spatial, and multivariate statistical analyses implemented in the R version 4.5.3 (R Foundation for Statistical Computing, Vienna, Austria) [29], using ten representative urban–rural interface polygons and cartographic indicators derived from previous territorial surveys [30].

Accordingly, this study develops and applies a socio-ecological taxonomy of adaptive territorial boundaries to characterize urban–rural interface dynamics in Loja, Ecuador. By integrating ecological permeability, functional hybridity, and adaptive tectonics within a unified analytical framework, the proposed taxonomy provides a transferable methodological approach for analyzing heterogeneous urban–rural interfaces in intermediate mountain cities. Beyond the case study, the framework contributes to resilience-oriented territorial planning by offering a reproducible tool to support planning and decision-making in rapidly transforming mountainous territories.

2. Materials and Methods

2.1. Study Area

Loja was selected as the case study because it represents a typical intermediate Andean city experiencing urban expansion under conditions of steep topography, fragmented peripheral occupation, productive land persistence, and increasing infrastructural pressure. These characteristics make Loja particularly suitable for examining urban–rural interface dynamics and socio-ecological transitions in mountainous urban environments. Located

in southern Ecuador, Loja constitutes an important regional center whose recent growth has increasingly expanded into environmentally sensitive and topographically complex peripheral areas. According to the VIII Population and VII Housing Census (INEC, 2022) [31], the city has a population of 203,496 inhabitants, while its officially delimited urban area of 5732 hectares is defined in the Land Use and Management Plan (PUGS) of Loja [32].

The peripheral sectors of Loja are characterized by fragmented occupation patterns in which agricultural plots, pastures, ecological remnants, and discontinuous settlements coexist within a heterogeneous urban–rural interface [8,9,15]. These territories reflect a socio-economic duality in which inhabitants frequently combine agricultural practices with employment in the public sector, construction, commerce, or informal urban activities. Rather than constituting merely incomplete urbanization processes, these peripheral landscapes operate as hybrid territorial systems where productive continuity, ecological permeability, and adaptive settlement dynamics remain partially active despite increasing urban pressure [21,22,24,28,30]. As a result, Loja’s periphery provides an appropriate setting for analyzing the interactions among urban expansion, ecological processes, productive land persistence, and terrain-adaptive occupation.

The analytical units of the study correspond to ten polygons located within the urban–rural interface of Loja. These polygons were selected through purposive sampling to capture the diversity of territorial conditions present across the city’s periphery. The objective was not statistical representativeness but analytical representativeness, ensuring the inclusion of contrasting situations in terms of population distribution, territorial structure, topographic conditions, built-footprint intensity, ecological permeability, productive land persistence, and land-use configuration. Consequently, the selected polygons encompass fragmented, transitional, and consolidated interface conditions, as well as residential, productive, ecological, recreational, industrial, and infrastructural territorial functions. This diversity enables the proposed framework to evaluate different socio-ecological trajectories operating across the urban–rural interface and to identify differentiated patterns of resilience, adaptation, and consolidation. Figure 1 shows the spatial location of the ten selected polygons within the study area.

2.2. Methodological Framework

The methodological framework was designed to examine the urban–rural interface as a multidimensional socio-ecological system in which territorial adaptation emerges from the interaction among ecological, productive, infrastructural, and topographic factors. Rather than analyzing these dimensions independently, the proposed approach integrates them within a unified analytical framework capable of characterizing heterogeneous territorial conditions across the urban periphery of Loja.

Four complementary indicators were selected to represent key dimensions of territorial performance within the urban–rural interface. Biotic Porosity (BP) was used to evaluate ecological permeability and landscape continuity, reflecting the capacity of territories to maintain environmental functions despite urban expansion. Degree of Hybridity (DH) was employed to assess the coexistence of residential, productive, and ecological functions within the same territorial unit. Infrastructure Dependency (ID) was incorporated to measure the degree of reliance on centralized urban systems, while Alimentary Autonomy Extent (AAE) was used to estimate the persistence of localized food-support capacities. Together, these indicators provide an integrated representation of socio-ecological resilience and territorial adaptation within the urban–rural interface.

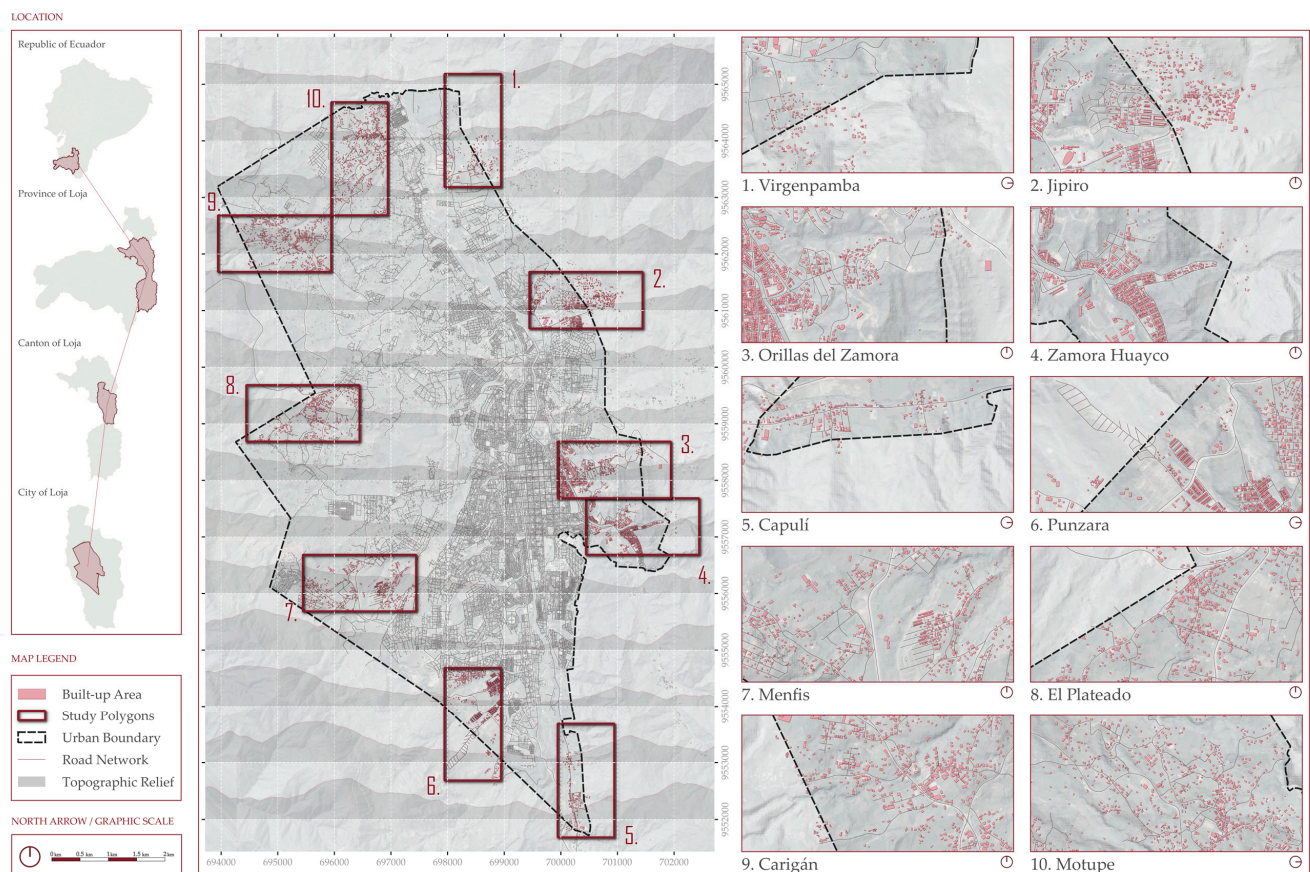


Figure 1. Location of the study area and distribution of the ten polygons selected within Loja's urban-rural interface. The selected polygons represent contrasting conditions of urban consolidation, topographic adaptation, productive land persistence, and environmental continuity within Loja's urban-rural interface. Source: Municipality of Loja; UTPL; GIZ (2019) [30], author's elaboration.

To operationalize this approach, the research was organized into four sequential and complementary phases integrating spatial morphology analysis, socio-territorial characterization, adaptive tectonic interpretation, and multivariate synthesis. Each phase was designed to address a specific analytical dimension of the urban-rural interface and to contribute progressively to the development of the proposed territorial taxonomy. Table 1 summarizes the methodological workflow, the analytical dimensions evaluated, the justification for each phase, the methods employed, and the principal outputs obtained throughout the study.

Table 1. Methodological workflow for urban interface characterization: dimensions and analytical tools.

Phase	Designation	Analytical Justification	Methods of Analysis (Data Layers)	Output/Analytical Contribution
I	Morphological configuration and ecological permeability assessment	To evaluate ecological permeability and morphological fragmentation as indicators of territorial continuity and landscape transformation.	- Figure-ground analysis (built vs. void) - GIS-based measurement of built footprint and permeable surfaces - Biotic Porosity (BP) calculation - DEM integration and terrain morphology analysis	Morphological gradient classification: fragmentation, transition, and coalescence patterns based on BP values and spatial continuity indicators

Table 1. *Cont.*

Phase	Designation	Analytical Justification	Methods of Analysis (Data Layers)	Output/Analytical Contribution
II	Socio-territorial characterization and functional hybridity assessment	To characterize socio-territorial hybridity, productive continuity, and infrastructural dependence within the urban–rural interface.	• GIS-based land-use mapping • Identification of productive, residential, ecological, and infrastructural uses • Evaluation of LUDI, PSP, ID, and AAE indicators • Five-point Likert normalization and DH index calculation	Degree of Hybridity (DH) model and socio-territorial characterization of productive continuity, alimentary autonomy, and infrastructural dependence
III	Identification of adaptive tectonic typologies	To identify terrain-adaptive settlement responses developed under steep Andean topographic conditions.	• Slope analysis and topographic adaptation assessment • Field surveys and architectural interpretation • Identification of retaining systems, cantilever structures, and platform urbanization patterns • Analysis of settlement adaptation strategies in steep terrains	Classification of adaptive tectonic typologies: Terracing, Cantilever, and Platform Urbanization
IV	Integrated Socio-Ecological Synthesis and Territorial Taxonomy	To integrate ecological, socio-territorial, and tectonic dimensions into a unified territorial taxonomy.	• Spearman correlation analysis among BP, DH, ID, and AAE variables using R [29] • Integrated spatial interpretation of morphological and socio-territorial variables • Comparative synthesis of systemic territorial behavior	Taxonomic classification of the urban–rural interface into Resilient, Adaptive, and Consolidating Edges

Source: Author's elaboration.

2.2.1. Phase I: Morphological Analysis and Biotic Porosity Assessment

The first analytical phase focused on evaluating the spatial morphology of the selected polygons through the assessment of built-up occupation patterns, ecological permeability, and figure–ground relationships. The objective was to identify gradients of fragmentation and consolidation associated with different stages of territorial transformation at the urban–rural interface.

Spatial analysis was conducted using cadastral information, GIS-based urban mapping, high-resolution satellite imagery, and figure–ground interpretation techniques. Built and non-built surfaces were quantified for each polygon to evaluate the spatial relationship between urban occupation and permeable land continuity.

Biotic Porosity (BP) was selected as the principal indicator of ecological permeability because it provides a direct measure of the proportion of permeable and non-built surfaces capable of supporting ecological continuity within the urban–rural interface. In fragmented Andean landscapes, ecological permeability constitutes a key dimension for evaluating environmental functionality and territorial adaptation under increasing urbanization pressure. The indicator was derived from established approaches in urban morphology and landscape analysis that relate built–void relationships to environmental continuity and spatial structure [3].

To operationalize ecological permeability, the Biotic Porosity (BP) index was calculated as the proportion of permeable and non-built surfaces relative to the total polygon area:

$$BP = \left(\frac{PS}{TA} \right) \times 100$$

where

BP = Biotic Porosity (%);

PS = Permeable Surface area;

TA = Total polygon area.

Permeable surface area was calculated through the aggregation of vegetated, productive, and unsealed open surfaces according to the following expression:

$$PS = GS + AS + CS$$

where

GS = Green surfaces;

AS = Agricultural surfaces;

CS = Unsealed circulation/open surfaces.

Higher BP values indicate greater environmental continuity and lower levels of urban consolidation, whereas lower BP values reflect increasing built saturation and reduced landscape permeability.

Based on BP values and figure-ground spatial interpretation, polygons were subsequently classified along a continuous gradient ranging from fragmentation to coalescence. The classification was based on the combined interpretation of BP values, built-footprint intensity, and spatial continuity patterns observed through GIS and figure-ground analysis. Rather than applying fixed universal thresholds, categories were established through comparative assessment of the ten polygons, allowing the identification of relative differences in ecological continuity and territorial consolidation within the study area.

Fragmented morphologies correspond to discontinuous built occupation and high levels of ecological connectivity, while coalescent morphologies exhibit compact urban fabrics, reduced permeable continuity, and stronger infrastructural consolidation. Intermediate conditions represent transitional configurations in which built structures and open spaces coexist under varying degrees of territorial transformation.

The resulting morphological gradient provided the basis for the subsequent socio-territorial and tectonic analyses by identifying the spatial patterns through which urban expansion, landscape structure, and environmental continuity interact across the urban-rural interface.

2.2.2. Phase II: Socio-Territorial Characterization and Functional Hybridity Assessment

The second analytical phase focused on evaluating the socio-territorial structure of the urban-rural interface through the identification of productive, residential, ecological, and infrastructural interactions within the selected polygons. The objective was to characterize the degree of functional hybridity present in each territorial unit by integrating variables associated with land-use diversity, productive land persistence, alimentary autonomy, and reliance on external urban systems.

The analysis combined cadastral information, GIS-based land-use mapping, high-resolution satellite imagery, and field verification surveys. These sources enabled the identification of territorial patterns associated with productive land persistence, residential occupation, infrastructural consolidation, and mixed-use spatial configurations across the urban periphery.

To operationalize the socio-territorial characterization, four analytical indicators were selected because they represent key dimensions through which resilience is expressed within the urban–rural interface. Land-use diversity reflects the capacity of territories to accommodate multiple functions simultaneously; productive soil presence indicates the persistence of local productive systems; infrastructure dependency captures the degree of reliance on external urban networks; and alimentary autonomy reflects the potential for localized food-support practices. Together, these indicators enable the identification of territorial configurations that balance environmental continuity, productive functions, and urban integration.

The indicators were defined as follows:

- Land Use Diversity Index (LUDI): evaluates the coexistence and heterogeneity of residential, productive, ecological, recreational, and infrastructural land uses within each polygon.
- Productive Soil Presence (PSP): measures the extent and spatial continuity of agricultural or productive land embedded within the urban fabric.
- Infrastructure Dependency (ID): assesses the degree to which territorial functioning depends on centralized urban infrastructure systems, including paved mobility networks, utilities, and external service provision.
- Alimentary Autonomy Extent (AAE): estimates the local capacity for food-related self-support based on productive land availability, cultivation continuity, and observable agricultural activity.

Each variable was evaluated using a five-point ordinal Likert scale to ensure comparability among polygons with different territorial characteristics. Scores ranged from 1 (very low presence or intensity) to 5 (very high presence or intensity), while intermediate values represented increasing levels of spatial continuity, functional relevance, and territorial expression.

Scores were assigned through a standardized classification protocol based on GIS interpretation, cadastral information, satellite imagery, and field verification. To improve consistency and reduce subjectivity, all polygons were evaluated comparatively using the same classification criteria and subsequently reviewed through expert interpretation. Table 2 summarizes the criteria used for the ordinal classification of the socio-territorial indicators evaluated in the study.

Table 2. Interpretation criteria for the ordinal classification of socio-territorial indicators.

Score	Interpretation
1	Very low presence or intensity
2	Low presence or intensity
3	Moderate presence or intensity
4	High presence or intensity
5	Very high presence or intensity

Variable normalization was conducted according to a standard min–max normalization procedure:

$$V_n = \frac{V_i - V_{min}}{V_{max} - V_{min}}$$

where

V_n = normalized variable value;

V_i = observed indicator score;

V_{min} = minimum ordinal value (1);

V_{max} = maximum ordinal value (5).

Indicator values were assigned through comparative spatial assessment of observed territorial conditions within each polygon. Higher LUDI values correspond to greater land-use heterogeneity, whereas higher PSP values indicate stronger persistence of productive land uses. In contrast, higher ID scores reflect greater reliance on centralized infrastructure systems and lower local autonomy. Higher AAE values represent stronger observed capacity for localized food-support functions and productive self-sufficiency.

To synthesize the combined socio-territorial characteristics of the analyzed polygons, a composite Degree of Hybridity (DH) index was developed. This index integrates the four indicators into a single measure representing the coexistence of productive, ecological, residential, and infrastructural dimensions within the urban–rural interface.

The Degree of Hybridity was calculated according to the following expression:

$$DH = \frac{LUDI + PSP + (6 - ID) + AAE}{4}$$

where

$LUDI$ = Land Use Diversity Index;

PSP = Productive Soil Presence;

ID = Infrastructure Dependency;

AAE = Alimentary Autonomy Extent.

Because Infrastructure Dependency (ID) represents an inverse condition relative to territorial hybridity, the variable was inverted through the expression $(6 - ID)$ prior to aggregation. This adjustment ensured conceptual consistency across the composite index, allowing higher DH values to consistently represent greater territorial diversity, stronger productive persistence, higher alimentary autonomy, and lower reliance on external infrastructure systems.

The resulting DH values range from 1 to 5. Values close to 1 indicate specialized and infrastructure-dependent urban configurations with limited productive integration. Intermediate values represent transitional conditions combining urban and productive functions. Values close to 5 indicate diversified territorial systems characterized by multifunctionality, environmental continuity, and relatively autonomous socio-spatial dynamics.

2.2.3. Phase III: Identification of Adaptive Tectonics Typologies

The third analytical phase focused on identifying adaptive tectonic responses developed within the urban–rural interface under steep Andean topographic conditions. The objective was to identify recurring spatial and constructive adaptation patterns associated with slope occupation, terrain stabilization, productive land use, and urban expansion processes across the analyzed polygons.

The analysis combined Digital Elevation Model (DEM) interpretation, slope assessment, architectural observation, cross-sectional spatial analysis, and direct observation of the selected polygons. Attention was given to the relationships between built structures, terrain adaptation mechanisms, productive occupation systems, and landscape configuration within steep-slope environments.

Field verification was conducted through direct observation of the selected polygons to contrast and complement the information obtained from GIS analysis, cadastral data, and satellite imagery. Attention was given to land-use conditions, terrain adaptation strategies, productive occupation patterns, and observable construction responses to topographic constraints. The resulting classifications were based on the combined interpretation of spatial information and expert assessment of the territorial characteristics observed within each polygon.

Slope gradients were calculated according to the following expression

$$S = \left(\frac{\Delta h}{d} \right) \times 100$$

where

S = slope gradient (%);

Δh = elevation difference;

d = horizontal distance.

Slope information was subsequently interpreted together with settlement morphology, construction characteristics, and field observations to identify terrain-adaptive responses at the urban–rural interface. This approach enabled the evaluation of how topographic conditions influence occupation patterns, construction strategies, and the spatial organization of peripheral settlements.

Based on the combined interpretation of topographic conditions, settlement morphology, construction characteristics, and field observations, three recurrent adaptive tectonic typologies were identified:

Terracing: stepped residential and productive adaptations integrated with topographic gradients through retaining systems and permeable cultivation platforms.

Cantilever: projecting or suspended occupation systems associated with abrupt terrain transitions and discontinuous urban expansion.

Platform Urbanization: stabilized occupation systems characterized by consolidated urban platforms, greater reliance on infrastructure networks, and reduced continuity of permeable surfaces.

Some polygons exhibited overlapping tectonic conditions due to differentiated environmental, morphological, and productive dynamics operating within the same territorial unit. Consequently, typological assignment was based on the predominant adaptive response observed within each polygon rather than on the exclusive presence of a single tectonic condition.

The identified typologies were subsequently incorporated into the integrated territorial analysis as indicators of terrain-responsive settlement adaptation, providing a complementary dimension for interpreting urban–rural interface dynamics in mountainous environments.

2.2.4. Phase IV: Integrated Socio-Ecological Synthesis and Territorial Taxonomy

The final analytical phase focused on the integrated interpretation of the morphological, socio-territorial, and tectonic dimensions previously evaluated in the study. The objective was to identify differentiated territorial behaviors within the urban–rural interface of Loja through the combined assessment of ecological, productive, infrastructural, and topographic characteristics.

The analysis incorporated the indicators Biotic Porosity (BP), Degree of Hybridity (DH), Infrastructure Dependency (ID), and Alimentary Autonomy Extent (AAE), together with the adaptive tectonic typologies identified during the previous phase. Rather than evaluating these variables independently, the framework emphasized their combined expression within each polygon to identify distinct territorial configurations.

The statistical relationships among indicators were explored using the procedures described in Section 2.3 and were used as complementary evidence to support the integrated interpretation of territorial patterns. The resulting associations were subsequently interpreted together with the morphological gradients and adaptive tectonic classifications developed during the previous analytical phases.

Rather than interpreting the urban periphery as a homogeneous expansion zone, the framework conceptualizes the urban–rural interface as a dynamic territorial continuum characterized by varying levels of environmental continuity, productive persistence, infrastructural reliance, and terrain-adaptive occupation.

The integrated interpretation of BP, DH, ID, AAE, and adaptive tectonic responses enabled the development of a territorial taxonomy composed of three differentiated edge conditions: Resilient Edges, Adaptive Edges, and Consolidating Edges.

Accordingly, the proposed taxonomy should be understood not merely as a classificatory output but as an operational analytical framework capable of supporting comparative evaluation and resilience-oriented planning in heterogeneous urban–rural interfaces.

Overall, the four-phase methodological framework provides a reproducible and adaptable analytical structure for evaluating socio-ecological dynamics within intermediate Andean cities and other urban–rural transition contexts characterized by mixed territorial configurations.

2.3. Data Analysis

The statistical analysis aimed to evaluate the relationships among the indicators used to characterize the urban–rural interface. Given the ordinal structure of the variables and the limited sample size ($n = 10$), associations were assessed using Spearman’s rank correlation coefficient, which is appropriate for identifying monotonic relationships without assuming normal data distribution.

Spearman’s coefficient was calculated according to the following expression:

$$\rho = 1 - \frac{6 \sum d^2}{n(n^2 - 1)}$$

where

ρ = Spearman’s rank correlation coefficient;

d = difference between paired variable ranks;

n = number of observations.

Correlation coefficients and significance levels were calculated using the R version 4.5.3 (R Foundation for Statistical Computing, Vienna, Austria) [29]. Correlation strength was interpreted according to the following thresholds: weak ($|\rho| < 0.40$), moderate ($0.40 \leq |\rho| < 0.70$), and strong ($|\rho| \geq 0.70$). The resulting correlation matrix was subsequently used to support the integrated interpretation of territorial patterns and the development of the proposed taxonomy.

Given the exploratory nature of the study, the limited sample size ($n = 10$), and the ordinal characteristics of several indicators, non-parametric Spearman correlation was considered more appropriate than regression-based approaches. The objective of the statistical analysis was not to establish causal relationships or estimate predictor effects, but rather to identify potential associations among the ecological, socio-territorial, and infrastructural dimensions incorporated into the territorial taxonomy.

3. Results

The spatial analysis revealed a continuous morphological gradient ranging from fragmented territorial configurations to increasingly coalescent urban structures. This gradient reflects differentiated levels of territorial consolidation within the urban–rural interface of Loja and highlights the progressive transformation of open landscapes into more consolidated urban environments.

The distribution of Biotic Porosity (BP) values and built-footprint ratios indicates three broad morphological conditions (Table 3). The first corresponds to fragmented

configurations characterized by low levels of built occupation and extensive permeable land systems. These areas maintain discontinuous settlement patterns and large open-space matrices, reflecting an early stage of urban consolidation.

Table 3. Morphological gradients and biotic porosity values across the analyzed urban polygons in Loja.

Order	Polygon	Built Footprint (%)	Porosity (BP %)	Gradient (1–5)
1	Virgenpamba	2.83	82.89	5 (Fragmentation)
2	Capulí	2.51	70.96	4 (Fragmentation)
3	Motupe	5.76	66.22	4 (Fragmentation)
4	El Plateado	4.77	59.65	3 (Transition)
5	Punzara	10.24	54.05	3 (Transition)
6	Carigán	6.12	53.69	3 (Transition)
7	Menfis	5.18	47.38	3 (Transition)
8	Jipiro	10.13	44.89	3 (Transition)
9	Zamora Huayco	7.98	25.80	2 (Coalescence)
10	Orillas del Zamora	11.49	17.66	1 (Highly Coalescent)

Note: BP = Biotic Porosity (%). Morphological classes were derived from the combined interpretation of porosity, built occupation, and spatial continuity patterns. Source: Municipality of Loja; UTPL; GIZ (2019) [30], author's elaboration.

A second group corresponds to transitional morphologies in which built structures and open spaces coexist in relatively balanced proportions. These territories exhibit heterogeneous spatial configurations, combining residential occupation, productive land uses, and remnant open areas. Rather than representing fixed conditions, these intermediate configurations illustrate active processes of territorial transformation where urban expansion interacts with pre-existing landscape structures.

The third condition corresponds to coalescent morphologies characterized by greater continuity of the built fabric, increasing plot occupation, and progressive reduction in permeable surfaces. In these sectors, urban consolidation becomes the dominant spatial process, resulting in more compact settlement patterns and reduced availability of open land.

Figure 2 illustrates the spatial contrast between the two extremes of the identified gradient.

Fragmented configurations preserve discontinuous occupation patterns and extensive open-land matrices, whereas coalescent sectors exhibit greater spatial saturation and stronger physical continuity of the urban fabric. The figure highlights how variations in built–void relationships contribute to differentiated territorial structures across the urban–rural interface.

Overall, the results indicate that fragmentation and coalescence should be understood as positions along a continuum rather than as discrete territorial categories. The identified gradient demonstrates that urban expansion operates through differentiated spatial trajectories, producing heterogeneous configurations that combine varying degrees of settlement consolidation, landscape transformation, and land-use diversification. These findings provide the morphological basis for the subsequent socio-territorial and adaptive tectonic analyses.

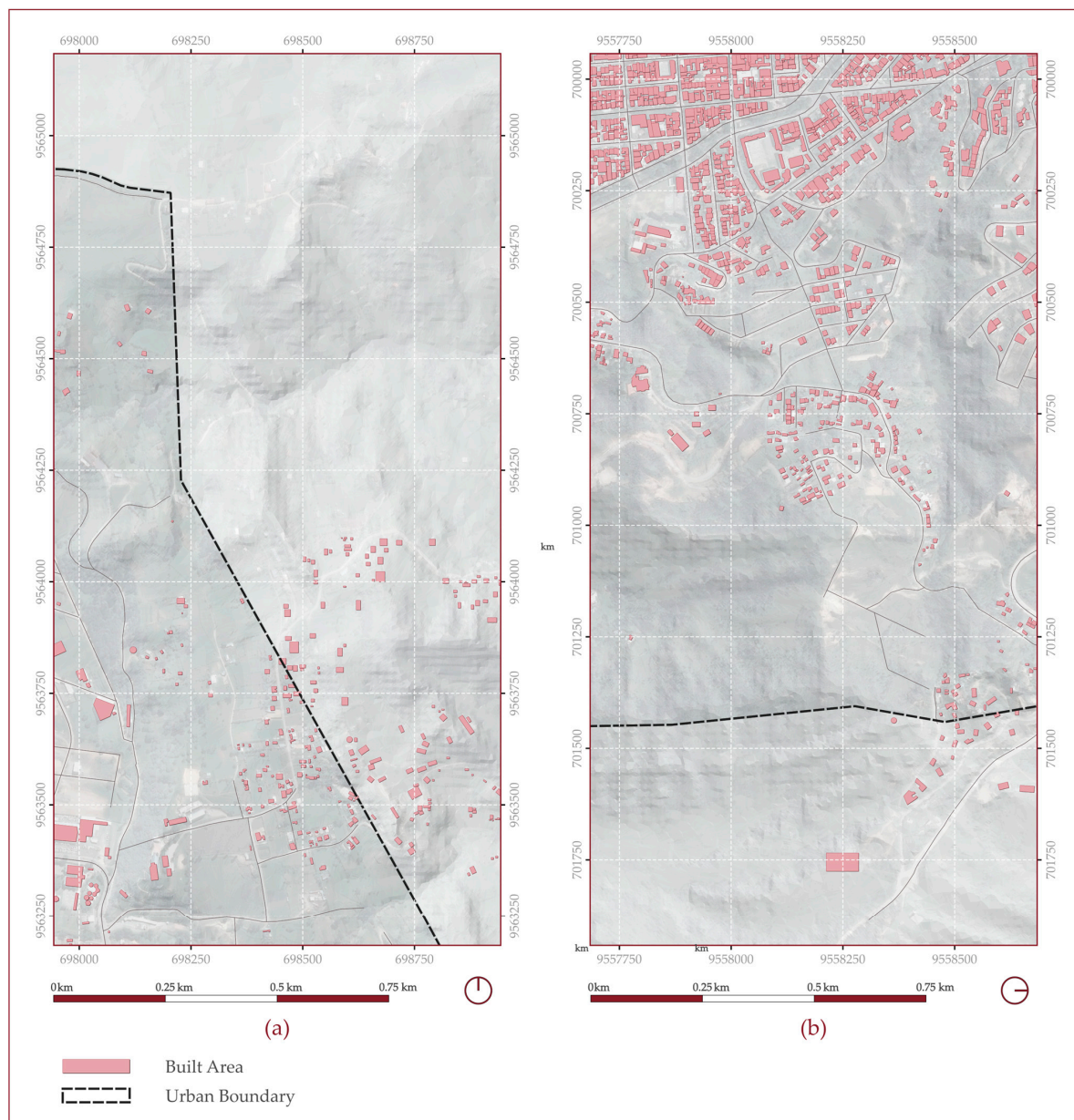


Figure 2. Patterns of porosity and built–void relationships: contrast between fragmentation in Virginpamba (a) and coalescence trends in Orillas del Zamora (b). Source: Municipality of Loja (2019) [30], author’s elaboration.

3.1. Socio-Territorial Characterization and Functional Hybridity

The socio-territorial assessment revealed marked differences in the functional composition of the analyzed polygons. Variations in land-use diversity, productive land persistence, alimentary autonomy, and infrastructure reliance produced contrasting territorial configurations across the urban–rural interface, reflecting different trajectories of socio-spatial transformation.

The distribution of the Degree of Hybridity (DH) values identified three broad territorial patterns (Table 4). The first corresponds to highly integrated configurations characterized by the coexistence of residential, productive, and ecological functions. These territories maintain stronger local productive capacity, greater alimentary autonomy, and lower reliance on external urban systems.

Table 4. Socio-territorial profiles and Degree of Hybridity (DH) across the analyzed polygons.

#	Polygon	Predominant Territorial Profile	LUDI	PSP	ID	AAE	DH
1	El Plateado	Dispersed Residential	5	5	1	5	5.0
2	Motupe	Productive Hybrid	4	4	2	4	4.0
3	Virgenpamba	Agricultural/Residential	4	5	2	3	4.0
4	Menfis	Adaptive Residential	4	3	3	4	3.5
5	Carigán	Logistic/Residential	3	4	3	2	3.0
6	Punzara	Residential/Forest	3	2	4	2	2.25
7	Capulí	Industrial/Residential	2	2	4	2	2.0
8	Orillas del Zamora	Recreational/Linear	2	1	4	2	1.75
9	Jipiro	Equipment/Recreational	1	1	5	1	1.0
10	Zamora Huayco	Edge Residential	2	1	3	1	1.75

Source: Municipality of Loja (2019) [30]; author's elaboration.

A second pattern corresponds to intermediate configurations where productive and residential functions remain present but operate under increasing urban pressure. These territories exhibit mixed spatial arrangements and represent transitional conditions between multifunctional and specialized land-use structures.

The third pattern includes territories characterized by greater functional specialization, reduced productive land availability, and stronger reliance on centralized infrastructure systems. In these areas, urban consolidation becomes increasingly dominant, reducing the coexistence of productive and residential activities traditionally associated with the urban–rural interface.

Overall, the results indicate that socio-territorial complexity is not distributed uniformly across the urban periphery. Instead, the analyzed polygons reveal differentiated trajectories ranging from multifunctional territorial configurations to increasingly specialized urban conditions. This gradient highlights the progressive transformation of productive and mixed-use landscapes under urban expansion pressures.

To further explore the relationships among the analyzed variables, the indicators of Biotic Porosity (BP), Degree of Hybridity (DH), Infrastructure Dependency (ID), and Alimentary Autonomy Extent (AAE) were examined through correlation analysis. The resulting associations are summarized in Figure 3.

The exploratory analysis identified a strong positive association between DH and AAE ($\rho = 0.92$), suggesting that territories characterized by greater multifunctionality also tend to maintain stronger localized food-support capacities. Likewise, a strong inverse relationship was observed between DH and ID ($\rho = -0.88$), indicating that increasing reliance on centralized infrastructure is generally associated with lower levels of socio-territorial integration.

A second inverse association was identified between ID and AAE ($\rho = -0.75$), suggesting that progressive infrastructure dependence may contribute to the reduction in localized productive functions. In contrast, BP and DH exhibited a moderate positive relationship ($\rho = 0.67$), indicating that more permeable territorial configurations tend to support greater multifunctionality, although this relationship is not deterministic.

Taken together, these associations suggest that environmental continuity, productive capacity, alimentary autonomy, and socio-territorial integration operate as interconnected dimensions within the urban–rural interface. However, these relationships should be interpreted cautiously given the limited number of observations included in the analysis ($n = 10$). Consequently, the correlation results are best understood as exploratory evidence

supporting the integrated interpretation of territorial patterns developed in the subsequent analytical phase.

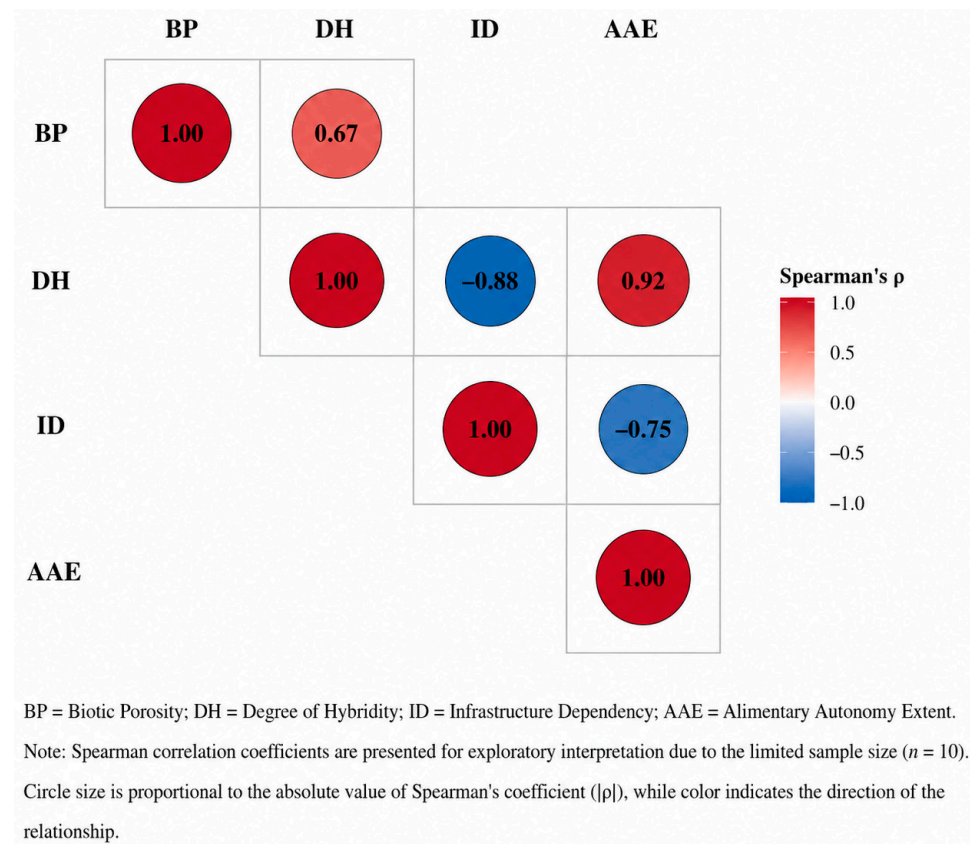


Figure 3. Spearman correlation matrix of the principal socio-territorial indicators across the analyzed polygons. Source: Author's elaboration.

3.2. Identification of Adaptive Tectonic Typologies

The analysis identified three recurrent adaptive tectonic typologies within Loja's urban–rural interface: Terracing, Cantilever, and Platform Urbanization. These typologies reflect different responses to steep topographic conditions and varying levels of urban consolidation. Their distribution across the analyzed polygons is summarized in Table 5.

Table 5. Adaptive tectonic typologies identified in the analyzed polygons.

Tectonic Typology	Polygon(s)	Predominant Adaptive Spatial Characteristics
Terracing	El Plateado; Motupe; Carigán	Stepped residential–productive adaptation integrated with topographic gradients, ecological permeability, and functional continuity between habitation and cultivation areas.
Terracing/Cantilever	Virgenpamba	Hybrid adaptive condition characterized by the coexistence of stepped productive occupation integrated into the slope system and localized cantilevered responses associated with abrupt edge transitions and discontinuous urban encroachment.
Cantilever	Menfis; Punzara; Capulí; Orillas del Zamora	Projecting or suspended tectonic responses associated with abrupt terrain transitions, infrastructural pressure, edge occupation processes, and discontinuous urban encroachment.
Platform Urbanization	Jipiro; Zamora Huayco	Consolidated urban occupation characterized by stronger infrastructural dependence, reduced ecological permeability, and limited integration between productive and residential systems.

Source: Author's elaboration.

The Terracing typology is associated with territories where settlement occupation remains closely adapted to topographic gradients. These configurations are characterized by stepped spatial arrangements that facilitate the coexistence of residential and productive activities while maintaining greater integration with the surrounding landscape.

Cantilever configurations are more frequently associated with abrupt terrain transitions and progressive edge occupation. In these cases, settlement adaptation occurs through projecting or suspended structural responses that accommodate topographic constraints under increasing urban pressure.

Platform Urbanization represents the most consolidated adaptive condition identified in the study area. This typology is characterized by stabilized occupation platforms, greater continuity of the built fabric, and stronger reliance on urban infrastructure networks. Compared with previous typologies, these territories exhibit lower levels of environmental continuity and a greater degree of spatial consolidation.

A particular condition was identified in Virgenpamba, where Terracing and Cantilever responses coexist within the same territorial unit. This overlap illustrates the internal heterogeneity of urban–rural interface environments and suggests that adaptive responses frequently operate as complementary rather than mutually exclusive strategies. Representative examples of the identified typologies are illustrated in Figure 4.

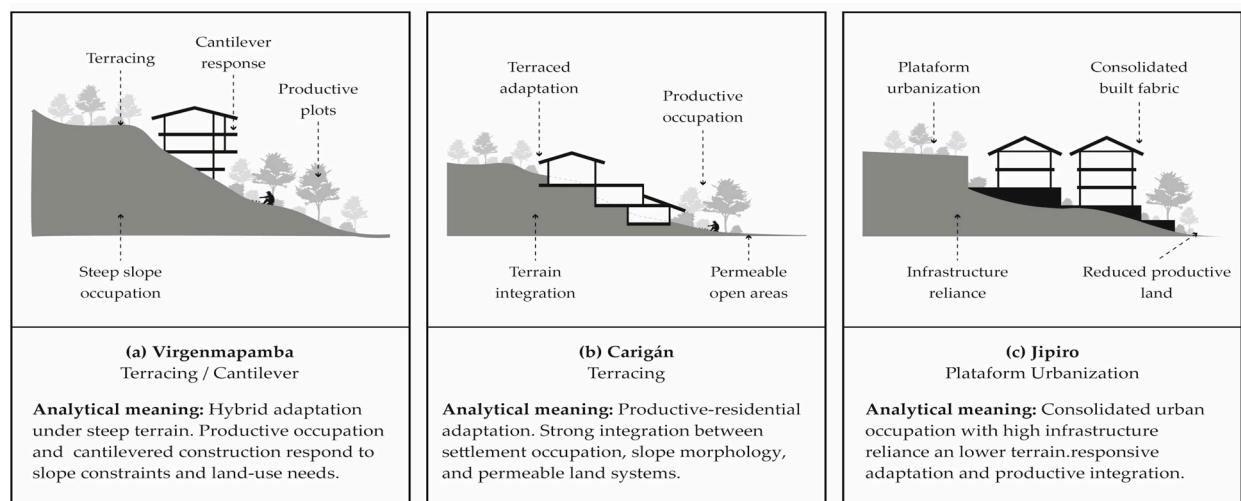


Figure 4. Representative adaptive tectonic typologies identified in Loja’s urban–rural interface: (a) hybrid Terracing–Cantilever condition in Virgenpamba; (b) Terracing in Carigán; and (c) Platform Urbanization in Jipiro. Source: Author’s elaboration based on field surveys and spatial interpretation.

Figure 4 illustrates the analytical contrast among the adaptive tectonic typologies identified in the study. The selected cases do not represent isolated examples, but rather differentiated territorial responses to slope conditions, productive persistence, and degrees of urban consolidation. Virgenpamba exhibits a hybrid condition in which Terracing and Cantilever responses coexist, revealing the internal heterogeneity that characterizes urban–rural interface environments.

Carigán represents a terrain-integrated Terracing condition, where residential and productive functions remain spatially connected through slope-adapted occupation patterns. In contrast, Jipiro exemplifies Platform Urbanization, in which terrain-responsive logics are progressively replaced by stabilized urban structures and greater infrastructural dependence. These differences indicate that adaptive tectonic typologies operate as indicators of territorial adaptation rather than merely as construction forms.

The selected examples demonstrate how terrain-adaptive responses vary according to topographic constraints and settlement consolidation processes. Terracing is associated

with stronger integration between settlement occupation, productive activities, and local topographic conditions, whereas Cantilever responses emerge under increasing spatial constraints and urban expansion pressures. Platform Urbanization reflects more advanced consolidation processes in which terrain-adaptive logics become progressively subordinated to stabilized occupation systems.

Beyond their constructive characteristics, the identified typologies reveal distinct trajectories of territorial adaptation within the urban–rural interface. Together, they demonstrate that topography remains an active factor shaping settlement organization and socio-ecological transitions in intermediate Andean cities. The observed patterns range from landscape-integrated occupation forms to increasingly consolidated urban structures, highlighting the role of adaptive tectonics as a key dimension of urban–rural interface dynamics.

3.3. Integrated Territorial Taxonomy of the Urban–Rural Interface

The integrated assessment of the analyzed polygons revealed differentiated territorial configurations across Loja’s urban–rural interface. Rather than representing a homogeneous expansion zone, the peri-urban edge exhibits distinct territorial dynamics associated with varying degrees of environmental continuity, productive persistence, urban consolidation, and terrain adaptation.

The synthesis of the morphological, socio-territorial, and tectonic dimensions resulted in the identification of three territorial categories: Resilient Edges, Adaptive Edges, and Consolidating Edges. These categories represent different positions along a continuum of territorial transformation operating within the urban–rural interface.

The resulting taxonomy is summarized in Table 6.

Table 6. Territorial taxonomy of the analyzed polygons within Loja’s urban–rural interface.

Taxonomic Category	Integrated Characteristics	Associated Polygons	Territorial Interpretation
Resilient Edge	High or relatively high BP values, elevated DH, strong productive continuity, low-to-moderate ID, and predominance of terracing adaptations associated with ecological permeability	El Plateado, Motupe, Virgenpamba	Territories characterized by strong ecological continuity, productive persistence, and adaptive integration between settlement and topography
Adaptive Edge	Intermediate BP gradients, moderate DH values, mixed productive–residential conditions, and coexistence of terracing and cantilever responses under increasing urban pressure	Carigán, Menfis, Punzara, Capulí	Transitional interface conditions where ecological and productive functions persist but exhibit growing vulnerability to residential specialization and infrastructural consolidation
Consolidating Edge	Reduced DH, stronger ID, limited alimentary autonomy, and predominance of platform urbanization or stabilized occupation systems associated with progressive ecological reduction	Jipiro, Zamora Huayco, Orillas del Zamora	Advanced urban consolidation characterized by reduced ecological permeability, weakened productive continuity, and increasing functional specialization

Source: Author’s elaboration.

The Resilient Edge category includes territories characterized by stronger integration between productive activities, settlement occupation, and environmental support systems. These areas maintain multifunctional territorial structures and exhibit greater capacity to accommodate urban occupation while preserving adaptive relationships with the surrounding landscape.

Adaptive Edges represent transitional conditions in which productive, residential, and environmental functions continue to coexist but are increasingly influenced by urban expansion processes. These territories retain important adaptive characteristics, although signs of functional specialization and greater infrastructure reliance become progressively more evident.

Consolidating Edges correspond to territories where urban stabilization has become the dominant spatial process. In these areas, multifunctional land-use structures are progressively replaced by more specialized urban configurations, resulting in reduced productive capacity and stronger dependence on urban infrastructure networks.

The classification demonstrates that territorial dynamics within Loja's urban–rural interface cannot be explained solely through porosity levels or built-density indicators. Instead, the identified categories emerge from the interaction among environmental conditions, productive capacity, alimentary autonomy, infrastructure reliance, and terrain-adaptive settlement responses. This integrated interpretation helps explain differences among polygons that exhibit similar morphological conditions but contrasting socio-territorial characteristics.

From a systemic perspective, the results indicate that fragmentation and coalescence should be understood as part of a continuous process of territorial transformation rather than as discrete spatial states. The identified categories reveal different trajectories through which settlements adapt to urbanization pressures while maintaining varying degrees of environmental functionality, productive activity, and spatial integration.

The integrated relationships among the identified territorial categories are summarized in Figure 5, which synthesizes the taxonomic structure of Loja's urban–rural interface based on the combined interpretation of the analyzed variables.

The distribution of polygons reveals that resilient conditions tend to be associated with territories where productive activities, ecological continuity, and terrain-adaptive occupation remain active, whereas consolidating conditions are concentrated in sectors characterized by greater urban stabilization, stronger infrastructure dependence, and increasing functional specialization. Adaptive Edges occupy an intermediate position, reflecting ongoing processes of territorial transition.

Figure 5 further demonstrates that the identified territorial categories are not randomly distributed across the urban–rural interface but reflect differentiated socio-ecological trajectories resulting from the interaction among ecological permeability, functional hybridity, productive continuity, infrastructure dependency, and terrain-adaptive settlement responses. Resilient Edges cluster in territories where high levels of biotic porosity coincide with stronger multifunctionality and productive persistence.

In contrast, Consolidating Edges are associated with lower levels of hybridity, greater infrastructural reliance, and more stabilized urban occupation patterns. Adaptive Edges represent transitional territorial conditions in which ecological and productive functions remain active but are increasingly influenced by urban consolidation processes. This differentiation reinforces the interpretation of the urban–rural interface as a heterogeneous territorial continuum shaped by multiple interacting dimensions rather than by urban expansion alone.

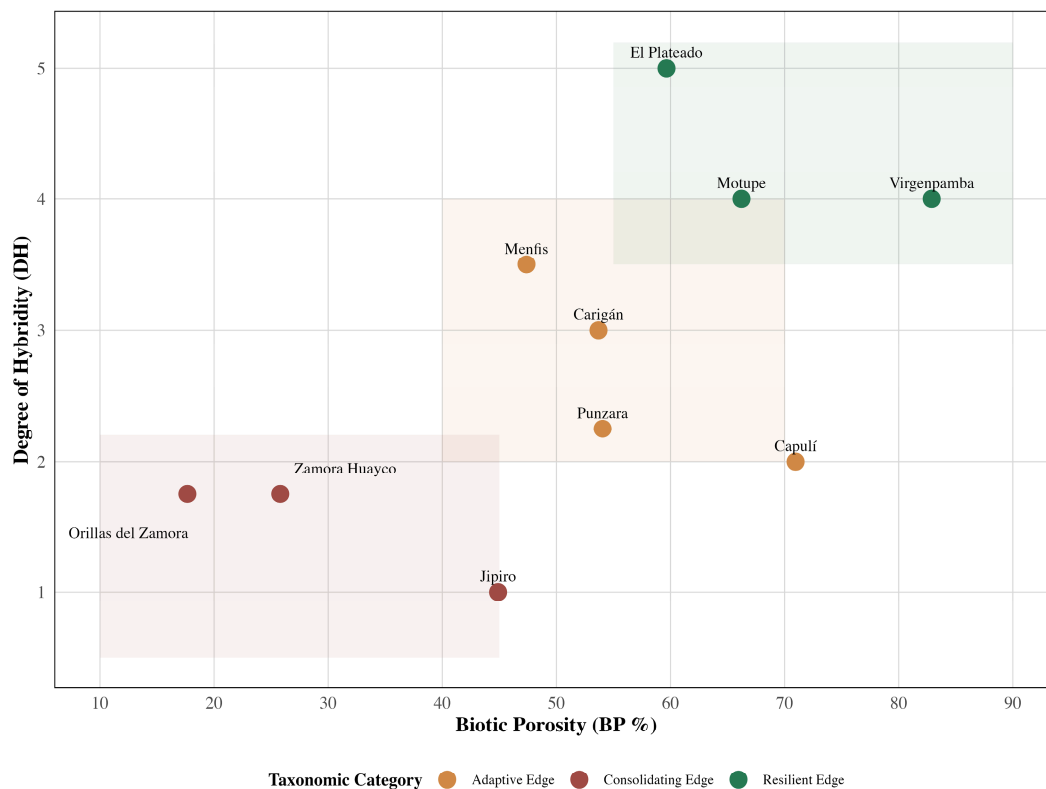


Figure 5. Integrated territorial taxonomy of Loja's urban–rural interface based on the combined interpretation of BP, DH, ID, AAE, and adaptive tectonic typologies. Source: Author's elaboration.

Overall, the proposed taxonomy demonstrates that Loja's urban–rural interface operates as a differentiated socio-ecological system rather than as a residual urban fringe. The identified categories reveal multiple pathways of territorial transformation shaped by the interaction among landscape structure, productive land use, settlement adaptation, and urban consolidation processes. By integrating these dimensions within a single analytical framework, the taxonomy provides a basis for understanding urban–rural dynamics in intermediate Andean cities and supports the development of more context-sensitive planning strategies.

4. Discussion

4.1. Urban–Rural Interfaces as Differentiated Territorial Systems

The results demonstrate that Loja's urban–rural interface cannot be understood as a homogeneous zone of peripheral expansion. Instead, the identified gradients of fragmentation, multifunctionality, and terrain adaptation reveal a differentiated territorial system composed of multiple socio-ecological configurations operating simultaneously across the urban edge.

This finding is consistent with previous studies that describe urban–rural interfaces as dynamic and hybrid environments rather than transitional spaces awaiting complete urbanization [1,2,8,9]. Similar patterns have been documented in peri-urban territories where productive land uses, residential occupation, and environmental functions coexist under varying degrees of urban pressure [19,22,25]. However, the present study suggests that in intermediate Andean cities these interactions are strongly influenced by topographic constraints, generating spatial responses that differ from those observed in more homogeneous metropolitan environments [11,15].

The identification of Resilient, Adaptive, and Consolidating Edges further demonstrates that urban transformation does not follow a linear trajectory. Territories with

similar morphological conditions may exhibit contrasting socio-territorial characteristics depending on the persistence of productive activities, levels of alimentary autonomy, and settlement adaptation strategies. This finding helps explain why built-density indicators alone are often insufficient for understanding territorial performance within urban–rural interfaces [3,8,28].

An important outcome of the study is the recognition that adaptive capacity emerges from the interaction of multiple dimensions rather than from any single territorial attribute. The exploratory relationships observed between biotic porosity, socio-territorial integration, alimentary autonomy, and infrastructure reliance suggest that resilience in Andean urban interfaces is associated with the coexistence of environmental, productive, and settlement functions operating at different spatial scales [5,16,21]. Although these associations should be interpreted cautiously due to the limited sample size, they provide evidence that urban–rural dynamics are better understood through integrated analytical approaches than through sector-specific indicators considered independently.

4.2. Adaptive Tectonics and Territorial Adaptation in Andean Cities

One of the principal contributions of this study is the incorporation of adaptive tectonics as a territorial dimension for interpreting urban–rural interface dynamics. While previous research has primarily focused on land-use change, landscape fragmentation, peri-urban expansion, and settlement morphology [8,9,20,25,28], the present framework explicitly considers how settlement forms respond to topographic constraints and environmental conditions within mountainous territories.

The identified tectonic typologies—Terracing, Cantilever, and Platform Urbanization—demonstrate that adaptation to steep terrain is not merely an architectural or engineering response but also a territorial process that influences the relationship between settlement occupation, productive activities, and environmental support systems. In this sense, adaptive tectonics provides an additional interpretative layer that complements conventional analyses based solely on land cover, density, or spatial expansion indicators [3,12,28].

The findings suggest that terrain adaptation remains an active organizing factor within the urban–rural interface of intermediate Andean cities. Terracing configurations tend to be associated with stronger integration between settlement occupation and local environmental conditions, whereas Platform Urbanization reflects more advanced consolidation processes in which terrain-responsive occupation strategies are progressively replaced by stabilized urban structures. These patterns indicate that topography continues to influence territorial organization even under increasing urbanization pressures.

An unexpected finding is that morphological conditions alone do not necessarily predict socio-territorial performance. Some polygons exhibiting intermediate levels of porosity or urban consolidation maintained adaptive characteristics and productive functions that would not have been identified through conventional morphological indicators alone. This result reinforces the importance of combining spatial, socio-territorial, and tectonic dimensions within a single analytical framework.

Consequently, the concept of adaptive tectonics proposed in this study extends current interpretations of urban–rural interfaces by recognizing terrain-responsive occupation patterns as indicators of territorial adaptation. Rather than viewing topography as a passive physical constraint, the framework interprets it as an active component shaping the evolution of peri-urban landscapes and influencing the capacity of territories to accommodate urban growth while maintaining environmental and productive functions [6,7,10].

4.3. Implications for Planning and Governance of Mountain Cities

The findings have important implications for planning and governance in intermediate mountain cities, where urban expansion frequently occurs under conditions of topographic complexity, environmental sensitivity, and competing land-use demands. The results suggest that urban–rural interfaces should not be treated as residual spaces awaiting urban consolidation, but rather as differentiated territorial systems that perform multiple environmental, productive, and social functions [1,2,22].

Conventional planning approaches often prioritize urban densification, infrastructure provision, and land-use specialization as indicators of development [13,15,20]. However, the territorial patterns identified in this study indicate that such approaches may overlook adaptive capacities embedded within peri-urban landscapes. Productive land systems, terrain-adaptive settlement practices, and multifunctional land-use configurations contribute to territorial performance in ways that are not captured by traditional urban growth metrics [16,21].

The proposed territorial taxonomy provides a practical framework for identifying differentiated planning priorities. Resilient Edges may require conservation-oriented strategies aimed at maintaining productive functions, environmental continuity, and adaptive settlement practices. Adaptive Edges may benefit from targeted interventions that balance urban development with the preservation of multifunctional territorial structures. Consolidating Edges, in contrast, may require measures focused on mitigating environmental degradation, improving connectivity, and enhancing the quality of increasingly specialized urban environments.

The results also highlight the importance of incorporating topographic adaptation into planning processes. In many mountain cities, slope conditions are addressed primarily through engineering or risk-management approaches. The findings of this study suggest that terrain-responsive occupation patterns can also be understood as sources of territorial knowledge that inform more context-sensitive urban development strategies.

More broadly, the framework supports a shift from static land-use classifications toward relational and process-oriented interpretations of urban–rural territories [7,10,22]. Such a perspective may be particularly valuable in rapidly urbanizing mountain regions, where productive land, environmental functions, and urban occupation frequently coexist within the same territorial units.

4.4. Theoretical Contribution, Transferability, and Limitations

The principal theoretical contribution of this study lies in the integration of morphological, socio-territorial, and adaptive tectonic dimensions within a single analytical framework for interpreting urban–rural interfaces. While previous studies have frequently examined landscape fragmentation, land-use change, peri-urban expansion, or settlement morphology as separate processes [8,9,25,28], the proposed approach emphasizes the interactions among environmental structure, productive functions, settlement adaptation, and infrastructure reliance. This integrative perspective contributes to a more comprehensive understanding of urban–rural dynamics in complex territorial environments.

A second contribution is the incorporation of adaptive tectonics as an analytical dimension that links topographic conditions to territorial organization. By recognizing terrain-responsive settlement patterns as indicators of territorial adaptation, the framework extends existing approaches that primarily evaluate urban–rural transitions through land-cover change, urban density, or morphological indicators [3,8,28]. The identified typologies provide a conceptual bridge between spatial morphology and socio-ecological functioning, offering a complementary perspective for the study of mountainous urban environments.

The proposed framework also contributes to current discussions on urban resilience by demonstrating that adaptive capacity emerges from the interaction of multiple territorial dimensions rather than from isolated environmental or infrastructural indicators [5,21]. The identification of Resilient, Adaptive, and Consolidating Edges provides a synthetic structure for interpreting differentiated trajectories of territorial transformation and highlights the heterogeneous nature of peri-urban landscapes.

Although developed in Loja, the framework has potential applicability to other intermediate cities characterized by active urban–rural interfaces, particularly in mountain regions where topography, productive land use, and environmental constraints continue to influence settlement patterns [11,22]. However, transferability should not be interpreted as direct replication. Several variables incorporated in this study are strongly influenced by local environmental and socio-economic conditions. Consequently, indicator thresholds, classification criteria, and interpretation protocols may require contextual adjustment when applied to different geographical settings.

The study presents several limitations. First, the analysis was conducted using a relatively small sample of polygons ($n = 10$), which limits the statistical robustness of the exploratory correlation analysis. Although Spearman's coefficient was appropriate given the ordinal nature of the variables and the sample size, the identified relationships should be interpreted as exploratory rather than predictive. Second, the classification framework relies partially on expert-based interpretation supported by spatial analysis and field verification, introducing an element of interpretative judgment. Third, the research provides a cross-sectional assessment of territorial conditions and does not capture temporal dynamics associated with long-term urban transformation processes.

An additional limitation relates to the restricted sample size available for statistical modeling. Although Spearman correlation provided an appropriate exploratory approach for identifying associations among territorial dimensions, the dataset does not provide sufficient statistical power for robust regression-based modeling or causal inference. Future applications incorporating larger samples could employ multivariate regression techniques to evaluate the relative influence of individual territorial factors on adaptation and resilience processes.

Future research could strengthen the framework through the incorporation of larger samples, longitudinal analyses, and comparative applications across different intermediate cities. Additional work may also explore the integration of socioeconomic, governance, ecosystem-service, and mobility indicators to further improve understanding of urban–rural adaptation processes under conditions of environmental and urban change. Such efforts would contribute to testing the robustness, applicability, and scalability of the framework across diverse territorial contexts.

5. Conclusions

This study examined the urban–rural interface of Loja, Ecuador, through an integrated framework combining morphological, socio-territorial, and adaptive tectonic dimensions. The results demonstrate that the urban periphery operates as a differentiated socio-ecological system rather than as a homogeneous expansion zone. The identified gradients of fragmentation, multifunctionality, terrain adaptation, and urban consolidation reveal diverse territorial trajectories associated with varying capacities for environmental support, productive persistence, and settlement adaptation.

The four-phase analytical framework enabled the identification of three adaptive tectonic typologies—Terracing, Cantilever, and Platform Urbanization—and three territorial categories—Resilient Edges, Adaptive Edges, and Consolidating Edges. Together, these findings show that territorial performance cannot be explained solely through urban

density or land-cover indicators. Instead, the interaction among environmental structure, productive functions, infrastructure reliance, and terrain-responsive occupation patterns provides a more comprehensive understanding of urban–rural dynamics in intermediate mountain cities.

From a planning perspective, the results highlight the need to move beyond conventional approaches that treat peri-urban territories as residual spaces awaiting urban consolidation. The proposed taxonomy offers a practical tool for recognizing differentiated territorial conditions and supporting context-sensitive planning strategies that strengthen adaptive capacity while maintaining environmental and productive functions within urban–rural interfaces.

More broadly, the study contributes to current debates on urban resilience and landscape transformation by demonstrating the value of integrating ecological, socio-territorial, and topographic dimensions within a single analytical framework. Although developed in Loja, the approach provides a basis for future comparative research on urban–rural interfaces in intermediate cities and other mountain environments undergoing rapid territorial change.

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Abbreviations

The following abbreviations are used in this manuscript:

AAE	Alimentary Autonomy Extent
BP	Biotic Porosity
DEM	Digital Elevation Model
DH	Degree of Hybridity
GIS	Geographic Information Systems
ID	Infrastructure Dependency
INEC	National Institute of Statistics and Census (Ecuador)
LUDI	Land-Use Diversity Index

PSP	Productive Soil Presence
PUGS	Land-Use and Management Plan
R	R Statistical Programming Environment
UTPL	Technical University of Loja
GIZ	German Agency for International Cooperation

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