Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Operationalizing the Urban Biotechnosphere Framework for Coastal Resilience Assessment: A Case Study of Manta, Ecuador

Diana Zuleta-Mediavilla

diana.zuleta@ute.edu.ec

UTE University

Natalia Alvarado-Arias

UTE University

Patricio Simbaña-Escobar

University of Seville

Mayte Cuesta-Tabares

Hungarian University of Agriculture and Life Sciences

Research Article

Keywords: Urban Biotechnosphere, Biotechnosphere Equilibrium Ratio, Coastal Resilience, Manta, Ecuador, Sustainable Development Goals, SDG 11, SDG 13, SDG 14, SDG 15

Posted Date: July 3rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10084730/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Operationalizing the Urban Biotechnosphere Framework for Coastal Resilience Assessment: A Case Study of Manta, Ecuador

Diana Zuleta-Mediavilla[1]*, Natalia Alvarado-Arias[1], Patricio Simbaña-Escobar[2] and Mayte Cuesta Tabares[3],

1 LL Liminal Lab Investigation Group, Architecture Department, Faculty of Architecture and Urbanism. UTE University, Quito 170527, Ecuador; diana.zuleta@ute.edu.ec., nathalia.alvarado@ute.edu.ec.
2 Department of Building Construction I, Escuela Técnica Superior de Arquitectura, University of Seville, 41012 Sevilla, Spain; patsimesc@alum.us.es.
3 Department of Landscape Protection and Reclamation, Hungarian University of Agriculture and Life Sciences, 1118 Budapest, Hungary; cuesta.tabares.mayte.alejandra@phd.uni-mate.hu
* Correspondence: diana.zuleta@ute.edu.ec.

Abstract:

In coastal port cities, resilience is shaped by the way urban growth remains in proportion to the natural systems that regulate the territory. This issue is especially visible in intermediate Latin American cities, where planning decisions are made with incomplete data and strong pressure on infrastructure, ecosystems and land. The article applies the urban biotechnosphere framework to assess the relationship between integrated urban development and natural-regulating capacity in Manta, Ecuador, between 2010 and 2024. The analysis uses a composite indicator structure organized around five components: natural component (KP), socio-economic component (KSE), functional component (KF), accessibility component (KD) and spatial-environmental quality component (KOSE). Final operational indicators were normalized, weighted through a theoretically informed AHP structure, and integrated into Kurban and BER. In 2024, BER reached 1.2480, showing that integrated urban development exceeded the estimated natural-regulating capacity by 24.80%. The strongest weakness was KOSE, which declined by 21.60%, followed by a moderate reduction in KP. Although functional capacity and accessibility improved, these advances did not compensate for the deterioration of natural and spatial-environmental conditions. A continuation scenario projects BER = 1.3520 by 2030. The main contribution is a planning-oriented diagnostic index for data-constrained coastal cities. For Manta, returning toward equilibrium depends on linking sanitation, port-city management, green infrastructure, land-use control and ecosystem restoration within the same territorial agenda.

Keywords: Urban Biotechnosphere; Biotechnosphere Equilibrium Ratio; Coastal Resilience; Manta, Ecuador; Sustainable Development Goals; SDG 11; SDG 13; SDG 14; SDG 15

1. Introduction

Coastal cities are among the most complex urban systems because they concentrate population growth, strategic infrastructure, economic activity, and fragile ecosystems within territories highly exposed to climate and environmental change. Their geographical position supports port logistics, fisheries, tourism, trade, and urban expansion, but also increases exposure to sea-level rise, coastal flooding, storm surges, erosion, ecosystem degradation,

and pollution. According to the IPCC, these risks are not only environmental; they also affect public health, infrastructure performance, livelihoods, housing conditions, and the long-term habitability of coastal settlements. For this reason, coastal urban resilience has become a central concern in contemporary urban planning, climate adaptation, and sustainability research [1], [2]

In Latin America, these pressures are intensified by rapid and often uneven urbanization, infrastructure deficits, socio-spatial inequality, and fragmented environmental governance. Many cities in the region have expanded faster than their sanitation, drainage, waste management, ecological protection, and monitoring systems. This generates a cumulative imbalance between demographic growth, technological infrastructure, and the ecological capacity of the territory to absorb or regulate environmental pressures. In such contexts, climate vulnerability cannot be understood only as exposure to natural hazards; it must also be analyzed as the result of interactions among urban growth, infrastructure gaps, pollution, ecosystem loss, and limited institutional capacity. [3], [4]

Coastal ecosystems play a decisive role in this relationship. Mangroves, estuaries, wetlands and coastal green areas contribute to shoreline stabilization, flood regulation, carbon storage, biodiversity conservation, fisheries productivity and livelihood protection. Their ecological functions are especially relevant in cities where built infrastructure alone is insufficient to reduce environmental risk. Yet these ecosystems are increasingly affected by land-use change, hydrological alteration, urban expansion, wastewater discharge, port-related activities and climate change. When the degradation of these systems occurs alongside urban growth, the city may improve in infrastructure or accessibility while simultaneously losing part of the natural capacity that sustains its resilience. [5], [6], [7], [8]

This tension is also visible from an urban-metabolism perspective. Cities operate through continuous flows of energy, water, materials, waste, emissions and land transformation. When these flows expand without adequate environmental regulation or infrastructure performance, urban systems may generate ecological debt and weaken their own resilience [9], [10]. In port cities, this condition becomes particularly relevant because maritime logistics, cargo handling, transportation, industrial activity, wastewater discharge and urban expansion converge in spatially constrained coastal areas. [11], [12]. Therefore, assessing a coastal port city requires an integrated approach that connects population dynamics, infrastructure performance, pollutant loads, spatial quality and ecosystem condition.

Current debates on coastal resilience, urban metabolism and social-ecological-technological systems help to read these interactions from different angles. Coastal resilience emphasizes adaptation to hazards and long-term habitability. Urban metabolism follows the flows of water, energy, materials, waste and emissions that sustain urban life and generate pressure on ecosystems.The social-ecological-technological perspective shows that social conditions, infrastructure and ecological processes operate together rather than as separate layers of the city [13] . For Manta, these perspectives are useful, but they still need an operational structure capable of comparing urban development with natural-regulating capacity through measurable indicators.

Within this broader discussion, the urban biotechnosphere framework offers a complementary approach for examining the balance between human development, technological infrastructure and the biospheric capacity of urban territories. Developed within the tradition of biosphere-compatible urbanism and later operationalized in scientific publications, this framework conceptualizes the city as an integrated system composed of human, functional-technological and natural components. [14], [15]. Its central contribution is the idea that urban development should be assessed not only through demographic, economic or infrastructural growth, but also through its relationship with the natural component that regulates and sustains the system over time.

Figure 1. Conceptual framework of the urban biotechnosphere applied to Manta, Ecuador.



Source: Authors' elaboration based on Bakaeva et al. (2020), Emelianov et al. (2019), and the urban biotechnosphere framework, with AI-assisted graphic design.

The contribution of the biotechnosphere framework lies precisely in this relational reading. It does not ask only whether a city grows, improves infrastructure or expands accessibility. It asks whether that development remains proportionate to the natural-regulating capacity of the territory. For coastal port cities, this distinction is relevant because urban growth, logistics, sanitation, land-use change and ecosystem degradation are not independent processes; they operate together within the same urban-coastal system. Operationalizing this framework can therefore help convert a broad theoretical concern into a planning-oriented diagnostic indicator

Manta, located on Ecuador's central Pacific coast in the province of Manabí, represents a relevant case for this type of assessment. It is one of the province's main urban and economic centers and one of Ecuador's strategic port cities. Its port function connects the city with national and international flows of goods, fisheries, logistics and maritime activity, while its urban expansion places increasing pressure on infrastructure systems and coastal environmental resources. According to official census information, Manta is the second most populated canton in Manabí after Portoviejo, confirming its demographic and territorial importance within the province. [16]

Manta was chosen because it represents a coastal intermediate city where uneven urban development, port activity, infrastructure demand and environmental pressure converge in the same planning problem. Its relevance for this research is not based on assuming that Manta is exceptional, but on recognizing that cities of this type need tools capable of connecting several dimensions at once. Sectoral information on population, services, port activity or vegetation is useful, but it remains insufficient when the planning question concerns the equilibrium of the whole urban-coastal system. Previous research on Manta has described the city as an intermediate port city shaped by demographic growth, urban land consumption, road axes and a fragmented expansion pattern linked to its strategic port vocation. [17] This background gives territorial meaning to the use of a multidimensional diagnostic framework.

This reading is also consistent with concrete planning decisions already documented in Manta. The city has advanced major water, sanitation, drainage and road-renewal works, including a World Bank-supported urban renewal project focused on water and sanitation services, roads, accessibility and mobility [18]. At the same time, recent work on the coastal edge reports fragmented green areas, ecological degradation and weak connectivity in spaces such as Playa Murcielago, Barbasquillo and the Malecon, linking these issues with urbanization pressure and the need for green infrastructure and participatory environmental governance[19]. These references do not replace the empirical matrix of this article, but they help situate why KOSE and functional infrastructure need to be interpreted together in Manta.

The diagnosis of Manta also reflects a common problem in intermediate Latin American cities: limited access to continuous, open and spatially consistent urban-environmental data. Population data are available through national census sources, but annual values require interpolation or projection when yearly demographic records are unavailable. Port-related emissions can be documented through institutional reporting, but they represent the port component of the urban technosphere rather than total citywide emissions. Wastewater treatment information remains more limited at the municipal scale, and satellite-derived indicators of tree cover or coastal vegetation may describe broader territorial trends rather than direct mangrove loss within the urban boundary [20]. These constraints define the level of inference of the article and make transparent data treatment a methodological requirement rather than a secondary detail.

For this reason, transparent and replicable modelling strategies are needed to support environmental planning in contexts where complete local datasets are still under construction. The biotechnosphere framework helps organize heterogeneous indicators and

identify relationships among demographic pressure, infrastructure performance, port activity, spatial quality and ecosystem condition, provided that data provenance, scale and treatment are explicitly declared.

Recent Latin American research also reinforces the value of place-based and indicator-based readings for urban planning in developing contexts. An assessment of urban sustainability perceptions in Lurin, Peru, shows how quantitative indicators support territorial decision-making when urban change, environmental quality and local perceptions need to be interpreted together [21]. Research on Ecuadorian river landscapes and participatory river governance adds another element: technical data become more useful when connected with territorial experience, social value and local environmental knowledge[22], [23] . This regional evidence supports diagnostic frameworks that connect physical, environmental and social dimensions without assuming that one sector explains the whole urban condition.

This reading also connects the article with the Sustainable Development Goals (SDGs). The diagnosis relates directly to sustainable cities and communities, climate action, coastal and marine protection, and terrestrial ecosystem functions, which correspond to SDG 11, SDG 13, SDG 14 and SDG 15. The SDGs are not used here as an additional scoring framework. They provide a policy horizon for understanding why urban growth, sanitation, ecosystem restoration and spatial-environmental quality need to be considered together in coastal planning.

Against this background, the article examines the relationship between integrated urban development and natural-regulating capacity in Manta during the period 2010-2024. The working hypothesis states that urban growth and functional improvement can coincide with a weakening of natural and spatial-environmental components, reducing the equilibrium of the urban-coastal system. The analysis therefore concentrates on the final operational structure that supports the results: KP, KSE, KF, KD, KOSE, Kurban and BER. These components allow the article to connect the problem, the method and the empirical interpretation without depending on statistical procedures that are not reported as central results.

The novelty of the article is methodological and territorial. Methodologically, it translates the biotechnosphere framework into a measurable diagnostic structure through BER, allowing the balance between urban development and natural-regulating capacity to be tracked over time. Territorially, it applies this logic to a Latin American coastal port city where planning decisions must be made despite fragmented data. The contribution is threefold: adapting the biotechnosphere framework to a coastal urban context; proposing BER as a planning-oriented indicator of equilibrium or imbalance; and showing how ecological restoration, sanitation, spatial-environmental quality, port-city environmental management and territorial monitoring can be read as connected dimensions of the same resilience agenda.

2. Materials and Methods

2.1. Methodological Design

The empirical work follows a multivariable design grounded in the urban biotechnosphere framework. Its purpose is to evaluate how the relationship between urban development and natural-regulating capacity changed in Manta between 2010 and 2024. The design is built around the evidence that is available for the city and its broader coastal context, rather than around an ideal dataset that does not yet exist for many intermediate Latin American cities.[14], [15] .

The assessment is exploratory, diagnostic and proportional to the data. It uses a transparent composite-index structure to identify whether Manta's urban-coastal system moved toward equilibrium, ecological overload or reserve natural capacity. The interpretation rests on the component indices, Kurban, BER and the 2030 continuation scenario; additional statistical checks belong in supplementary material when complete outputs are available.

The methodological procedure comprises seven stages: (i) selection and justification of the final operational indicators; (ii) data collection and classification; (iii) normalization of variables; (iv) theoretically informed AHP weighting; (v) construction of component indices; (vi) calculation of Kurban and BER; and (vii) descriptive trend and sensitivity analysis. The construction of the composite index follows general recommendations for transparent indicator design, including explicit indicator selection, normalization, weighting, aggregation and sensitivity assessment.[24], [25], [26]

2.2. Study Area

Manta is located on the central Pacific coast of Ecuador, in the province of Manabí. It is one of the main urban and economic centers of the province and one of Ecuador's strategic port cities. Its urban dynamics combine maritime logistics, fisheries, commerce, tourism, residential growth, infrastructure development and coastal environmental pressure.

Manta was selected because it represents a coastal urban system in which demographic growth, port activity, sanitation infrastructure, accessibility, spatial expansion and ecosystem condition interact within the same territory. Its port function generates economic benefits, but also produces technospheric pressures associated with atmospheric emissions, cargo-related transport flows, energy demand, pollution, land-use conflicts and ecological degradation, which are commonly identified as key environmental challenges in port-city systems [11]. At the same time, the city's coastal location increases its exposure to climate-related hazards, making the condition of natural ecosystems and green infrastructure directly relevant to urban resilience and long-term coastal sustainability. [12]

For analytical purposes, Manta is treated as an urban-coastal system embedded within the broader territorial context of Manabí. Municipal data are used when available; institutional port data are used for port-related indicators; and regional, national or satellite-derived indicators are used as proxies when continuous annual municipal data are incomplete or unavailable. Each indicator is therefore classified according to source, unit, spatial scale, data treatment and methodological reliability (Section 2.5).

2.3. Theoretical Basis of the Indicator System

The urban biotechnosphere framework assumes that a comfortable, safe and sustainable urban environment depends on the balance between the natural environment and the other

components of urban life [1], [2]. Following Bakaeva et al. [14], the study adopts five analytical components:

- KP — natural component;
- KSE — socio-economic component;
- KF — functional component;
- KD — accessibility component;
- $KOSE$ — diversity, structural order and spatial-environmental quality component.

The natural component KP is treated as the *regulating* component of the system, because it represents the ecological capacity of the territory to absorb impacts, regenerate environmental functions and sustain urban life. The remaining components represent the human, infrastructural, accessibility and spatial dimensions of the city.

The general equilibrium condition of the urban biotechnosphere is expressed as:

$$\frac{1}{n}\sum_{i=1}^{n} K_i = KP, \qquad KP \to \max$$

where K_i is the level of implementation of each urban component, n is the number of components considered, and KP is the level of the natural-regulating component. The condition $KP \to \max$ expresses the normative goal of preserving the regulating capacity of the natural component as urban development proceeds.

Following Ilyichev's formulation [15], three systemic states are distinguished. The state of **balanced comfort** (biotechnosphere equilibrium):

$$C1: \quad \frac{1}{n}\sum_{i=1}^{n} K_i \approx KP$$

The state of **fatal comfort** (ecological overload), in which urban and technological pressures exceed the regulating capacity of the natural component:

$$C2: \quad \frac{1}{n}\sum_{i=1}^{n} K_i > KP$$

And the state of **reserve comfort**, in which the natural component retains a greater capacity than the pressure generated by the urban system:

$$C3: \quad \frac{1}{n}\sum_{i=1}^{n} K_i < KP$$

These three states provide the interpretive basis for the empirical equilibrium indicator developed in Section 2.10.

2.4. Indicator Selection and Justification

The indicator set was designed to approximate the main dimensions of the urban biotechnosphere with the information that was available, reconstructable or reasonably proxied for 2010-2024. Five criteria guided selection: theoretical relevance to the Bakaeva-Ilyichev framework [14], [15]; relevance to the coastal urban condition of Manta; availability or reconstructability of annual data for the study period; suitability for normalization; and usefulness for interpreting the relationship between urban development and natural-regulating capacity. The article reports the operational indicator domains used to construct KP, KSE, KF, KD and KOSE; the supplementary matrix documents the final use, source, treatment category and normalized value of each variable.

2.4.1. Natural Component (KP)

The natural component represents the environmental-regulating capacity of the territory and combines a stock indicator of ecological capacity with three pressure indicators: KP_1 coastal vegetation, mangrove or tree-cover area; KP_2 inverse port-related atmospheric emissions; KP_3 inverse wastewater discharge or treatment deficit; and KP_4 inverse solid-waste generation or final-disposal pressure. These indicators are central because KP is the regulating variable of the framework: if KP deteriorates while urban pressure increases, the system moves toward ecological overload.

2.4.2. Socio-Economic Component (KSE)

The socio-economic component represents the demographic and social conditions that generate urban demand: KSE_1 urban population; KSE_2 population density; KSE_3 inverse poverty or unsatisfied basic needs (NBI); and KSE_4 employment or economically active population. These indicators capture demographic magnitude, intensity of occupation, social vulnerability and economic capacity, jointly describing the human demand placed on infrastructure, services, land and natural resources.

2.4.3. Functional Component (KF)

The functional component measures the capacity of the city to provide basic urban services: KF_1 wastewater-treatment coverage; KF_2 drinking-water coverage; and KF_3 sewerage or sanitation-network coverage. These indicators are essential because sanitation, water supply and wastewater treatment directly mediate the relationship between urban growth and environmental quality in a coastal setting.

2.4.4. Accessibility Component (KD)

The accessibility component measures the capacity of the population to reach essential urban functions: KD_1 accessibility to health facilities; KD_2 accessibility to educational facilities; and KD_3 accessibility to public transport or main urban roads. Accessibility is included because the framework treats access to vital urban functions as part of a comfortable and socially oriented urban environment; unequal access can increase vulnerability even where infrastructure exists.

2.4.5. Spatial-Environmental Quality Component (KOSE)

The spatial-environmental quality component represents diversity, structural order, urban form and the relationship between built and green areas: $KOSE_1$ green area per inhabitant or

urban green coverage; $KOSE_2$ inverse built-up expansion or impervious-surface growth; and $KOSE_3$ urban compactness or land-use efficiency. These indicators matter because spatial expansion, impermeabilisation and the loss of green areas affect urban heat, runoff, accessibility and ecosystem continuity.

2.5. Data Sources and Data Treatment

The study period covers 2010–2024. Data are obtained from official, institutional, municipal, satellite-derived and international sources. The main sources are: the National Institute of Statistics and Census (INEC) for population, density, poverty/NBI and employment; the Decentralized Autonomous Government of Manta (GAD Manta), its Land-Use and Development Plan (PDOT) and municipal public-service companies for drinking water, sewerage, sanitation, solid waste, facilities and road networks; the Manta Port Terminal (TPM) for port-related emissions and environmental reports; Global Forest Watch, the Ministry of Environment (MAATE) and satellite/GIS analysis for vegetation, tree cover, mangroves, built-up expansion, impervious surface and green areas; the Ministry of Public Health (MSP) for health facilities; the Ministry of Education (MINEDUC) for educational facilities; and OpenStreetMap or municipal cartography for road and transport accessibility. International databases (e.g., the World Bank) are used as proxies only where continuous local series are unavailable.

Each annual value is classified into one of five data-treatment categories: observed data, obtained directly from official or municipal records; institutional data, obtained from entities responsible for specific urban functions such as port operations; interpolated data, estimated between official reference years such as census years; proxy data, representing the closest available approximation to a missing municipal indicator; and spatially derived data, obtained through GIS, remote sensing or satellite-based analysis. This classification is necessary because the indicators differ in spatial resolution and temporal continuity: population data rest on census values and inter-census projections; port emissions represent the port component of the technosphere rather than total urban emissions; wastewater indicators may require proxies where municipal annual data are incomplete; and vegetation indicators may describe the broader Manabi coastal context rather than the exact administrative limits of Manta. The treatment type of every value should be documented in the Supplementary Material and considered in the robustness checks.

The complete dataset is organized as a longitudinal indicator matrix:

$$X = [x_{ij}]$$

where x_{ij} is the value of indicator j in year i. Rows index years and columns index indicators:

$$i = 2010,2011, \dots ,2024$$

$$j = KP_1, KP_2, \dots , KOSE_3$$

The complete annual data matrix and metadata are treated as Supplementary Material for transparency and reproducibility. This file documents the source, scale, treatment category, normalization direction and use status of each indicator.

2.6. Normalization of Indicators

Because the selected indicators have heterogeneous units, they cannot be directly compared or aggregated. All indicators are therefore transformed into dimensionless values in the interval $[0,1]$ using min–max normalization.

For **positive indicators**, where higher values represent a more favorable condition:

$$K_{ij} = \frac{Q_{ij} - Q_{j,\min}}{Q_{j,\max} - Q_{j,\min}}$$

For **negative indicators**, where higher values represent a less favorable condition, the inverse transformation is applied:

$$K_{ij} = \frac{Q_{j,\max} - Q_{ij}}{Q_{j,\max} - Q_{j,\min}}$$

where K_{ij} is the normalised value of indicator j in year i; Q_{ij} is the observed value; and $Q_{j,\min}$ and $Q_{j,\max}$ are the minimum and maximum values of indicator j over the study period. After transformation, all indicators range from 0 to 1, with values closer to 1 indicating a more favorable condition and values closer to 0 a less favorable condition. Positive indicators include wastewater-treatment coverage, drinking-water coverage, accessibility to health and education facilities, and green area per inhabitant; negative indicators include atmospheric emissions, wastewater discharge, solid-waste pressure, poverty/NBI, built-up expansion and impervious-surface growth.

2.7. Weighting through the Analytic Hierarchy Process

A theoretically informed Analytic Hierarchy Process (AHP) structure is used to make the weighting assumptions explicit and internally consistent. AHP is appropriate because the biotechnosphere framework involves multidimensional criteria that cannot be reduced to raw statistical values alone [25]. In this manuscript, the weighting structure is treated as theoretical and author-defined from the conceptual hierarchy of the framework, unless a formal expert consultation is documented by the authors.

First, the decision hierarchy is defined: the goal is the evaluation of the biotechnosphere equilibrium of Manta; the criteria are the five components KP, KSE, KF, KD and $KOSE$; and the subcriteria are the individual indicators within each component.

Second, pairwise-comparison matrices are constructed according to the theoretical priorities of the framework. In this article, the AHP structure functions as a theoretical weighting scheme derived from the internal logic of the biotechnosphere framework. It makes the weighting assumptions explicit, ordered and internally consistent, while keeping open the possibility of later validation through expert consultation or participatory AHP procedures.

$$A = [a_{ij}]$$

subject to the reciprocal and diagonal conditions:

$$a_{ji} = \frac{1}{a_{ij}}, \qquad a_{ii} = 1$$

Third, the priority (weight) vector is obtained by normalizing each column of A and averaging across rows:

$$w_i = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}}$$

where w_i is the weight of criterion i, a_{ij} is the pairwise-comparison value, and n is the number of criteria.

Fourth, the consistency of the pairwise-comparison matrix is evaluated. The consistency index is:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

where $\lambda_{\max}$ is the maximum eigenvalue of A. The consistency ratio is:

$$CR = \frac{CI}{RI}$$

$RInCR < 0.10CR \geq 0.10$ where is the random index for a matrix of size. A value of is considered acceptable. The resulting AHP weights are used as coefficients in the construction of the component indices and the integrated index. Because the weights express a theoretical modelling decision, an equal-weight comparison is used as a sensitivity check rather than as an alternative claim of objectivity.

2.8. Construction of Component Indices

After normalization and weighting, indicators are aggregated into the five component indices. The general form is:

$$Kc_i = \sum_{j=1}^{m} w_j \, K_{ij}$$

where Kc_i is the component index in year i, w_j is the AHP weight of indicator j, K_{ij} is the normalised value of indicator j in year i, and m is the number of indicators in the component. The five component indices are:

$$KP_i = \sum_{j=1}^{m_{KP}} w_{KP,j} \; K_{KP,ij}$$

$$KSE_i = \sum_{j=1}^{m_{KSE}} w_{KSE,j} \; K_{KSE,ij}$$

$$KF_i = \sum_{j=1}^{m_{KF}} w_{KF,j}\ K_{KF,ij}$$

$$KD_i = \sum_{j=1}^{m_{KD}} w_{KD,j}\ K_{KD,ij}$$

$$KOSE_i = \sum_{j=1}^{m_{KOSE}} w_{KOSE,j}\ K_{KOSE,ij}$$

The weights within each component sum to one:

$$\sum_{j=1}^{m} w_j = 1$$

These indices transform the individual indicators into a structured system representing the main dimensions of the urban biotechnosphere.

2.9. Integrated Urban Development Index

The urban development component integrates the four non-natural dimensions of the model:

$$Kurban_i = w_{KSE}KSE_i + w_{KF}KF_i + w_{KD}KD_i + w_{KOSE}KOSE_i$$

where $Kurban_i$ is the integrated urban development index in year i and w_{KSE}, w_{KF}, w_{KD} and w_{KOSE} are the AHP weights assigned to each urban component. If component-level AHP weights are not applied, equal weights are used:

$$Kurban_i = \frac{KSE_i + KF_i + KD_i + KOSE_i}{4}$$

This index represents the average level of socio-economic, functional, accessibility and spatial-environmental development of the urban system.

2.10. Biotechnosphere Equilibrium Ratio

The Biotechnosphere Equilibrium Ratio (BER) compares the integrated urban development index with the natural-regulating component:

$$BER_i = \frac{Kurban_i}{KP_i}$$

where BER_i is the ratio in year i, $Kurban_i$ is the integrated urban development index, and KP_i is the natural-regulating component. The interpretation follows the three systemic states:

$$BER_i \approx 1 \ \Rightarrow\ C1 \text{ (balanced comfort)}$$

$$BER_i > 1 \ \Rightarrow\ C2 \text{ (fatal comfort / ecological overload)}$$

$$BER_i < 1 \Rightarrow C3 \text{ (reserve comfort)}$$

Because BER is a ratio of normalized indices, it is interpreted comparatively across years rather than as an absolute physical magnitude. The logic is relational: Kurban approximates integrated urban development, while KP approximates natural-regulating capacity. The C1, C2 and C3 states are conceptually derived from the biotechnosphere framework, whereas the numerical BER thresholds used here are proposed as an operational classification for the Manta case study. The ratio therefore translates the Bakaeva-Ilyichev equilibrium principle into a measurable urban-environmental indicator [14] while remaining open to refinement through comparative applications.

2.11. Temporal and Component-Based Diagnostic Analysis

The temporal diagnostic focuses on the evolution of the five component indices, Kurban and BER between 2010 and 2024. The primary analytical objective is to determine whether the relationship between integrated urban development and natural-regulating capacity moved toward equilibrium or imbalance. Component behavior is interpreted jointly with the BER trajectory, the operational classification scale and the 2030 continuation scenario.

The BER trajectory is examined through a linear regression as a function of time:

$$BER_i = \alpha + \beta t_i + \varepsilon_i$$

where BER_i represents the equilibrium ratio in year, α is the intercept, β is the annual trend coefficient, $t_i \; is \; the \; time \; variable$ and $\varepsilon_i$is the residual term. The model is interpreted as a description of the constructed index trajectory.

Given the limited number of annual observations and the use of interpolated, proxy and spatially derived indicators, the article is framed as a diagnostic composite-index assessment. Its evidentiary basis is the internal coherence among component indices, the magnitude and direction of BER, and the consistency between descriptive trends and the 2030 scenario.

The central argument rests on the component indices, Kurban, BER, the descriptive temporal trend and the 2030 continuation scenario. Additional statistical outputs belong in the Supplementary Material only when complete tables, figures and diagnostics are available.

2.12. Sensitivity and Robustness Checks

Sensitivity analysis evaluates the dependence of the interpretation on modelling assumptions. The prioritized checks are: theoretical AHP weights versus equal weights; inclusion versus exclusion of proxy and interpolated indicators; and consistency between component-level trends and the BER trajectory. These checks support the article as a diagnostic composite-index assessment when the supplementary matrix documents sources, treatment categories and normalized values.

2.13. Internal Validation and Transparency

R^2FR^2FInternal validation focuses on the transparency and coherence of the indicator system. It verifies the direction of normalization, the consistency of the AHP matrix, the influence of proxy and interpolated values, and the stability of the BER interpretation under alternative weighting assumptions.

The conclusions are considered robust when the classification of Manta as C2 remains stable across the main sensitivity checks and when the components explaining the imbalance remain consistent with the descriptive results.

2.14. Scenario Analysis to 2030

Exploratory scenarios to 2030 are constructed from the component indices and the Biotechnosphere Equilibrium Ratio. These scenarios are heuristic planning instruments used to compare the continuation of the current trajectory with a resilience-oriented target pathway.

$$Kurban_{2030} = w_{KSE}KSE_{2030} + w_{KF}KF_{2030} + w_{KD}KD_{2030} + w_{KOSE}KOSE_{2030}$$

and the projected equilibrium ratio is:

$$BER_{2030} = \frac{Kurban_{2030}}{KP_{2030}}$$

Each scenario is classified as $C1$, $C2$ or $C3$ depending on whether the projected relationship between urban development and natural-regulating capacity approaches equilibrium, exceeds ecological capacity, or maintains reserve capacity. The contrast between scenarios illustrates the sensitivity of the city–nature balance to coordinated environmental and infrastructural policy.

2.15. Methodological Scope and Limitations

The methodological structure organizes the final operational indicator domains into a multivariable system aligned with the Bakaeva-Ilyichev biotechnosphere framework [14], [15]. It is distributed across natural, socio-economic, functional, accessibility and spatial-environmental components.

Three methodological considerations are central to the interpretation of the results. First, complete annual municipal data are uneven, making it necessary to distinguish observed, interpolated, proxy, institutional and spatially derived values. Second, some indicators operate at spatial scales broader than the municipal boundary. Third, the weighting structure is theoretical unless the authors provide evidence of formal expert consultation. These considerations limit causal claims but strengthen the transparency and reproducibility of the diagnostic model.

Table 1 summarizes the operational indicator structure used to apply the urban biotechnosphere model to Manta, including component, indicator domain, type, source, data treatment and reason for inclusion.

Table 1. Final operational indicator structure used for the urban biotechnosphere analysis of Manta. The table reports the indicator domains used to construct KP, KSE, KF, KD and KOSE; the Supplementary Information

documents raw values, sources, treatment categories, normalization, weights and final use in the calculation matrix.

Component	Indicator	Type	Suggested source	Data treatment	Reason for inclusion
KP	Vegetation / mangrove / tree-cover area	Positive	Global Forest Watch; MAATE; GIS	Spatially derived	Ecological capacity and coastal regulation
KP	Port atmospheric emissions (inverse)	Negative	TPM	Observed / institutional	Technospheric pressure of the port
KP	Wastewater treatment deficit (inverse)	Negative	GADManta ; MAATE; WorldBank (proxy)	Observed / proxy	Pressure on water bodies
KP	Solid waste generated / disposed (inverse)	Negative	GAD Manta; PDOT	Observed / interpolate d	Material urban pressure
KSE	Urban population	Per interpretation	INEC	Observed / interpolate d	Human demand on the system
KSE	Population density	Per interpretation	INEC; GIS	Observed / spatially derived	Intensity of occupation
KSE	Poverty / NBI (inverse)	Negative	INEC	Observed / interpolate d	Social vulnerability
KSE	Employment / EAP	Positive	INEC	Observed / interpolate d	Socio-economic capacity
KF	Wastewater treatment coverage	Positive	GAD Manta; MAATE (proxy)	Observed / proxy	Sanitation capacity
KF	Drinking water coverage	Positive	GAD Manta; INEC	Observed / interpolate d	Basic service provision
KF	Sewerage / sanitation	Positive	GAD Manta; INEC	Observed / interpolate d	Urban infrastructure

	network coverage				
KD	Accessibility to health facilities	Positive	MSP; GIS	Spatially derived	Access to vital facilities
KD	Accessibility to educational facilities	Positive	MINEDUC; GIS	Spatially derived	Access to urban functions
KD	Accessibility to roads / transport	Positive	GAD Manta; OpenStreetMap; GIS	Spatially derived	Territorial connectivity
KOSE	Green area per inhabitant	Positive	GIS / satellite; GAD Manta	Spatially derived	Urban environmental quality
KOSE	Built-up expansion (inverse)	Negative	GIS / satellite	Spatially derived	Spatial pressure
KOSE	Impervious surface (inverse)	Negative	GIS / satellite	Spatially derived	Hydrological and thermal alteration

Notes: Per interpretation indicates an indicator whose normalization direction depends on the analytical reading adopted for the case study and is fixed a priori in the Supplementary Material. EAP = economically active population; NBI = unsatisfied basic needs; TPM = Manta Port Terminal; GAD Manta = Decentralized Autonomous Government of Manta; PDOT = Land-Use and Development Plan.

3. Results

3.1. Multivariable Data Structure and Component Indices

The empirical reading is based on a multivariable data matrix constructed for 2010-2024. The matrix integrates annual indicators grouped according to the urban biotechnosphere framework: the natural component (KP), the socio-economic component (KSE), the functional component (KF), the accessibility component (KD) and the spatial-environmental quality component (KOSE). Rather than evaluating Manta through a single demographic, environmental or infrastructural variable, the analysis reads the interaction among natural regulation, urban demand, service capacity, accessibility and spatial-environmental quality.

Because complete annual municipal values were not available for all indicators, interpolation and proportional estimation were applied when necessary. These procedures allowed the construction of a continuous analytical series for Manta from 2010 to 2024. The results are therefore interpreted as a structured diagnostic analysis supported by observed, institutional, proxy, spatially derived and estimated indicators.

The components of the model are presented in Table 3.

Table 3. Components of the urban biotechnosphere model.

Code	Component name	Meaning in the model	Interpretation
KP	Natural component	Natural-regulating capacity	Vegetation, green areas, ecosystem condition and environmental absorption capacity
KSE	Socio-economic component	Human and demographic pressure	Population, density, socio-economic demand and urban pressure
KF	Functional component	Infrastructure and service capacity	Water, sanitation, wastewater treatment and basic urban services
KD	Accessibility component	Access to essential urban functions	Access to health, education, mobility and socially important facilities
KOSE	Spatial-environmental quality component	Urban form and environmental quality	Green area per inhabitant, built-up pressure, impervious surface and spatial-environmental order

Each component was transformed into an index using 2010 as the baseline year, where a value of 1.0000 represents the 2010 reference condition. Values above 1.0000 indicate growth or increase relative to the baseline, while values below 1.0000 indicate reduction or deterioration relative to the baseline. The estimated component values for 2024 were KP_{2024} = 0.9390, KSE_{2024} = 1.2602, KF_{2024} = 1.2789, KD_{2024} = 1.2107 and $KOSE_{2024}$ = 0.7840. These values show that the natural-regulating component declined by 6.10% relative to 2010, while the socio-economic, functional and accessibility components increased. The strongest deterioration was observed in *KOSE*, which decreased to 0.7840 (a 21.60% reduction relative to the baseline), indicating that spatial-environmental quality is one of the main weaknesses of Manta's urban-coastal system. The complete set of indices and their interpretation is reported in Table 4.

Table 4. Component indices and interpretation, 2010–2024.

Component	**2010**	**2024**	**Change**	**Interpretation**
KP — Natural component	1.0000	0.9390	−6.10%	Natural-regulating capacity declined
KSE — Socio-economic component	1.0000	1.2602	+26.02%	Socio-economic and demographic pressure increased
KF — Functional component	1.0000	1.2789	+27.89%	Functional capacity increased, but also reflects higher infrastructure demand
KD — Accessibility component	1.0000	1.2107	+21.07%	Accessibility improved relative to the baseline

KOSE — Spatial-environmental quality	1.0000	0.7840	−21.60%	Spatial-environmental quality deteriorated
Kurban — Integrated urban index	1.0000	1.1719	+17.19%	Integrated urban development pressure increased
BER — Biotechnosphere Equilibrium Ratio	1.0000	1.2480	+24.80%	Low-to-moderate imbalance

Figure 2. Biotechnosphere component indices, 2010 vs. 2024.

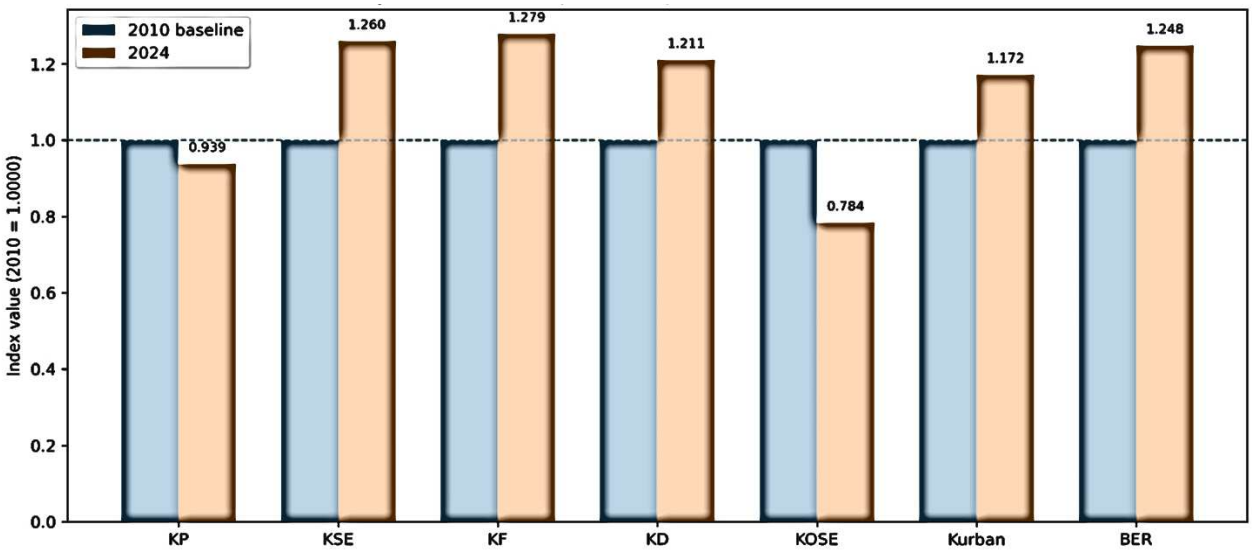


Fig. 2 compares the 2010 baseline with the 2024 values of the five components and the integrated indices. The figure shows that KSE, KF and KD increased over the period, whereas KP and KOSE declined. This divergence is central to the interpretation of the results: the urban system expanded and improved in several service and accessibility dimensions, while the natural and spatial-environmental components weakened. The most pronounced decrease is observed in KOSE, which is consistent with spatial-environmental deterioration being a key factor in the loss of equilibrium

3.2. AHP Weighting Procedure and Integrated Urban Index

The Analytic Hierarchy Process (AHP) was used to assign weights to the components of the model. The weighting structure follows the theoretical hierarchy of the Bakaeva-Ilyichev biotechnosphere framework, where the natural component has a regulating function and the other components represent different dimensions of urban development and pressure.

The component weights were w_{KP} = 0.35, w_{KF} = 0.25, w_{KSE} = 0.18, w_{KOSE} = 0.12 and w_{KD} = 0.10, which sum to unity:

$$w_{KP} + w_{KF} + w_{KSE} + w_{KOSE} + w_{KD} = 0.35 + 0.25 + 0.18 + 0.12 + 0.10 = 1.00$$

The pairwise-comparison matrix was constructed from these theoretical priorities. Because the weighting was derived by the authors from the conceptual hierarchy of the framework, it is interpreted as a theoretical AHP weighting scheme. Later applications can validate or

adjust these weights through expert consultation, participatory AHP procedures or comparison with equal-weight scenarios.

Table 5. AHP theoretical pairwise-comparison matrix.

Component	*KP*	*KSE*	*KF*	*KD*	*KOSE*	Weight
KP	1.000	1.944	1.400	3.500	2.917	0.35
KSE	0.514	1.000	0.720	1.800	1.500	0.18
KF	0.714	1.389	1.000	2.500	2.083	0.25
KD	0.286	0.556	0.400	1.000	0.833	0.10
KOSE	0.343	0.667	0.480	1.200	1.000	0.12

The consistency of the matrix was evaluated using the consistency index (*CI*) and the consistency ratio (*CR*):

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

For the proposed matrix, λ_{max} = 5.000, CI = 0.000 and CR = 0.000 < 0.10. The weighting matrix is mathematically consistent. Because the weights are theoretically defined by the authors, later applications can validate or adjust this structure through formal expert consultation or participatory processes.

The integrated urban development index, *Kurban*, was calculated from the four non-natural components (*KSE*, *KF*, *KD* and *KOSE*). The natural component *KP* was excluded from *Kurban* because it functions as the regulating component against which urban pressure is compared:

$$Kurban_i = \frac{w_{KSE}\, KSE_i + w_{KF}\, KF_i + w_{KD}\, KD_i + w_{KOSE}\, KOSE_i}{w_{KSE} + w_{KF} + w_{KD} + w_{KOSE}}$$

Replacing the weights:

$$Kurban_i = \frac{0.18\, KSE_i + 0.25\, KF_i + 0.10\, KD_i + 0.12\, KOSE_i}{0.65}$$

For 2024:

$$Kurban_{2024} = \frac{0.18(1.2602) + 0.25(1.2789) + 0.10(1.2107) + 0.12(0.7840)}{0.65}$$

$$Kurban_{2024} = \frac{0.2268 + 0.3197 + 0.1211 + 0.0941}{0.65} = 1.1719$$

This result indicates that the integrated urban development index increased by 17.19% relative to the 2010 baseline, mainly associated with the rise of *KSE*, *KF* and *KD*. The reduction of *KOSE*, however, suggests that this urban-development trajectory is not spatially or environmentally balanced.

3.3. Biotechnosphere Equilibrium Ratio and Operational Classification

The Biotechnosphere Equilibrium Ratio (*BER*) was calculated by comparing *Kurban* with the natural component *KP*:

$$BER_i = \frac{Kurban_i}{KP_i}$$

For 2024:

$$BER_{2024} = \frac{1.1719}{0.9390} = 1.2480$$

This result means that, in 2024, the integrated urban development index exceeded the estimated natural-regulating component by 24.80%. The original biotechnosphere framework defines C1, C2 and C3 conceptually; the numerical BER ranges used here are proposed as an operational classification for the Manta case study.

Table 6. Operational interpretation scale for *BER*.

BER range	State	Interpretation	Meaning
BER < 0.75	*C3* strong reserve	Strong natural reserve	Natural capacity substantially exceeds urban pressure
0.75 ≤ BER < 0.90	*C3* moderate reserve	Moderate natural reserve	Natural capacity remains higher than urban pressure
0.90 ≤ BER ≤ 1.10	*C1* equilibrium	Approximate harmony	Urban development and natural capacity are approximately balanced
1.10 < BER ≤ 2.50	*C2* low-to-moderate imbalance	Urban pressure exceeds natural capacity	The system is outside equilibrium but not yet critical
2.50 < BER ≤ 5.00	*C2* high imbalance	Strong ecological pressure	Urban development is highly incompatible with natural regulation
BER > 5.00	Critical *C2*	Severe structural imbalance	Urban pressure greatly exceeds natural-regulating capacity

According to this scale, BER2024 = 1.2480 satisfies 1.10 < 1.2480 <= 2.50, so Manta is classified as C2 - low-to-moderate imbalance. The value remains close to the lower limit of C2, indicating that the imbalance requires corrective action but has not reached the highest operational category.

Figure 3. Evolution of the Biotechnosphere Equilibrium Ratio for Manta, 2010–2024.

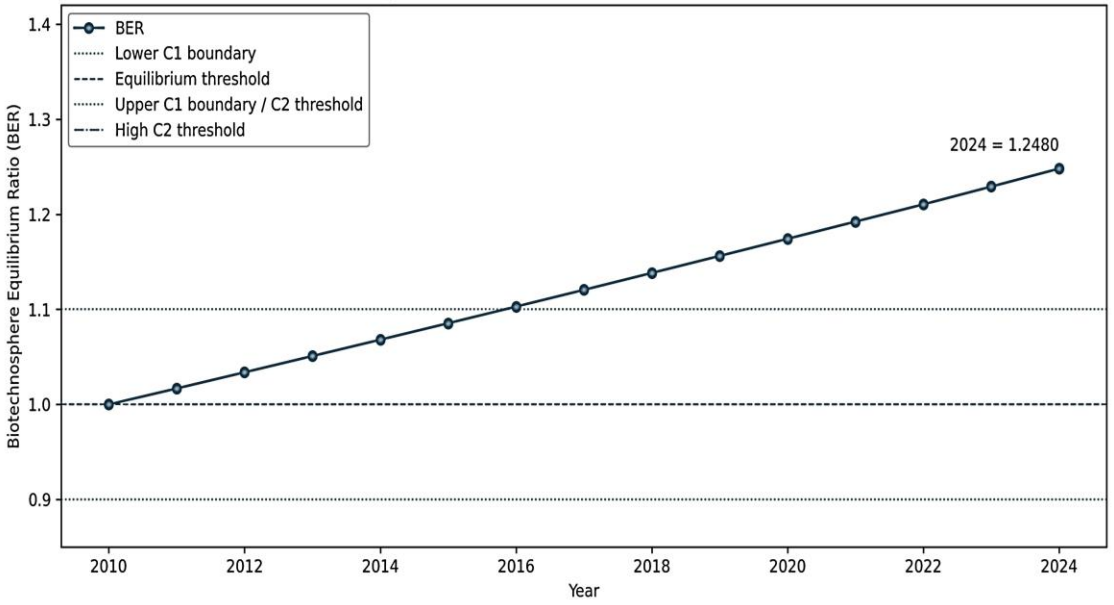


Fig. 3 shows the evolution of BER between 2010 and 2024. The index increases from 1.0000 to 1.2480, moving beyond the C1 equilibrium range and into the C2 low-to-moderate imbalance range. This trajectory indicates a gradual but persistent departure from equilibrium and suggests that urban-functional pressure increased faster than the natural-regulating component over the study period.

3.4. Component Weaknesses Explaining the Imbalance

The *BER* result must be interpreted through the behavior of the components. The main weakness is observed in *KOSE*, which declined from 1.0000 to 0.7840, a 21.60% deterioration in spatial-environmental quality relative to 2010. This decline is consistent with pressure associated with built-up expansion, reduced green-area availability, impervious-surface growth and the loss of spatial-environmental order. The second weakness is the decline of *KP*, from 1.0000 to 0.9390, indicating that the natural-regulating capacity weakened by 6.10%; although moderate, this decline becomes more significant when compared with the growth of the urban components. By contrast, *KSE* increased to 1.2602 (a 26.02% increase in demographic and socio-economic pressure), *KF* increased to 1.2789 (improved infrastructure and services but also higher demand on the urban system), and *KD* increased to 1.2107 (better access to urban functions). These improvements in *KF* and *KD* do not compensate for the decline in *KP* and *KOSE*.

The desired equilibrium condition can be expressed as $Kurban_i \approx KP_i$. For 2024, $Kurban_{2024}$ = 1.1719 and KP_{2024} = 0.9390, so the absolute gap is:

$$Kurban_{2024} - KP_{2024} = 1.1719 - 0.9390 = 0.2329$$

In relative terms:

$$\frac{Kurban_{2024} - KP_{2024}}{KP_{2024}} \times 100 = \frac{1.1719 - 0.9390}{0.9390} \times 100 = 24.80\%$$

This gap explains why Manta is classified as *C2*. The imbalance is not caused by a single isolated factor but by the combined effect of increasing socio-economic and functional demand, declining spatial-environmental quality and weakening natural-regulating capacity.

Figure 4. Percentage change of biotechnosphere components, 2010–2024.

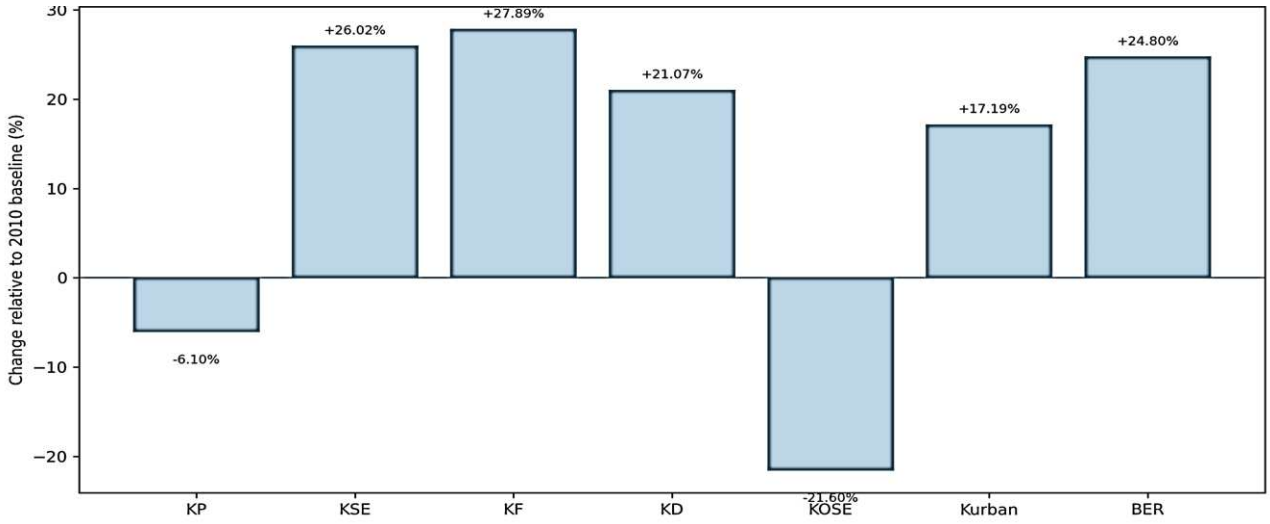


Fig. 4 shows the percentage change of each component between 2010 and 2024. KOSE presents the strongest negative change, followed by KP, while KSE, KF and KD increased. This contrast visually summarizes the imbalance: urban demand and functional expansion increased, whereas spatial-environmental quality and natural-regulating capacity declined.

3.5. Statistical Trend Analysis of the Equilibrium Ratio

A descriptive trend analysis was applied to the BER values for 2010-2024. The objective was to evaluate whether the equilibrium ratio shows a consistent temporal tendency. The linear trend was specified as:

$$BER_i = \alpha + \beta t + \varepsilon_i$$

and the estimated tendency was:

$$BER_i = 0.9980 + 0.0177\, t$$

where t = 0 corresponds to 2010. This indicates that BER increased by approximately 0.0177 units per year during the study period, a tendency consistent with the observed increase from 1.0000 in 2010 to 1.2480 in 2024. Because BER is derived from the component indices, the trend model is interpreted as a description of the constructed index trajectory rather than as independent causal evidence; the key finding is the direction and magnitude of the index —

its progressive movement from the C1 equilibrium range toward a low-to-moderate C2 imbalance — not the explanatory power of a causal model.

3.6. Projection of the Biotechnosphere Equilibrium to 2030

A continuation scenario for Manta was estimated using the observed tendency between 2010 and 2024. This scenario extends the current BER trajectory as an exploratory planning reference. Using the trend equation:

$$BER_i = 0.9980 + 0.0177\,t$$

for 2030 (t = 20):

$$BER_{2030} = 0.9980 + 0.0177(20) = 1.3520$$

According to the operational scale proposed in this article, this value remains within the range 1.10 < BER <= 2.50, so under a continuation scenario Manta remains in C2 - low-to-moderate imbalance. The projection also places the city farther from the C1 equilibrium range. A resilience-oriented target requires reducing the index toward BER2030 -> 1.0000, which corresponds to the condition Kurban2030 ≈ KP2030. In policy terms, returning toward C1 requires strengthening KP, improving KOSE and ensuring that functional infrastructure reduces environmental pressure rather than simply accompanying urban expansion.

Figure 5. BER projection for Manta to 2030.

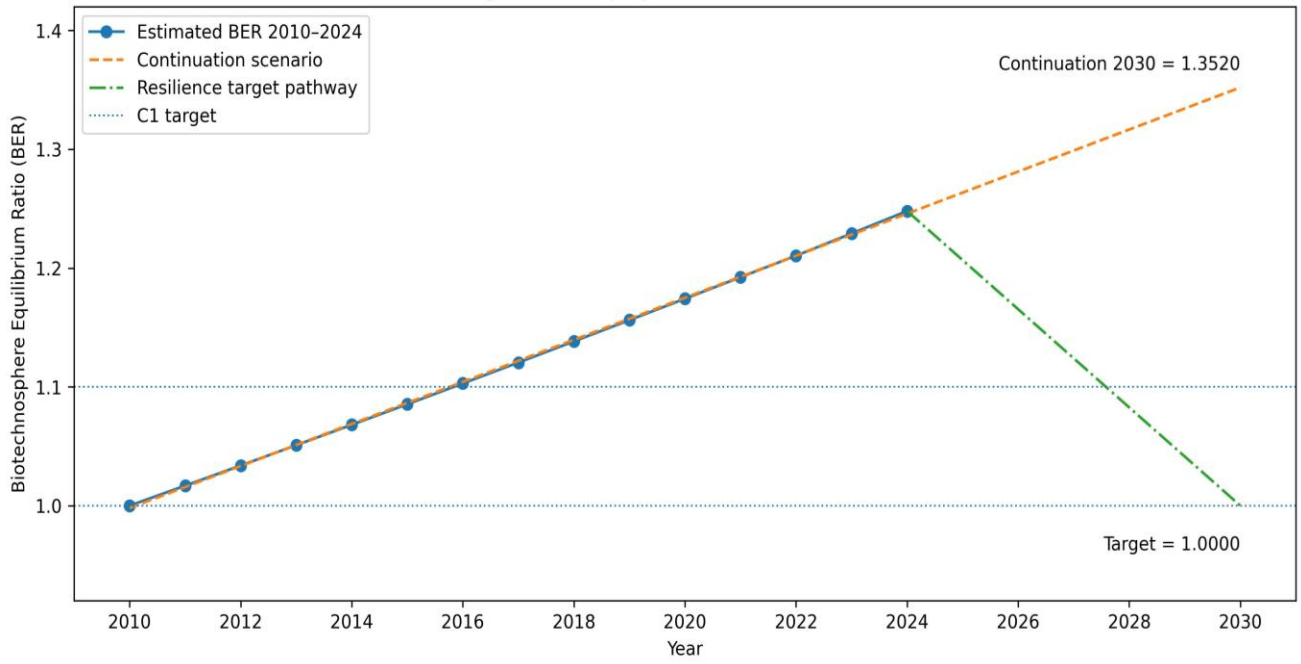


Fig. 5 compares the continuation scenario with a resilience-oriented target pathway. The continuation scenario projects BER2030 = 1.3520, keeping Manta in C2 and farther from equilibrium, whereas the resilience target pathway shows the desired transition toward BER = 1.0000, the operational condition for C1 equilibrium. The figure illustrates the difference between continuing the current trend and orienting policy toward biotechnosphere equilibrium.

3.7. Synthesis of Results

The central empirical signal is BER2024 = 1.2480, placing Manta in a state of C2 low-to-moderate biotechnosphere imbalance: integrated urban development exceeds the natural-regulating component by 24.80%. The weakest dimension is KOSE, followed by the decline of KP, which links the imbalance to spatial-environmental quality and natural-regulating capacity. Improvements in KF and KD did not compensate for the growth of socio-economic pressure and the deterioration of the natural-spatial system. Under the continuation scenario, BER would increase to 1.3520 by 2030. The biotechnosphere reading therefore indicates that Manta's transition toward equilibrium depends on restoring natural capacity, improving spatial-environmental quality, controlling urban expansion, reducing environmental pressure and ensuring that infrastructure development contributes to ecological balance.

4. Discussion

4.1. Interpretation of the Biotechnosphere Imbalance in Manta

Manta's urban-coastal system has moved away from its initial equilibrium reference condition and entered a low-to-moderate state of biotechnosphere imbalance. Over the study period, the Biotechnosphere Equilibrium Ratio increased from BER = 1.0000 in 2010 to:

$$BER_{2024} = 1.2480 \;\Rightarrow\; C2 \text{ (low-to-moderate imbalance)}$$

This increase describes a system in transition. Manta remains below the highest imbalance categories, yet its urban-functional trajectory is no longer proportionate to the ecological and spatial-environmental components that sustain long-term habitability. The interpretation follows the logic of the urban biotechnosphere framework: improvements in socio-economic demand, functional capacity or accessibility acquire resilience value only when they remain aligned with the regulating capacity of KP[14], [15].

4.2. The Critical Role of KOSE and KP

The behavior of the *BER* must be interpreted through the behavior of the components rather than as an isolated value. The principal weakness identified in the system is the deterioration of the spatial-environmental quality component:

$$KOSE_{2024} = 0.7840$$

which corresponds to a reduction of 21.60% relative to the 2010 baseline. This decline can be interpreted as evidence that spatial-environmental quality has become one of the most

vulnerable dimensions of Manta's urban-coastal system. In conceptual terms, *KOSE* expresses urban form, the availability of green areas, impervious-surface dynamics, ecological continuity and the spatial organization of growth; its deterioration therefore suggests that the imbalance is not explained only by population or infrastructure demand, but also by the way in which the city is spatially structured.

The second critical component is the natural-regulating component:

$$KP_{2024} = 0.9390$$

Although numerically moderate, this decline is significant because KP is the regulating component of the model. In the biotechnosphere framework, the natural component forms the basis that enables long-term comfort, safety and habitability. [14], [15]. Consequently, even a moderate reduction in KP becomes relevant when the socio-economic and functional components grow simultaneously:

$$Kurban_{2024} = 1.1719, \qquad Kurban_{2024} > KP_{2024}$$

This inequality summarizes the imbalance: the rise of KSE, KF and KD does not compensate for the decline of KP and KOSE. The framework makes this contradiction visible. A city can expand services, improve accessibility and increase functional capacity while still drifting away from equilibrium when the natural and spatial-environmental components weaken. This is one of the main interpretive contributions of the approach: it avoids treating urban growth or infrastructure expansion as sufficient evidence of sustainable development [14]

4.3. Theoretical Contribution of the Biotechnosphere Equilibrium Ratio

One methodological contribution of the article is the operationalization of the biotechnosphere framework through a measurable ratio. The original framework defines the states C1, C2 and C3 conceptually, according to the relationship between the average development of the urban components and the natural component. BER translates that principle into a diagnostic ratio:

$$BER_i = \frac{Kurban_i}{KP_i}$$

The interpretation is direct: BER ≈ 1 indicates approximate equilibrium; BER > 1 indicates that integrated urban development exceeds natural-regulating capacity; and BER < 1 indicates reserve natural capacity. The operational thresholds applied in this article classify the distance from equilibrium in the Manta case study. Comparative applications in other coastal cities, expert consultation and sensitivity analysis can refine these thresholds. In this sense, BER is best understood as a diagnostic bridge between systemic theory and planning practice: it translates an abstract equilibrium principle into a monitorable indicator without reducing the complexity of the urban-coastal system to a single causal mechanism.

4.4. Planning and Policy Implications for Manta

For planning, the case of Manta shows why coastal resilience cannot be reduced to infrastructure provision or isolated environmental actions. The increase in functional and accessibility components suggests improvement in some dimensions of urban development. However, the simultaneous decline of KOSE and KP indicates that these improvements have not been sufficient to maintain equilibrium with the natural-regulating capacity of the territory. Infrastructure contributes to resilience only when it reduces pressure on the natural component and improves the spatial-environmental quality of the urban system. This interpretation is consistent with urban-metabolism research, which links urban sustainability to the organization of flows of water, energy, materials, waste and emissions [9], [10], and with port-city literature, where environmental challenges emerge from the concentration of logistics, transport, industry, waste generation and coastal ecological pressure within the same territory[11], [12].

KOSE is especially important because it connects urban form with environmental performance. A city can expand services and improve connectivity while still increasing impervious surfaces, reducing green areas, fragmenting ecological continuity or weakening the spatial conditions that support environmental regulation. For this reason, KOSE is not a secondary landscape variable. It expresses the territorial form through which environmental pressures are produced, accumulated or mitigated.

4.5. Interpretation of the 2030 Projection

The projection to 2030 reinforces this interpretation. It is constructed as an analytical extension of the tendency observed between 2010 and 2024. Using the estimated linear trend of the equilibrium ratio:

$$BER_i = 0.9980 + 0.0177\,t$$

with t = 0 corresponding to 2010, the projection for 2030 (t = 20) is:

$$BER_{2030} = 0.9980 + 0.0177(20) = 1.3520$$

The projected value keeps Manta within the C2 low-to-moderate imbalance range, but farther from the C1 equilibrium threshold. Its analytical value lies in showing the direction of the system under current tendencies. In this sense, BER works as an early-warning indicator: it does not explain every causal mechanism behind urban-environmental change, but it helps identify when the overall trajectory of the city is moving away from equilibrium.

$$BER_{2030}^{\text{target}} \rightarrow 1.0000, \qquad Kurban_{2030} \approx KP_{2030}$$

In practical terms, future urban development in Manta needs to strengthen the natural-regulating component, improve spatial-environmental quality and ensure that infrastructure expansion contributes to ecological balance.

Similar lessons appear in post-disaster planning research in Manabí. Work on Ecuadorian housing resettlements after the 2016 earthquake emphasizes that long-term urban wellbeing depends on design processes connected with local geography, social conditions, public space and the capacity to co-produce solutions with local actors [27]. For this article, that lesson reinforces the planning meaning of BER: the indicator does not prescribe a

single intervention, but it helps identify when several sectors need to be coordinated in the same territorial agenda.

4.6. Methodological Caution and Data Constraints

Interpretation remains tied to the nature of the underlying data. The analysis combines observed, institutional, proxy, interpolated and spatially derived indicators because continuous municipal series are not available for every variable. This is not a minor technical detail; it reflects the way many intermediate Latin American cities still produce and share environmental information. The value of the method depends on making these decisions visible and traceable.

BER and the component indices work as a structured diagnostic approximation. They organize available evidence, show which components explain the imbalance and point to where planning needs to intervene. For this reason, the annual matrix and metadata are part of the scientific argument, not only supporting material. They show how each value was treated before it became part of KP, KSE, KF, KD, KOSE, Kurban or BER.

For Manta, the value of this reading is not that it reduces the territory to a single number. The value lies in forcing several dimensions of the urban-coastal system to be interpreted together. Place-based research on participatory river governance in Ecuador and sustainability perceptions in Peru has shown that urban socio-environmental problems are experienced through specific landscapes, infrastructures, public spaces and local forms of knowledge [22], [23]. BER adds a comparable diagnostic layer to that discussion by linking the spatial form of growth with the natural capacity that supports urban life.

From the perspective of the SDG agenda, this contribution is practical rather than rhetorical. SDG 11 places cities, safety and resilience at the center of sustainable development; SDG 13 frames climate adaptation as a development concern; SDG 14 and SDG 15 remind planning institutions that coastal and terrestrial ecosystems are part of the same environmental support system. In Manta, these goals meet in very concrete decisions: where urban expansion is allowed, how sanitation infrastructure is prioritized, how port-related pressures are managed, how green areas are protected and how coastal vegetation is restored. BER does not measure the SDGs directly, but it gives planners a way to read whether those decisions are moving in the same direction or pulling the city apart. This is useful in a context where responsibilities are distributed across municipal, port, environmental and community actors.

4.7. Contribution to Biotechnosphere Research and Coastal Urban Resilience

Beyond the specific case, the article contributes to biotechnosphere research by bringing a mainly conceptual framework into an applied urban-coastal context. The Manta case makes visible a planning problem that is difficult to see through isolated indicators: a city can improve accessibility and functional infrastructure while losing spatial-environmental quality and natural-regulating capacity. This relational reading is the main reason for using BER.

Taken together, the evidence supports a clear but cautious interpretation: in 2024, Manta presents a low-to-moderate C2 imbalance because integrated urban development exceeds the natural-regulating component. The imbalance remains within a range where corrective

action is feasible, but the continuation scenario indicates that it can deepen by 2030. The transition toward C1 requires restoring the balance between urban development, spatial-environmental quality and natural-regulating capacity.

5. Conclusions and Recommendations

The urban biotechnosphere framework made it possible to assess the relationship between integrated urban development and natural-regulating capacity in Manta, Ecuador, between 2010 and 2024. Five components - KP, KSE, KF, KD and KOSE - were used to calculate Kurban and BER. This structure kept the analysis focused on what the available data support: the proportional relation between the city's development trajectory and its natural-regulating base.

Manta moved away from its 2010 equilibrium reference condition. BER increased from 1.0000 in 2010 to 1.2480 in 2024, indicating that integrated urban development exceeded the estimated natural-regulating capacity by 24.80%. According to the operational scale proposed for this case, the city is classified as C2, a low-to-moderate imbalance condition.

$$BER_{2024} = 1.2480$$

The imbalance is explained mainly by the deterioration of the spatial-environmental quality component *KOSE*, which decreased to 0.7840 in 2024, and by the decline of the natural component *KP*, which decreased to 0.9390. These results suggest that the central challenge for Manta is not only demographic growth or infrastructure demand, but the weakening of spatial-environmental quality and natural-regulating capacity. Although the functional component *KF* and the accessibility component *KD* increased over the period, these improvements were not sufficient to compensate for the decline in KP and KOSE.

The 2030 continuation scenario projects BER = 1.3520, keeping Manta within the C2 range and moving the city farther from the C1 equilibrium threshold. The projection is an early-warning signal derived from the observed trajectory, not a deterministic forecast.

$$BER_{2030} = 1.3520$$

A methodological contribution lies in translating the biotechnosphere framework into an operational diagnostic index applicable to a coastal Latin American city. BER does not replace detailed environmental, hydrological or spatial studies; its value is to monitor whether the relationship between urban development and natural-regulating capacity is moving toward equilibrium or imbalance.

$$BER_i = \frac{Kurban_i}{KP_i}$$

For Manta, strengthening the natural component KP needs to become a central resilience strategy rather than a secondary environmental action. This requires protecting and restoring coastal vegetation, green areas, ecological corridors and natural buffers capable of improving environmental regulation.

Recovering KOSE is equally important because the form and quality of urban space influence environmental comfort, runoff, heat exposure and ecosystem connectivity. Planning

therefore needs to control built-up expansion, reduce impervious-surface growth, increase green area per inhabitant, improve the continuity of public and ecological spaces and integrate nature-based solutions into urban development.

Functional infrastructure needs to be oriented toward environmental performance. Service expansion is necessary, but its resilience value depends on reducing pressure on the natural system. Priority must be given to wastewater treatment, sanitation improvement, solid-waste management, water efficiency and infrastructure that reduces pollutant loads and supports ecological regeneration.

BER also works as a monitoring tool for urban planning. Periodic calculation allows local authorities, planners, researchers and decision-makers to assess whether Manta is moving toward C1 equilibrium or deeper into C2 imbalance.

The municipal data system remains a priority. Future applications need more precise annual data on wastewater treatment, emissions, solid waste, green areas, impervious surfaces, accessibility, land-use change and ecosystem condition. The AHP weighting scheme and the BER thresholds also require validation through expert consultation, participatory processes and comparative applications in other coastal or port cities.

The results reinforce the need for systemic perspectives in public policy. For Manta, the transition toward equilibrium is not a sequence of isolated sectoral actions. It is a planning agenda that connects sanitation, port-city environmental management, land-use control, green infrastructure, territorial monitoring and ecosystem restoration. This agenda also contributes to the SDG horizon, especially SDG 11, SDG 13, SDG 14 and SDG 15. [28]

Transversally, these results highlight the importance of incorporating systemic perspectives into public policy, approaches capable of connecting environmental performance, social well-being, and economic viability, while addressing real sustainability demands. As noted by Simbaña-Escobar, Mena-Hernández, Chérrez-Córdova & Alvarado-Arias (2025), systemic approaches enable the integration of technical, environmental, and financial criteria into planning processes, optimizing public investment decisions [29]. Applied to coastal management, this principle entails articulating sanitation, logistics decarbonization, and ecosystem restoration strategies within a single framework of institutional coordination and community participation.

Moreover, this study relates to previous research in Ecuador showing that inequalities in access to services are linked to the coexistence of various structural, urban, social, and climatic challenges. [30], [31], [32]. These studies suggest that sustainability and resilience in Ecuadorian cities cannot be understood only from a technical or environmental perspective, but must also consider spatial inequalities, infrastructure conditions, urban dynamics, and local climatic contexts. In this sense, they highlight that developing cities require integral and context-specific responses, rather than the application of generic solutions.

In summary, Manta still has room to redirect its development trajectory. The city is not in a critical imbalance condition, but BER indicates a clear movement away from equilibrium. Returning toward C1 requires more than adding infrastructure. It requires treating spatial-

environmental quality and natural-regulating capacity as central planning variables, with the same relevance as services, accessibility and economic functions.

Abbreviations

The following abbreviations are used in this manuscript:

	Analytic Hierarchy Process
AHP	Article Processing Charge
APC	Biotechnosphere Equilibrium Ratio
BER	Consistency Index
CI	Consistency Ratio
CR	Economically Active Population
EAP	Decentralized Autonomous Government
GAD	Geographic Information System
GIS	National Institute of Statistics and Census
INEC	Intergovernmental Panel on Climate Change
IPCC	Accessibility Component
KD	Functional Component
KF	Natural Component
KP	Socio-Economic Component
KSE	Spatial-Environmental Quality Component
KOSE	Integrated Urban Development Index
Kurban	Ministry of Environment, Water and Ecological Transition of Ecuador
MAATE	Ministry of Education of Ecuador
MINEDUC	Ministry of Public Health of Ecuador
MSP	Unsatisfied Basic Needs
NBI	Principal Component Analysis
PCA	Land-Use and Development Plan
PDOT	Random Index
RI	Manta Port Terminal
TPM	Universidad UTE
UTE	Variance Inflation Factor
VIF	

Declarations

Funding:
This research received no external funding; the Article Processing Charge (APC) is covered by UTE. The authors gratefully acknowledge the institutional support and technical resources provided, which were essential to the development of this study.

Conflicts of Interest:
The authors declare no conflicts of interest.

Data availability:
The datasets generated and analyzed during the present study are available from the corresponding author upon request. The methodology, indicator definitions, normalization procedures, and weighting approach are comprehensively described in the manuscript.

Author contributions:
Diana Zuleta Mediavilla: conceptualization, methodology, indicator structure and validation.
Natalia Alvarado-Arias: conceptual framing, writing, discussion and planning implications.
Patricio Simbaña-Escobar: thematic and conceptual guidance, reference verification, proofreading, and manuscript preparation.
Mayte Cuesta Tabares: reference verification, formal editing.
All authors reviewed and approved the final manuscript.

Ethics approval and consent to participate:
Not applicable. The article uses secondary, institutional, municipal and spatially derived data, and does not report research involving human participants, animals or biological materials.

Acknowledgments:
During the preparation of this manuscript, the authors used generative AI (ChatGPT-5.5) as a supporting tool to enhance sentence clarity and refine English grammar. All AI-generated suggestions were carefully reviewed, edited, and validated by the authors, who take full responsibility for the final content of this publication.

References:

[1] I. P. on C. C. (IPCC), “Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,” *Climate Change 2022 – Impacts, Adaptation and Vulnerability*, Jun. 2023, doi: 10.1017/9781009325844.

[2] M. Wannewitz *et al.*, “Progress and gaps in climate change adaptation in coastal cities across the globe,” *Nature Cities 2024 1:9*, vol. 1, no. 9, pp. 610–619, Aug. 2024, doi: 10.1038/s44284-024-00106-9.

[3] A. D. Slovic *et al.*, “Climate hazards in Latin American cities: Understanding the role of the social and built environments and barriers to adaptation action,” *Clim. Risk Manag.*, vol. 45, p. 100625, Jan. 2024, doi: 10.1016/J.CRM.2024.100625.

[4] P. E. Simbaña, D. Rocchio, K. R. Chérrez, and N. Alvarado-Arias, “Passive Strategies for thermal comfort in Amazonian Cities: The Case of Tena’s Waterfront",” *Bitácora Urbano Territorial*, vol. 34, no. 3, pp. 55–70, Nov. 2024, doi: 10.15446/bitacora.v34n3.115029.

[5] D. M. Alongi, “The Impact of Climate Change on Mangrove Forests,” *Curr. Clim. Change Rep.*, vol. 1, no. 1, pp. 30–39, Mar. 2015, doi: 10.1007/S40641-015-0002-X/FIGURES/3.

[6] R. D. Ward, D. A. Friess, R. H. Day, and R. A. Mackenzie, “Impacts of climate change on mangrove ecosystems: a region by region overview,” *Ecosystem Health*

and Sustainability, vol. 2, no. 4, p. e01211, Apr. 2016, doi: 10.1002/EHS2.1211;PAGE:STRING:ARTICLE/CHAPTER.
[7] C. M. Duarte *et al.*, “Rebuilding marine life,” *Nature*, vol. 580, no. 7801, pp. 39–51, Apr. 2020, doi: 10.1038/S41586-020-2146-7.
[8] J. Su, D. A. Friess, and A. Gasparatos, “A meta-analysis of the ecological and economic outcomes of mangrove restoration,” *Nature Communications 2021 12:1*, vol. 12, no. 1, pp. 5050-, Aug. 2021, doi: 10.1038/s41467-021-25349-1.
[9] C. A. Kennedy *et al.*, “Energy and material flows of megacities,” *Proc. Natl. Acad. Sci. U. S. A.*, vol. 112, no. 19, pp. 5985–5990, May 2015, doi: 10.1073/pnas.1504315112.
[10] C. Kennedy, J. Cuddihy, and J. Engel-Yan, “The changing metabolism of cities,” *J. Ind. Ecol.*, vol. 11, no. 2, pp. 43–59, Mar. 2007, doi: 10.1162/JIE.2007.1107.
[11] T. Roberts, I. Williams, J. Preston, N. Clarke, M. Odum, and S. O’Gorman, “Ports in a Storm: Port-City Environmental Challenges and Solutions,” *Sustainability 2023, Vol. 15,* vol. 15, no. 12, Jun. 2023, doi: 10.3390/SU15129722.
[12] D. A. E. Ogara *et al.*, “An indicator-based approach to assess sustainability of port-cities and marine management in the Global South,” *Front. Mar. Sci.*, vol. 10, p. 1052128, Mar. 2023, doi: 10.3389/FMARS.2023.1052128/TEXT.
[13] Y. Wang, Y. Cai, Y. Xie, P. Zhang, and L. Chen, “A quantitative framework to evaluate urban ecological resilience: broadening understanding through multi-attribute perspectives,” *Front. Ecol. Evol.*, vol. 11, p. 1144244, Nov. 2023, doi: 10.3389/FEVO.2023.1144244/BIBTEX.
[14] N. V. Bakaeva, L. V. Tchaikovskaya, and D. P. Zuleta, “Toward the construction of a comfort model for urban environment,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 775, no. 1, p. 012006, Mar. 2020, doi: 10.1088/1757-899X/775/1/012006.
[15] S. G. Emelianov, N. V. Bakaeva, and D. P. Zuleta, “Criteria for reconstruction of urban environment on principles of harmonizing nature, society and human being,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 687, no. 6, p. 066002, Dec. 2019, doi: 10.1088/1757-899X/687/6/066002.
[16] Instituto Nacional de Estadística y Censos (INEC). 2023, “201.279 Personas más viven en Manabí - Censo Ecuador.” Accessed: Jun. 16, 2026. [Online]. Available: https://www.censoecuador.gob.ec/201-279-personas-mas-viven-en-manabi/
[17] Y. S. Grasst, “Transformaciones en el desarrollo urbano de Manta, Ecuador: desde la ciudad colonial hasta la ciudad fragmentada,” *ReHuSo: Revista de Ciencias Humanísticas y Sociales*, vol. 8, no. 1, pp. 113–131, Jan. 2023, doi: 10.33936/REHUSO.V8I1.5433.
[18] World Bank Group. 2021, “Manta, Underground Transformation for the Future.” Accessed: Jun. 16, 2026. [Online]. Available: https://www.worldbank.org/en/news/feature/2021/11/05/manta-underground-transformation-for-the-future
[19] J. R. A. Fiallos and G. S. Andrés–Zevallos, “Environmental Management of the Coastal Boundary: Sustainable Solutions for the Green Area Deficit in Manta,” *SAP Land and Architecture*, vol. 4, pp. 221–221, Aug. 2025, doi: 10.56294/LA2025221.
[20] Global Forest Watch, “Ecuador Deforestation Rates & Statistics | GFW.” Accessed: Oct. 26, 2025. [Online]. Available: https://www.globalforestwatch.org/dashboards/country/ECU/

[21] R. Ojeda-Zaga, V. Moya-Almeida, N. Alvarado-Arias, and D. Zuleta-Mediavilla, “Quantitative assessment of urban sustainability perceptions in Lurin, Peru,” *One Ecosystem*, vol. 9, Jan. 2024, doi: 10.3897/ONEECO.9.E118668.
[22] N. Alvarado-Arias, J. Soria-Delgado, J. Staines, and V. Moya-Almeida, “Towards Participatory River Governance Through Citizen Science,” *Water 2025, Vol. 17,* vol. 17, no. 9, Apr. 2025, doi: 10.3390/W17091358.
[23] N. Alvarado-Arias, “PAISAJE FLUVIAL DEGRADADO: UNA MIRADA DESDE EL VALOR SOCIAL. Ríos Urbanos de la ciudad de Loja - Ecuador,” *Seminario Internacional de Investigación en Urbanismo*, no. 14, Dec. 2022, doi: 10.5821/SIIU.12043.
[24] M. Nardo, M. Saisana, A. Saltelli, S. Tarantola, A. Hoffmann, and E. Giovannini, “Handbook on Constructing Composite Indicators: Methodology and User Guide,” *OECD Statistics Working Papers*, vol. 2005, no. 3, Aug. 2005, doi: 10.1787/533411815016.
[25] M. Saisana, A. Saltelli, and S. Tarantola, “Uncertainty and sensitivity analysis techniques as tools for the quality assessment of composite indicators,” *J. R. Stat. Soc. Ser. A Stat. Soc.*, vol. 168, no. 2, pp. 307–323, Mar. 2005, doi: 10.1111/J.1467-985X.2005.00350.X;SUBPAGE:STRING:ABSTRACT;ISSUE:ISSUE:DOI.
[26] A. Saltelli *et al.*, “Global Sensitivity Analysis. The Primer,” *Global Sensitivity Analysis. The Primer*, pp. 1–292, Jan. 2008, doi: 10.1002/9780470725184.
[27] O. Iuorio and M. Russo, “Future scenarios for housing (re)settlements in Ecuador,” *Architecture, Structures and Construction 2022 2:4*, vol. 2, no. 4, pp. 711–722, May 2022, doi: 10.1007/S44150-022-00052-X.
[28] C. A. Schipper, G. G. J. Dekker, B. de Visser, B. Bolman, and Q. Lodder, “Characterization of SDGs towards Coastal Management: Sustainability Performance and Cross-Linking Consequences,” *Sustainability 2021, Vol. 13,* vol. 13, no. 3, pp. 1–33, Feb. 2021, doi: 10.3390/SU13031560.
[29] P. Simbaña-Escobar, S. Mena-Hernández, E. Chérrez Córdova, and N. Alvarado-Arias, “Comparative Thermal Performance and Return on Investment of Glazing Configurations in Building Envelopes: The Case of the Plataforma Gubernamental Norte in Quito, Ecuador,” *Buildings 2025, Vol. 15,* vol. 15, no. 19, Sep. 2025, doi: 10.3390/BUILDINGS15193522.
[30] M. M. Benalcázar Jarrín, D. P. Z. Mediavilla, R. Rispoli, and D. Rocchio, “Urban Sustainability of Quito Through Its Food System: Spatial and Social Interactions,” *Sustainability 2025, Vol. 17,* vol. 17, no. 14, Jul. 2025, doi: 10.3390/SU17146613.
[31] P. ; Simbaña Escobar, D. ; Paredes, D. & Jácome, and O. Piña, “THE URBAN IMPACT OF SUSTAINABLE DESIGN INTERVENTIONS IN QUITO Case study of the implementation of the Eco-Efficient tool in ‘La Carolina’ neighborhood in Quito,” *Seminario Internacional de Investigación en Urbanismo*, no. 12, Sep. 2020, doi: 10.5821/SIIU.9937.
[32] M. P. Arias Córdova, P. Simbaña Escobar, J. F. Arroba, C. V. García, and M. G. Obando, “Análisis del desempeño climático y de sistemas sostenibles pasivos del hotel ‘Ciudad de Catamayo’ en el centro de Catamayo,” *EÍDOS, ISSN-e 1390-5007, Vol. 17, Nº. 23, 2024 (Ejemplar dedicado a: ESPACIO Y TECNOLOGÍA: LA ARQUITECTURA EN EL ENTORNO DIGITAL), págs. 97-108*, vol. 17, no. 23, pp. 97–108, 2024, Accessed: Oct. 26, 2025. [Online]. Available:

https://dialnet.unirioja.es/servlet/articulo?codigo=9617488&info=resumen&idioma=ENG