Appendix

MapBiomas Urban Venezuela Module (Beta)

Delineation of Urban and Peri-Urban Areas

Collection 3 LULC

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2026

Executive Summary

The MapBiomas Venezuela Urban Module constitutes the most comprehensive and detailed analysis of historical human-settlement cartography produced in the country to date. In light of the pronounced lack of updated census and geospatial data in Venezuela, this technical document describes the methodology developed to transform those information gaps into scientific evidence useful for territorial analysis, as well as to characterize national urban dynamics over the last four decades (1985–2024).

Unlike automated global classifications, this module implements an approach based on expert supervision and multi-source integration. Using the Esri land-cover map (10 m), derived from Sentinel-2 imagery, as a reference, the historical land use and land cover (LULC) series of Collection 3 was refined, which made it possible to mitigate systematic spectral-confusion errors in mining areas and arid regions. As a result, 1,124 Urban Units (UU) were identified and delineated, validated by an interinstitutional network of scholars from Simón Bolívar University (USB), Central University of Venezuela (UCV), Universidad Centroccidental Lisandro Alvarado (UCLA), and remote-sensing specialists.

The main innovation of this product lies in its multidimensional vision of the territory, structured around three fundamental axes:

1. **Territorial differentiation:** the consolidated Urban Area (UA) and its Peri-Urban Area (APU) are rigorously delineated. The latter is defined on the basis of legal instruments, such as Master Plans, which makes it possible to identify expansion fronts and informal occupation processes.

2. **Urban and peri-urban green space:** understood as the set of elements with vegetation cover—parks, sports fields, and other natural or agricultural spaces—located within cities. In this module, urban green space can be identified when its surface area exceeds 1 hectare.
3. **Hazard exposure analysis:** the module integrates critical seismicity layers based on data from the Venezuelan Foundation for Seismological Research (FUNVISIS), as well as hydrogeomorphological variables such as the slope of the terrain and the height above the nearest drainage (HAND), making the urban module a key tool for disaster risk management.

Presented in its beta version, this module not only offers a precise chronology of urbanization in Venezuela but also constitutes an open and transparent science platform. Its objective is to make high-resolution data available to planners, researchers, and civil society to contribute to safer, more sustainable territorial development grounded in scientific evidence.

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Acronyms and Abbreviations

ATBD Algorithm Theoretical Basis Document.

DPT Political-Territorial Division.

FAO Food and Agriculture Organization of the United Nations.

FUNVISIS Venezuelan Foundation for Seismological Research.

HAND Height Above Nearest Drainage.

INE National Institute of Statistics.

INTI National Land Institute.

LSIGMA-USB Geographic Information Systems and Environmental Modeling Laboratory of Simón Bolívar University.

LULC Land Use/Land Cover.

MINEC Ministry of People's Power for Ecosocialism.

PDUL Local Urban Development Plan.

POU Urban Planning Plans.

POT Land Use and Territorial Planning Plans.

PUA Peri-urban Area.

SIGOT Geographic Information System for Territorial Planning.

UA Urban Area.

UCLA Universidad Centroccidental Lisandro Alvarado.

UCV Central University of Venezuela.

USB Simón Bolívar University.

UN United Nations.

UU Urban Unit.

1. Introduction

This document, "Appendix to the MapBiomas Urban Venezuela Module (Beta), Delimitation of Urban and Peri-urban Areas," constitutes the fundamental methodological guide for the analysis of the dynamics of urban and peri-urban areas of Venezuela during the period 1985-2024. Unlike other thematic modules of MapBiomas Venezuela, the Urban Module does not execute an independent primary spectral classification; on the contrary, it represents a phase of refinement, supervision and delimitation of contours from Collection 3 of land cover and use.

This process is grounded in a protocol of expert supervision and multi-source validation. As a reference input, the Esri land-cover map (2023), a high-spatial-resolution product (10 m) derived from Sentinel-2 imagery, was integrated in order to audit and optimize the historical land use and land cover series of MapBiomas Venezuela (Collection 3). This integration made it possible to mitigate systematic commission and omission errors and improve the spatial consistency of the detected settlements.

The result is a consolidated national layer of 1,124 Urban Units (UU), which go beyond spectral classification by incorporating official toponymy and political-administrative hierarchy attributes. This data structure not only delineates the urban area, but also provides a platform for geospatial analysis and decision-making with a level of historical detail unprecedented in the country.

The UUs are made up of the Urban Area (UA) and the Peri-Urban Areas (PUA), the latter understood as dynamic spaces of transition, tension, and mixed uses between the consolidated urban footprint and the rural area (Aguilera-Martínez *et al*., 2019). This delineation offers strategic advantages for governance and sustainable territorial planning. By technically defining the peri-urban area, the module provides objective foundations for public administrations to reduce urban ambiguity and apply specific planning instruments, such as the Master Plans compiled by the National Land Institute (INTI). This makes it possible to control phenomena such as urban sprawl and informal occupation, processes that not only increase the cost of public infrastructure but also degrade the landscape and ecosystem services.

Finally, this technical effort, validated by an inter-institutional network of academic and union experts, is made available to the public through the MapBiomas Urban Venezuela Module (beta version), integrating layers of exposure to hazards and urban vegetation to support comprehensive disaster risk management.

1.1. Overview

As a participating node in the Pan-Amazonian and Global Network, MapBiomas Venezuela aims to generate historical series of land use and land cover (LULC) maps, with a spatial resolution of 30 meters, for the entire national territory—including the state of Guayana Esequiba—from 1985 to the present.

In versions prior to Collection 3, the representation of human settlements was limited to the functional classes “Urban use” and “Other non-vegetated anthropic areas.” However, the complexity of Venezuelan urban growth required an approach that went beyond the spectral detection of construction materials.

The MapBiomas Venezuela Urban Module emerged as a value-added layer designed to refine, characterize, and describe the urban phenomenon from a multidimensional perspective. This module not only delineates the built-up footprint, but also segments the territory into Urban Units (UU), more rigorously differentiating the consolidated Urban Area (AU) from its expanding Peri-Urban Area (APU).

Beyond geometric delineation, the module integrates critical indicators of resilience and livability:

- **Urban and peri-urban green:** multi-temporal evaluation of vegetation cover that allows analyzing the ecological connectivity between the natural remnants of the peri-urban and intra-urban green areas, essential for the mitigation of the urban heat island effect, among other processes.

- **Hazard exposure:** seismic based on national zoning. Associated with relief, expressed by the slope of the land, and hydrological proximity, estimated through the HAND indicator.

This comprehensive vision turns the module into one of the most complete geospatial databases on the Venezuelan urban system, providing a relevant tool for historical monitoring and the prospective management of risk and sustainability.

1.2. Study area and operational definitions

The study area covers the entire territory of the Bolivarian Republic of Venezuela. To capture the complexity of human settlements over a 40-year time frame, the module goes beyond basic spectral classification and establishes a hierarchy of operational definitions based on three fundamental components: the urban areas, the peri-urban areas , and the urban unity.

1.2.1. Urban Areas (UA)

The essence of Urban Areas lies in their uninterrupted spatial configuration and their physical persistence on the territory. More than a statistical aggregation of demographic data, UAs are defined by the consolidation of a morphological fabric that transcends jurisdictional borders, responding to a logic of organic expansion and systemic functionality.

This "continuous matrix" amalgamates various types of occupation into a cohesive spatial unit. In this sense, the urban phenomenon manifests itself as a unified territorial reality – the real city – that goes beyond the administrative fragmentation of municipal or district boundaries – the legal city – through processes of conurbation and consolidation of infrastructures.

From the operational and methodological point of view, this definition integrates the following classes from Collection 3 of MapBiomas Venezuela:

- **Urban Use (Class 24):** areas with a high density of buildings and impervious surfaces.
- **Other Non-Vegetated Anthropic Areas (Class 25):** functional infrastructure that, although it does not always contain housing, forms an intrinsic part of urban dynamics, such as industrial yards, ports, airports, roads, and transportation nodes.

Likewise, the internal heterogeneity of the urban matrix is recognized. For this reason, intra-urban green areas are also integrated as functional components, whose existence is conditioned and contained by the surrounding built structure.

1.2.2. Peri-Urban Areas (PUA)

They represent the dynamic space of transition and mixed uses between the consolidated urban area and the rural area. This definition is key to identifying expansion fronts and informal occupation processes. The APU is delineated through proximity criteria (buffers) and, as a priority, through the integration of territorial planning instruments, such as Master Plans, which makes it possible to map territory with growth potential in accordance with national regulations.

1.2.3. Urban Unit (UU): the unit of analysis

The Urban Unit is the fundamental unit of analysis of this module. It results from the topological union of the consolidated urban area and its peri-urban fringe (UU = UA + PUA; see Figure 1).

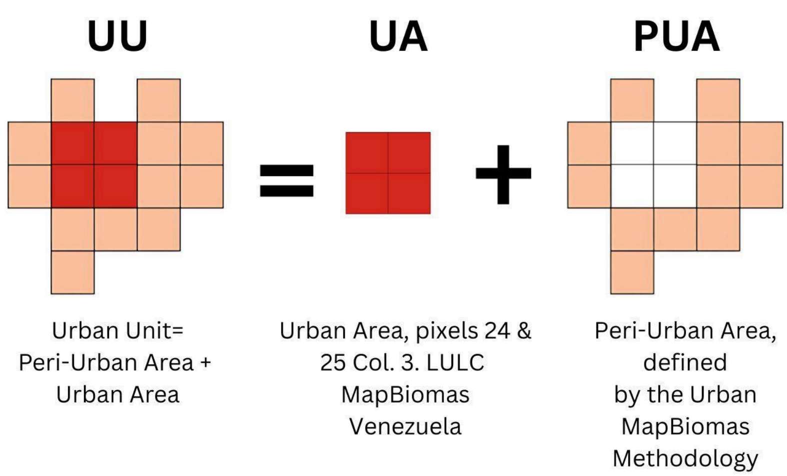

Figure 1. *Construction of the Urban Units.*

This definition makes it possible to move from an analysis of isolated pixels to an analysis of geographic entities with their own identity, associated with official toponymy and political-administrative hierarchy.

Under this logic, 1,124 units were consolidated to make up the system of cities and populated centers in the country, facilitating statistical comparability and the monitoring of public policies.

1.3. Applications and strategic value of the product

The development of the Urban Module responds to the critical need for updated and accurate geospatial data, the absence of which has historically limited territorial management in Venezuela. This product is not merely a cartographic base, but also a technical input aimed at strengthening the following areas:

1.3.1. Territorial planning and sustainable governance

- **Informed decision-making:** it provides an objective technical framework for the design of public policies, enabling local and national administrations to base their planning on real data on urban expansion rather than on estimates.
- **Urban growth control:** it facilitates monitoring of urban sprawl and occupation in peri-urban areas, allowing for more effective application of territorial planning instruments, such as Master Plans.

1.3.2. Socio-environmental management and resilience

- **Monitoring of urban and peri-urban green space:** it supports the conservation and management of urban and peri-urban vegetation, which is essential for mitigating heat islands and preserving ecosystem services in cities.

- **Multitemporal impact analysis:** it facilitates the study of how land-use change has affected the immediate surroundings of populated centers over the last 40 years.

1.3.3. Integrated disaster risk management

- **Hazard mitigation:** it contributes directly to disaster risk management by superimposing the urban sprawl with seismicity variables and hydrogeomorphological indicators, such as the slope of the terrain and the height above the nearest drainage, which makes it possible to identify areas exposed to flooding or mass movements.

1.3.4. Democratization of information and citizen science

- **Awareness and participation:** it strengthens civil society and organized communities by offering a transparent, freely accessible tool for understanding transformations in their territory.
- **Technological benchmark:** it promotes the use of remote sensing and cloud-computing platforms, such as Google Earth Engine, as essential tools for the consistent, automated, and objective mapping of urban forms in the country.

2. Background information

MapBiomas Venezuela is a collaborative network of specialists in remote sensing, geographic information systems, and programming dedicated to mapping land use and land cover in the country. The network of MapBiomas Venezuela co-creators is made up of organizations with extensive experience in geospatial data management and environmental conservation, including the Geographic Information Systems and Environmental Modeling Laboratory of Simón Bolívar University (LSIGMA-USB), the non-governmental organization Provita, and the civil association Wataniba.

In the case of the Geographic Information Systems and Environmental Modeling Laboratory (LSIGMA-USB), it is a research center in digital geography affiliated with Laboratory C of Simón Bolívar University in Venezuela. Since 2022 it has been part of MapBiomas Venezuela, assuming responsibility for generating land use and land cover classes in the regions of the Central and Eastern Llanos, as well as in the Unare and Barlovento basin. On this occasion, LSIGMA-USB assumed the role of improving the “Urban use” and “Other non-vegetated anthropic areas” classifications, classes that represent Venezuelan built-up areas in MapBiomas Venezuela Collection 3 land use and land cover, in order to develop the beta version of the urban module for the country.

2.1. Historical context and relevance of urban and peri-urban areas in Venezuela

2.1.1. Historical context of urban development

The foundation of the Venezuelan urban system arose from Spanish colonization, which established an ordered settlement pattern in terms of location and layout (Martínez, 2006). By the end of the nineteenth century, the country’s structure was predominantly rural, and only three cities—Caracas, Valencia, and Maracaibo—had more than 20,000 inhabitants (Bolívar, 2006). Beginning in the twentieth century, oil exploitation transformed the territory and drove massive migration from the countryside toward urban nodes associated with investment and public spending. This generated an accelerated demographic transition: the urban population rose from 35 % in 1936 to 83 % in 1981 (Bolívar, 2006).

At present, a marked territorial asymmetry persists: the north-central coastal axis—made up of Capital District, Miranda, Aragua, La Guaira, and Carabobo states—together with the state of Zulia, concentrates 46 % of the population in only 9 % of the territory (Bolívar, 2006). According to the latest national census of 2011, nine states account for approximately two thirds of the country's total population: Zulia, Miranda, Carabobo, Capital District, Lara, Aragua, Anzoátegui, Bolívar, and Táchira (INE, 2014). This demographic growth, combined with the limited availability of land suitable for urbanization and the existing planning framework, led to urban expansion toward peripheral areas, consolidating peri-urban development often associated with informality and limited access to basic services.

2.1.2. Relevance of peri-urban areas

The peri-urban area is understood as the transition space between the urban area and the rural area. With a variable structure and use profile, it constitutes the territory of future growth of the urban area, where peripheral urban activities can develop in an uncontrolled and random manner, as well as rural activities functionally linked to the city.

Delineating this dynamic space of transition and mixed uses between the consolidated urban area and the rural area (Aguilera-Martínez *et al*., 2019) offers advantages for governance and sustainable territorial planning. By establishing technical limits for the peri-urban area, public administration can reduce urban ambiguity and facilitate the application of specific regulations aimed at regulating urban sprawl and informal occupation;

processes that would otherwise increase infrastructure costs and compromise the integrity of the landscape.

Defining these urban limits is fundamental for territorial monitoring and technical analysis, especially in projects such as MapBiomas. By establishing a clearly defined spatial unit of analysis, the ability to quantify expansion rates, model future scenarios, and evaluate conservation policies is strengthened. In addition, it favors international statistical comparability and accountability.

2.2. Toward the MapBiomas Urban Venezuela Module (justification and scope)

Venezuela faces a critical gap in updated demographic and geospatial information. The absence of recent official data on urban expansion has limited institutions' ability to make informed decisions, leaving ecological and agricultural areas unprotected as they have been absorbed by uncontrolled peripheral growth.

In this context, the classes "**Urban use**" and "**Other non-vegetated anthropic areas**" in MapBiomas Venezuela Collection 3 (2025) represented a milestone, as they constituted the first systematic and multitemporal approximation of the national urban footprint. Nevertheless, the **Urban Module (beta version)** emerged to raise that standard, moving from a cover classification to an integral characterization of the urban ecosystem.

The scope of this module is defined along three transformative axes:

- **Historical refinement and consistency:** through post-processing algorithms and expert supervision, the module optimizes LULC classifications and offers more accurate and detailed cartography of populated centers for the 1985–2024 period.

- **Data multidimensionality:** the module transcends infrastructure detection by integrating intra-urban vegetation and hazard exposure variables. This makes it possible to recognize, for the first time and on a national scale, critical areas in the face of seismic and hydrogeomorphological threats, such as landslides and floods.
- **Transparency and continuous updating:** conceived as a freely accessible tool, the module proposes annual data updates. This seeks to ensure that researchers, planners, and civil society have an updated and transparent source of information for studying the socio-environmental consequences of urbanization.

With a 40-year historical archive, the Urban Module is positioned as a key tool for building more resilient cities and for territory management based on scientific evidence.

2.3. Initiatives and methodological references

To ensure data interoperability and scientific rigor, the delineation of urban and peri-urban areas in Venezuela was aligned with international standards and previous experiences from the MapBiomas network.

The main reference adopted was the *Methodological Manual for Defining Cities, Towns and Rural Areas* (EU, FAO, UN-Habitat, OECD, and World Bank, 2022). This international standard proposes a harmonized definition that facilitates statistical comparison between countries.

- **Technical basis:** the methodology is based on a 1 km^2 population grid that classifies the territory along an urban-rural continuum using population-density and contiguity criteria.

- **Adaptation to the module:** the use of this reference makes it possible to classify Venezuela's Urban Units under a logic of "semi-dense areas" and "urban centers," overcoming the traditional urban-rural dichotomy and favoring a standardized characterization comparable with other countries in the region.

In addition, the experience of MapBiomas Brazil was taken as a reference, as it has constituted a technical and operational pillar for this project. The evolution from an initial binary classification (Collection 1) to an advanced module based on Collection 9 (1985–2023) served as a methodological and analytical roadmap for development of the module in Venezuela.

3. Methodology

The delineation of urban and peri-urban areas in the context of MapBiomas Venezuela is conceived as a process of geographic and technical refinement applied to the base land use and land cover (LULC) classification. The main result of this module is the generation of an information layer called Urban Units (UU), which integrates the historical spectral dynamics derived from satellite data with territorial-planning criteria and expert validation.

The central objective is to precisely define the boundaries of **Urban Areas (UA)** and **Peri-urban Areas (PUA)** at national scale, establishing a hierarchy of populated centers that makes it possible to analyze urban expansion beyond the spectral response of the pixel.

3.1. Inputs and information sources

To achieve the precision required for delineating the peri-urban area, a multi-source approach was implemented that goes beyond the spatial resolution of the Landsat series.

- **Global cartographic sources (high-resolution baseline):** the primary input for identifying “built-up areas” came from the Esri Land Cover Map (2023). This database, derived from Sentinel-2 imagery with 10-meter spatial resolution, made it possible to capture subtle urban textures that served as a reference framework for contemporary peri-urban delineation.
- **Local and institutional cartographic sources:** the inti_CARTOINTI_PLANES_RECTORES database (INTI, 2005) was integrated, compiling legal planning instruments such as Urban Planning Plans (POU), Land Use and Territorial Planning Plans (POT), Local Urban Development Plans (PDUL), and Master Plans. This information was essential for providing the delineation with legal and administrative support.
- **Auxiliary data and toponymy:** populated-center layers (scale 1:250,000) and the Political-Territorial Division (DPT), from the Geographic Information System for Territorial Planning (SIGOT), the Ministry of People’s Power for Ecosocialism (MINEC), and the National Land Institute (INTI), were used. These sources made it possible to correctly associate official names and political-administrative hierarchies with each identified polygon.

3.2. Definition of criteria and expert-judgment validation

To ensure territorial relevance and scientific rigor in urban and peri-urban delineation, a transdisciplinary consultation network was established involving academic, technical, and professional institutions in the country. This expert-validation process acted not only as a source of information, but also as a normative and technical framework for methodological decision-making.

3.2.1. Interinstitutional network of experts

Specialists associated with the following sectors participated:

- **Academic sector:** Urban Planning and Biology departments of Simón Bolívar University (USB), the Faculty of Architecture and Urbanism and the Institute of Urbanism of the Central University of Venezuela (UCV), and the Dean's Office of Civil Engineering and Urbanism of Universidad Centroccidental Lisandro Alvarado (UCLA).
- **Technical and institutional sector:** National Institute of Statistics (INE), Venezuelan Foundation for Seismological Research (FUNVISIS), and the Center for Integral Environmental Studies of the Central University of Venezuela (CENAMB-UCV).
- **Professional and environmental sector:** Metropolitan Real Estate Chamber, Venezuelan Council for Sustainable Construction, La Salle Society of Natural Sciences, and the World Commission on Protected Areas (IUCN).

3.2.2. Critical contributions from the consultation

Interaction with this network made it possible to:

- **Threshold adjustment:** validate that the area filters—4 ha and 20 ha—are representative of the morphology of Venezuelan settlements.
- **Consensus on peri-urban delineation:** define the distances of areas of influence (buffers), between 250 m and 1,000 m, according to political-administrative hierarchy and the expansion dynamics of cities.

- **Legal and environmental integration:** align the cartography with territorial-planning instruments, especially Master Plans, and with current environmental legislation.

3.3. Supervision and quality-assurance phase

Because the "built-up areas" in the Esri Land Cover Map (2023) may present commission errors in bare soils or rocky outcrops, a progressive supervision and filtering protocol was applied.

- **Critical-area filtering:** from an initial universe of 144,436 polygons corresponding to Esri class 7, a first area filter was applied to select only those patches larger than 4 hectares. This reduced the sample to 12,865 polygons representative of emerging urban fabrics.
- **Proximity and connectivity criteria:** on the polygons resulting from the first filter, a second filter was executed through a spatial intersection analysis with a search radius of between 250 and 1,000 meters, according to political-administrative hierarchy, relative to the official populated-centers layer (INTI, 2005). Polygons smaller than 20 hectares that were not close to a registered populated center were discarded, thereby eliminating false positives associated with isolated infrastructure or spectral errors in the Esri Land Cover Map (2023).
- **Regionalized visual audit:** the final sample of 5,826 polygons, resulting from application of the proximity filter, was subjected to visual supervision divided into five geographic regions. Using very-high-spatial-resolution imagery (Esri World Imagery), the team of experts validated location, identified official toponymy, and verified correspondence with pixels 24 (Urban use) and 25 (Other non-vegetated anthropic areas) in MapBiomas Venezuela

Collection 3. This process led to consolidation of a final layer of 1,124 urban units.

3.4. Processing and delineation of Urban Areas (UA) and Peri-Urban Areas (PUA)

Once the layer of validated and supervised polygons (1,124) was obtained, the final structuring of the Urban Units (UU) proceeded through an overlay analysis of spatial-information layers and Boolean logic. The objective of this phase was to differentiate the consolidated urbanized core from its immediate expansion surroundings.

3.4.1. Definition of the Urban Area (UA)

The consolidated Urban Area was defined from the historical data of MapBiomas Venezuela Collection 3 land use and land cover.

- **Inputs:** pixels classified specifically as Urban use (class 24) and Other non-vegetated anthropic areas (class 25) were used.
- **Procedure:** to guarantee the continuity of the urban sprawl and eliminate artificial fragmentations typical of the 30-meter resolution, the Eliminate Polygon Part tool was applied, which fill the holes in polygons. This process generated a solid and consistent urban perimeter for the entire 1985-2024 time series.

3.4.2. Delineation of the Peri-Urban Area (PUA)

Delineation of the Peri-Urban Area constitutes the main technical innovation of this module, as it combines the greater spatial precision of Sentinel-2 with technical and administrative criteria linked to national urban management.

- **Generation of differentiated areas of influence (buffers):** on the layer of supervised "built-up area" polygons, derived from Esri/Sentinel-2, a proximity analysis was applied using buffers whose distance was defined according to the political-administrative hierarchy of the populated center:
    - State capitals: 1,000 meters.
    - Municipal capitals: 750 meters.
    - Parish capitals: 500 meters.
    - Other populated centers: 250 meters.
- **Integration with legal instruments:** these buffers were intersected with the polygons of the Master Plans and POU (INTI, 2005). When a legal instrument existed, it acted as the definitive limit of projected growth.
- **Calculation of the transition fringe:** to obtain precise PUA delineation, a geometric difference was performed between the enclosing set—based on buffers and plans—and the Urban Area. The result was an edge band representing the peri-urban area.

3.4.3. Final product: Urban Units (UU) layer

The result of this workflow is a nationwide vector file (.shp), structured under topological-consistency criteria that guarantee the absence of overlaps and gaps between categories and between political-administrative units. This product contains the following attributes:

- **Location attributes:** official name (toponymy), state, municipality, and parish.
- **Hierarchy:** classification according to administrative importance (capitals, populated centers, among others).

- **Zoning:** clear differentiation between consolidated core (UA) and transition or peripheral zone (PUA).

For the first time, this product makes it possible to analyze not only how much the urban area in Venezuela has grown, but also where the urban frontier is shifting with respect to its legal planning, improving the precision of spatial-metric calculations.

4. Results

The processing and refinement of the geospatial information contained in the urban module made it possible to consolidate an unprecedented geospatial database for Venezuela, characterized by the integration of historical spectral dynamics derived from satellite data and official territorial-planning information.

4.1. Characterization of Urban Units (UU)

After application of the surface-area and proximity filters, and subsequent expert supervision, a national layer of 1,124 polygons validated as Urban Units (UU) was consolidated. These units represent the diversity of settlements in the country and are organized under the following hierarchical structure:

- **State capitals:** they represent the country's most consolidated nuclei and highest functional hierarchy. Their relevance as centers of regional power and nodes of specialized services—such as health care, higher education, and banking—translates into more extensive and complex peri-urban areas, where pressure on land use is greater and urban planning becomes more critical.

- **Municipal capitals:** these are units that act as local service centers and points of economic articulation for their immediate surroundings. They exhibit dynamic expansion closely linked to the main road axes, functioning as connectors between large cities and the rural area.
- **Parish capitals:** these correspond to smaller settlements with official administrative status, essential for the presence of the State in the territory. Their delineation makes it possible to understand the base of the national urban network and its role in the socio-territorial cohesion of less densely populated regions.
- **Other populated centers:** these are small settlements that could be mapped and incorporated thanks to the spatial resolution of Sentinel-2 and the application of proximity and area criteria (4 and 20 ha filters). These units, often underestimated or rendered invisible in global classifications, are fundamental for understanding the capillarity of settlement in Venezuela and emerging occupation fronts.

4.2. Analysis of the Urban Area (UA) and the Peri-Urban Area (PUA)

One of the most significant contributions of this module is the technical differentiation between the consolidated urban core and its immediate zone of influence. Delineation of the **Peri-Urban Area (PUA)** enables a multiscale reading of territorial expansion, revealing patterns that usually remain hidden in binary urban/non-urban cartographies.

The main findings indicate the following:

- **Urban Area (UA):** It represents the densest, most stable, and highest-reflectance fabric identified in the historical series of MapBiomas Venezuela Collection 3. This unit constitutes the central core where service infrastructure and the road network show the greatest degree of consolidation.
- **Peri-Urban Area (PUA):** defined through the integration of hierarchical buffers and Master Plan zoning, this layer identifies transition zones and areas in direct contact with the natural or agricultural matrix. It is in the APU where the main pressure vectors associated with urban growth and land-use transformation are concentrated.

This methodological differentiation makes it possible to observe that, in metropolises with dynamic expansion, the peri-urban area effectively captures spontaneous settlements in edge zones lacking basic services, residential and industrial developments on the periphery, and areas where the urban fabric begins to disrupt local ecosystems. This facilitates identification of zones with high demand for specific territorial-planning instruments.

4.3. Improvement in thematic and spatial consistency

The comparison between the original MapBiomas Venezuela land use and land cover layer (Collection 3) and the refined Urban Units layer reveals three relevant improvements:

- **Reduction of commission errors:** visual supervision of World Imagery (Esri) images and application of area filters made it possible to eliminate false positives in mining areas of Bolívar State and in arid areas of Falcón State, where the Random Forest algorithm tended to incorrectly classify certain surfaces as urban.

- **Recovery of dispersed settlements:** thanks to Sentinel-2's 10-meter spatial resolution, it was possible to delineate peri-urban areas in small populated centers that were not clearly detectable at Landsat's 30-meter resolution.
- **Topological consistency:** the final product presents a consistent spatial structure, without overlaps between categories, which facilitated its integration into the analysis submodules.

5. Urban Module

The Urban Module constitutes an analysis platform that transcends the basic classification of land cover and use. The products contained herein, generated for the period 1985-2024, allow a multidimensional understanding of the urban phenomenon in Venezuela, by integrating spatial dynamics with environmental risk factors and ecological resilience. Below are 6 by-products available in the beta version of the module.

5.1. Annual urbanization

Mapping of urban areas on a year-by-year basis, allowing for municipality- or city-specific growth rates (Figure 2). Below is the description of the legend of the Annual Urbanization by-product:

- **Urban Use:** human settlement area with built environment infrastructure, with buildings and roads. It also incorporates the urban peripheries that are constantly expanding. The Amazon, it includes indigenous communities.

- **Other anthropic areas without vegetation:** areas devoid of vegetation cover, composed of various infrastructures such as industrial yards, ports, airports, dams, aerodromes, main land routes, and other infrastructures outside urban areas.

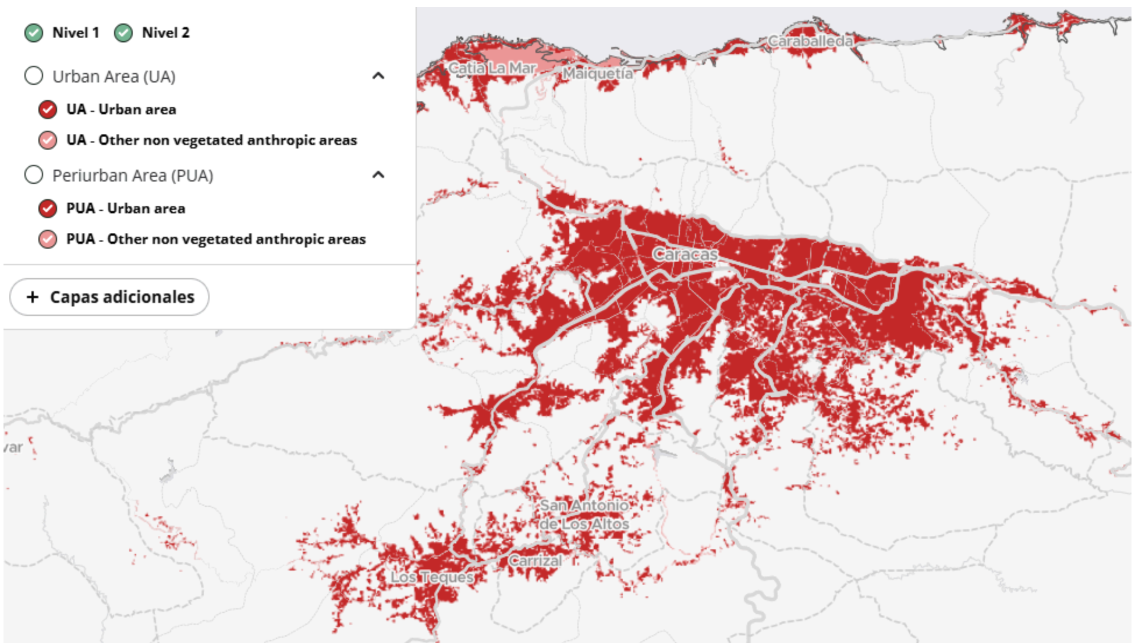

Figure 2. *Partial view (from the platform) of the urban and peri-urban area of La Guaira, Miranda, and Capital District states.*

5.2. Urbanization periods

Visual synthesis that groups urban expansion into five-year blocks, useful for identifying milestones in the transformation of the territory and its relationship with socioeconomic contexts (Figure 3). Below is the description of the legend of the by-product Periods of urbanization:

- **Urbanized up to 1985:** represents the extent of built-up infrastructure and consolidated impervious surfaces at the start of the study period.
- **Urbanized between 1986 and 1990:** land surface incorporated into the urban fabric during this five-year period. It results from the spatial subtraction of the 1985 urban footprint from the 1990 coverage, isolating the net growth of the period.
- **Urbanized between 1991 and 1995:** land surface incorporated into the urban fabric during this five-year period. It results from the spatial subtraction of the 1990 urban footprint from the 1995 coverage, isolating the net growth of the period.
- **Urbanized between 1996 and 2000:** land surface incorporated into the urban fabric during this five-year period. It results from the spatial subtraction of the 1995 urban footprint from the 2000 coverage, isolating the net growth of the period.
- **Urbanized between 2001 and 2005:** land surface incorporated into the urban fabric during this five-year period. It results from the spatial subtraction of the 2000 urban footprint from the 2005 coverage, isolating the net growth of the period.
- **Urbanized between 2006 and 2010:** land surface incorporated into the urban fabric during this five-year period. It results from the spatial subtraction of the 2005 urban footprint from the 2010 coverage, isolating the net growth of the period.
- **Urbanized between 2011 and 2015:** land surface incorporated into the urban fabric during this five-year period. It results from the spatial subtraction of the 2010 urban footprint from the 2015 coverage, isolating the net growth of the period.
- **Urbanized between 2016 and 2020:** land surface incorporated into the urban fabric during this five-year period. It results from the

spatial subtraction of the 2015 urban footprint from the 2020 coverage, isolating the net growth of the period.

- **Urbanized between 2021 and 2024:** land surface incorporated into the urban fabric during the final period. It results from the spatial subtraction of the 2020 urban footprint from the coverage detected at the end of the collection, isolating the most recent expansion.

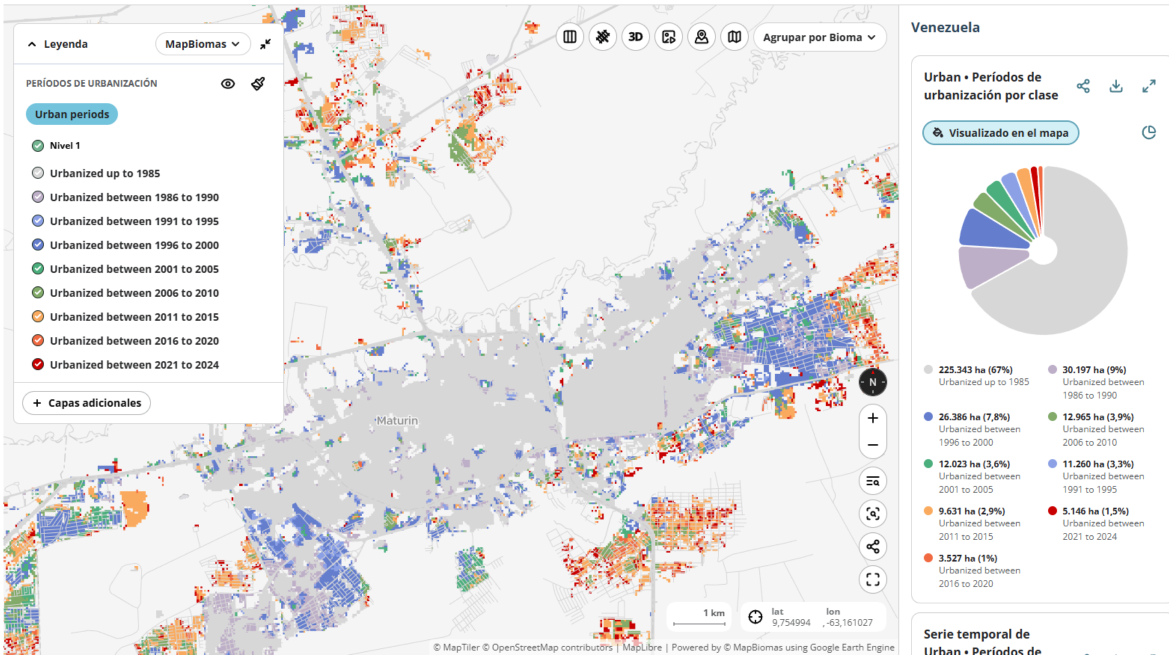

Figure 3. *Division of the 1985–2024 period into five-year urbanization intervals for the city of Maturín, Monagas. View from the platform.*

5.3. Urban vegetation

Unlike other global mapping products, this module disaggregates the vegetation present in and around cities (Figures 4 and 5) into four levels of detail, allowing for the analysis of urban ecosystem services and processes such as heat islands.

- **Level 1:** delimitation of urban area (UA) and peri-urban area (PUA)

- **Level 2:** classification of internal cover (Area without vegetation and urban/peri-urban vegetation)

- **Level 3:** general classification of vegetated and non-vegetated cover, including forest formations, grasslands, agricultural areas, and surfaces without vegetation, based on the first level of the land use and land cover legend of MapBiomas Venezuela Collection 3.
- **Level 4:** more detailed taxonomic and structural characterization, for example, floodplain forests, forest plantations, and rocky outcrops, based on the second level of the Collection 3 legend. This level is especially useful for urban and peri-urban biodiversity analysis.

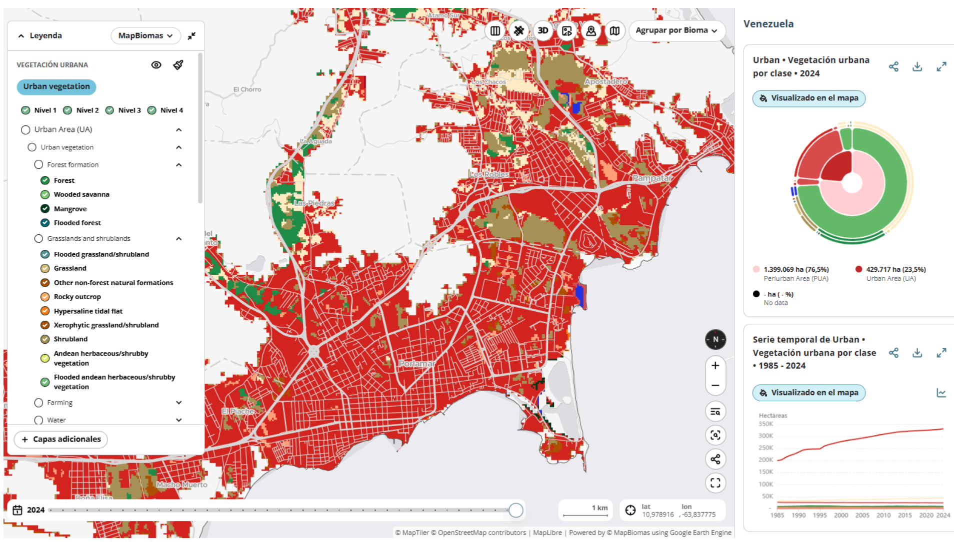

Figure 4. *Visualization (from the platform) of vegetation in urban areas of Margarita Island, Nueva Esparta.*

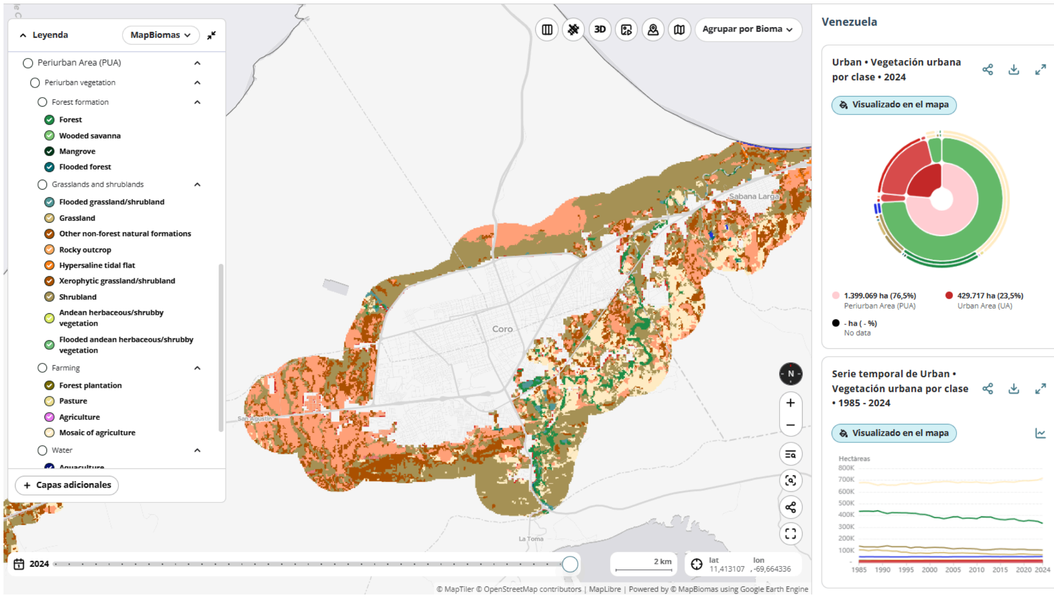

Figure 5. *Visualization (from the platform) of vegetation in peri-urban areas of Coro, Falcón.*

5.4. Urban slope

Classification of the slope of the land in percentage, divided into four ranges, which are described below:

- **Up to 10 %:** areas with predominantly flat to gently undulating relief. These represent surfaces with the fewest physical constraints for urban development.
- **Between 10-25 %:** areas with undulating relief. These indicate transition zones where urban development requires moderate technical interventions for land grading and drainage.
- **Between 25-45 %:** areas with rugged or mountainous relief. These surfaces present significant restrictions for urbanization.
- **Above 45 %:** areas with steep relief or high slopes. These represent zones of high ecological fragility and geomorphological, where urbanization is limited or considered critical.

This layer makes it possible to identify settlements, especially informal ones, located on terrain with potential slope instability (Figures 6 and 7).

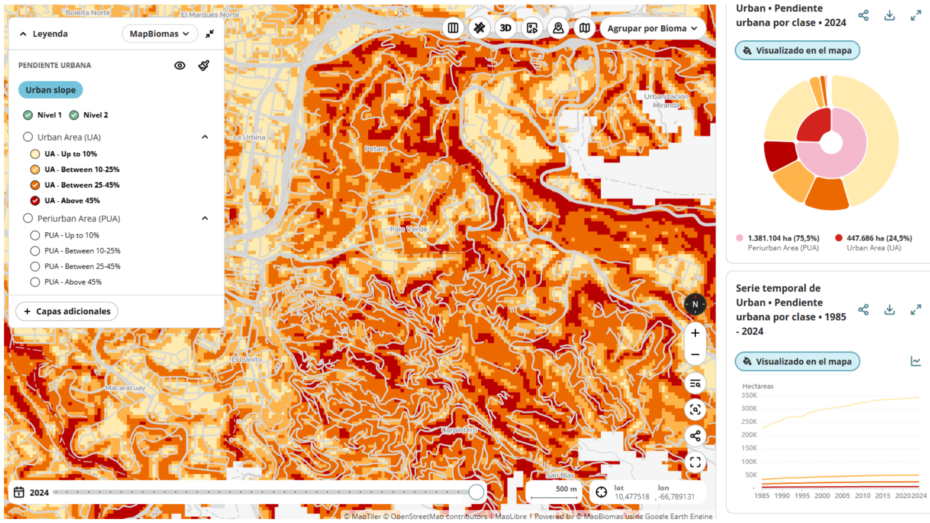

Figure 6. *Classification of terrain slope in urban zones of Petare, Miranda. View from the platform.*

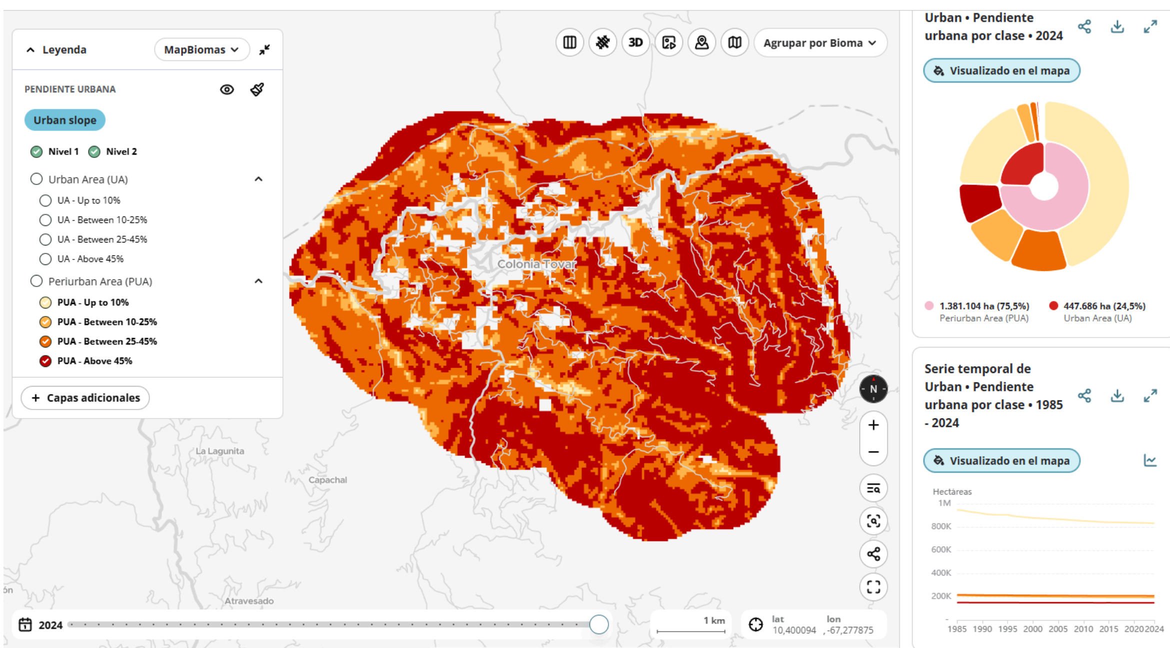

***Figure 7**. Classification of terrain slope in peri-urban zones of Colonia Tovar, Aragua. View from the platform.*

Data source: SRTM 30 m Digital Elevation Model (NASA, 2013).

5.5. Height Above Nearest Drainage (HAND)

This indicator of vertical proximity to the nearest drainage network (HAND). It categorizes the territory into three threat levels that are described below:

- **Up to 3 m:** areas with very low vertical elevation relative to the nearest watercourse.
- **Between 3 and 6 m:** areas of moderate elevation above drainage.
- **Above 6 m:** areas with greater relative height with respect to the drainage system.

This variable makes it possible to model zones with possible susceptibility to fluvial flooding (Figures 8 and 9).

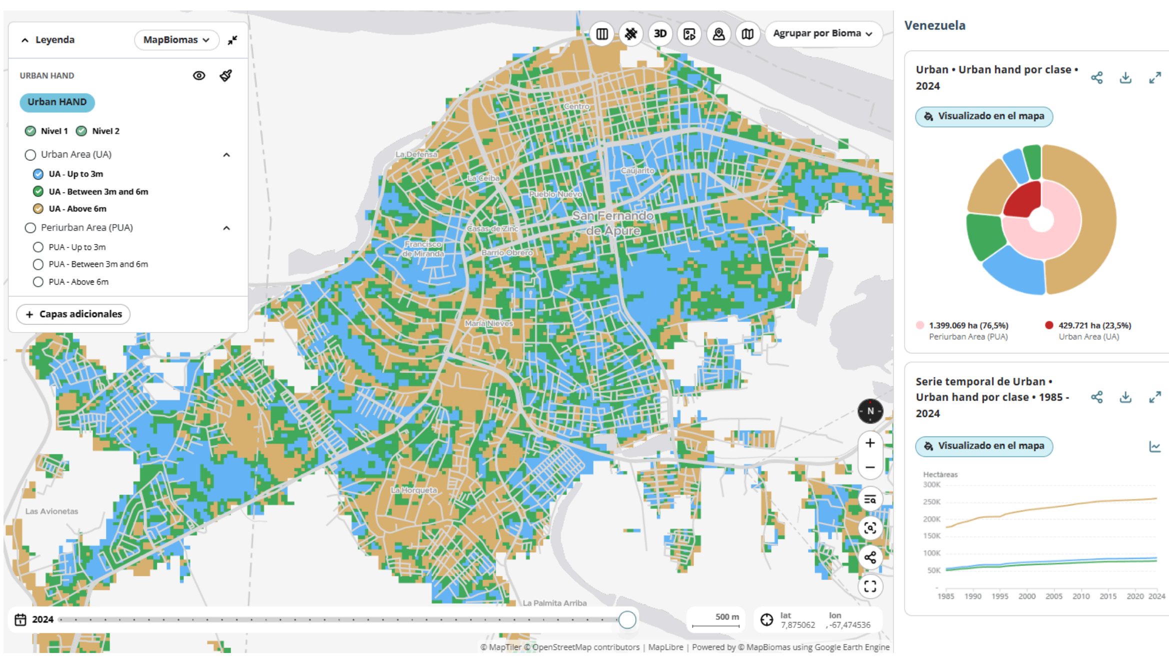

Figure 8. *Classification of proximity to hydrography (height above the nearest drainage) in the urban area of San Fernando de Apure, Apure. View from the platform.*

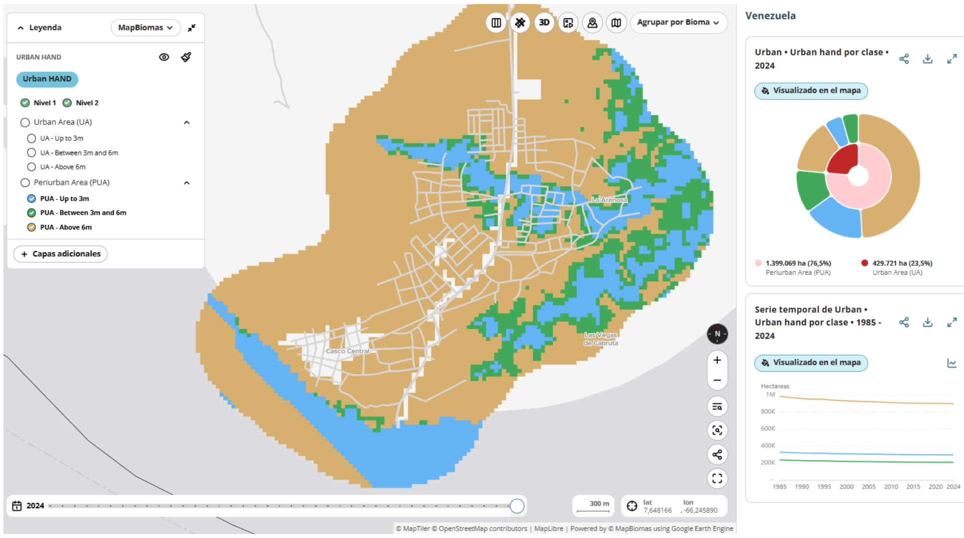

Figure 9. *Classification of proximity to hydrography (height above the nearest drainage) in the peri-urban area of Cabruta, Guárico. View from the platform.*

Data source: Height Above Nearest Drainage (HAND) (Donchyts *et al*., 2016).

5.6. Urban seismicity

Given Venezuela's location on the interaction boundary between the Caribbean and South American plates, seismicity is a critical variable for urban risk management. This module integrates national seismic zoning, based on FUNVISIS historical and neotectonic data, to classify the 1,124 Urban Units according to their level of seismic exposure.

For a technical and standardized interpretation, a seismic hazard scale categorized into five levels of criticality was used, directly linked to the maximum expected acceleration of the terrain and the proximity to the main fault systems (Boconó, San Sebastián and El Pilar):

- **Very Low:** zone located very far from seismic faults, where vibrations may be felt very slightly.
- **Low:** zone located far from seismic faults, but where slight vibrations may still occur.
- **Moderate:** zone distanced from seismic faults, with the occurrence of earthquakes and moderate vibrations.
- **High Zone:** located near major seismic faults, with the occurrence of large earthquakes and severe vibrations.
- **Very High:** zone located very near to the most important seismic faults, with the occurrence of large earthquakes and very intense vibrations.

This categorization makes it possible to identify critical cases in which urban and peri-urban expansion occurs on soils with liquefaction potential or in immediate proximity to fault traces, providing a key input for updating planning instruments and civil-protection protocols (Figure 10).

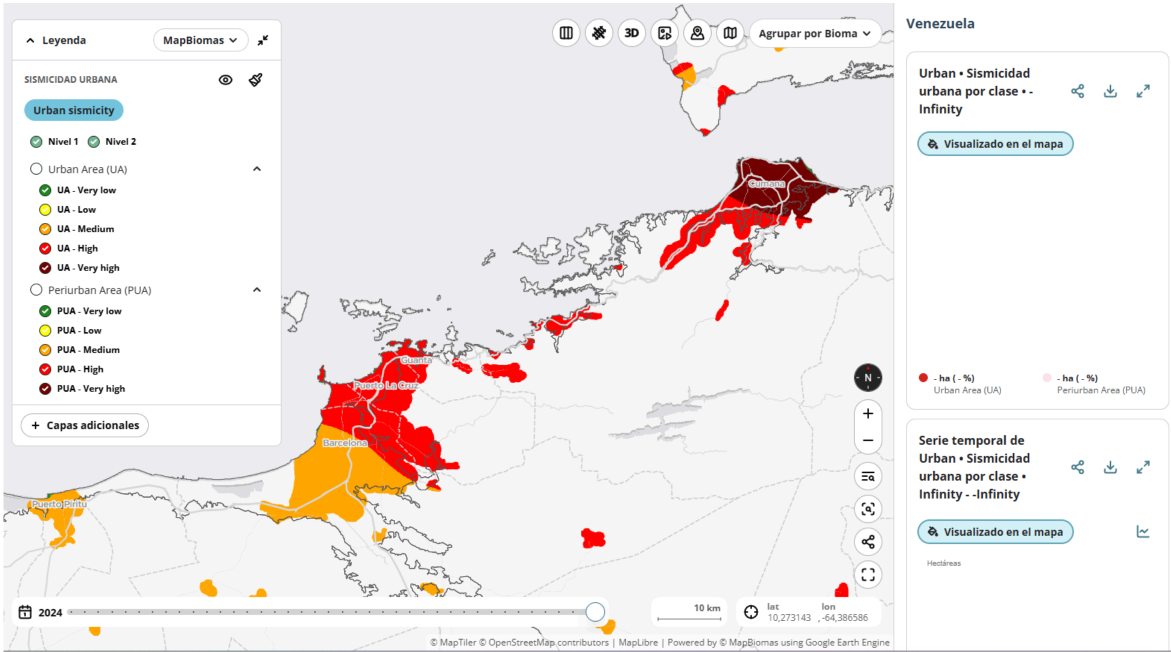

Figure 10. *Classification of seismic activity in part of the Venezuelan northeastern axis, with the city of Cumaná at the highest threat level. View from the platform.*

Data source: Geology and Seismicity (Singer et al., n.d.), Seismic Hazard (Hernández and Delgado, 2019), and Thematic Cartography (Coronel et al., 2025).

6. Conclusions

The development of the MapBiomas Urban Venezuela Module (beta version) represents a significant advance in the precision of the country's thematic cartography. From the implementation of the proposed methodology and analysis of the results obtained, the following conclusions emerge.

First, integration of the "built-up areas" polygon layer, derived from Esri/Sentinel-2 and with 10-meter spatial resolution, as the basis for supervising the historical land use and land cover series of MapBiomas Venezuela, proved to be an effective strategy. This approach made it possible to correct systematic commission errors, especially in regions with spectral signatures similar to urban ones, such as mining areas south of the Orinoco and bare-soil areas in semi-arid environments, helping ensure that the 1,124 polygons in the Urban Units (UU) layer correspond to real human settlements.

Second, the delineation of the Peri-urban Areas (PUA), grounded in legal criteria—such as Master Plans—and in differentiated areas of influence according to political-administrative hierarchy, goes beyond mere satellite observation. By distinguishing the consolidated urban core from its transition zone, the module offers a useful tool for territorial planning and risk management by making it possible to identify expansion areas where pressure on natural ecosystems and exposure to hazards may be greater.

Likewise, the participation of a network of experts from universities and technical agencies in the country, including UCV, USB, UCLA, FUNVISIS, and INE, strengthens the technical robustness of the document. Adjustment of filtering thresholds—4 and 20 hectares—through expert judgment helps ensure that the final product more faithfully reflects Venezuela's morphological and political-administrative reality, overcoming the limitations of a fully automated classification process.

On the other hand, a final product with topological consistency was obtained, without overlaps or gaps between spatial categories, which facilitates its immediate incorporation into geographic information systems at national and regional scales. In this regard, the module constitutes a robust basis for future analyses of historical urban dynamics, peri-urban expansion, and territorial assessment.

Finally, the results of this process are integrated into the Urban Module platform as an information system applicable to territorial analysis. In addition to tracking urban expansion, this tool incorporates monitoring of urban and peri-urban vegetation, as well as characterization of relevant physical variables, including slope, seismicity, and height above the nearest drainage (HAND). Taken together, MapBiomas Venezuela makes available a robust and transparent geospatial database aimed at strengthening planning, risk management, and evidence-based decision-making.

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How to cite this document

MapBiomas Venezuela. (2026). Appendix: MapBiomas Urban Venezuela Module - Delimitation of Urban and Peri-urban Areas (Beta Version). In Algorithm Theoretical Basis Document (ATBD): MapBiomas Venezuela - Collection 3 (Version 1). [Link or DOI if available].

How to cite the data collections

MapBiomas Venezuela. (2026). Beta version of the annual series of urban-expansion maps of Venezuela. MapBiomas Venezuela. DOI pending.