

MAPBIOMAS
BOLIVIA

Manual general MapBiomás

Theoretical Background Document on Algorithms (ATBD)

Collection 4

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Collection 4

Executive Summary

Fundación Amigos de la Naturaleza (FAN) is a civil society organization committed to environmental conservation that promotes, with technical and scientific backing, innovative pathways toward integral and sustainable development.

FAN is the Bolivian member of the Amazon Network of Georeferenced Socio-Environmental Information (RAISC), a collaborative alliance comprised of Brazil, Peru, Colombia, Ecuador, Venezuela, Guyana, French Guiana, and Surinam. Its purpose is to generate information aimed at the region's socio-environmental sustainability in a coordinated manner. Since 2009, within the framework of RAISC, the construction of deforestation maps for the Bolivian Amazon began using advanced satellite data processing tools. Seeking alternatives to automate processes and generate timely information, in March 2017 RAISC agreed with the General Coordination of the MapBiomas Network to create the MapBiomas initiative.

MapBiomas is a collaborative network formed by non-governmental organizations, universities, and companies, whose objective is to apply high-quality, low-cost technology to produce annual series of land cover and land use maps (from 1985 onwards). As a result of this joint effort with RAISC and MapBiomas, FAN presents the MapBiomas Bolivia Collection 4 of Annual Land Cover and Land Use Maps, which covers the period 1985–2025 and is accessible through the MapBiomas Bolivia interactive platform.

This Algorithm Theoretical Basis Document (ATBD) aims to detail the methodological steps and computational algorithms used to produce Collection 4, providing users with a clear technical understanding of the annual mapping of land cover and land use between 1985 and 2025.

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1 Introduction

1.1 Scope and content of the document

The objective of this document is to describe the theoretical basis, justification and methods applied to produce annual maps of land cover and use from 1985 to 2025 from Collection 4 of MapBiomas Bolivia.

This document covers Landsat image classification methods (L5, L7, L8, and L9), image processing architecture, and the approach to integrating the biomes and regions present in the country. There is also historical context and background, as well as an overview of satellite imagery data and the accuracy assessment method applied.

The specific procedures applied in each cross-cutting theme are found in the appendices (<https://bolivia.mapbiomas.org/en/download-of-atbds>). The classification algorithms are available on the MapBiomas Bolivia Github (<https://github.com/raisgmb/mapbiomas-bolivia>)

1.2 Overview

The MapBiomas Bolivia project began in July 2021 with the purpose of contributing to the understanding of land cover and use dynamics (LULC) throughout the national territory. The project is developed thanks to: i) technological advances that allow the processing of large amounts of spatial data in the cloud using algorithms hosted on the Google Earth Engine platform; ii) the implementation of image processing methods focused on the monitoring of LULC by MapBiomas; iii) the multidisciplinary technical team that with its experience carries out the mapping of the territory; and iv) the support of visionary institutions and funders who support the project.

The products of MapBiomas Bolivia are composed of annual thematic maps of 30 meters of spatial resolution for the entire country, in its methodology it uses annual mosaics of satellite images made up of layers of information (spectral bands, derived indices, physical variables); Statistics are also obtained from maps by department, biome, watershed, indigenous territories, among others.

MapBiomas Bolivia's mapping, to date, presents its third collection of annual maps; which will evolve in methodology, analysis period, detail of coverage mapped over time and an improvement in their quality.

Collection 1.5: covers the mapping of coverage and uses from 1985 to 2022. Although it was not published, it presented improvements in the classification of cross-cutting topics such as Mining and Urban Infrastructure in all biomes.

Collection 2: Mapping of Coverage and Uses between 1985 and 2023 uses *machine learning* (Random Forest), with 156 layers of information (original Landsat bands, fractional and texture information derived from them, and indices. Physical

variables). Collection 2 has the 14 classes of the previous version and includes five additional classes, totaling 19 classes mapped, plus other improvements to cover and soil in the Water Transverse class.

Collection 3 expands the time series for the period 1985–2024 and integrates 23 mapped classes (four more than Collection 2), incorporating methodological improvements that increase accuracy in detecting natural and anthropogenic covers.

Collection 4 expands the land cover and land use analysis for the 1985–2025 period, consolidating a structure of 27 mapped classes. This version incorporates methodological improvements in classification that allow for greater accuracy in detecting natural and anthropogenic covers. In addition to previous categories, new key classes are integrated to strengthen the specific representation of regional ecosystems and productive activities, such as: Andean grassland and shrubland, Flooded Andean grassland and shrubland, Aquaculture, Soy, Other crops, Rice, Rocky soils, Steppe, and Sparse shrubland.

The MapBiomass collections aim to contribute to the development of a fast, reliable, collaborative, and low-cost method for processing large-scale datasets and generating historical time series of annual LULC maps. All data, classification maps, statistical codes and other analyses are freely accessible through the MapBiomass Bolivia (<http://bolivia.mapbiomas.org>) platform.

The points of Collection 4 of MapBiomass Bolivia are the following:

- Annual classification rasters of the entire Bolivian territory;
- Rasters of annual transitions between classes and years chosen by the user;
- Pre-processed tiles generated from Landsat file collections (Landsat 5, Landsat 7, Landsat 8, Landsat 9);
- Image processing infrastructure and algorithms (scripts in Google Earth Engine and source code);
- Annual and transitional LULC statistics with various units of analysis;
- Quality assessment of Landsat tiles. Each scene may have a proportion of clouds and other interference. Thus, each pixel of a given year is classified according to the number of observations available, varying from 0 to 41 observations per year. The quality assessment of the Landsat tiles is available on the MapBiomass website;
- Wall Map of Land Cover and Use to 2025;
- National infographic on land cover and use;
- Document of key findings in the analysis of the results; and
- Technical documents for knowledge of the processes by theme.

1.3 Study Area

The scope of the study encompasses the entire territory of Bolivia, whose official area is 1,098,581¹ km². For the Land Cover and Land Use Classification of the Fourth Collection of MapBiomas Bolivia, the area considered for mapping is 1,083,875 km². Within this area, seven biomes were defined (Figure 1): Amazonia, Andes, Valleys, Chaco, Chiquitano, Pantanal, and Tucumano-Bolivian. The difference between the country's official area and the mapped area is due to the cartographic criteria and boundaries used to delineate the area of analysis for MapBiomas Bolivia.

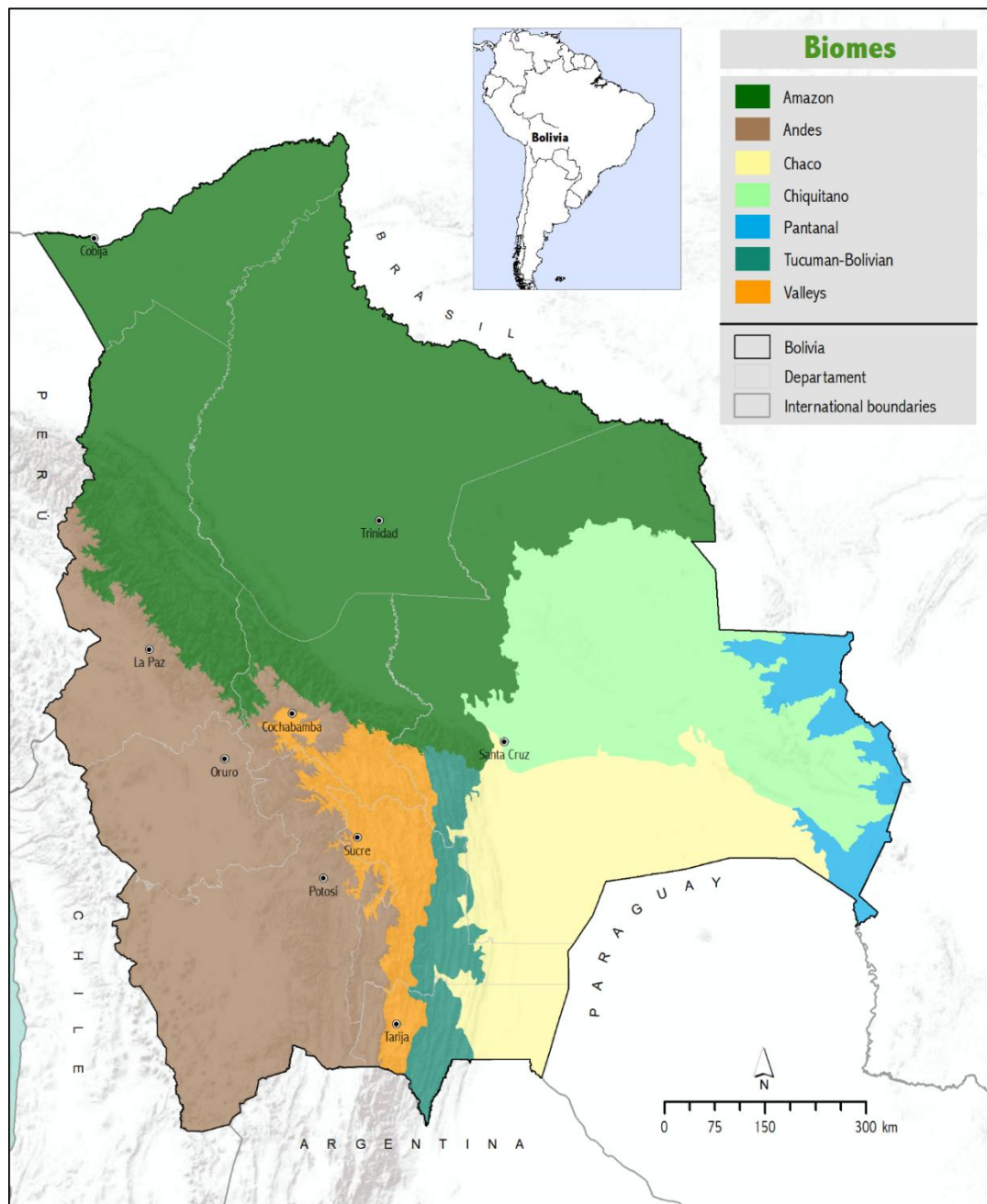
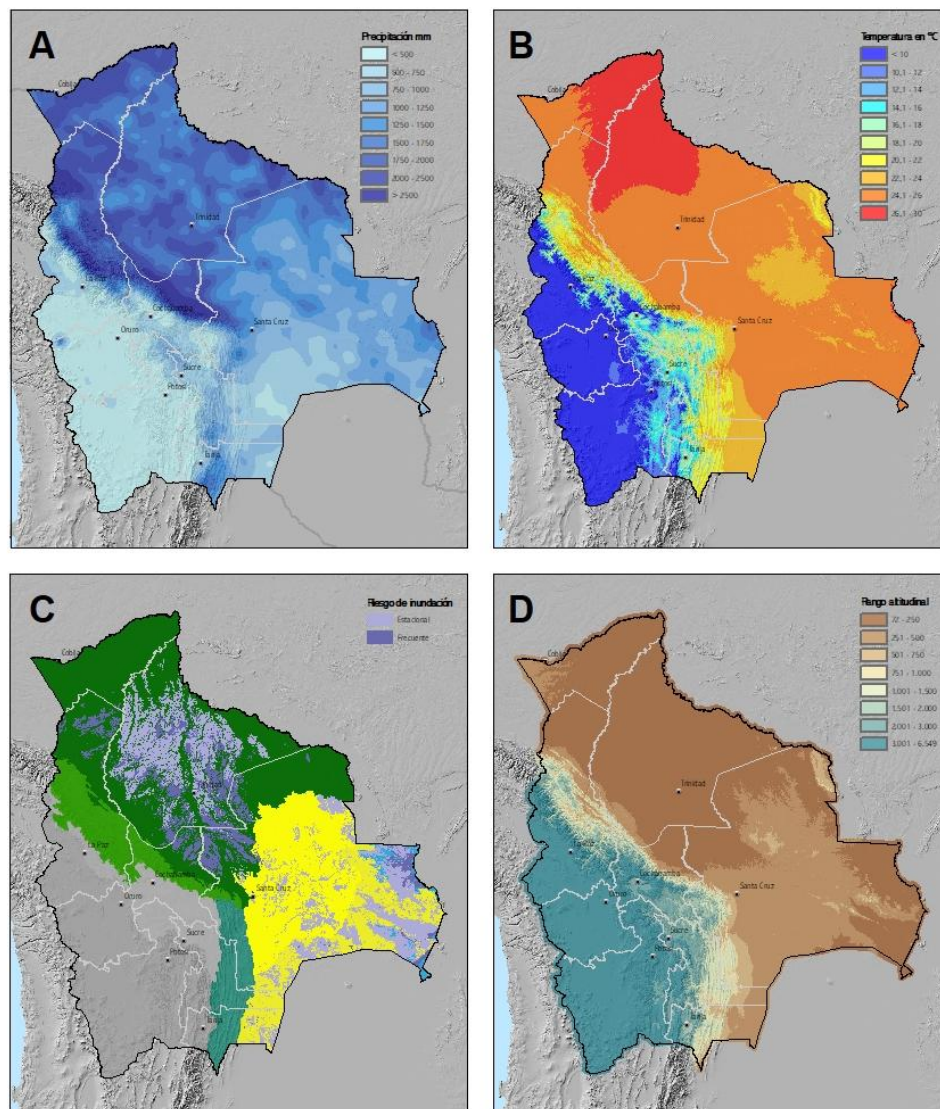


Figure 1. Location and boundaries of biomes identified in Bolivia.

The biomes and regions identified in MapBiomias Bolivia Collection 4 are distinguished by a set of biotic characteristics—such as physiognomies and species composition—and abiotic features, such as climate, flood regimes, and elevation (Figure 2). Technical criteria based on Pierre Ibisch (2003) ecoregion regionalization were applied for their delimitation. This division into biomes optimizes the classification process, enabling more accurate and representative results.



Note. A) Precipitation; B) Temperature; C) Flood zones; D) Altitudinal floors.
Figure 2. Abiotic characteristics of Bolivia.

¹ National Institute of Statistics (INE). Collected from: <https://www.ine.gob.bo/index.php/bolivia/aspectos-geograficos/>

The largest biome is that of the Amazon, occupying 44% of the total surface and partially located in five of the country's nine departments. While the Pantanal biome has the smallest area and occupies 2.7% located in the east of the department of Santa Cruz.

Below is a brief description of the characteristics of each Bolivian biome, followed by a summary table of it.

1.3.1 Amazon Biome

The Amazon biome is heterogeneous because it has different altitudinal levels, forest formations, countryside landscapes, pastures, lakes, and very diverse rivers, which is why the following division is made that describes its high diversity:

- High Amazon: It mainly occupies the eastern portion of the tropical Andes. It is mainly made up of evergreen forest formations and grassland and shrubland. The forest formations generally develop above 1,100 m in altitude, reaching approximately 3,800 m. They have a tree canopy with heights ranging between 15 and 25 meters, with emergent trees that can exceed 30 m.

Grassland and shrub formations, dominated by grasses and herbs, usually appear above 2,500 m of altitude, in areas with shallow soils (such as mountain tops), or in areas of less rugged topography above 3,000 m, where they are known as yungueño moors. Due to its physiographic characteristics – such as steep and steep slopes – the main economic activities of this region include small-scale agriculture, cattle, sheep and goat farming, selective extraction of forest species.

This section of the biome encompasses the Yungas region, characterized by a rugged topography with steep slopes, high ambient humidity, and constant dense cloud cover. It is dominated by evergreen montane forests that harbor extraordinary biological diversity, as well as deep valleys where traditional agricultural activities take place, notably the small-scale cultivation of coca, coffee, fruit trees, and vegetables.

- Lower Amazon: Made up mainly of evergreen forest physiognomies, as well as grassland and savannas (Amazonian savannas) but in a smaller proportion. In forests, the tree canopy varies between 30 and 35 m, with emergent trees that can exceed 40 m. In this region, the Amazonian forests are divided into: i. Amazonian forests of terra firma (they grow in areas with well-drained soils, they cover the largest area of surface); and ii. Amazonian flood forests (seasonally flooded as a result of the overflow of large rivers), which in turn are subdivided into Várzea forests (flooded by white waters, rich in sediments and minerals) and igapó forests (flooded by black waters, rich in organic matter). The savannah-countryside formations are distributed in scattered patches, mainly in the extreme east and southeast of this region.

They appear in areas with lateritic and shallow soils, and where the water table is shallow and/or areas that are seasonally flooded. The country physiognomies are dominated by grasses and herbs; and the savannahs, in addition to presenting these forms of life, also appear scattered trees and shrubs (campinaranas and similar to the cerrado sensu stricto).

The main economic activities that have traditionally been developed are the extraction of timber and non-timber forest products (Brazil nuts, cocoa, cupuaçu, etc.), as well as commercial fishing and livestock using native fodder. However, in recent years, livestock activities have been increasing, causing a change in land use through the implementation of introduced pastures. Also, small-scale agriculture and the planting of coca, coffee and citrus crops (lower western Amazon) are practiced, as well as large-scale agriculture (southern lower eastern and western Amazon, respectively).

- Lower Plains Amazon: Made up mainly of grassland, savannah and wooded physiognomies, but in a smaller proportion. All these physiognomies are distributed forming a landscape mosaic on a flat and/or undulating physiography, with elevations that do not exceed 300 m in altitude. Geologically it is divided into two zones, the northern zone that develops on well-drained, lateritic soils, acidic and poor in nutrients; and the southern zone, which is seasonally flooded as a result of the overflow of the large rivers that cross the region.

The soils of these areas that tend to flood are made up of sediments of recent origin (quaternary), being relatively fertile and with a neutral to slightly alkaline pH. The savannah and country physiognomies are dominated by grasses and grasses, but the savannah includes the presence of scattered trees and shrubs. On the other hand, the forest physiognomies correspond to humid and evergreen forests, which are an extension of the Amazonian forests into a savanna-countryside landscape matrix.

The distribution of these forests in this region is restricted only to the main watercourses, so, as in other parts of the Amazon, they can be divided into várzea forests (flooded by white waters, rich in sediments and minerals) and igapó forests (flooded by black waters, rich in organic matter). Physiognomically, they are also called gallery forests. The tree canopy is variable, but generally reaches heights of between 20 and 25 m, with emergents of up to 35 m.

Due to the limiting factor of seasonal floods, the main economic activity is extensive livestock, with the main source of fodder being the native pastures of the fields and savannahs of the region, however, the technological growth of the meat and milk production chain, made livestock begin to take on greater prominence because it is less demanding in the quality of the soils that are shallow. Accompanying these changes the legal regulations on land use in this region favoring this activity,

programs for the implementation of mechanized agriculture were also initiated in the eastern zone, with rice cultivation currently being the most practiced.

1.3.2 *Andes Biome*

- The dominant physiognomy in this biome is the Andean grassland and shrub, which generally grows above 3,000 m elevation. In Bolivia it is called Puna, it has a cover dominated by grasslands, with some scattered shrubs. The soils are generally dry, although there are areas that become waterlogged and remain moist throughout the year (bofedales). On the other hand, there are also forest formations, although in smaller proportions, these being the dry inter-Andean forests (i. low, deciduous and thorny forests, with shrubby tree canopy of 3 to 5 m in height, with trees and emergent columnar cacti of up to more than 10 m; and ii. semi-deciduous forests, with tree canopy of 10 to 15 m, and pop-ups up to 20 m.) and the Polylepis forests (*kewiñales*, distributed above 3,000 m altitude and forming scattered patches in the middle of countryside physiognomies).

Among the main economic activities developed in this region are sheep, goat and camelid farming, as well as the seasonal cultivation of quinoa (*Chenopodium quinoa*), small-scale agriculture and mechanized agriculture.

1.3.3 *Valles Biome*

- The central valleys contain a remarkable diversity, with a forest formation composed of deciduous dry forest (10-20 m). Mostly destroyed or heavily disturbed. Different formations and floristic types; important forests of potential natural vegetation, especially: mixed forests with *Schinopsis haenkeana* and *Aspidosperma quebracho-blanco*, churqui forest, forests with *Acacia visco* and *Prosopis alba*. Partially with the presence of very tall columnar succulents (e.g. *Neoraimondia herzogiana*, Cactaceae).

Its main activity is agriculture, livestock, firewood/wood harvesting; they have severe soil erosion problems.

1.3.4 *Chaco Biome*

- The main forest formation is called Chaco forest, and to a lesser extent the savannah and grassland physiognomies included within the complex called cerrado sensu lato (more used in Brazil). These descriptions are differentiated by their physiognomic and structural characteristics, as well as climatic, geological and physiographic characteristics. On the other hand, the Chaco forest, distributed in the southern region, is deciduous, microfoliate and thorny. It has a shrubby tree canopy between 3 and 5 m high, with emergents that exceed 10 m, with the presence of columnar cacti being frequent. It also has a low semi-deciduous vegetation type with columnar succulents (5-15 m) and differentiation according to humidity.

Zonal Vegetation: Carob grove with *Prosopis nigra* (high water table), seasonally flooded *Copernicia alba* forest. In well-drained red soils with rocky outcropping. Geologically, the Chaco forest develops on sediments of recent origin (Quaternary), and whose physiography is called the Chaco-Beniana plain.

The most frequent economic activities were cattle ranching and extraction of vegetable fuel (firewood and charcoal production). However, recently, as a result of the new colonization that has been established in the Chaco region, all traditional economic activities are being replaced by small-scale agriculture (peasant communities) and large-scale agriculture (agricultural enterprises and Mennonite colonies).

1.3.5 Chiquitano Biome

- The forest formation corresponds to the Chiquitano forest which sits on the Precambrian shield, which varies between semi-deciduous and deciduous, and the closed sensu lato, both developed on an undulating plain physiography. Medium-tall semi-deciduous forest with columnar succulents (15-20 / -25 cm). The forest tree canopy is distributed between 15 to 20 m in height, with emergent trees reaching up to just over 25 m. It forms a complex mosaic with other ecoregions such as the cerrado and flooded savannahs.

In the mountains there is practically an evergreen forest that is very little known, housing very interesting relicts. It is an ecoregion exclusive to Bolivia, one of the richest dry forests in plant species on a global scale. The highest altitude montane forests in the lowlands of Bolivia and adjacent regions.

The economic activity traditionally practiced is industrialized agriculture and large-scale cattle ranching through introduced pastures, use of native fodder, use of wood, mining and transport of petroleum products (gas pipeline).

1.3.6 Tucuman-Bolivian Biome

- The forest formation of this biome is composed of semi-humid (semi-) deciduous forests with lapacho (*Tabebuia lapacho*) to evergreen on lower floors (with Myrtaceae: *Blepharocalyx salicifolius*, *Myrcianthes spp.*, and Lauraceae). On upper floors (1,800/2,200 m to 2,500/3,200 m) evergreen forest with pine (*Podocarpus parlatorei*) and deciduous forests with *Alnus acuminata*. Higher up, at altitudes up to 3,900 m, there are relicts of *Polylepis crista-galli*. *Polylepis* forests, grasslands, shrublands and saxicolous vegetation of Bolivian-Tucumán highlands could be considered part of the Biome. The forests can be semi-deciduous, humid and evergreen, reaching heights between 15 to 25 m.

The economic activity traditionally practiced is the use of wood, an agricultural activity and growing grazing. Small and medium-scale agriculture; Browsing livestock. Selective extraction of species of forest value. Threats: Entry of hydroelectric and hydrocarbon projects. Expansion of livestock and agricultural activity.

1.3.7 Pantanal Biome

- The Bolivian Pantanal, which is part of the largest freshwater wetland in the world, distributed in three countries: Brazil, Bolivia and Paraguay with an estimated area of 340,500 km² of which 28,659 km² correspond to the biome.

Its vegetation is dominated by flooded savannas made up of grasses and sedges; swamps, aquatic herbaceous vegetation, flooded riparian forests, low, open forests and extensive palm groves. Its surface is flat with an extensive flood area and large lagoons due to overflows of the Paraguay River, it has alluvial soils frequently with drainage problems, with an altitudinal distribution between 100 and 800 m.

Its main activity is cattle ranching followed by tourism, since within this there are two national protected areas: San Matías Integrated Management Natural Area and the Otuquis National Park and Integrated Management Natural Area.

Table 1. Summary of the characteristics of land cover and land use of Bolivian biomes.

Biome	Area (km ²) (% Country)	Description of coverage
Amazon	476.181 44%	Humid evergreen and almost evergreen forests, Chiquitano dry forest, gallery forest and forest islands. They have a tree canopy of 15 to 35 m. This biome encompasses seven national protected areas such as Madidi, TIPNIS, Carrasco, among others.
Andes	233.257 22%	The vegetation is located above 3,000 m of altitude, such as: high Andean grasslands, scrublands, herbaceous formations, scattered shrubs and to a lesser extent inter-Andean dry forests and Polylepis, The presence of salt deserts and glaciers stands out in this biome, which originates lagoons, lakes and flooded covers such as wetlands.
Valleys	49.088 4%	Forest formation composed of deciduous dry forest (10-20 m). Partially with the presence of very tall columnar succulents

Chaco	121.691 11%	Chaco forest, characterized by being deciduous or semi-deciduous microfoliate and thorny, with a shrubby tree canopy between 3 to 5 m high. Also, physiognomies of savannas and grasslands.
Chiquitano	142.794 13%	Chiquitano forest, semi-deciduous to deciduous with a tree canopy between 15 and 20 m high. It highlights the driest, most extensive and richest forest in plant species on a global scale. It has savannas such as the cerrado sensu lato and floodable.
Tucuman-Bolivian	32.205 3%	Polylepis forests, grasslands, shrublands and saxicolous vegetation of the Bolivian-Tucuman highlands. They are located between 800 and 3,500 meters in elevation. The forests can be semi-deciduous, evergreen and humid, reaching heights between 15 and 25 m.
Pantanal	28.659 3%	Wooded savannahs, hydrogeophytic, flooded palm groves, flooded forests, open forests located between 100 and 800 m above sea level.

1.4 Applications

The applications of MapBiomass Bolivia's products span various fields of analysis and research, notably including:

- Annual monitoring of areas threatened by the conversion of natural covers and at risk of deforestation.
- Estimation and support for studies on greenhouse gas (GHG) emissions derived from land use and land cover change.
- Mapping and quantification of land use transitions, as well as forest cover gains and losses.
- Tracking processes of forest regeneration and secondary growth.
- Analysis of water bodies and their interaction with different classes within land use and cover dynamics.
- Evaluation of agricultural, livestock, and urban expansion.
- Monitoring of natural disasters and identification of desertification processes.
- Support for territorial planning and the strategic management of protected areas.
- Input and enhancement for climate and environmental distribution models.

MapBiomass Bolivia not only complements existing efforts at the national and global levels, but also brings with it additional advantages such as: 1) the maps of

MapBiomass Bolivia have been built using the complete collection of Landsat data (41 years) with an annual temporality; 2) the entire product shares the same methodology, legend, temporal and spatial resolution, thus allowing comparisons between regions; 3) the product is prepared by experts knowledgeable about the national reality, generating a product with a view to local applications; 4) MapBiomass Bolivia makes its methods, tools and products available to the public through a public consultation platform on the internet.

2 Basic information and background

2.1 Institutional context

In this section, complementary but significant critical and contextual information will be provided to understand the products and methods of MapBiomass to generate the collections.

2.1.1 *Fundación Amigos de la Naturaleza - FAN*

The Fundación Amigos de la Naturaleza - (FAN) is a non-profit civil society organization, created in 1988. In its more than 30 years of institutional work in Bolivia, its actions are aimed at the implementation of conservation and maintenance actions of the Natural Heritage through mitigation and adaptation to climate change, biocommerce, municipal management, research and planning for conservation, and communication.

The projects and more information about the work carried out by FAN are available on its website: <https://www.fan-bo.org/>

2.1.2 *MapBiomass*

The MapBiomass Global Network is an international, multi-institutional collaborative network comprised of non-governmental organizations, universities, and technology companies <https://mapbiomas.org>. Currently, the network continuously monitors territorial transformations across 17 countries, extensively covering South America as well as regions in Mexico, Indonesia, India, and the Democratic Republic of Congo.

These initiatives operate through massive cloud-based data processing and automated classifiers developed and run on the Google Earth Engine platform, to contribute to the understanding of land cover and land use change dynamics globally. All data, methodologies, and collections generated are public, open, and transparent, and are available through each country's official platforms and the main portal. This Network features a series of common practices across all its initiatives and MapBiomass products:

- Easy-to-use, easy-to-access, and easy-to-use data platform for applications
- Transparency in methodology and technology
- Free Open Data
- Local experience and thematic knowledge of Land Use and Cover

- Cloud Processing (Google Earth Engine Platforms)
- Technical knowledge in remote sensing and programming
- Independence for data publication
- Collections that allow for constant evolution and improvement
- Distributed and decentralized networks, collaborative spirit
- Committed to technical-scientific soundness
- Promoting capacity development

2.2 Remote sensing data

The mapping data used by the MapBiomass Bolivia initiative for its Collection 4 were obtained from satellite images from the period 1985 to 2024 from the Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager and Thermal Infrared Sensor (OLI-TIRS), on board the Landsat 5 satellites (L5, for the years 1985-2012 of the series). Landsat 7 (L7, for the years 2000-2022), Landsat 8 (L8, available from 2013 onward) and Landsat 9 (L9, from 2022 onward). The Surface Reflectance images are from Collection 2 of the Landsat Data Catalog² with Tier 1 correction level, which were subjected to radiometric calibration, ground control point-based orthorectification, and digital elevation models to ensure pixel-level recording and atmospheric correction.

The collections of Landsat imagery of 30 m spatial resolution were accessed through the Google Earth Engine platform, provided by NASA and the United States Geological Survey (USGS).

2.3 Google Earth Engine and MapBiomass Amazonia

Google Earth Engine (GEE) is a cloud platform for the analysis of geospatial data at a global level. It offers access to extensive satellite data catalogs, petabyte-scale processing, JavaScript and Python APIs, and an online development environment (Code Editor). These tools allow complex analyses to be carried out, such as the classification of satellite images and the mapping of land use cover, uses and changes. GEE also promotes collaboration between regional teams, such as RAISG, and facilitates the application and replication of methodologies on the same dataset by different users.

The MapBiomass processing chain is based entirely on Google technology and, as such, the MapBiomass Amazon initiative has relied on GEE to 1) process satellite images in cloud computing infrastructure, 2) develop codes (scripts) in Javascript and Python, 3) store the data generated using cloud storage, and 4) display the results (tiles, annual land use maps, transition analysis, statistics by class and by transition, methodological information, among others) through a web platform for public consultation accessible in <http://plataforma.bolivia.mapbiomas.org>.

MapBiomass' image processing is based on Google technology, which includes image processing in cloud computing infrastructure, programming with

² <https://developers.google.com/earth-engine/datasets/catalog/landsat/>

Javascript and Python through Google Earth Engine (GEE) and data storage with Google Cloud Storage. Google defines Google Earth Engine as: "a platform for petabyte-scale scientific analysis and visualization of geospatial datasets, both for public benefit and for businesses and government users."

2.4 Other mapping initiatives

In recent years, various tools have been developed for land cover and land use mapping, some of them global in scope, with increasingly robust approaches. They all have in common their interest in contributing to one of the most urgent issues today: knowing the current state of land cover types and monitoring changes in them for the detection of deforestation, monitoring of terrestrial and aquatic ecosystems and strengthening conservation, detection of heat sources and forest degradation. Below, we list the most relevant initiatives.

2.4.1 Global Region Sources

- GLC 2000 - Global Land Cover mapping for the year 2000: The project was an international partnership of some 30 research groups coordinated by the Joint Research Centre of the European Commission 13, with the aim of producing a global land cover database by the year 2000. The database contains land cover maps with detailed and regionally relevant map legends and a global product that combines all regional classes into one coherent legend
- Global Forest Watch (GFW): In collaboration between the GLAD (*Global Land Analysis & Discovery*) laboratory at the University of Maryland, Google, USGS and NASA, it measures areas of tree cover loss across the Earth (except Antarctica and other Arctic islands) in resolution of 30 × 30 meters. Her project focuses on the development of global tree cover change data products based on Landsat satellite imagery, available on the Global Forest Watch 2.0 web platform. It includes the annual change in forest cover (gains and losses) from 2000 to 2024.
- GlobeLand30: It is an initiative of the *National Geomatics Center of China*, which comprises spatial datasets collected at a resolution of 30 meters. This collection considers ten types of land cover, including forests, artificial surfaces, and wetlands, for the years 2000 and 2010. They were extracted from more than 20,000 satellite images from Landsat and the Chinese HJ-1 satellite.
- ESA CCI Land cover: The European Space Agency (ESA) and the Climate Change Initiative (CCI) make available annual global land cover maps, which describe the earth's surface in 22 classes. The series of annual global land cover maps cover the period from 1992 to 2018.
- CORINE Land Cover: The CORINE Land Cover (CLC) inventory was started in 1985 (reference year 1990). Updates have been made in 2000, 2006, 2012, and 2018. It consists of an inventory of land coverage in 44 classes. CLC uses a Minimum Mapping Unit (MMU) of 25 hectares (ha) for area phenomena and a minimum width of 100 m for linear phenomena. The time series are

complemented by layers of change, which highlight changes in land cover with an MMU of 5 ha.

- ESRI 2020 Global Land Use Land Cover by Sentinel-2: This layer shows a 2020 Global Land Use/Land Cover Map (LULC). The map is derived from ESA Sentinel-2 imagery with a resolution of 10 meters and contains 10 classes. This map was produced by a deep learning model trained on more than 5 billion hand-labeled Sentinel-2 pixels, sampled at more than 20,000 sites. distributed in the main biomes of the world.
- ESA WorldCover 2020 and 2021: It is a reference global land cover product with a spatial resolution of 10 m, generated from Sentinel-2 and Sentinel-1 imagery with 10 classes of ground cover and an overall accuracy of 75%. The legend includes 11 generic classes that adequately describe the land surface: "Tree cover", "Shrubland", "Grasslands", "Cropland", "Built-up", "Bare/sparse vegetation", "Snow and ice", "Permanent water bodies", "Herbaceous wetland", "Mangroves" and "Mosses and lichens".
- Dynamic World: A global land use land cover dataset with a resolution of 10 m in near real-time, generated from Sentinel-2 imagery, produced using deep learning, freely available and under open license. The legend presents the probabilities per pixel in 9 classes of land cover: Water, Forest formation, shrub and shrubland, grasslands, flooded vegetation, crops, buildings, bare ground, snow and ice. This data is the result of a partnership between Google and the World Resources Institute to produce a dynamic dataset of physical material on the Earth's surface.

2.4.2 Sources for the Amazon region

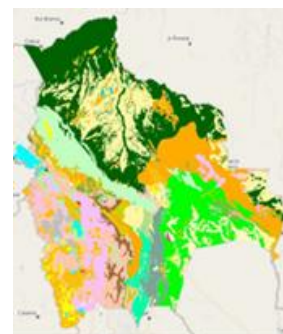
- Ecological Systems of Latin America and the Caribbean: Presents and outlines the conceptual basis for a classification unit of ecological systems. These represent recurring groups of biological communities that are in similar physical environments and are influenced by similar dynamic ecological processes, such as fires or floods. The goal was to provide a "mesoscale" classification unit that is easily mappable, often from satellite imagery, and easily identifiable in the field. The project was developed by *NatureServe* and its member programs, with funding from *The Nature Conservancy*, completing a functional classification of terrestrial ecological systems in Latin America and the Caribbean. The report summarizes the nearly 700 ecological systems that are currently classified and described, emphasizing the natural portion of the landscape
- Land Cover Map Of South America: Digital map of the land cover of South America based on satellite images taken between 1995 and 2000. The mapping scale has a spatial resolution of 1 km. This map was produced as part of the Global Land Cover project - "GLC 2000"
- Land cover map of Latin America and the Caribbean in the framework of the SERENA project: It is a land cover map for Latin America and the Caribbean (LAC) for the year 2008. It was developed within the framework of the Latin American Network for the Monitoring and Study of Natural Resources (SERENA) project. The SERENA land cover map for LAC

integrates: 1) the local expertise of SERENA network members to generate the training and validation data, 2) a methodology for land cover mapping based on decision trees using MODIS time series, and 3) class membership estimates to account for pixel heterogeneity issues.

- Deforestation in the Amazon: This is a study carried out by RAIG that analyzes historical and recent trends in deforestation for five years from 2000 to 2015. The deforestation data was produced by the RAISC members using their own, standardized methodology, which allowed analyses to be carried out at the regional level, without neglecting national differences. The issue is analyzed in different cuts: the entire Amazon, the Amazon of each country, the Natural Protected Areas, the Indigenous Territories and the scale of watersheds.
- MapBiomias Amazonia Collections of Cover and Use, is a study based on Landsat satellite images that generates annual maps of land cover and use in the Amazon, with a spatial resolution of 30 m. The project was developed by the RAISC network and its partners in the Amazon countries. To date, it uses the Landsat C2 imagery catalog and presents a legend of 19 classes mapped for the Bolivian Amazon in the period from 1985 to 2023.

2.4.3 Sources for the national territory

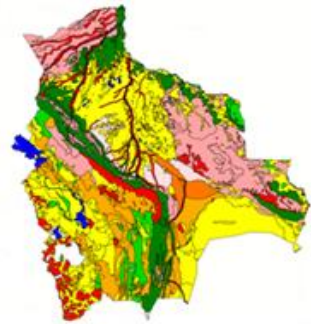
- Land cover and use map, 1978: produced at a 1:1,000,000 scale in 1978 by the ERTS-Bolivia program of GEOBOL and updated in 2001, represents the country's environmental characteristics, natural resources, and land use. Its creation was based on the manual interpretation of the first Landsat satellite images from 1978, applying the Land Cover Classification System (LCCS) methodology designed by the FAO.



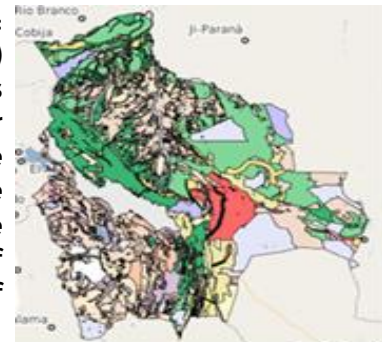
- Map of current land cover and use Bolivia, 2001: The map represents the natural and anthropic elements of the earth's surface, the information it describes is an important input for planning and modeling. It was prepared by the Agrarian Superintendence based on a five-year monitoring of Landsat 7 satellite images, captured in 1999 and 2000, which made it possible to observe the changes in land cover and use throughout the national territory. Published in 2002 at a scale of 1: 1,000,000.



- Map of major land use capacity Bolivia, 2001: The map presents the classification of land according to its capacity for use (CUMAT). It is based on the combined effects of climate and permanent soil characteristics, productive capacity of the land, limitations on land use, risks of soil damage and soil management requirements. This classification unites soils based on surface terrain features and soil properties that can be evaluated by observation and touch, classifying them into three categories of soils: classes, subclasses, and units for Bolivia.



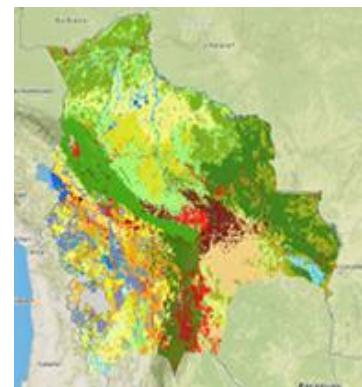
- Agroecological zoning map of Bolivia, 2002: Agroecological and socioeconomic zoning (ASZ) represents zones of sustainable use of land and its renewable natural resources. Zoning seeks to order use, according to its suitability, considering the socioeconomic conditions under which the population would use the land. Prepared by the Territorial Planning Unit of the Ministry of Development Planning in 2002 at a scale of 1:1,000,000



- Map of current land cover and use Bolivia, 2010: The map is a technical instrument that describes in terms of land cover, all the existing resources in our country, identifying the current use for each category of coverage. It was prepared by the National Technical Unit for Earth Information - UTNIT based on medium-range Landsat 5 TM satellite images, corresponding to the period 2006 - 2010. Published in 2011 at a scale of 1:1,000,000



- Map of Bolivia's Productive Potentials, 2013: The map shows the country's productive potential in its different areas and geographical areas. Identified based on the type of land use, biophysical specialization and socioeconomic specialization at the departmental and municipal levels of Bolivia. Prepared by the Ministry of Productive Development and Plural Economy, through the Productive Analysis Unit (UDAPRO) and the Territorial Information System for Production Support (SITAP) in 2013 at a scale of 1:100,000.



3 Methodology

The processing chain adopted for the generation of Collection 4 MapBiomass Bolivia is synthesized in the Figure 3 and is detailed in the following sections: Generation of annual mosaics (section 3.1), Classification (section 3.2), Post classification (section 3.3) and Validation (section 3.4).

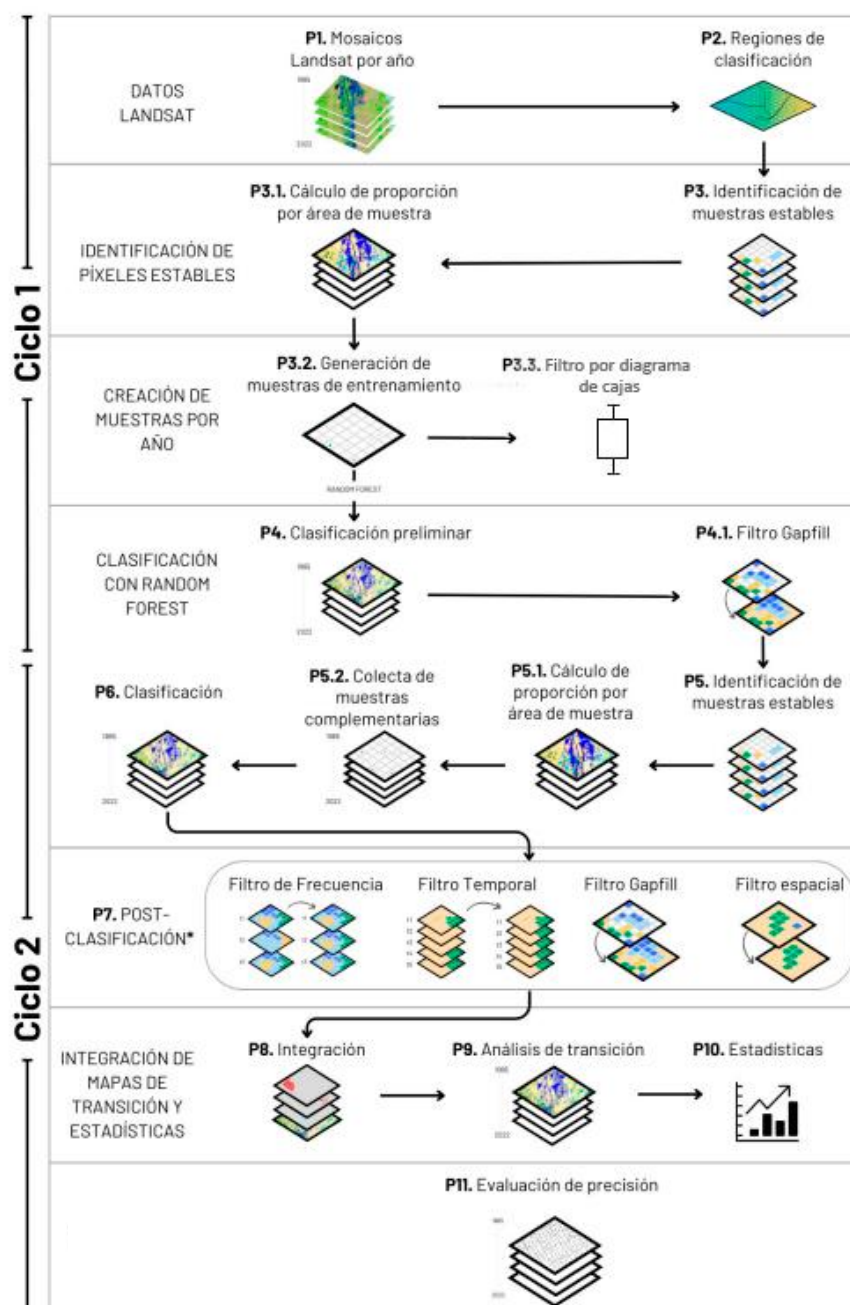


Figure 3. Methodological synthesis of Collection 4 of MapBiomass Bolivia.

3.1 Annual Tile Generation

3.1.1 Dividing the analysis space into cards

This methodology divides the national territory into a grid of regular charts defined based on the grid of International Charts of the World at the Millionth, at a scale of 1:250,000. Each chart covers an area of 1°30' longitude by 1° latitude. Bolivia is covered by 87 letters, of which 27 are shared with Brazil, 13 with Peru, 8 with Paraguay, 8 with Argentina and 8 with Chile (Figure 4). The charts were subdivided by the boundaries of the biomes: Amazon (Upper and Lower), Andes (Desert, Dry, Semi-humid), Valleys, Chaco, Chiquitano, Tucumano-Boliviano, and Pantanal, with a total of 143 charts. The period of analysis covers 41 years from 1985 to 2025, giving a total of 5,863 Landsat tiles (143 charts/biomes x 41 years, Table 2).

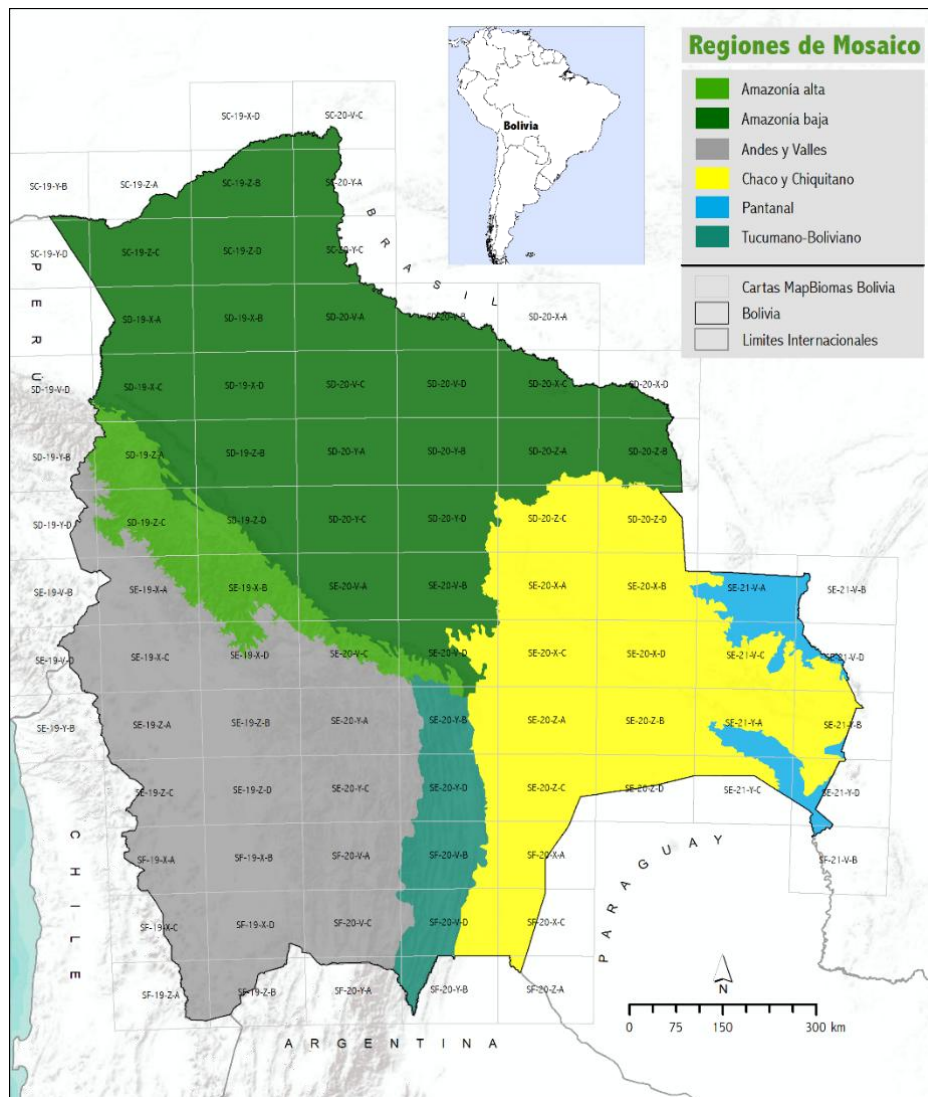


Figure 4. Mosaic and chart regions in Bolivia used in Collection 4 MapBiomias Bolivia.

Table 2. Number of satellite image mosaics processed for MapBiomass Bolivia.

Mosaic Regions	Number of images	Total tiles
Amazonia Alta	14	574
Amazonia Baja	42	1.722
Andes and Valleys	32	1.312
Chaco	19	779
Chiquitano	17	697
Tucuman-Bolivian	9	369
Pantanal	10	410
Total Mosaics	143	5.863

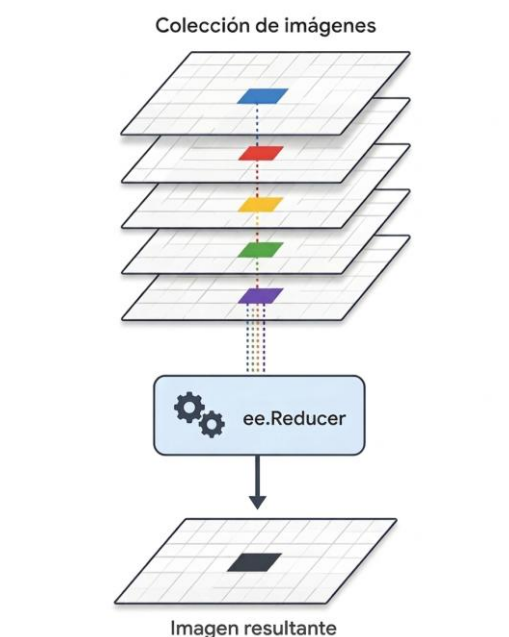
Note. The total number of mosaics is referred to over 41 years per biome.

3.1.2 Parameterization of annual tiles

An annual mosaic that is built in this methodology is formed by adding pixels from a set of Landsat images from which a representative mosaic is generated for a respective year, it is built based on the following parameters:

- ID: Unique identifier of the card-region unit
- Year: Year of the series (1985 to 2025) to which the mosaic corresponds.
- Letter: Letter vector identifier code
- Country: Identification code for Bolivia
- Start/End Date: Period of the year (start and end date) for the selection of imagery from the Google Earth Engine Landsat Imagery Data Catalog.
- Sensor: The satellite and its respective sensor: Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI and Landsat 9 OLI-2 TIRS-2.
- Cloud cover: The maximum percentage of cloud cover accepted from each Landsat image that will be used to construct the image mosaic.
- Probability of clouds:
 - o ShadowSum: A TDOM parameter for cloud shadow detection. A lower number mask fewer pixels with cloud.
 - o CloudThreshn: A CloudScore parameter for cloud detection. Lower numbers increase masking, higher numbers decrease masking.
 - o Blacklist: Images that are excluded from the construction of the mosaic due to their quality.

The annual tile construction parameters are defined by the interpreter and represent the image selection criteria available in the Landsat Data Collection from which the annual tile is constructed. The images selected per year were reduced to an individual image, or annual mosaic, using operators called reducers existing in Google Earth Engine, as illustrated in Figure 5.



Note. Google, 2020

Figure 5. Schematic of applying a reducer to a collection of images³

When parameterizing the mosaics, it was considered that higher precision values can be achieved by using satellite image mosaics whose data have the least amount of noise. That is why it was sought that each mosaic has the least possible presence of clouds and interference and the greatest extension of Landsat data coverage available within the defined period. In exceptional cases, it was the case that there were no images available for the selected period, where it was decided to extend the image search period.

Clouds and cloud shadows are pre-masked so that only cloud-free pixels and cloud shadows are selected from the available images. The cloud masking and cloud shadow methods were the CFmask and CloudScore.

Each mosaic is obtained by putting together a series of Landsat images to compose the best possible image in a certain period of time, taking temporality as parameters. The percentage of cloud cover up to 30% and sensor (L5, L7, L8 and L9, is defined depending on the year and the availability of images). The results of the generation of mosaics for the entire Bolivian territory for the 40 years of study, 1985-2025 in the Table 3.

³ Taken from: https://developers.google.com/earth-engine/guides/reducers_image_collection

Table 3. Summary of parameters used in the construction of mosaics.

Mosaic Region	Satellite	Year	Period	% Clouds
Amazon	L5	1985-1999, 2003-2011	June 1 - December 30	>30%
	L7	2002, 2012		
	L8	2013-2025		
	L9	2022-2025		
Andes and Valleys	L5	1985-1999, 2003-2011	January 1 - December 30	>30%
	L7	2002, 2012		
	L8	2013-2025		
	L9	2022-2025		
Chaco and Chiquitano	L5	1985-1999, 2003-2011	June 1 - December 30	>30%
	L7	2002, 2012		
	L8	2013-2025		
	L9	2022-2025		
Tucuman-Bolivian	L5	1985-1999, 2003-2011	January 1 - December 30	>30%
	L7	2002, 2012	April 1 - December 30	
	L8	2013-2025		
	L9	2022-2025		
Pantanal	L5	1985-1999, 2003-2011	April 1 - December 30	>30%
	L7	2002, 2012		
	L8	2013-2025		
	L9	2022-2025		

The analysis of the quality of the images was carried out through a visual evaluation of each of the mosaics based on the criteria of the Table 4. Where in the end three categories were obtained: 1) Good, 2) Fair and 3) Bad.

Table 4. Parameters for Quality Assessment of Landsat Image Tiles

Quality	Symbol	% Covered	% Cloud Noise	% Noise Banding	% Noise Shadow Relief
Good	B	> 89	< 5	< 5	< 5
Regular	R	> 65 - 95	5 - 10	5 - 10	5 - 10
Bad	M	< 65	> 10	> 10	> 10

Out of the 5,863 mosaics generated for the 41-year period, 89% were evaluated as good, 7% as fair (concentrated in Andean regions, valleys, and areas with high cloud cover or atmospheric complexity), and 4% as poor or low quality. The years 1985 and 1987 present the highest number of low-quality mosaics, located primarily in the Upper Amazon, Andean, and Tucuman-Bolivian regions. However, this proportion decreases drastically and almost completely disappears in recent

decades, thanks to improved satellite data availability and cloud-processing tools (Figure 7).

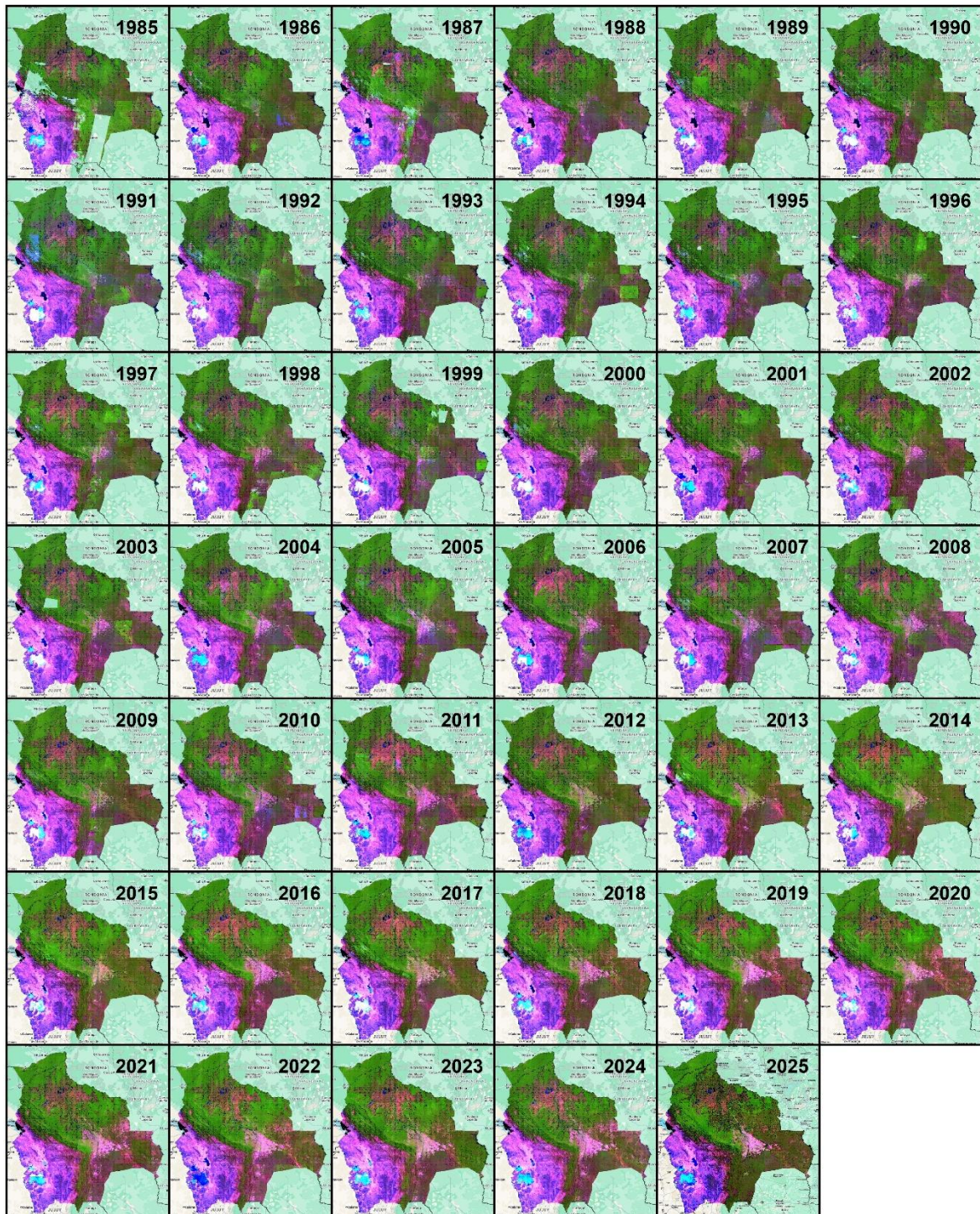
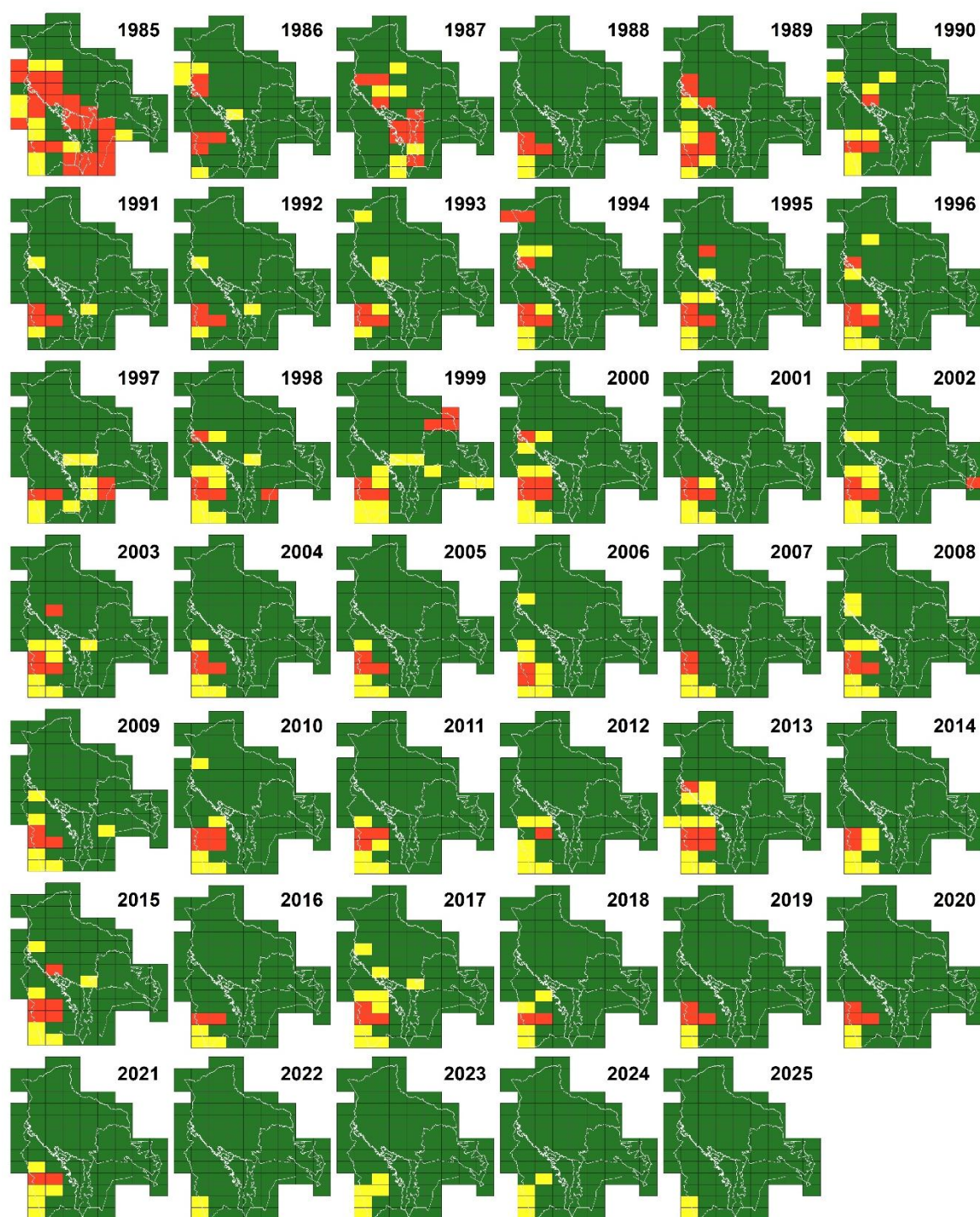


Figure 6. Annual series of mosaics from Collection 4 MapBiomass Bolivia.



Calidad en la clasificación B Bueno R Regular M Malo

Figure 7. Annual series of mosaic quality from Collection 4 MapBiomass Bolivia.

3.2 Variables of classification or feature space

Classification variables (feature space) were calculated from the annual mosaic that represents the inputs of the classification process. The Landsat bands, along with the classification variables, are consolidated in raster files composed of 156 bands in total⁴ that include: the spectral landsat bands, spectral indices, fractional and texture information derived from them and indices of the spectral fractions.

Additionally, 7 static variables were used: HAND, shademask2, slppost, altitude, slope, latitude and longitude; which helped to classify classes that spectrally are very similar, but are differentiated by these topographical aspects. To the images available in each year, the calculation of statistical reducers was applied to generate the values of each pixel. These gearboxes are:

- Median: Median⁵ of all available values in the yearly tile for that location (pixel).
- Median dry season: Calculation of the statistical median applied to the pixels of quartile 25 (with the lowest values) of NDVI (dry season proxy). Wet Weather Median: Calculation of statistical median applied to pixels in quartile 75 (with the highest values) of NDVI (Rainy Season Proxy).
- Amplitude: The extent of the variation between all the pixels available in the annual tile.
- Standard deviation: Standard deviation of the values of all available pixels in the annual tile for a given location.
- Minimum: The lowest value of all available pixels in the annual tile in a given location. Maximum: Highest value of all available pixels in the annual tile in a given location.
- Dry Period Minimum: Calculation of the lowest value of all available pixels of the images in the quartile with the lowest NDVI (dry season proxy) values. Wet Period Minimum: Calculation of the lowest value of all available pixels of the images in the quartile with the highest NDVI (rainy season proxy) values.
- Dry Period Maximum: Calculation of the highest value of all available pixels of the images in the quartile with the lowest NDVI (dry season proxy) values. Wet Period Maximum: Calculation of the highest value of all available pixels of the images in the quartile with the highest NDVI (Rainy Season Proxy) values.
- QMO of the dry period: The highest value that the band has in the EVI2 index in the dry season. QMO of the rainy period: The highest value that the band has in the EVI2 index in the wet season.

⁴ Available for download on the MapBiomass Bolivia platform.

⁵ Median is the value that separates the top half from the bottom half of a data sample or population. [Documentation](#) of the tool in Google Earth Engine.

Table 5. Description of bands and variables used for MapBiomass Bolivia Collection 4

Type	Number	Formula	Description	Reducer ⁶												Quality Band ⁷	
				Median	Median_dry	Median_wet	Amp	stdDev	Min	Max	Dry_min	Dry_max	Wet_min	Wet_max	Dry_qmo	Wet_qmo	
Band	blue	B1 (L5 and L7); B2 (L8 and L9)	Blue visible spectrum	X													
	green	B2 (L5 and L7); B3 (L8 and L9)	Green visible spectrum	X	X				X				X		X	X	
	red	B3 (L5 and L7); B4 (L8 and L9)	Visible spectrum red	X	X	X			X		X	X		X	X		
	nir	B4 (L5 and L7); B5 (L8 and L9)	Near-infrared	X	X	X		X	X						X	X	
	swir1	B5 (L5 and L7); B6 (L8 and L9)	Shortwave Infrared 1	X	X	X			X			X	X	X	X	X	
	swir2	B7 (L5); B8 (L7); B7 (L8 and L9)	Shortwave Infrared 2	X	X	X			X		X			X	X	X	
Indexes	ndvi	(nir - network) / (nir + network)	Normalized Difference Vegetation Index	X	X	X	X	X									
	evi2	(2.5 * (NIR - RED) / (NIR + 2.4 * RED + 1)	Modification of the Improved Vegetation Index (EVI) that only uses NIR and Red, ignoring the blue band.	X	X	X	X	X									
	ndwi_gao	(nir - swir)/(nir + swir)	Normalized Difference Water Index (GAO)	X	X	X	X				X		X	X		X	
	ndwi_mcfeters	(green - nir)/(green+nir)	Normalized difference water index (mcfeters)	X			X										
	gcvi	(nir/green) - 1	Relationships between near-infrared and green bands	X	X	X											
	hallcover	(-red * 0.017) - (nir * 0.007) - (swir2 * 0.079) + 5.22	Land cover spectral index	X													
	pri	(blue - green)/(blue + green)	Photochemical Reflectance Index	X	X												
	Savi	(1+L)* (nir - red)/(nir + red + 0,5)	Soil-adjusted vegetation index	X	X	X		X									
	textG	('median_green').entropy(ee. Kernel.square({radius: 5}))	Entropy in the Blue Band	X													
	Nuggets	UNTL*(1-√(NDWI-aNDWI)) ² +(NDVI	Composite Normalized Index of Urban Areas	X													

⁶ Each product calculated with the statistical gearboxes makes up a band of the integrated product.

⁷ It composes all the images in a collection, using a quality band (evi2) as a pixel sorting function.

		$i - aNDVI)^2 + (NDBI - aND BI)^2$											
	NDSI	$(\text{green} - \text{swir1}) / (\text{green} + \text{swir1})$	Normalized Differential Snow Index	X					X				
	Falls	$(\text{swir2} / \text{swir1})$	Color Alteration Index	X					X	X	X		
	the	$((2 * \text{green}) - \text{red} - \text{blue}) / ((2 * \text{green}) + \text{red} + \text{blue})$	Green Leaf Index	X	X				X	X			
	mndwi	$(\text{green} - \text{nir}) / (\text{green} + \text{nir})$	Normalized difference water index	X	X	X				X			
	ndbi	$(\text{swir1} - \text{nir}) / (\text{swir1} + \text{nir})$	Cumulative normalized difference index	X	X				X	X			
	ndgb	$(\text{green} - \text{blue}) / (\text{green} + \text{blue})$	Normalized Difference Green Blue	X	X	X		X		X			
	ndmi	$(\text{nir} - \text{swir1}) / (\text{nir} + \text{swir1})$	Normalized Humidity Difference Index	X	X				X				
	mdmir	$(\text{swir1} - \text{swir2}) / (\text{swir1} + \text{swir2})$	Normalized Difference Mid-Infrared Index	X			X		X	X	X		
	ndrb	$(\text{red} - \text{blue}) / (\text{red} + \text{blue})$	Normalized Difference Red Blue			X		X	X				
NDSI2	$(\text{swir1} - \text{nir}) / (\text{swir1} + \text{nir})$	Normalized Soil Difference 1	X	X	X				X	X			
MME Fraction ^a	gv		Fractional abundance of green vegetation within the pixel	X				X	X				
	npv		Fractional abundance of non-photosynthetic vegetation within the pixel	X					X				
	soil		Fractional abundance of soil within the pixel	X				X	X				
	shade	$100 - (\text{gv} + \text{npv} + \text{soil} + \text{cloud})$	Fractional Shadow Abundance Within the Pixel	X									
	snow		Fractional abundance of snow within the pixel	X						X			
	cloud		Fractional cloud abundance within the pixel	X									
$\sum$	gvs	$\text{gv} / (\text{gv} + \text{npv} + \text{soil} + \text{cloud})$	Shade-normalized green vegetation	X	X	X		X					

⁸ MME = Spectral Mixing Model

	ndfi	$\frac{(gvs - (npv + soil))}{(gvs + (npv + soil))}$	Normalized Difference Fraction Index	X	X	X	X	X
	sefi	$\frac{(gv+npv - soil)}{(gv+npv + soil)}$	Savannah Ecosystem Fraction Index	X	X			X
	Wefi	$\frac{((gv+npv)-(soil+shade))/(gv+npv)+(soil+shade)}{((gv+npv)-(soil+shade))/(gv+npv)+(soil+shade)}$	Wetland ecosystem fraction index			X	X	X
	FN	$\frac{((gv+shade) - soil)}{((gv+shade) + soil)}$	Index based on gv, shade and soil fractions		X			X
	ndfib	$\frac{GV-(NPV+Soil+Snow)}{GV+(NPV+Soil+Snow)}$	Adaptation of the NDFI for the Andes	X			X	
Static and/or topographic variables	shademask2		Shadow Map					
	slppost		Stratified Slope					
	altitude		Altitude					
	slope		Pending					
	latitude		Latitude					
	longitude		Length					
	HAND (Height Above the Nearest Drainage)	hand30_100 hand30_1000 hand30_5000 hand90_1000 water_HAND_0m water_HAND_10m water_HAND_1m water_HAND_2m water_HAND_5m	Index- Height above the nearest drain					

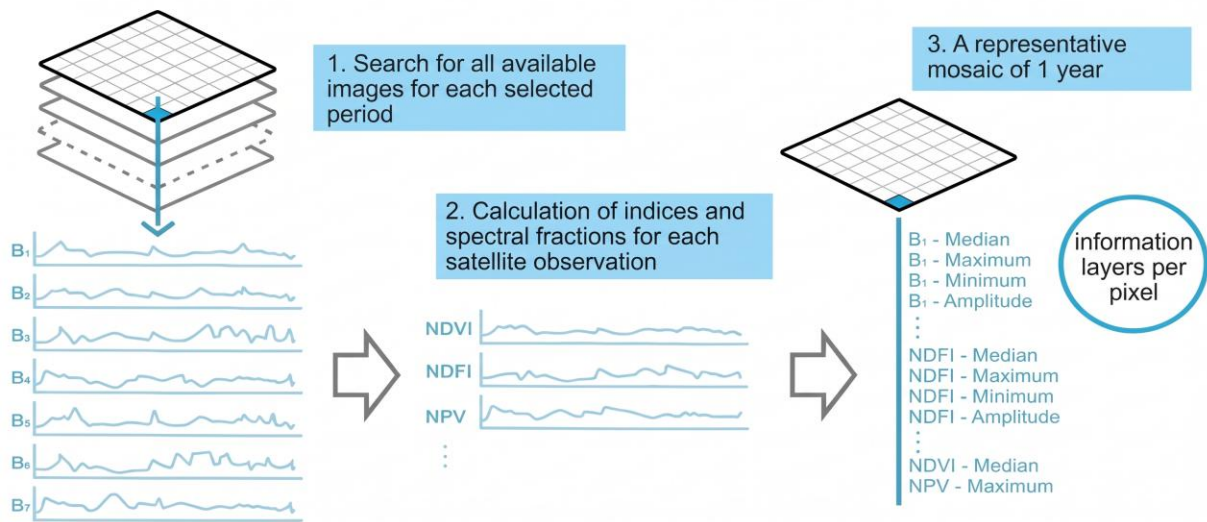


Figure 8. Process of calculating the bands that make up the annual mosaics of Landsat images.

3.3 Classification

3.3.1 Legend

The MapBiomass classification scheme is a hierarchical system with a combination of land cover and land use classes. In the MapBiomass Bolivia Collection 4 collection, 27 classes were mapped, which belong to 6 areas (level 1): Forest formation, Grassland and shrubland, Agricultural area, Area without vegetation, Body of water and Not observed. Each biome varies the number of classes according to their presence or absence of the defined classes within their area.

Table 6. Legend of MapBiomass Bolivia Collection 4

Class	Natural/ Anthropic	Biome	ID	Hexagesimal Code	Co lor
1. Forest formation			1	#1f8d49	
1.1. Forest	Natural	All	3	#1f8d49	
1.2. Open forest	Natural	Amazon and Chiquitano	4	#7dc975	
1.3. Flooded forest	Natural	Amazon, Chaco, Chiquitano and Pantanal	6	#007785	
2. Herbazal y arbustal			10	#d6bc74	
2.1. Herbazal/arbustal inundable	Natural	All	11	#519799	
2.2. Herbazal/arbustal	Natural	All	12	#d6bc74	
2.3. Rocky outcrop	Natural	Amazon, Andes, Valleys, Chaco, Chiquitano and Tucuman-Bolivian	29	#ffaa5f	
2.4. Scrub	Natural	Amazon, Andes, Valleys and Tucuman-Bolivian	66	#a89358	
2.5. Open shrublands (beta)	Natural	Andes	77	#86b074	
2.6. Steppe (beta)	Natural	Andes	63	#c7e0ab	

2.7. Andean grassland and shrub	Natural	Amazon, Andes, Valleys and Tucuman-Bolivian	81	#dfeb62	
2.8. Andean floodable grasslands and shrubs	Natural	Amazon, Andes and Valleys	82	#66b2a3	
2.9. Other non-forest natural formation	Natural	All	13	#d89f5c	
3. Agricultural			14	#ffefc3	
3.1. Pasture	Anthropic	All	15	#edde8e	
3.2. Agriculture	Anthropic	Amazon, Andes, Valleys, Chaco, Chiquitano and Tucuman-Bolivian	18	#e974ed	
3.2.1. Soybeans (beta)	Anthropic	Amazon, Chaco, Chiquitano and Tucuman-Bolivian	39	#f5b3c8	
3.2.2. Flooded rice (beta)	Anthropic	Amazon and Chiquitano	40	#c71585	
3.2.3. Other crops	Anthropic	Amazon, Andes, Valleys, Chaco, Chiquitano and Tucuman-Bolivian	72	#c1799c	
3.3. Mosaic of uses	Anthropic	All	21	#ffefc3	
4. Area without vegetation			22	#d4271e	
4.1. Beach, dune or sandbar	Natural	All	23	#ffa07a	
4.2. Urban infrastructure	Anthropic	All	24	#d4271e	
4.3. Mining	Anthropic	Amazon, Andes, Valleys, Chaco, Chiquitano and Pantanal	30	#9c0027	
4.4. Salt flat	Natural	Andes	61	#f5d5d5	
4.5. Rocky surface	Natural	Andes	92	#d98a45	
4.6. Another natural area without vegetation	Natural	All	68	#e97a7a	
4.7. Another anthropic area without vegetation	Anthropic	All	25	#db4d4f	
5. Body of water			26	#2532e4	
5.1. River, lake	Natural	All	33	#2532e4	
5.2. Aquaculture	Anthropic	Amazon, Chaco and Chiquitano	31	#091077	
5.3. Glacier	Natural	Andes	34	#93dfe6	
6. Not Observed			27	#ffffff	

Note. Table 6 shows 6 columns, the third indicates in which biome the class is present, the fourth column is the number with which you identify the class.

Table 7. Description of the Legend of MapBiomias Bolivia Collection 4

MapBiome Class (ID)	Biome	Description of the vegetation
Forest (ID:3)	Amazon	In the High Amazon region, it corresponds to a plant formation characterized by wooded and evergreen physiognomies, which are generally distributed above 1,100 m of altitude, mainly occupying the eastern portion of the tropical Andes. It also includes the Yungueño forests. In the Lower Amazon region, it is mainly made up of almost evergreen (30-45m), evergreen (30-35m) humid forest, evergreen forests in transition to seasonal semi-deciduous forests of the Chiquitano Dry Forest (>25 (30) m), gallery forest and forest islands.
	Andes	Composed of seasonal evergreen trees (<i>Polylepis altimontano</i>) located in the transition zone from Tucumano-Boliviano to Andes. They are mostly trees 5 to 10 meters tall. Seasonal evergreen <i>Polylepis altimontano</i> forests, distributed between 3,200-3,900 m altitude, reaching 5,000 m as the species <i>P. tarapacana</i> .
	Valleys	Inter-Andean dry forests and <i>Polylepis</i> forests. The former are distributed up to 3,200 m of altitude, occupying valleys and lower parts of slopes. They include low, deciduous and thorny forests, with a shrubby tree canopy 3 to 5 m high; and semi-deciduous forests, with a tree canopy of 10 to 15 m. On the other hand, the <i>Polylepis</i> forests (<i>kewiñales</i>) are dominated by various species of this genus that are above 3,000 m.
	Tucuman-Bolivian	Forests that change in structure, composition and periodicity according to their altitudinal distribution in the tropical Andes (between 800 and 3,500 m.a.s.l.). Generally, below 2,000 m altitude it is semi-deciduous, with a tree canopy distributed between 15 and 20 m high, and emergent trees that reach just over 25 m. Above 2,000 m altitude the forests are humid and evergreen, thanks to the trade winds. The trees form a canopy distributed between 20 and 25 m high, with emergents reaching up to 30 m.

	Chaco	The Chaco forest is distributed in the south of the country and is generally deciduous, microfoliate and thorny. It has a shrubby tree canopy between 3 and 5 m high, with emergents that exceed 10 m, with the presence of columnar cacti being frequent. The Chaco forest develops on sediments of recent origin in well-drained red soils with rocky outcropping, characterized by hardwood trees, whose leaves are shed during the dry season.
	Chiquitano	The forests in this biome are characterized by the presence of numerous succulents, mostly thorny, the canopy is continuous and low with isolated emergent species, whose floristic composition and structure varies according to edaphic and topographic conditions. The medium-high semi-deciduous forest with trees between 15-25 m high, which form a complex mosaic with other ecoregions such as the Cerrado and the Flooded Savannahs.
	Pantanal	It has medium to low altitude forests (6-10 m) accompanied by chaparral that can be semi-dense to open, they are found in areas of low flooding. They are characterized by being semi-deciduous rainfall. This class includes: Palmar-Tajibá, of different types of Palma; Floodable paratodal and flooded riparian forest.
Open forest	Amazon, Chiquitano and Chaco	Areas with natural vegetation made up of trees, shrubs or a mixture of both, with a coverage between 20 and 65%.
Bosque inundable (ID:6)	Amazon	Amazonian flood forests, várzea forests and with a plant community that are usually flooded for about two months a year and igapó forests that are flooded for periods of five to six months. Amazon flood forest, várzea forests (flooded by white water, rich in sediments and minerals) and igapó forests (flooded by black water, rich in organic matter).
	Chaco	Chaco forests that are usually flooded are found along the rivers, in the Chaco plain in the downstream landscape and the alluvial plains (old, Parapetí and flood), the soils are deep, moderate and well developed.

	Chiquitano	It develops in the riverbed and floodplain of seasonal streams in the transition zone between the northeast of the Chaco and the Chiquitania and seasonally floodable forest by stagnant waters of the Chaco-Chiquitania transition. Low forest, with a dense canopy of 6-8 m. high, and emergent of 10-12 m, which develops in shallow depressions.
	Pantanal	The flooded forest of the Bolivian Pantanal is composed of species adapted to long periods of seasonal flooding. This ecosystem is essential for water regulation, the maintenance of biodiversity. The dynamics of flooding favor essential ecological processes such as seed dispersal.
Herbazal/arbustal inundable (ID:11)	Amazon	Vegetation cover located in the floodplain, such as grasslands and hydrophytic savannahs, which are flooded for a long period of the year. It develops on clayey or silty soils, with poor drainage seasonally flooded in river valleys, which are flooded for a long period of the year.
	Chaco	Floods are not very frequent, they occur every eight or ten years. The most affected areas are those located in the foothills, downhill and river slopes.
	Chiquitano	Hydrophytic savannah vegetation with mounds, developed on poorly drained and seasonally floodable soils in plains and valleys of the southern and eastern Chiquitania Cerrado in the Chiquitania (Pampas- termite mounds, which are temporarily flooded to varying degrees depending on the topography.
	Pantanal	Herbaceous vegetation with a predominance of grasses subject to permanent or temporary flooding (at least once a year) according to natural flood pulses. Swampy areas usually occur on the margins of temporary or permanent lakes occupied by emerging, submerged, or floating aquatic plants (e.g., curichis and swamps). Area of frequent and seasonal flooding (3-4 months). In addition, it includes in a smaller proportion: herbaceous savannahs, reeds, rice fields, scrublands, swampy patujusals, reedbeds.

Herbazal/arbustal (ID:12)	Amazon	Savannas with grasses, sedges and scattered shrubs, closed savannas with high grasslands and on the tops of the mountains in areas with shallow soils. They are present in areas above >3,000 m.a.s.l. They appear in areas with shallow soils (mountain tops).
	Valleys	Areas with subhumid, montane and grassland shrub vegetation present greater than 65% and scattered tholar and shrubland.
	Tucuman-Bolivian	Presence of mixed communities of grassland with scattered to dense presence of woody species of Bolivian-Tucuman highland and high Andean shrublands distributed in the Tucuman mountain ranges. On rocky outcrops or steep slopes, saxicolous vegetation (ferns, xeromorphics, bromeliads and cacti) develops.
	Chaco	It develops in plant formations of extremely xeric climates called savannah and that have shrub and tree elements that do not develop, on a continuous layer of grasses and/or are dominated by grasses.
	Chiquitano	Composed mainly of herbaceous species and open shrub savannahs. The grass-herbaceous stratum forms a continuous layer that generally does not exceed 1 m in height. Sclerophyllous chaparral and wooded savannas of the Chiquitania on well-drained soils.
	Pantanal	Vegetation with a predominance of herbaceous strata, with the presence of isolated shrubs and stunted woody trees. The botanical composition is influenced by edaphic and topographic gradients. It presents herbaceous savannas that include the Pampas de tacuarilla and Cola de ciervo, accompanied by herbaceous vegetation (grasses).
Rocky Outcrop (ID 29)	Amazon	There are rocky outcrops that correspond to the Paleozoic, normally this class presents consolidated rock, outcrops and rocky sediments dragged mainly by ice.
	Valleys	Areas formed by exposed rocks with little or no vegetation that can be saxicolous and/or rocky. It is located in areas with slopes.

	Chaco	They are exposed areas of sedimentary rock that influence the landscape, hydrology and biodiversity. They represent areas with low agricultural capacity and serve as a refuge for species adapted to arid environments.
	Chiquitano	It has surfaces with rocky outcrops or steep slopes that are very stony. The terrain is undulating and very eroded (Serranía de Santiago de Chiquitos).
	Tucuman-Bolivian	Areas with little or no vegetation, present in undulating and heavily eroded terrain; formed from various granitic and metamorphic rocks. May include exposed rock.
Matorral (ID 66)	Amazon	Areas made up of several communities of open and/or semi-enclosed low shrubs (tholars); reaching a height between 1-1.5m. They develop on piedmont surfaces, flat topographies and/or fluvial terraces.
	Andes	High Andean shrublands with resistant shrubs that protect the soil and conserve biodiversity in arid and cold areas above 3,000 meters above sea level.
	Valleys	In the inter-Andean valleys, shrublands develop between 1,800 and 3,200 m a.s.l. in semi-arid areas, with eroded soils and low shrub vegetation adapted to dry and extreme climates
	Tucuman-Bolivian	In these regions, the shrubs dominate with low shrubs such as Baccharis, Parastrephia and Acantholippia, coexisting with cardonales of columnar cacti typical of the dry highlands and intermediate areas of Chuquisaca, Potosí and Tarija
Open shrublands (Beta) (ID 77)	Andes	This region is characterized by the predominance of open xeromorphic and thorny shrubs of southern Bolivia, which include cacti vegetation, grasses, and various herbaceous species adapted to severe water deficit conditions and arid environments, areas that are commonly used for livestock farming.
Steppe (Beta) (ID 63)	Andes	Typical of the arid and cold environments of the Bolivian Altiplano (>3,200 meters above sea level), these formations feature open or moderate vegetation cover—with <i>to/a</i> shrublands standing out—alternating with bare

		soil, rocks, and salt flats, and are mainly used for camelid and sheep grazing.
Andean grassland and shrub (ID 81)	Amazon and Valleys	Andean grasslands and shrubs are typical vegetation covers of the high Andean areas that are generally found above the forest line and the transition between the two covers depends on local conditions. It is usually made up of a diversity of forms of growth.
	Andes	High Andean grasslands of the humid Puna distributed in different types of soils from humid to eroded. It occurs in areas >3,000 m.a.s.l. In the southern area grasslands and high Andean shrublands of the southern Xerophytic Puna. Areas with grasslands with camelid grazing.
Andean grassland and floodable shrub (ID 82)	Valleys	High Andean wetland of the Xerophytic Puna. They are located in topographic depressions, near bodies of water or melting phenomena, typical of high tropical mountains. Its shape is flat or in the form of cushioned cushions, it occurs at an altitude >3,000 m.a.s.l.
	Andes	The high Andean wetland of the Xerophytic Puna is found in topographic depressions and areas near bodies of water or melting ice, typical of high tropical mountains. It has a flat shape or cushioned cushions and is located above 3,000 meters above sea level
Other non-forest natural formation (ID:13)	Amazon	Shrubs, chaparral trees present in the upper Amazon region, with several altitudinal levels and different types of evergreen vegetation, generally <3,000 m.a.s.l.
	Andes	In this region, the dominant physiognomy corresponds to shrubs or shrubs which generally grow below 3,000 m of altitude. Highland shrublands and grasslands of the Puna and Xerophytic Altiplano on well-drained soils with fallow land and extensive meadows. It is mainly made up of xeromorphic shrubs with grasses and cacti.
	Valleys	Areas made up of several communities of low shrubs, closed and scattered chaparrals.
	Tucumano-Bolivian	It has mixed vegetation of grassland with the presence of shrubs or small shrubs and saxicolous vegetation of the highlands. They are distributed

		above 2,800 - 3,000 m on the summits of the Bolivian-Tucumán mountain ranges and/or areas with shallow soils.
	Chaco	It is made up of chaparral trees in very sandy soils, where the sands have covered the soil with silty and clayey sediments, deposited in the old alluvial plains. Wooded savannas of the sandbanks of the Chaco.
	Chiquitano and Pantanal	They are floristically made up of the chaparral of the Abayoy, which mostly includes large elements of the Cerrado, followed by some floristic components of the Gran Chaco, characterized by its sandy soils. In addition, it has shrubs, shrubs and low forests with frequent thorny bromeliads, cacti and xeromorphic ferns.
Mosaic of uses (ID:21)	Amazon	Small-scale agricultural activity in the higher areas and mechanized in the lower areas. Livestock activity: livestock rotation and cultivated pastures.
	Andes	Livestock area of sheep, camelids and few cattle, coincidentally crops of vegetables, potatoes, corn, alfalfa, barley, oca, beans, quinoa, oats, wheat, among others.
	Valleys, Tucumano-Bolivian	Cattle browsing, selective extraction of species with forest value, and small-scale agricultural activities. Corn, wheat, soybean and vegetable crops.
	Chaco	Staggered planting is practiced in their corn crops, followed by wheat and soybeans in both the winter and summer seasons. Semi-intensive and extensive community-based livestock farming.
	Chiquitano	Chiquitana intensive livestock. Summer crops mainly soybeans and in winter sunflower, corn, wheat, rice, chia, cassava, among others.
	Pantanal	Agricultural and livestock activity mostly.
Pastura (ID:15)	Amazon, Andes, Valleys, Chaco, Chiquitano, Tucumano-Boliviano and Pantanal	Activity practiced in natural grasslands and perennial cultivated pastures that keep the soil covered all year round. In the Andean Puna (>4,000 meters above sea level), ancestral practices are used for sheep, goats and cattle, with grazing rotation according to altitude and season. In the Chaco, sustainable community livestock farming is implemented with semi-intensive management and construction of cut-offs to ensure water. In the

		Chiquitano Biome, cattle ranching is semi-extensive, with a predominance of sown pastures and rotation due to water scarcity, being a key area for meat production. Cultivated pastures (brachiarias, fescue, ryegrass, etc.) and natural pastures, for cattle feed.
Agriculture (ID:18)	Amazon, Chaco, Chiquitano	Extensive agriculture and to a lesser extent on a medium scale.
	Andes, Valles and Tucuman-Bolivian	Small-scale agriculture due to its geographical location.
Soybean (Beta) (ID: 39)	Amazon and Chiquitano	Soy is one of the main agro-productive activities in Bolivia, especially in the Amazon, favored by fertile soils and a warm climate. Production is mechanized and technified, with direct seeding and crop rotation. The main campaign is in summer, complemented by a winter campaign for seed production.
	Chaco and Tucuman-Bolivian	Soy production is growing in the transition zones between the inter-Andean valleys and the southern lowlands (Tarija, Chuquisaca and southern Santa Cruz). Despite having fragile soils, moderate slopes and challenging agro-ecological conditions such as irregular rainfall and risk of erosion, soybeans are incorporated into rotation systems with corn or sorghum.
Flooded rice (Beta) (ID: 40)	Amazon and Chiquitano	Areas cultivated with flooded rice, through controlled irrigation systems, during the productive cycle of the summer season.
Other crops (ID 72)	Amazon and Andes	Agricultural areas where the original vegetation has been replaced by annual, temporary and perennial crops, intended mainly for domestic consumption
	Valleys and Tucuman-Bolivian	It is developed through agroforestry systems with crops such as grapes, peaches and apples, combined with traditional practices aimed at self-consumption (beans, peas, corn, vegetables) and the commercialization of tubers, cereals and fruit trees, under irrigation or rainfed conditions.

	Chaco and Chiquitano	Maize, kumanda, peanuts and vegetables are grown with sustainable practices. Agricultural expansion has been remarkable, with soybeans in summer and sunflower, sorghum, wheat and other crops in winter, in a context of deforestation and increased burned areas.
Mosaic of uses (ID:21)	Amazon	Small-scale agricultural activity in the higher areas and mechanized in the lower areas. Livestock activity: livestock rotation and cultivated pastures.
	Andes	Livestock area of sheep, camelids and few cattle, coincidentally crops of vegetables, potatoes, corn, alfalfa, barley, oca, beans, quinoa, oats, wheat, among others.
	Valleys, Tucuman-Bolivian	Cattle browsing, selective extraction of species with forest value, and small-scale agricultural activities. Corn, wheat, soybean and vegetable crops.
	Chaco	Staggered planting is practiced in their corn crops, followed by wheat and soybeans in both the winter and summer seasons. Semi-intensive and extensive community-based livestock farming.
	Chiquitano	Chiquitana intensive livestock. Summer crops mainly soybeans and in winter sunflower, corn, wheat, rice, chia, cassava, among others.
	Pantanal	Agricultural and livestock activity mostly.
Beach, dune and sand spot (ID: 23)	Amazon, Andes, Valleys, Chaco, Chiquitano and Tucuman-Bolivian	These regions are characterized by periodic obstruction of the river drainage by the sediments of the river itself. In addition, the secondary riverbeds dry up seasonally forming sandbanks.
Urban infrastructure (ID:24)	Amazon, Andes, Chaco, Chiquitano, Tucumano-Bolivian	Area covered by urban infrastructure, with human settlements of more than 1,000 inhabitants.

Mining (ID:30)	Amazon, Andes, Chaco, Chiquitano and Tucuman-Bolivian	The mining present in underground and/or open-pit mining is characterized by the fact that the mineral extracted in both cases is taken to treatment or concentration plants, mechanical or explosive means are also used to remove the soil that covers or surrounds the geological formation that forms the deposit, or bank of materials.
Salt flat (ID:61)	Andes	Salt desert at an altitude of 3650 m.a.s.l. The Salar de Uyuni and Coipasa stand out.
Rocky surface (ID 92)	Andes	Natural rocky surface with sparse rupicolous vegetation, located above 4,100 meters above sea level in cold and arid environments. It is mainly found on ancient ground moraines formed by glacial sediments compacted against the bedrock.
Another natural area without vegetation (ID 68)	Amazon, Andes, Chaco, Chiquitano and Tucuman-Bolivian	In the Amazon area, it is usually found on low and gentle slopes with some type of erosion or landslide; On the plateaus generally with reduced surfaces with rock fields, rock towers are also distinguished in the cliffs. Its soils are shallow and have little organic matter, they are poor in nutrients. In the Andes, Valleys and Tucumano-Bolivian Biome they are found on surfaces composed of saline or clayey soils, finally, within these biomes they are found in the sediments of water bodies.
Another anthropic area without vegetation (ID:25)	Amazon, Andes, Chaco, Chiquitano, Tucuman-Bolivian	Areas with little or no vegetation can be of natural or anthropic origin, not mapped in other classes. It can include exposed rock, crop transition areas, roads and highways, airstrips, industrial yards, and areas of recent deforestation.
	Amazon	Plentiful rivers, wide rivers, lagoons

River or lake (ID: 33)	Andes and Valleys	Despite the adverse climatic conditions, the region shows surface water bodies such as: low-flow rivers, in the form of rows, lagoons, fresh lakes, and salt lakes.
	Chaco	Seasonally dry rivers
	Chiquitano	Permanent rivers and perennial lagoon
	Tucuman-Bolivian	Groundwater recharge areas
	Pantanal	Extensive flat flood areas and alluvial soils.
Aquaculture (ID 31)	Amazonia, Chiquitano, Chaco	It focuses on the breeding of native species such as pacu, surubí and cachama, which are in high demand both locally and regionally. This activity contributes to food security and the sustainable development of communities, with practices that seek to minimize environmental impact.
Glacier (ID:34)	Andes	A permanent ice cover area or mass, located on the Andean peaks, as a result of the accumulation, compaction and recrystallization of snow.

3.3.2 Classification regions

To facilitate the mapping of Bolivia's diverse landscapes and ecosystems, 40 operational classification regions were defined and processed independently for each year of the time series. This spatial subdivision was based on the subregions from the Map of Ecoregions of Bolivia (Ibisch et al., 2003).

Using these operational regions helps optimize classification algorithms on the Google Earth Engine platform, adapting them to the specific spectral, climatic, and physiognomic particularities of each territory. This minimizes confusion errors between similar classes and ensures higher accuracy in detecting annual land cover and land use changes nationwide.

Table 8. MapBiomass Bolivia Classification Regions

Classification Region		Code of the operating regions	Description
High Amazon		20101 20102 20103	Yungas: Perhumid Andean forests.
Northern Amazon	Lower	20201	Amazon Forests of Pando Amazon Flooded Forests
Lower Amazon	Western	20202 20203 20204 20210	Sub-Andean Amazon Forests Pre-Andean Amazon Forests
Lower Amazon East		20205 20206	Amazon Forests of Beni and Santa Cruz
Lower Amazon Llano		20207 20208 20209 20211	Cerrado Paceño Cerrado Beniano Floodable Savannas of the Llanos de Moxos
Andes		20601 20602 20605 20603 20604 20606 20607 20608	High Andean vegetation of the Eastern Cordillera with snow and sub-nival floors Semi-humid Puna Inter-Andean Dry Forests Dry Puna Desert Puna
Valleys		20701 20702 20703	Seasonal evergreen Polylepis altimontano forests.
Chiquitano		21001 21005 21002	Chiquitano Closed Dry Forest Chiquitano Floodable Savannas

	21003	
	21004	
Chaco	21101 21102 21103 21104 21105 21106	Gran Chaco: Forests vary according to humidity and drained or undrained soils.
Tucuman-Bolivian	21201 21202	Tucuman-Bolivian ForestChaco Serrano
Pantanal	20501 20502	Pantanal floodable savannas

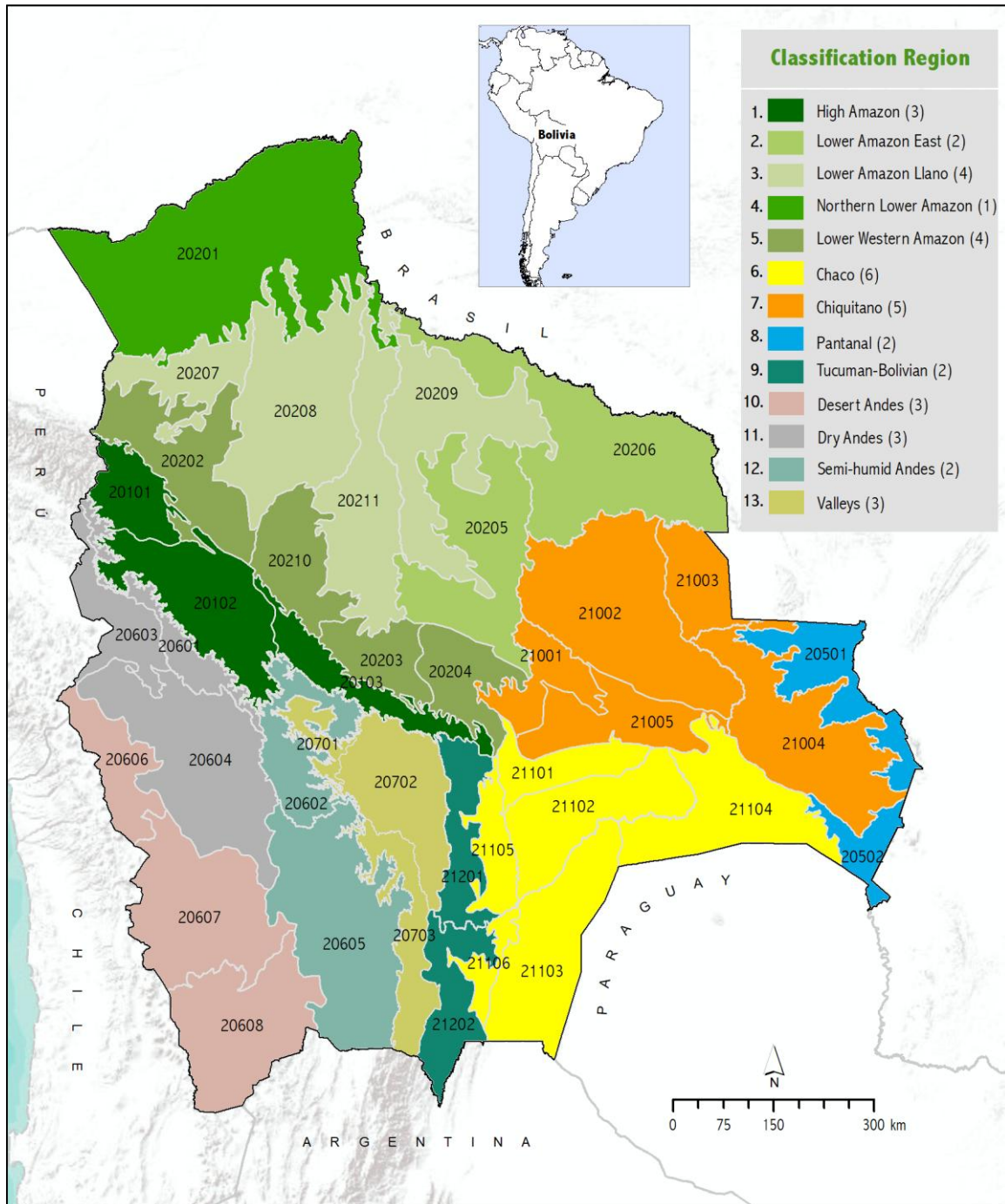


Figure 9. Classification operating regions.

3.3.3 Sample Collection

The classification process starts with the taking of training samples. To do this, only those pixels that maintained the same class in a stable way (that did not change) throughout all the years of the time series (between 1985 and 2025) were identified and selected. On this layer, random points were drawn and balanced according to the extent of each class. The values of each location served as input to train the Random Forest classifier.

The stable pixel layer was visually revised and corrections were made where necessary. Optionally, additional samples were manually included and called complementary samples, using the tools for creating geometries directly in Google's EE.

3.3.4 Random Forest

Random forest⁹ is a classification method that uses a machine learning algorithm and reports high accuracy values, even in the face of complex scenarios due to their heterogeneity. The conceptual basis of Random Forest is based on what Tumer and Ghosh (1996) found when demonstrating that the product resulting from the combination of multiple classifiers achieves high precisions. Random Forest uses training data to construct multiple decision trees from which each pixel is assigned a class. Random Forest has gained importance in recent years, due to its robustness against noise and outliers.

The Random Forest algorithm is part of the suite of machine learning classifiers available on Google's EE platform. The methodology applies a pixel-based classification criterion.

One of the parameters that Random Forest requires is a defined number of trees. In addition, a list of variables (see section "Classification variables"), and training data (see section "Spectral collection"). For Collection 4 of MapBiomass Bolivia, the number of trees varied according to the needs and characteristics of each classification region.

3.3.5 Cross-cutting themes

In particular cases, limitations were detected in the differentiation of specific classes that motivated the decision to map them separately, which were:

- Flooded forest (ID = 6);
- Flooded grassland/shrubland (ID = 11);
- Flooded Andean grassland and shrubland (ID = 82);
- Mining (ID = 30);
- Glacier (ID = 34);
- Pasture (ID = 15);
- Rocky outcrop (ID = 29);
- Scrublands (ID = 66);
- Beach, dune and sand spot (ID = 23);
- Agriculture (ID = 18);
- Soybean (ID = 39) *Beta (2016-2025)*;
- Flooded rice (ID = 40) *Beta (2020-2025)*;
- Urban infrastructure (ID = 24); and

These classes were mapped independently, so they are called Cross-Cutting Themes, using algorithms that consider only the class of interest. Subsequently,

⁹ Leo Breiman, "Random Forests," *Machine Learning* 45, no. 1 (October 1, 2001): 5–32, <https://doi.org/10.1023/A:1010933404324>

this information is included in the final map using integration rules in the phase we call "integration" (Figure 10).

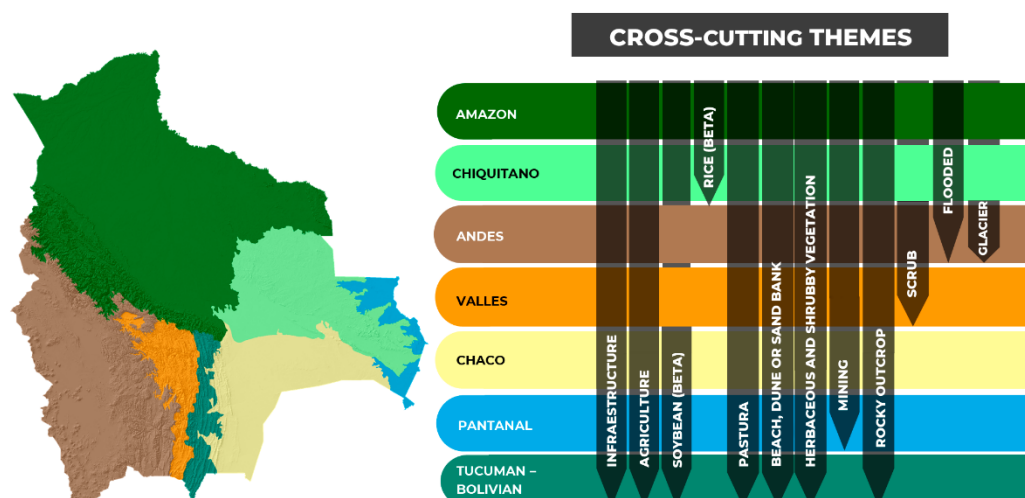


Figure 10. Cross-cutting themes for MapBiomass Bolivia Collection 4.

3.4 Post Classification

After making the classifications for the 41 years, it was necessary to apply a sequence of filters to reduce temporal inconsistencies, classification noises less than the minimum mapping unit¹⁰ (approximately half a hectare = 5 pixels) and fill information gaps obtaining a better classification. The post-sorting process includes a gap-fill filter, temporal filter, a spatial filter, and frequency filters. All of them were implemented from the Google Earth Engine platform, using scripts written in JavaScript. Below is a description of each filter.

3.4.1 Gap Fill

The Gap fill filter is used to fill in information gaps presented by the mosaics due to their atmospheric and climatic conditions in some regions of the country. The algorithm identifies pixels where there is no time series information and fills these empty spaces with data from the previous 3 years, as illustrated in the Figure 11.

¹⁰ 5 pixels = about half a hectare.

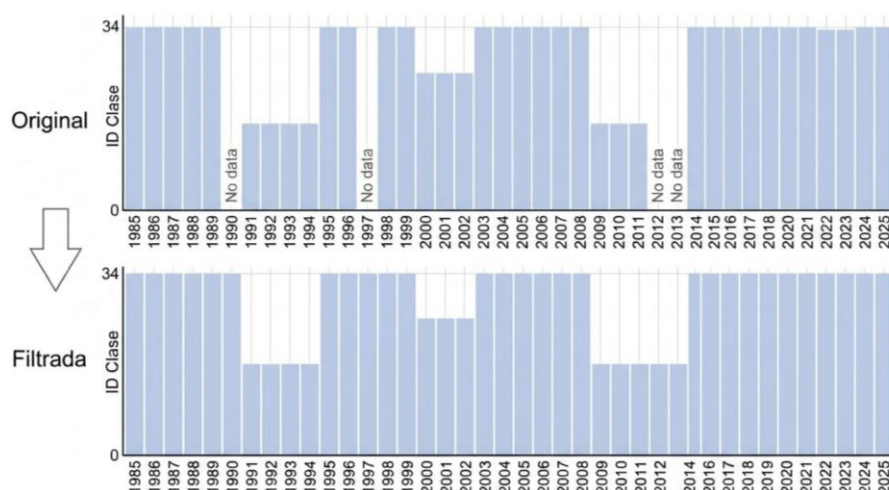


Figure 11. Gap Fill Filter Functionality

3.4.2 Temporary Filter

The rules are categorized into 3 groups:

1. *General rules (GR)*, seek to correct the data for the central year (T), based on the data corresponding to the previous years (T-1, T-2) and subsequent years (T+1, T+2);
2. *First Year (PR) Rules*, update the value of the first year (1985), based on the values of the following two years (T+1, T+2); and
3. *Senior Year (RU) Rules*, seek to update the value of the last year (2025) based on the values of the previous two years (T-1, T-2) (Figure 12).

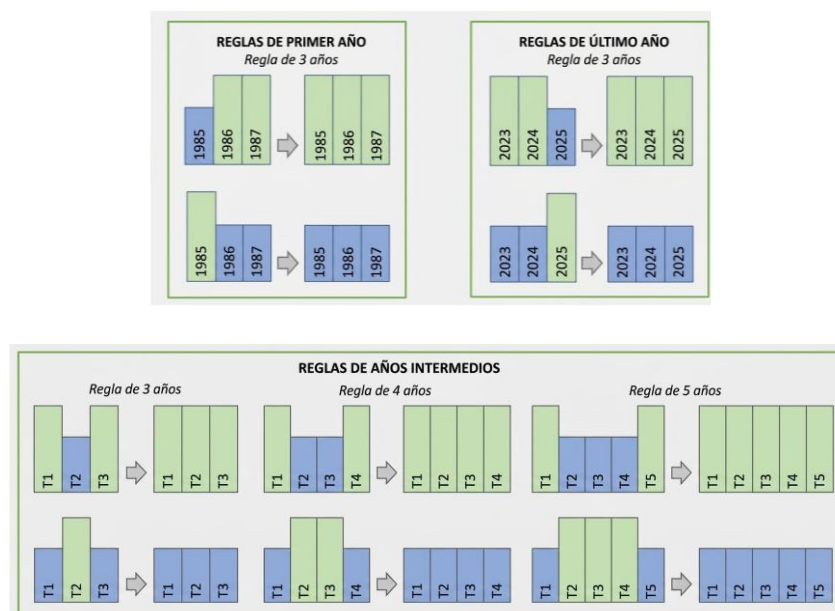


Figure 12. Temporal filter functionality

3.4.3 Spatial Filter

The spatial filter is intended to eliminate isolated or edge pixels. Neighborhood rules are defined that can lead to changing the pixel rating. Collection 4 MapBiomass Bolivia has two sizes (kernel 3 and kernel 5) of spatial filter; in Bolivia, kernel size 3 (Figure 13).

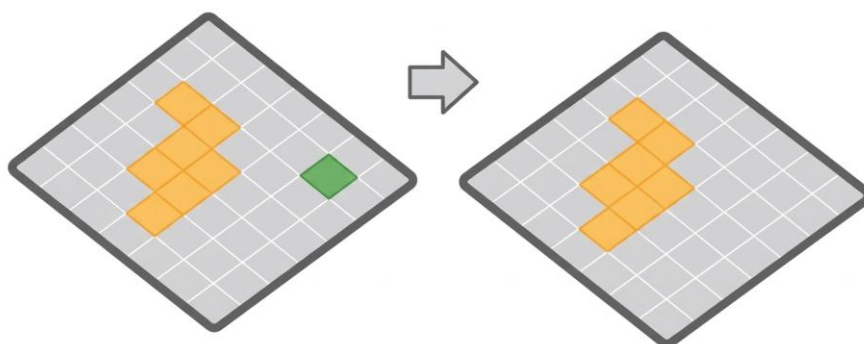


Figure 13. Spatial Filter Functionality

3.4.4 Frequency filter

This filter takes into account the frequency of occurrence of natural classes throughout the time series. Therefore, all the lower percentages of occurrence of the data are replaced by the one that meets the minimum frequency. This mechanism helps to reduce the temporal oscillation associated with a given class, reducing the false positive (Figure 14).

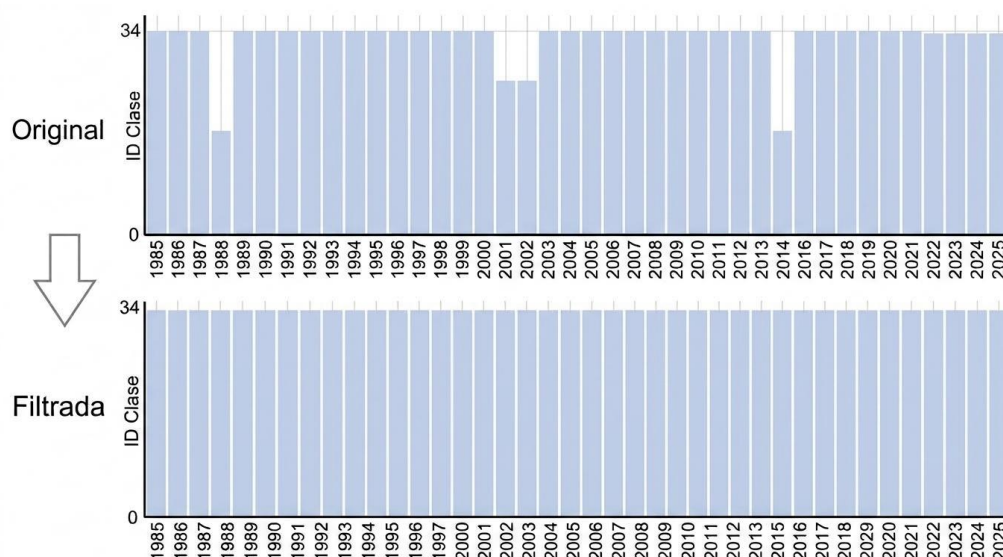


Figure 14. Frequency filter functionality

3.4.5 Incident filter

The incidence filter stabilizes the value of natural-class pixels that changed classes too many times over the 41-year time series. All pixels that change more than a user-defined number of times and that are connected with at least n pixels were replaced by the value of that pixel's fashion class. This reduces shifts along the edges of classes and helps stabilize noise-mistaken transitions. According to the needs of each subregion and/or cross-cutting theme, the criteria of the filter (Figure 15). Its application in several subregions was discarded.

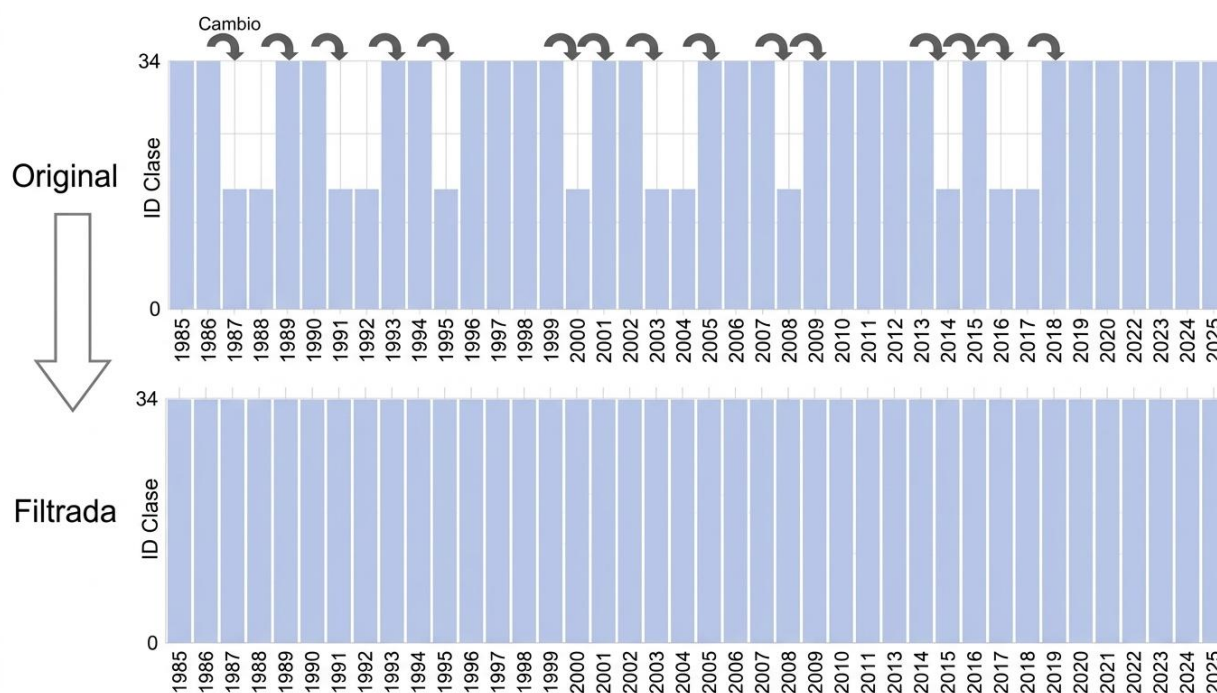


Figure 15. Issue filter functionality

3.4.6 Reclassification

Reclassification was used as a strategy to improve the data, where there was no class continuity. A series of polygons extracted from other reference maps were used, which were called masks. With the masks, it was possible to indicate changes to a class when it was inside or outside of it.

3.5 Integration

The results obtained from classification at the general level and cross-cutting themes were integrated as a single map for each year of analysis, following the rules of integration.

Table 9. Prevalence rules by biome for the integration phase

Prevalence	Class Name	Class ID	Source
1	Mining	30	Cross-cutting map
2	Glacier	34	Cross-cutting map
3	Salt flat	61	General map
4	Aquaculture	31	Cross-cutting map
5	River, lake	33	General map
6	Urban infrastructure	24	Cross-cutting map
7	Soybean Beta (2016-2025)	39	Cross-cutting map
8	Flooded rice Beta (2020-2025)	40	Cross-cutting map
9	Other crops	72	Cross-cutting map
10	Pasture	15	Cross-cutting map
11	Mosaic of uses	21	General map
12	Flooded forest	6	Cross-cutting map
13	Flooded grassland/shrubland	11	General map
14	Flooded Andean grassland and shrubland	82	General map
15	Grassland/shrubland	12	General map
16	Andean grassland and shrubland	81	General map
17	Shrubland	66	General map
18	Open shrubland	77	General map
19	Steppe	63	General map
20	Other non-vegetated anthropogenic area	25	General map
21	Other non-forest natural formation	13	General map
22	Beach, dune or sand spot	23	General map
23	Other non-vegetated natural area	68	General map
24	Rocky outcrop	29	General map
25	Rocky surface	92	General map
26	Open forest	4	General map
27	Forest	3	General map

Note. Table 9 shows the order of prevalence for integration in all the biomes of the country, if the biome does not have a class it jumps to the next class.

3.6 Transition maps

Based on the annual maps of integrated coverage and use, transitions are calculated. These represent the changes between pairs of maps, that is, between

two periods. The results are available on the MapBiomass Bolivia Collection 4 platform. Transitions are calculated for different periods, such as:

- Consecutive, annual years (e.g., 2001 to 2002, or 2013 to 2014, etc.)
- Five-year periods (e.g. 2000-2005)
- Ten-year periods (e.g., 2000-2010)
- Complete time series (1985-2025)
- Special periods (e.g., 2000-2025)

3.7 Statistics

From the annual maps of integrated coverage and use, the annual zonal and annual statistics of the mapped classes are calculated. The spatial units considered for the calculation of the statistics are:

- Country
- Biome
- Department
- Municipality
- Watershed
- Indigenous territories
- Protected natural areas
- Ramsar sites
- Ecoregions
- Geographic region

4 Practical considerations and challenges

The Collection 4 of annual land cover and land use maps in Bolivia constitutes a strategic monitoring instrument that documents the country's socio-environmental evolution over more than three decades. The generation of this multi-annual information volume has fostered various scientific and technical applications, facilitating the estimation of trends in land surface change and the understanding of the socio-economic and environmental drivers modifying its dynamics.

To materialize this project of unprecedented spatial and temporal scope, a standardized and highly replicable methodology was implemented globally. The use of the Google Earth Engine cloud computing platform, combined with open-source tools, has proven to be a highly efficient approach for the massive processing of geospatial data at scale.

Thanks to the knowledge accumulated during the development of Collection 4 and the collaborative effort within the MapBiomass network, processing times and operational efficiency were significantly optimized. The approach adopted methodologies tailored to the specific characteristics of each territory using the Random Forest classification algorithm and a flexible mapping protocol. This allowed for the calibration of specific samples and attributes per region, the application of spatio-temporal filters to raise the quality of the final product, and

the incorporation of cross-cutting themes that provide a greater level of thematic detail. As future goals, the project aims to refine the legend, increase mapping accuracy, and integrate state-of-the-art remote sensing technologies.

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